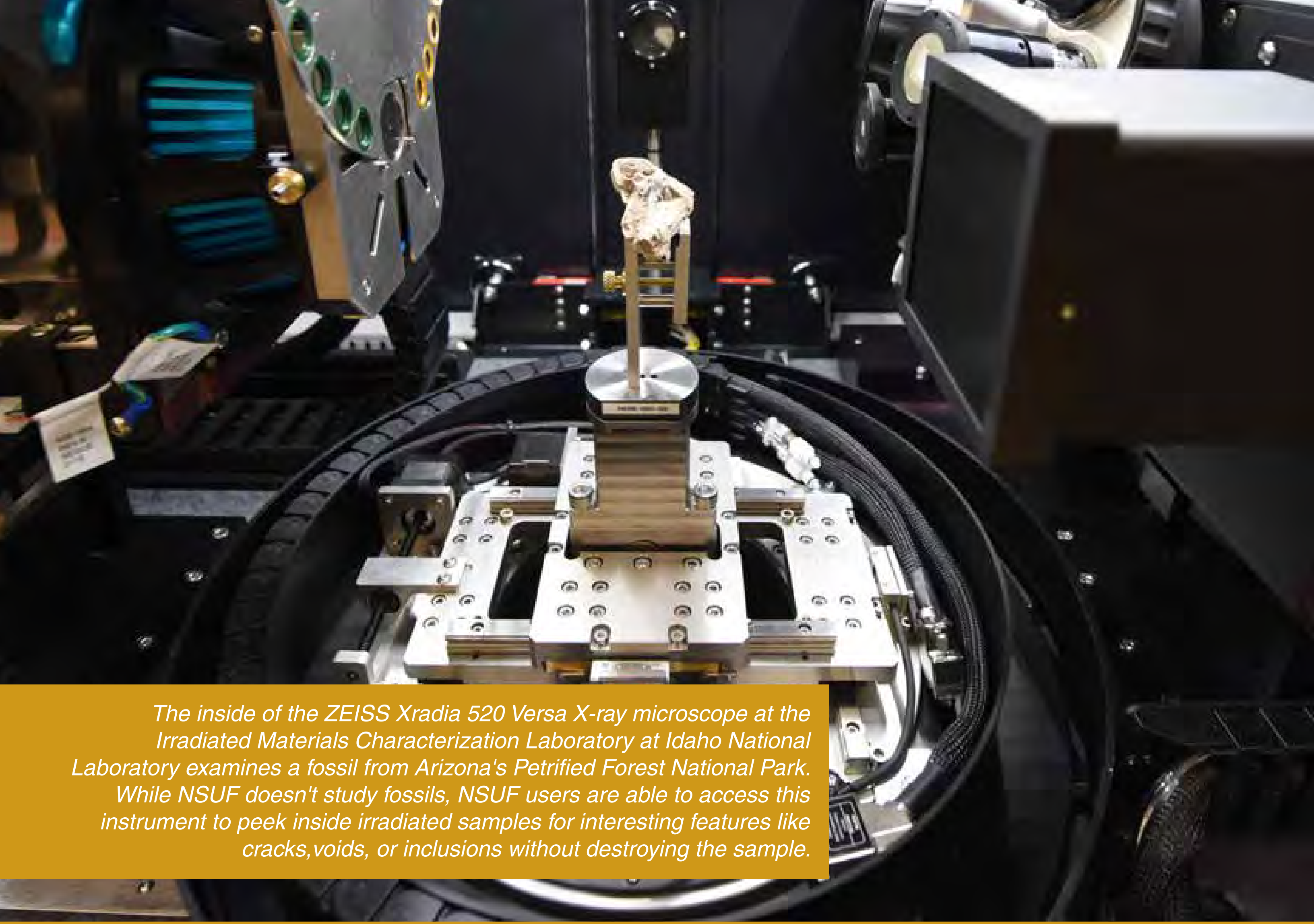
2019 ANNUAL REPORT

NSUF Nuclear Science User Facilities



The inside of the ZEISS Xradia 520 Versa X-ray microscope at the Irradiated Materials Characterization Laboratory at Idaho National Laboratory examines a fossil from Arizona's Petrified Forest National Park. While NSUF doesn't study fossils, NSUF users are able to access this instrument to peek inside irradiated samples for interesting features like cracks,voids, or inclusions without destroying the sample.

Nuclear Science User Facilities
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nsuf.inl.gov

On the front and back cover: The Irradiated Materials and Characterization Laboratory at Idaho National Laboratory was funded in large part by NSUF in order to provide users with enhanced capabilities with a focus on microstructural, thermal, and mechanical characterization of irradiated nuclear fuel and material (photos courtesy of Idaho National Laboratory).

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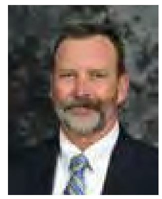

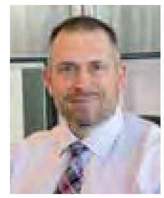

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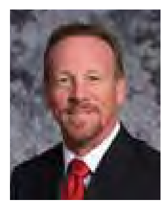

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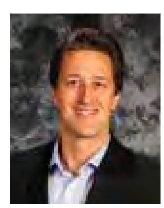

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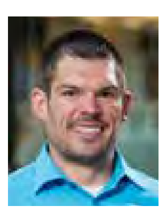

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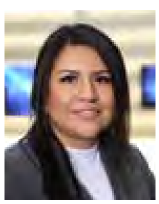

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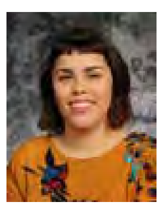

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FROM THE NSUF DIRECTOR

J. Rory Kennedy, Ph.D.
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Needless to say, Fiscal Year 2019 (FY-19) was another successful year for NSUF. In FY-19, we provided more funding to more researchers than ever before, which certainly fulfills our mission of enabling researchers to do what they do best, research.

Overall, we awarded 108 projects led by 95 different researchers from 41 separate organizations. Nine of our awards were of the larger cost and longer-term type from the annual Consolidated Innovative Nuclear Research (CINR) Funding Opportunity Announcement (FOA) and were awarded to university, national laboratory, and industry research groups for a total of $16.2 million. This is a significant increase from FY-18. These projects will address questions important to the nuclear community, and industry researchers are leading four projects and collaborating on two others.

In addition to our CINR work, our Rapid Turnaround Experiments (RTEs) continue to be popular among researchers and are highly productive. We awarded a higher percentage of RTEs than in FY 2018, funding 54 percent in FY-19 compared to 37 percent in FY-18. Overall in FY-19, we awarded approximately $4.3 million in RTE access awards. Of course, our publications continue to rise as does our impact and, as this annual report goes to print, the NSUF H-index score is 24.

During the fiscal year, we also completed our annual gap analysis of NSUF infrastructure. When we were tasked by DOE in 2014 to build and manage a database to track all DOE-NE supported or related infrastructure, this also came with the task of annually identifying gaps. During our FY-19 gap analysis, NSUF users and researchers in the field identified a good number of needs including Halden Reactor Project expertise, capabilities, and technologies and the Materials in a Radiation Environment (MRE) facility at NSLS-II at Brookhaven National Laboratory, the Activated Materials Laboratory (AML) at the APS at Argonne National Laboratory, and the TN Lab or "Flying Pig" irradiated fuel transport cask just to name a few. We use these and the other identified gaps as our guide when making infrastructure funding decisions for the national laboratories, and I want to thank everyone who participated in this annual project.

Additionally, the NSUF's global influence continued to expand in FY-19, particularly with respect to the United Kingdom. I was invited to participate in the UK's Engineering and Physical Sciences Council review of the Phase 2 solicitation for equipment requests. The available funds totaled £81.5M (>$100M) and will represent a major boost to nuclear energy research in the UK. The Nuclear Energy R&D Cooperative Action Plan between the DOE and the UK's Department for Business, Energy, and Industrial Strategy (BEIS) was signed in late 2018 and the NSUF is tasked with collaborating with the UK National Nuclear User Facility (NNUF) in the Enabling Technologies Working Group. Finally, I participated in the 8th annual UK Nuclear Academics Discussion Meeting (NADM) and presented an overview of NSUF and an update on its strategic direction, capabilities, operational model, and initiatives. All this is not to forget the advances made in our important collaboration with

Lindy Bean, Collin Knight, Jeff Benson, Renae Soelberg, Dan Ogden and Rory Kennedy at INL's Laboratory Director Awards.

the Belgian Nuclear Research Centre in executing the Disc Irradiation for Separate Effects testing with Control of Temperature (DISECT) project designed to better understand metallic fuel behavior.

Overall, the NSUF is continuing the trend of previous years. We are receiving high-quality proposals, awarding a high number of projects, and growing in influence. I am proud of the role the NSUF plays in fostering and promoting nuclear energy research, and I look forward to the continued success of the program and its researchers. Lastly, let me offer my congratulations to the NSUF team of Dan Ogden, Collin Knight, Lindy Bean, Jeff Benson, and Renae Soelberg who won an INL Laboratory Director's Award acknowledging their outstanding contributions to advancing nuclear research through the NSUF.

J. Rory Kennedy

NSUF BY THE NUMBERS

99 RTE AWARDS

108 TOTAL AWARDS

9 CINR AWARDS

Forty user organizations won awards in FY-19

Industry	International Organizations	National Laboratory	Universities
4%	8%	23%	65%

17
conferences and meetings attended

NSUF program staff attended **17 conferences and meetings** either as organizers, presenters, session chairs, or exhibit representatives.

Ninety-five

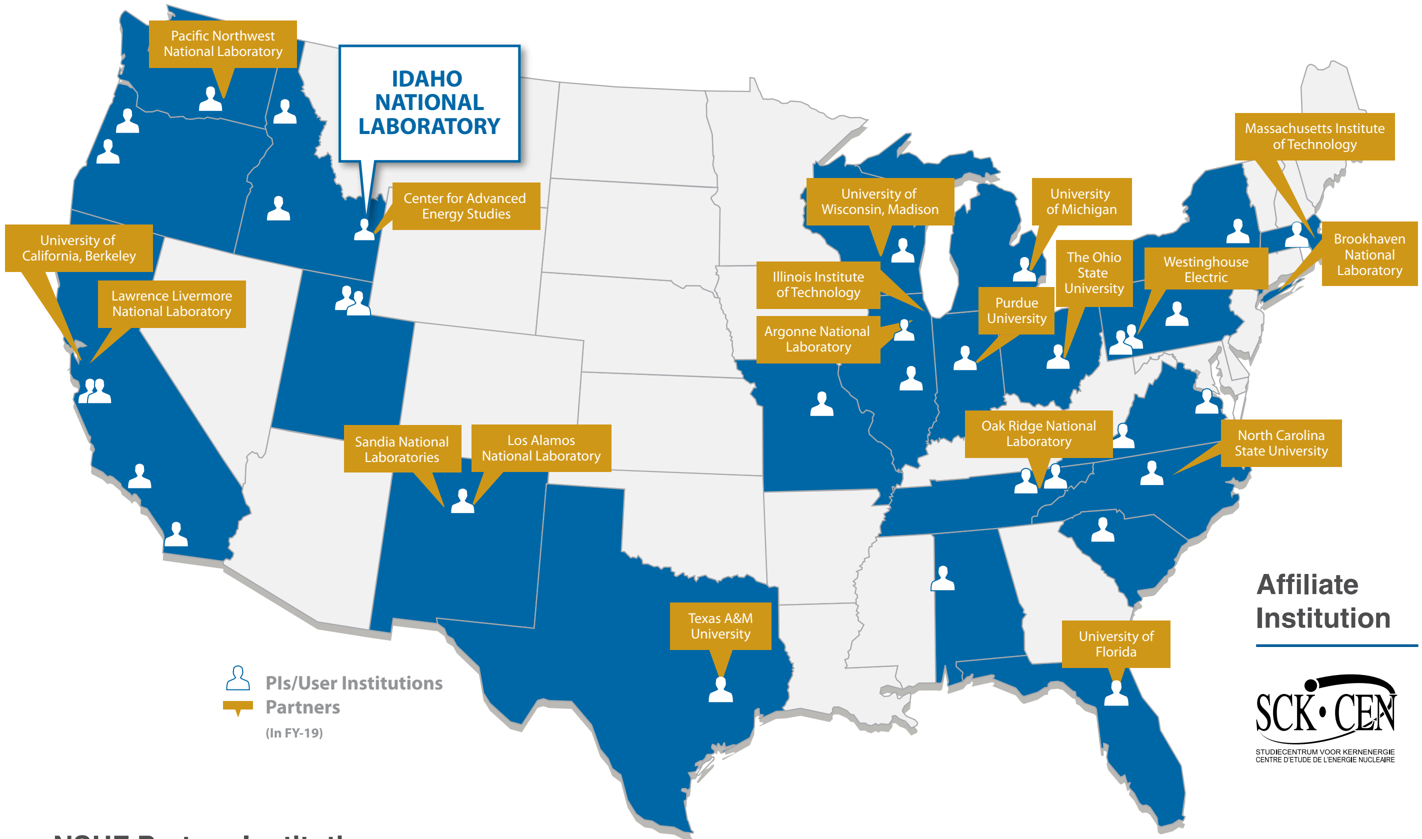
Number of PIs

12%
Increase from FY-18

25
Number of PIs who have received 3 or more NSUF awards

Number of new PIs
NEW
57

NSUF ACROSS THE NATION



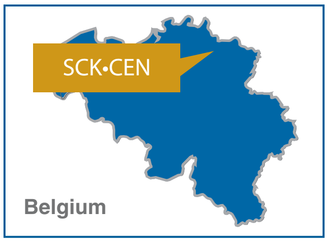
Affiliate Institution

SCK•CEN
STUDIECENTRUM VOOR KERNENERGIE
CENTRE D'ETUDE DE L'ENERGIE NUCLEAIRE

NSUF Partner Institutions

Argonne National Laboratory · Brookhaven National Laboratory · CAES Center for Advanced Energy Studies · Berkeley University of California · UF University of Florida · Illinois Institute of Technology · Lawrence Livermore National Laboratory · University of Michigan · MIT Massachusetts Institute of Technology · NC State University · Oak Ridge National Laboratory · The Ohio State University · Pacific Northwest National Laboratory · Purdue University · Los Alamos National Laboratory · Sandia National Laboratories · A&M · Westinghouse · Wisconsin University of Wisconsin–Madison

Idaho National Laboratory



NSUF User Institutions (FY-19)

Alabama
University of Alabama

California
Kairos Power
Stanford University
University of California, Irvine
University of California, Santa Barbara

Florida
University of Florida

Idaho
Boise State University
Idaho National Laboratory
University of Idaho

Illinois
Argonne National Laboratory
University of Illinois

Indiana
Purdue University

Massachusetts
Massachusetts Institute of Technology

Michigan
University of Michigan

Missouri
Missouri University of Science & Technology

Nebraska
University of Nebraska

New Mexico
Los Alamos National Laboratory

New York
Rensselaer Polytechnic Institute

North Carolina
North Carolina State University

Ohio
The Ohio State University

Oregon
NuScale Power
Oregon State University

Pennsylvania
Pennsylvania State University
University of Pittsburgh
Westinghouse Electric

South Carolina
University of South Carolina

Tennessee
Oak Ridge National Laboratory
University of Tennessee

Texas
Texas A&M University

Virginia
NASA Langley Research Center
Virginia Polytechnic Institute and State University

Washington
Pacific Northwest National Laboratory

Wisconsin
University of Wisconsin

Canada
Canadian Nuclear Laboratories

Italy
Italian Institute of Technology

Sweden
Studsvik Nuclear AB

Turkey
Sabanci University

United Kingdom
University of Bristol
University of Sheffield
University of Oxford

HIGHLIGHTS FROM THE YEAR

NSUF, INL's ATR hosted University Research Reactor Workshop

On July 16 and 17, NSUF and INL's Advanced Test Reactor hosted a workshop, bringing together representatives from 15 university research reactor programs to discuss future operations and reactor sustainability. Participants discussed capital infrastructure, regulatory burden, staffing and knowledge transfer, and utilization and relevancy.

Attendees

- Massachusetts Institute of Technology
- Missouri University of Science and Technology
- North Carolina State University
- Oregon State University
- Pennsylvania State University
- Purdue University
- Reed College
- The Ohio State University
- University of Idaho
- University of Maryland
- University of Massachusetts Lowell
- University of Missouri
- University of Texas at Austin
- University of Utah
- University of Wisconsin

NSUF Holds Users Group Meeting with Student ANS

On April 4 and 5, the NSUF Users Group held its annual meeting in Richmond, Virginia, in conjunction with the American Nuclear Society (ANS) Student Conference. Presenters updated the group on completed NSUF projects and educated student attendees on the opportunities found within NSUF.

NSUF also hosted a poster session to show capabilities found at INL and NSUF's 19 partner organizations.

NSUF hosted a poster session during one of the ANS Student Conference's evening banquets.

INL's new Research Collaboration Building at the Materials and Fuels Complex makes it easier for INL researchers to collaborate with visiting researchers and students.

INL held a ribbon cutting ceremony to celebrate the new building on August 8. U.S. Representative Mike Simpson (second from left), DOE Idaho Operations Office Manager Bob Boston (second from right), DOE's Acting Deputy Assistant Secretary, Mike Worley (far right), and INL's Deputy Laboratory Director, Marianne Walck (far left), are pictured cutting the ribbon.

INL Opens New Research Collaboration Building at Materials and Fuels Complex

INL opened the new Research Collaboration Building at the Materials and Fuels Complex, 40 miles west of Idaho Falls. The new building, funded by NSUF, has 28 offices for MFC researchers, NSUF staff and long-term visitors, plus 23 workstations, five collaborations stations, a small nonradiation laboratory for instrument and equipment testing, and a station to monitor equipment in MFC's Irradiated Materials Characterization Laboratory.

This new building sits outside of the MFC fence, making it easier for INL researchers to collaborate with visiting researchers and students.

Colin Judge Joins NSUF Program Staff

In September 2019, Colin Judge joined NSUF's Program Office as the Industry Program Lead. Judge took over for John Jackson who was serving as the acting director of the Gateway for Accelerated Innovation in Nuclear (GAIN) program.

Judge comes to INL from Canadian Nuclear Laboratories, in Chalk River, Ontario, where he was a research scientist in the Materials Science branch.

In addition to industry outreach, Judge is also a technical lead for NSUF, working with experiment managers and moving projects forward at INL and at other NSUF partner facilities. For Judge, it's the best of both worlds. He gets to continue his research into materials irradiation, making use of some of the best resources in North America, and continues his relationships with the partners he first engaged at CNL.

Colin Judge
Industry Program Lead

A YEAR IN THE LIFE NSUF

INL's Irradiated Materials and Characterization Laboratory was funded in large part by NSUF to help provide its users with enhanced capabilities.

A large portion of NSUF's work and funding is related to the access awards it provides to researchers around the world. But beyond these access awards, NSUF funding is used to coordinate those awarded experiments, provide infrastructure upgrades to its facilities, fund scientist and instrumentation support for NSUF researchers, expand capabilities for its researchers, and fund key NSUF initiatives.

Leadership Team

NSUF's leadership team is led by Rory Kennedy, director, and Dan Ogden, deputy director. Kennedy and Ogden oversee the science and operations of NSUF ensuring that NSUF stays on budget and on mission, while also maintaining relationships with Department of Energy Office of Nuclear Energy (DOE-NE) federal stakeholders and partner facilities.

The chief scientists, Brenden Heidrich (overseeing irradiations) and Simon Pimblott (overseeing post-irradiation examination) along with Kennedy guide the science NSUF enables. They take care of reviewing all projects (which also go through peer, relevancy, and feasibility reviews) to ensure projects are of high scientific value, align with the DOE-NE's mission and research priorities, and can be executed at cost and schedule before the projects go to DOE-NE staff for final approval.

Project Coordination

Like with most research, NSUF experiments require collaboration from several people including technical leads, experiment managers, project schedulers, and shipment coordinators.

NSUF technical leads start their work early in the proposal process and then work closely with the principal investigators (PIs) to establish scope and feasibility of the project. They serve as capability and instrument experts and work to make sure that the expectations of the PI fit within what a facility or instrument is capable of.

Experiment managers also work closely with PIs, technical leads, and the broader experiment team to make sure experiments stay on track. If an awarded project involves irradiation at Idaho National Laboratory's Advanced Test Reactor (ATR) or the Transient Reactor Test (TREAT), either Katie Anderson or Matthew Arrowood, both experiment managers, are involved. Anderson and Arrowood work directly with PIs to outline budgets, build and maintain schedules, track progress and spending, assemble an experiment team, and run weekly experiment meetings.

"I get to work with some very brilliant people and I'm always amazed at the ingenuity and ideas they come up with to solve even the toughest problems," Anderson said.

Project scheduling is also a large component of effectively managing an experiment, and at INL, John Coody fills that role. As a project scheduler, Coody builds the schedules for design, fabrication, assembly, irradiation, post-irradiation examination, and disposition of materials.

If an awarded project involved post-irradiation examination at INL's Materials and Fuels Complex (MFC), Collin Knight is the point person. As the post-irradiation examination project manager, Knight coordinates all experiments with work being done at INL's MFC. Like Anderson and Arrowood, Knight works closely with Coody to schedule MFC instrumentation and resources.

For work at NSUF facilities that aren't INL, similar processes are involved. Each NSUF facility has a primary contact who coordinates all incoming NSUF experiments using their facility. For example, Kory Linton and his team at Oak Ridge National Laboratory work with PIs using any of ORNL's facilities, like the High-Flux Isotope Reactor (HFIR) or the Low Activation Materials Design and Analysis Laboratory (LAMDA).

Donna Guillen
Technical Lead

Katie Anderson
Experiment Manager

Travis Howell
Planning and Financial Controls Specialist

Lindy Bean
Acting CINR FOA Administrator

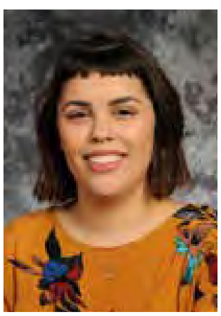
Financial Administration

Managing the financials, Lindy Bean and Travis Howell work together closely to predict, measure and report NSUF's performance baseline. They do this by interfacing with all project leads and experiment managers to determine and track milestones, estimate budgets, and report actual spending. In FY-19, Bean also took on the additional responsibility of administering the CINR FOA and Howell will be an experiment manager in FY-20.

Dain White
Technical Lead Software Engineer

Web Development

Dain White, NSUF's software engineer, is continuously updating and improving the NSUF website and applications. Some of White's work can be seen in the NSUF proposal system, which is used for the Rapid Turnaround Experiment (RTE) solicitation and the mailing application used to send NSUF's monthly newsletter, announcements, and reminders. In all his work, White is looking for new ways to make the lives of program office staff and NSUF users easier.



Tiffany Adams
Communications Liaison

Communications and Outreach

The communications lead, Tiffany Adams, coordinates all communications activities for NSUF. This includes managing the NSUF website, writing and editing feature stories, sending out the monthly newsletter, working with social media teams at INL, DOE-NE and partner facilities to amplify NSUF content, and attending technical conferences to speak with existing and potential users.

"NSUF and its users are enabling such important science, and my goal is to highlight it and them as much as possible," Adams said.

Nuclear Energy Infrastructure Database

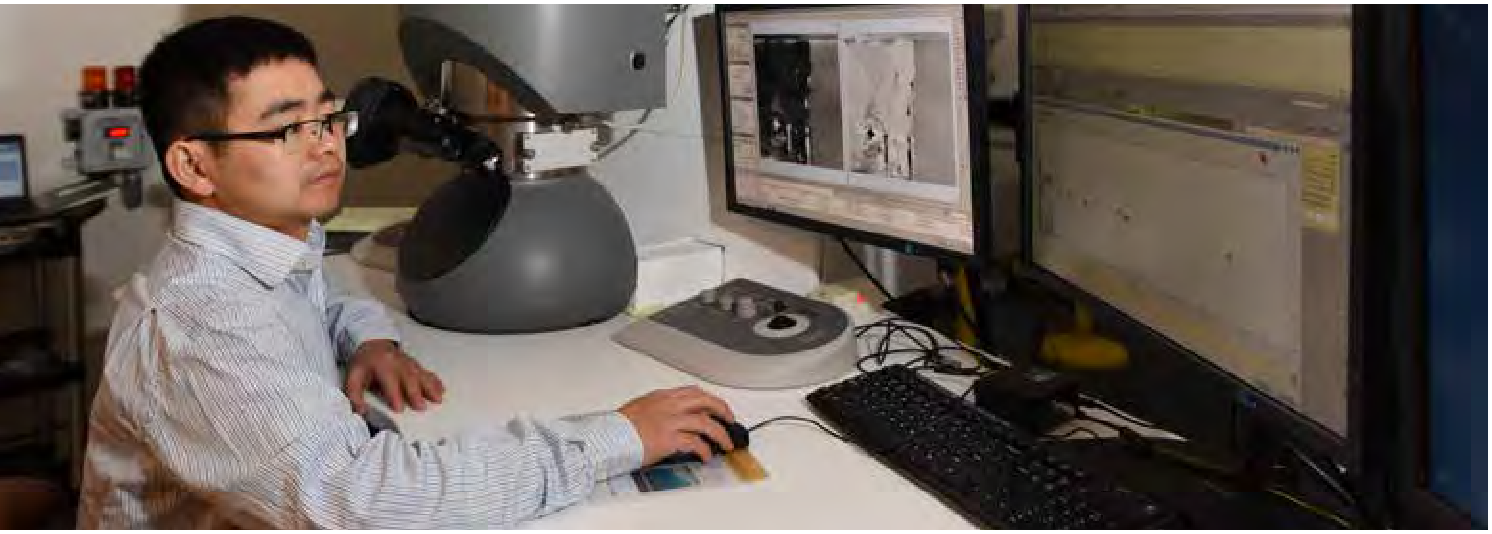
NSUF was tasked in 2014 with building and managing a database that tracks all DOE-NE funded or related infrastructure. The Nuclear Energy Infrastructure Database (NEID) includes 145 institutions, many with multiple facilities. While not all facilities are NSUF partners, those that are have their facility information fed into the NSUF website giving users without an NEID account access to NSUF facility details. Managing all this information is Jon Kirkham, the NEID coordinator. Kirkham works with facility points of contact to keep information updated and approve any changes that are made.

Infrastructure and HPC Upgrades

Each year, NSUF conducts a gap analysis to determine future infrastructure needs. Several of those needs are found at national laboratories, and in FY-19 NSUF funded infrastructure upgrades at Brookhaven National Laboratory, Argonne National Laboratory, INL, and Oak Ridge National Laboratory.

In addition, NSUF funds, in part, the purchase of additional high-performance computing resources at INL including the recent purchase of Sawtooth, a 100,000-core super-computer installed in INL's new Collaborative Computing Center (C3). This, along with other HPC upgrades funded by NSUF, ensure that NSUF researchers have access to the latest and highest quality HPC capabilities.

INL's Lemhi supercomputer, also supported by NSUF, has 20,000 cores, 94 TB of memory, and a lINPACK rating of 1 Petaflop/s.



Lingfeng He, an instrumentation scientist at IMCL, receives some funding to enhance instrument capability and continue to hone his scientific expertise.

Scientific and Instrumentation Expertise

One of the benefits NSUF researchers get when working on an NSUF project is the access to scientific and instrumentation expertise. If NSUF PIs are having work done at any of INL's facilities, NSUF provides funding for several INL instrument scientists working on electron beam, X-ray and chemical and thermal analysis instrumentation. The goal of this funding is to enhance instrument capability and develop scientific expertise.

One of those instrument scientists, Lingfeng He, enjoys working with users to develop proposals and assist with their material characterization. "I like to work with the users, especially students," He said. By providing this funding to instrument scientists like He, NSUF ensures that NSUF users have access to the latest capabilities and knowledge for the characterization of their materials.

Kelly Cunningham
Nuclear Fuels and Materials Library Coordinator

Nuclear Fuels and Materials Library

The Nuclear Fuels and Materials Library (NFML) is an archive of material specimens from past and ongoing irradiation test campaigns and from real-world components retrieved from decommissioned power reactors. The contents of the NFML grow each year and are available to NSUF users to study. Managing the collection of this library and the database that houses all the library's information is Kelly Cunningham, NFML Coordinator. In order to add new specimens, Kelly works with the owner of the specimens to gather and verify all necessary provenance before the samples are added to the library. In FY-19, NSUF added 175 samples to the library.

Irradiation Assisted Stress Corrosion Cracking

As the current fleet of commercial nuclear reactors age, it is important for researchers and industry to understand and predict how the materials in a reactor will deteriorate. INL's high activity Irradiation Assisted Stress Corrosion Cracking (IASCC) instrumentation is helping researchers and industry do just that. The IASCC instrumentation is located in the Fuels and Applied Science Building (FASB) at INL's MFC and is funded by NSUF. This test rig is located in a heavily shielded test cell and is capable of performing crack-growth rate measurements on full-size specimens under the same conditions as the current fleet of light water reactors.

"The capability represents one of only approximately five such facilities in the world and enables work that supports mitigation of material degradation in light water reactors," John Jackson, NSUF's Industry Program Lead, said.

Hot cells housing INL's Irradiation Assisted Stress Corrosion Cracking instrumentation

Nuclear Materials Discovery and Qualification Initiative

The Nuclear Materials Discovery and Qualification Initiative (NMDQi) is a project with the goal of accelerating the discovery and qualification of new fuels and materials in order to fulfill the short timelines of potential advanced reactors. NSUF's involvement in this initiative is key as NSUF's overarching goal is to provide no-cost access to NSUF facilities as well as expertise for researchers to study the effects of irradiation on nuclear materials and fuels. This new initiative plans to use high-throughput characterization techniques to address critical knowledge gaps, use data analytics and physics-based modeling to discover and optimize new materials, manufacture and test potential materials and fuels, and establish strategic partnerships with universities, national laboratories, and industry.

Combined Materials Experiment Toolkit

The Combined Materials Experiment Toolkit (CoMET) is a web-based application for irradiation testing experiment development, specifically NSUF funded CINR proposals. The application provides an online toolkit for researchers to build their CINR proposal using NSUF facilities. The tool guides users through experiment design providing them with all the information they need about the facility, instruments, technical leads, and all other information necessary in the project design. While not officially available to users yet, the application will be made available to users in FY-20.

NFML UPDATE

INL's Analytical Laboratory has a broad range of analytical chemistry capabilities like this focused ion beam instrument, which is available for NSUF users to characterize materials found in the NFML.

Materials and fuels find new life in NFML

Since its inception a decade ago, the Nuclear Fuels and Materials Library (NFML) has blossomed into one of the largest assortments of nuclear fuels and materials available to the general nuclear research community for individual testing and research. These specimens range from conventional and advanced steels to experimental alloys, as well as ceramics and fuels, many of which were used inside of nuclear reactors.

The NFML was initially conceptualized by the NSUF staff who identified an abundance of legacy materials from past research and development programs being stored without use in hot cells and laboratories across the country, including Idaho National Laboratory. However, thanks to the NFML, over 6,000 individual samples are available for new or follow-on research.

"There's a lot of valuable research material being stored in hot cells," says NFML administrator Kelly Cunningham. "Over the years, we've added roughly 3,500 irradiated specimens as a result of NSUF sponsored projects."

Unemployed materials and fuels that were utilized at one point in time all face the same problem: disposal. "If materials don't have programmatic use, they'll get disposed of," says chief irradiation scientist Brenden Heidrich. "These materials represent tens of millions of dollars of research and development effort that would otherwise go to waste. They also represent not only a wide body of knowledge, but a huge savings to the government and taxpayer in that we don't have to redo the work."

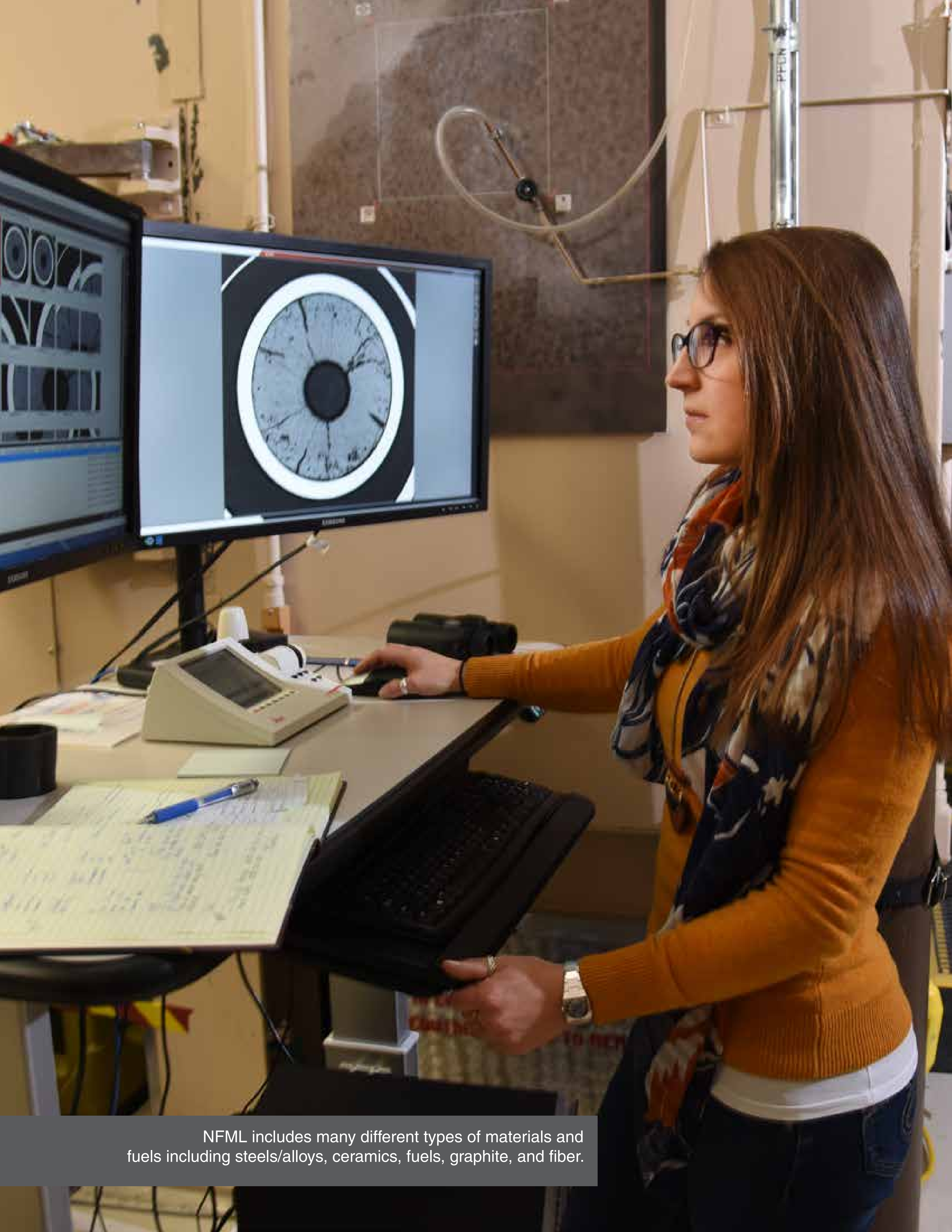
The NFML also benefits researchers in the amount of time they save by having specimens readily accessible through the library. According to Heidrich, the process of irradiating and reproducing materials is lengthy, taking several years to accomplish, and may reproduce work that was already done. The purpose of NSUF nuclear energy research is to study materials and fuels that can be used in the construction and powering of both commercial and noncommercial reactors. This is all in hopes of leading to further innovation in nuclear sciences, as opposed to repeating previous work, which only lengthens the process. "Saving them is pretty cheap. Redoing it is a lot more expensive," says Heidrich.

Through the NFML, users can examine previously irradiated fuels and materials saving time and money.

For example, reflector materials that surrounded the core of EBR-II were placed inside of the reactor in the late 11960s and weren't removed for over 20 years. Instead of having to reproduce the variables and conditions they were stored in and having them incubate for several years, these materials are available through the NFML.

Previously, researchers interested in studying materials used in experimental and commercial reactors would have to track down individual samples housed in different national laboratories around the nation, which is a lengthy and laborious operation in itself.

As a result of the creation of NFML, the process of obtaining materials has been streamlined. Interested parties access the library via NSUF's website, find the individual sample they'd like to research and submit a proposal for approval. If a specific material isn't available through NFML, or one they'd like to add to the library's collection, researchers can submit their suggestions through a Request For Information available through the site. The NSUF requests information and/or suggestions on the potential additions to the NFML that can be produced through further irradiation tests.



NFML includes many different types of materials and fuels including steels/alloys, ceramics, fuels, graphite, and fiber.

In the past year, the NSUF has made several additions to the NFML's catalogue, including metallic fuel samples resulting from an NSUF project awarded to the University of Central Florida and stainless steel baffle former bolts from commercial reactors. Both can be used in the innovation to make civilian power plants cheaper and safer.

As Heidrich and Cunningham reflect on the past year, they're beginning to look toward the future. Aside from adding even more materials to the library, one of the most prominent projects the duo is working on moving into 2020 is a complete overhaul of the NFML's user interface to make it more accessible and intuitive.

In addition to making the library more congenial, the NFML is hoping to begin supplying testing data found in prior studies of individual specimens, saving researchers both time and money in that they don't have to conduct studies that have already occurred in the past. The availability of the information opens up avenues of partnership between researchers from around the world. "It enables collaboration," says Heidrich. "You can find research projects that are of interest to you, the materials associated with that, where they were tested, the people that did it and their contact information so you can build a team entirely inside the NSUF structure."

As the year draws to a close, the NFML believes that the incorporation of testing data, coupled with the widespread availability of materials and centralization of information, will lead to a more safe and sustainable nuclear future.

175

Number of new material samples that NFML added in FY-19

NSUF AND GAIN COLLABORATIONS

John Jackson
Acting Director, GAIN

How John Jackson's upbringing led him to GAIN

John Jackson grew up on a dairy farm in North Central Washington without electricity or a telephone. He did his homework by kerosene lantern, and his family had to find innovative ways to refrigerate their food. He spent his summers driving a tractor and fixing and fabricating equipment. It was a lifestyle that primed the now acting director of the Department of Energy (DOE) Gateway for Accelerated Innovation in Nuclear (GAIN) initiative for a career in mechanical engineering.

"You just had to make things work," he said. "And that's a fundamental part of mechanical engineering."

It is also a fundamental part of Jackson's efforts with GAIN, which along with the NSUF, is helping the nuclear industry remain a relevant and important part of the country's energy strategy by providing companies with funding and access to laboratories such as the one at INL for research.

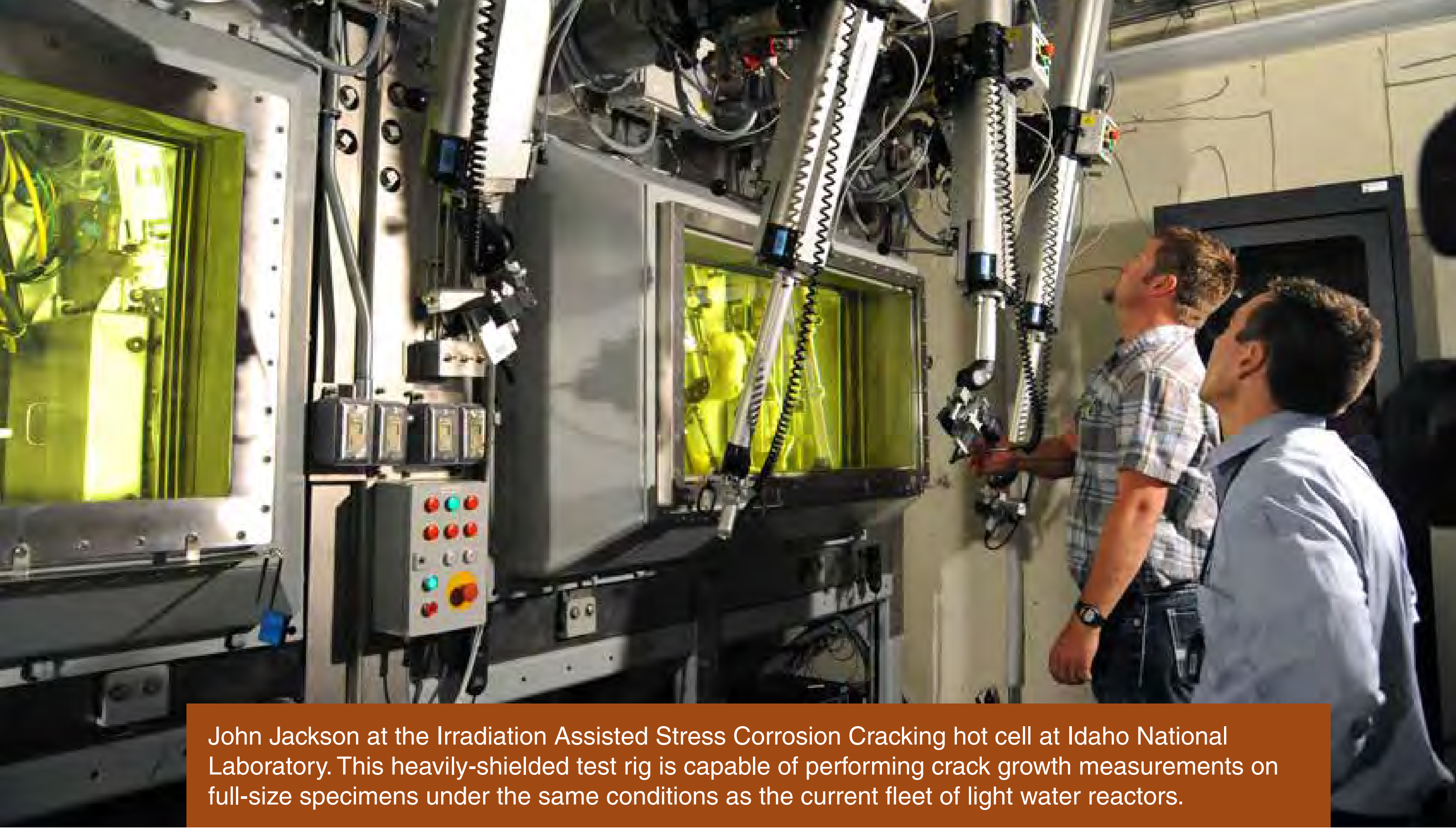
The efforts to involve industry provide a way to see concrete changes in nuclear energy, said Dan Ogden, deputy director of NSUF.

"With these partnerships with industry, we can really help open the door for innovation that might lead to implementation," Ogden said. "The whole purpose of the GAIN initiative is to help drive innovation. We aren't just doing research for the sake of publication, but so that something actually changes out there."

While the initiative is still relatively new, Jackson has been working with the GAIN team to lay its groundwork for years.

Jackson earned a bachelor's degree in mechanical engineering technology from Central Washington University, and then a master's degree in mechanical engineering and a doctorate in mechanical engineering, where he specialized in fracture mechanics, from the University of Washington.

His career at INL started with an internship in 1996 after he finished his bachelor's degree. He came back as a postdoctoral researcher in 2002, and then went to work as a staff scientist for ExxonMobil in Texas. Jackson credits much of his career success to his time with ExxonMobil, which instilled an instinct to ensure rapid applicability for technologies. However, the Northwest lured him back, and he returned to INL in 2006. Since returning to INL, Jackson has worked in a variety of roles. In 2015, he was tapped to help coordinate five workshops across the country that investigated two questions: Why was the U.S. nuclear industry failing, and what could be done to address it?



John Jackson at the Irradiation Assisted Stress Corrosion Cracking hot cell at Idaho National Laboratory. This heavily-shielded test rig is capable of performing crack growth measurements on full-size specimens under the same conditions as the current fleet of light water reactors.

Workshop participants mentioned the DOE laboratories with hundreds of millions of dollars of unique infrastructure and expertise that the nuclear industry could not logistically or financially replicate. With access to things like specialized hot cells, test reactors, and the modeling and simulation capabilities that labs like INL possess, the companies could conduct research that could lead to advancements in nuclear energy.

Those workshops were one of the catalysts that led to the start of the GAIN initiative. GAIN is different from previous programs, which focused on specific problems the nuclear energy industry faced, Jackson said. The GAIN initiative did not put restrictions or limitations on the type of nuclear technologies and supporting research companies could explore through the initiative. GAIN empowers companies to focus on the innovation that will help the industry. The program allows, and even fosters, commercialization resulting from participants' research. The goal is to allow industry to pursue the projects it needs to help move nuclear energy in the U.S. forward. That's how it can impact the entire nuclear energy portfolio, Jackson said.

"GAIN is ambitious in that it attempts to take on the whole problem and allow the best technologies to survive, but it's not so rigid in formation and purpose," he said. "It has adaptability for an evolving industry."

NSUF is a key partner with the GAIN initiative. Through the DOE's Consolidated Innovative Nuclear Research (CINR) Funding Opportunity Announcement (FOA), NSUF provides industry with the opportunity to access unique materials science capabilities to study irradiated fuels and materials at INL and 19 other partner facilities at no cost to the researcher.

The first company that received an NSUF access only award was GE Hitachi Nuclear Energy in 2016 for research on irradiation testing of innovative additively manufactured materials. In the following year, 10 industry projects received awards for access to labs, and then another four received awards in 2018. The numbers show a high level of engagement from industry, Ogden said.

"When we start working with industry, things start moving ahead," Ogden said. "It's a pretty important thing to help change the flavor of nuclear energy in the country. We have been stuck in the 1970s for a long time. We haven't moved forward. It's really time for new technology to come into play."

Q&A WITH MIKE WORLEY

What are your responsibilities in your current role at DOE-HQ?
As the Associate Deputy Assistant Secretary for Reactor Fleet and Advanced Reactor Deployment, I work closely with the Acting Deputy Assistant Secretary, Alice Caponiti (NE-5), and her team to manage the overall coordination, integration, and deployment of the Office of Nuclear Energy's research capabilities to support the rapid development and commercial deployment of innovative nuclear technologies. This includes managing the overall coordination and integration of the Gateway for Accelerated Innovation in Nuclear (GAIN) initiative, the Nuclear Science User Facilities (NSUF) program and promoting the use of these unique nuclear research facilities for research, development and demonstration of innovative nuclear technologies within the university, industry and laboratory research communities.

I also oversee the planning and management of the Office of Nuclear Energy's advanced modeling and simulation programs to ensure the delivery of improved modeling and simulation capabilities relevant to existing and future nuclear systems.

Further, I manage research, development, and demonstration activities that provide the technical and economic basis for continued long-term operation of existing U.S. light water reactor nuclear power plants, and I manage collaborative and cost-shared activities with industry, including design certification, licensing and first of a kind engineering for the deployment of advanced reactor concepts.

Finally, our office is responsible for managing the Office of Nuclear Energy's engagement with U.S. universities through the Nuclear Energy University Programs, Integrated University Program, Traineeship Program, and Research Reactor Infrastructure Program, along with cross-cutting nuclear energy research efforts through the Nuclear Energy Enabling Technologies Crosscutting Technology Development Program and the Laboratory-Directed Research and Development Program at Idaho National Laboratory

How long have you been with DOE?
I joined DOE in November 1991.

What other areas have you worked in at DOE?
Before joining the Office of Nuclear Energy in 2003, I worked in Defense Programs on the restart of the

K-Reactor, the Office of Environmental Management as the Mound Site program manager, the Departmental Representative to the Defense Nuclear Facilities Safety Board, and then a second stint with the Office of Environmental Management as the Idaho High Level Waste program manager.

What did you do prior to joining DOE?
After graduating from the Naval Academy, I spent eight years in the Navy Nuclear Propulsion Program as a submarine officer.

What got you interested in nuclear energy?
I had planned to be a Navy pilot, but once that fell through, I chose to pursue the Navy nuclear program because it was a premier program and it paid quite a bit more than service in the conventional surface fleet. When I left the Navy in 1991, there was a strong pipeline of nuclear Navy staff joining DOE.

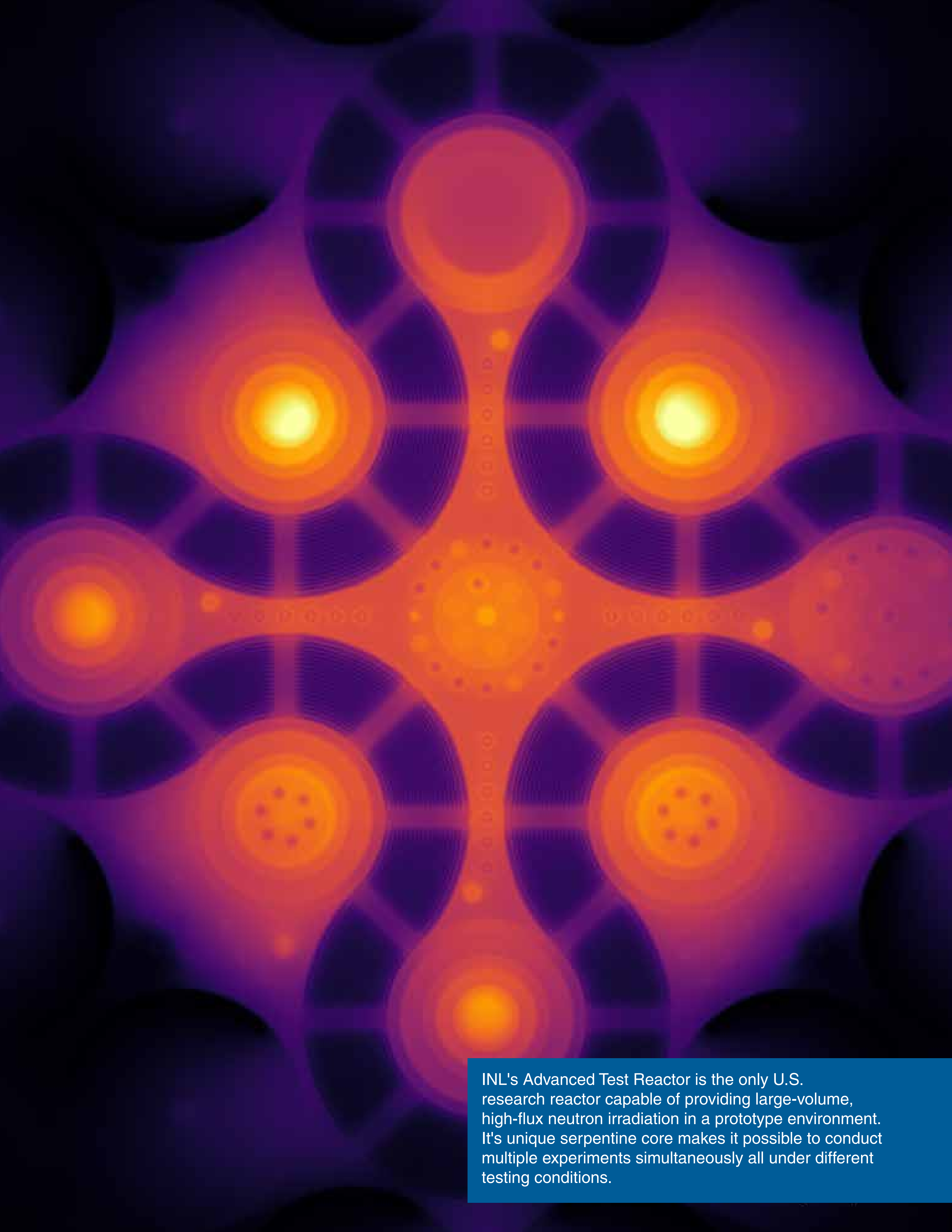
What is your involvement with NSUF?
I am part of the headquarters management team for NSUF, and in that role we coordinate with Dr. Kennedy and his senior staff to develop and defend our annual budget requests, set major NSUF policies and priorities, and work issues as they arise. I've also participated in a number of international conferences to help grow the NSUF through appropriate engagements with countries with mutual interests in the study of materials in irradiated environments.

What changes do you see for NSUF over the next ten years?
With an appropriate budget development scheme over the next ten years and additional program office expertise, it is very easy to imagine the NSUF broadened its research areas to include such topics as radiochemistry and thermal hydraulics. Particularly the addition of thermal hydraulics experimental capabilities would be of high interest and use for the nuclear industry. I see expansion of the great work the NSUF has done to date on establishing and maintaining user friendly databases to include all ongoing and legacy research projects involving irradiations tests and post irradiation examinations. With NSUF curating these databases, they could be made available for machine learning and artificial intelligence (AI) applications that may really accelerate the advancement of nuclear energy concepts and discovery. Because of the growing recognition of the importance of nuclear energy to the US total energy mix, I see much closer cooperation between other large user facilities, for example those from the Office of Science, and the NSUF in advancing our understanding in all areas of nuclear energy research. Increasing this cooperation will certainly offer a bigger bang for the buck to the US tax payor. Finally, I see the NSUF moving beyond our borders and leading international cooperation to the eventual establishment of an international user facility based on the NSUF model of managing access to a multitude of capabilities and facilities to most efficiently address the important issues of the nuclear industry and general nuclear research community.

What do you like to do outside of the office (hobbies, volunteer activities, interests)?
Over the last several years, I have not done well in this regard, so it is my goal to work on this area going forward. Ask me again in three years!

AWARDED PROJECTS

Call	Title	Principal Investigator	PI Organization	NSUF Facilities
FY 2019 CINR	High Fluence Active Irradiation and Combined Effects Testing of Sapphire Optical Fiber Distributed Temperature Sensors	Josh Daw	Idaho National Laboratory	Massachusetts Institute of Technology The Ohio State University
FY 2019 CINR	High Power Irradiation Testing of TRISO Fuel Particles with UCO and UO_2 Kernels in Miniature Fuel Specimen Capsules in HFIR	Ryan Latta	Kairos Power	Oak Ridge National Laboratory
FY 2019 CINR	Integral Fuel Rod Real-Time Wireless Sensor and Transmitter Irradiation Test and Post Irradiation Examination	Jorge Carvajal	Westinghouse Electric	Oak Ridge National Laboratory
FY 2019 CINR	Irradiation of Optical Components of *in-situ* Laser Spectroscopic Sensors for Advanced Nuclear Reactor Systems	Igor Jovanovic	University of Michigan	The Ohio State University
FY 2019 CINR	Irradiation Studies on Electron Beam Welded PM-HIP Pressure Vessel Steel	Janelle Wharry	Purdue University	Idaho National Laboratory Westinghouse Electric Center for Advanced Energy Studies
FY 2019 CINR	Irradiation-assisted Stress Corrosion Cracking of PWR-irradiated Type 347 Stainless Steel	Mike Ickes	Westinghouse Electric	Westinghouse Electric University of Michigan
FY 2019 CINR	Neutron Radiation Effect on Diffusion between Zr (and Zircaloy) and Cr for Accurate Lifetime Prediction of ATF	Ji-Cheng Zhao	The Ohio State University	Idaho National Laboratory
FY 2019 CINR	NuScale SMR Materials Irradiation and Testing	Hongqing (HQ) Xu	Nuscale Power	Idaho National Laboratory Westinghouse Electric
FY 2019 CINR	Thermal Conductivity Measurement of Irradiated Metallic Fuel Using TREAT	Heng Ban	University of Pittsburgh	Idaho National Laboratory



INL's Advanced Test Reactor is the only U.S. research reactor capable of providing large-volume, high-flux neutron irradiation in a prototype environment. It's unique serpentine core makes it possible to conduct multiple experiments simultaneously all under different testing conditions.

Call	Title	Principal Investigator	PI Organization	NSUF Facilities
FY 2019 RTE 1st Call	3D Microstructure Reconstruction of the Peripheral Region of MOX FBR Fuel	Casey McKinney	University of Florida	Idaho National Laboratory
FY 2019 RTE 1st Call	A Study of the Tensile Response of HT-9 Alloys Following ATR Irradiation to Doses between 0.01 and 10 dpa at 300°, 450° and 550° C	Huan Yan	University of Illinois at Urbana-Champaign	Los Alamos National Laboratory
FY 2019 RTE 1st Call	Atom Probe Tomography Study of the Fuel Cladding Chemical Interaction (FCCI) Layer in Irradiated U-10Zr Fuel with HT-9 Cladding	Xiang Liu	Idaho National Laboratory	Center for Advanced Energy Studies
FY 2019 RTE 1st Call	Bubble Formation of *in-situ* He-Implanted 14YWT and CNA Advanced Nanostructured Ferritic Alloys	Yan-Ru Lin	University of Tennessee	Argonne National Laboratory
FY 2019 RTE 1st Call	Changes in Mechanical and Chemical-Structural Properties of Gamma Irradiated Calcium Silicate Hydrates to an Absorbed Dose of 200 MGy with Respect to Pristine Samples	Nishant Garg	University of Illinois at Urbana-Champaign	Oak Ridge National Laboratory
FY 2019 RTE 1st Call	ChemiSTEM Study of Nb Redistribution in M5 Irradiated at High Burnup	Adrien Couet	University of Wisconsin, Madison	Oak Ridge National Laboratory
FY 2019 RTE 1st Call	Critical Evaluation of Solute Segregation and Precipitation Across Damage Rates in Dual Ion Irradiated T91 Steel	Stephen Taller	University of Michigan	Oak Ridge National Laboratory
FY 2019 RTE 1st Call	Defect Clustering in 316H Stainless Steel and High Entropy Alloy Under *in-situ* Irradiation at 600-700°C	Weiying Chen	Argonne National Laboratory	Argonne National Laboratory
FY 2019 RTE 1st Call	EBSD Characterization of Neutron Irradiated Mineral Concrete Aggregates	Thomas Rosseel	Oak Ridge National Laboratory	Oak Ridge National Laboratory
FY 2019 RTE 1st Call	Effect of Laser Weld Repairs on Deformation Mechanisms of Neutron Irradiated Austenitic Steels	Keyou Mao	Purdue University	Idaho National Laboratory
FY 2019 RTE 1st Call	Effects of Dose and Temperature on Microstructural Evolution of Zircaloy-4 Alloys During Proton Irradiation	Daniel Jädernäs	Studsvik Nuclear AB	Center for Advanced Energy Studies
FY 2019 RTE 1st Call	He^{++} Irradiation of Aerosol Jet Printed Silver Structures	Troy Unruh	Idaho National Laboratory	University of Michigan

Call	Title	Principal Investigator	PI Organization	NSUF Facilities
FY 2019 RTE 1st Call	Impact of Grain Boundary Mobility on Fission Gas Bubble Distribution of Ion-Irradiated Monolithic U-Mo Fuel	Charlyne Smith	University of Florida	Argonne National Laboratory
FY 2019 RTE 1st Call	*In-situ* Irradiation Study of Carbides/ Nitrides/Carbo-Nitrides in Additively Manufactured Ferritic-Martensitic Steels	Shradha Agarwal	University of Tennessee	Argonne National Laboratory
FY 2019 RTE 1st Call	*In-situ* Observation of Radiation-Induced Phase Transformation in U-Mo	Bei Ye	Argonne National Laboratory	Argonne National Laboratory
FY 2019 RTE 1st Call	*In-situ* SEM Irradiation Enhanced Creep Studies of 14YWT	David Frazer	Los Alamos National Laboratory	Sandia National Laboratories
FY 2019 RTE 1st Call	*In-situ* Separate Effect Studies of Thermal and Radiation Effects on Xe Diffusion in Alpha-U and U-10Zr	Fidelma Di Lemma	Idaho National Laboratory	Argonne National Laboratory
FY 2019 RTE 1st Call	*In-situ* Small-Scale Mechanical Testing of Fast Reactor Advance Metallic Fuel Alloy	Luca Capriotti	Idaho National Laboratory	Idaho National Laboratory
FY 2019 RTE 1st Call	Ion Irradiation for High Fidelity Simulation of High Dose Neutron Irradiation	Todd Allen	University of Wisconsin	University of Michigan
FY 2019 RTE 1st Call	Ion Irradiation of ThO_2 and UO_2 Single Crystals	Marat Khafizov	The Ohio State University	Texas A&M University Idaho National Laboratory
FY 2019 RTE 1st Call	Local Deformation Mechanism of Neutron-Irradiated NF709 Austenitic Stainless Steel	Tianyi Chen	Oregon State University	Center for Advanced Energy Studies
FY 2019 RTE 1st Call	Mechanical Characterization of Three Lower Dose HT-9 Heats (ORNL, LANL and EBR II) after Side-By-Side Neutron Irradiation at LWR and Fast Reactor Relevant Temperatures	Ramprashad Prabhakaran	Pacific Northwest National Laboratory	Pacific Northwest National Laboratory
FY 2019 RTE 1st Call	Mechanical Property and Microstructural Characterization of Irradiated Stainless Steel via *in-situ* SEM-EBSD Mechanical Testing	Mahmoud Mostafavi	University of Bristol	Oak Ridge National Laboratory
FY 2019 RTE 1st Call	Microstructure Characterization on Neutron Irradiated and Post-Tensile Duplex Stainless Steels	Yu Lu	University of Florida	Center for Advanced Energy Studies

Dr. Lynne Ecker, Brookhaven National Laboratory's NSUF technical lead, stands with BNL's X-ray Powder Diffraction beamline at the National Synchrotron Light Source II in the background.

Call	Title	Principal Investigator	PI Organization	NSUF Facilities
FY 2019 RTE 1st Call	Nanoindentation of Phases in Irradiated and Control U-10Zr Fuels	Maria Okuniewski	Purdue University	Idaho National Laboratory
FY 2019 RTE 1st Call	On Surprising Dose Rate Effects in Neutron Irradiated Fe-Cr Alloys: A TEM Study of Composition Effects at DPA Rates that Vary by Only a Factor of 4	Jack Haley	University of Oxford	Center for Advanced Energy Studies
FY 2019 RTE 1st Call	Radiation Tolerance of Ln_3TaO_7 Weberite-Type Nuclear Waste Matrix Materials	Rodney Ewing	Stanford University	Argonne National Laboratory
FY 2019 RTE 1st Call	Resolving the Puzzle of Flux Effects on High Fluence Precipitation and Embrittlement of RPV Steels	Nathan Almirall	University of California, Santa Barbara	Center for Advanced Energy Studies
FY 2019 RTE 1st Call	TEM Characterization of Highly Irradiated Stainless Steel	Philip Edmondson	Oak Ridge National Laboratory	Oak Ridge National Laboratory
FY 2019 RTE 1st Call	Thermal Diffusivity and Microstructure Analysis of In-Core Molten Salt Irradiated Graphite	Guiqiu Zheng	Massachusetts Institute of Technology	Idaho National Laboratory
FY 2019 RTE 1st Call	Thermal Driven Grain Growth and Fission Gas Bubble Coarsening in Nano-grain Sized U_3Si_2	Tiankai Yao	Rensselaer Polytechnic Institute	Idaho National Laboratory
FY 2019 RTE 2nd Call	A Study Using Stoichiometry to Control Structural Disorder and Subsequent Radiation Tolerance of Rare-Earth Based Zirconates and Titanates	Nestor Zaluzec	Argonne National Laboratory	Argonne National Laboratory
FY 2019 RTE 2nd Call	Alleviating Irradiation-Induced Precipitation in a Fe-21Cr-5Al Alloy via Nano Structuring	Maalavan Arivu	Missouri University of Science and Technology	Center for Advanced Energy Studies
FY 2019 RTE 2nd Call	APT Study of Zr-(Mo, Nb, Ta) Diffusion for Designing the Diffusion Barrier Interlayer of Cr Coated Zircaloy Accident-Tolerant Fuels	Ji-Cheng Zhao	The Ohio State University	Center for Advanced Energy Studies
FY 2019 RTE 2nd Call	Atom Probe Tomography (APT) Investigation of Radiation Stability of Oxide Nanoclusters in Oxide Dispersion Strengthened (ODS) Steel Manufactured by the Cold Spray Process	Mia Lenling	University of Wisconsin	Center for Advanced Energy Studies
FY 2019 RTE 2nd Call	Atom Probe Tomography Investigation on the Precipitation of Neutron-Irradiated Alloy 800H/800H-TMP	Weicheng Zhong	Oak Ridge National Laboratory	Center for Advanced Energy Studies

Call	Title	Principal Investigator	PI Organization	NSUF Facilities
FY 2019 RTE 2nd Call	BET And TEM Characterization of Nuclear Graphite Irradiated at Temperatures Below 230°C	Wenjing Li	Canadian Nuclear Laboratories	Oak Ridge National Laboratory
FY 2019 RTE 2nd Call	Characterization of Alpha Irradiated and Control Cementitious Grouts/Grout Components Used for Nuclear Waste Encapsulation	Sarah Kearney	University of Sheffield	Oak Ridge National Laboratory
FY 2019 RTE 2nd Call	Correlation of *in-situ* TEM Characterization and Ex-Situ Microchemistry Analysis of Radiation Damage In Metal/Oxide Multilayers	Djamel Kaoumi	North Carolina State University	Argonne National Laboratory
FY 2019 RTE 2nd Call	Density Functional Theory Study of Defects, Solubility of Fission Products and Pu, and Phase Separation in U_3Si_2 Nuclear Fuel	Vancho Kocevski	University of South Carolina	Idaho National Laboratory
FY 2019 RTE 2nd Call	Effect of Irradiation on Nuclear Graphite Microstructure in Relation to Oxidation in Oxygen Environments	Miao Song	University of Michigan	Center for Advanced Energy Studies
FY 2019 RTE 2nd Call	Elevated Temperature *in-situ* Scanning Electron Microscopy Microcantilever Testing of U_3Si_2	David Frazer	Los Alamos National Laboratory	University of California, Berkeley
FY 2019 RTE 2nd Call	EPMA and TEM Characterization of a UO_2 Fuel Pellet and Cladding Interaction Layer	Sarah Finkeldei	University of California, Irvine	Idaho National Laboratory
FY 2019 RTE 2nd Call	High-Burnup U-Mo Pore Morphology Analysis as a Function of Fission Density and Rate	Alejandro Figueroa	Purdue University	Idaho National Laboratory
FY 2019 RTE 2nd Call	*In-situ* Investigation of Irradiation Damage on Non-Volatile Memory	Biswajit Ray	University of Alabama	Sandia National Laboratories
FY 2019 RTE 2nd Call	*In-situ* Nanomechanical Characterization of Neutron-Irradiated HT-9 Steel	Tanvi Ajantiwalay	University of Florida	Sandia National Laboratories
FY 2019 RTE 2nd Call	*In-situ* Observation of Helium Out-Gassing Mechanism in Percolating 1D/2D Nano Dispersoids for Advanced Reactor Structural Material and Fuel Cladding	Michael Short	Massachusetts Institute of Technology	Argonne National Laboratory
FY 2019 RTE 2nd Call	*In-situ* TEM Observation of Microstructural Evolution of Sodium-Ion Battery Materials Under Ion Irradiation	Xianming Bai	Virginia Polytechnic Institute	Argonne National Laboratory

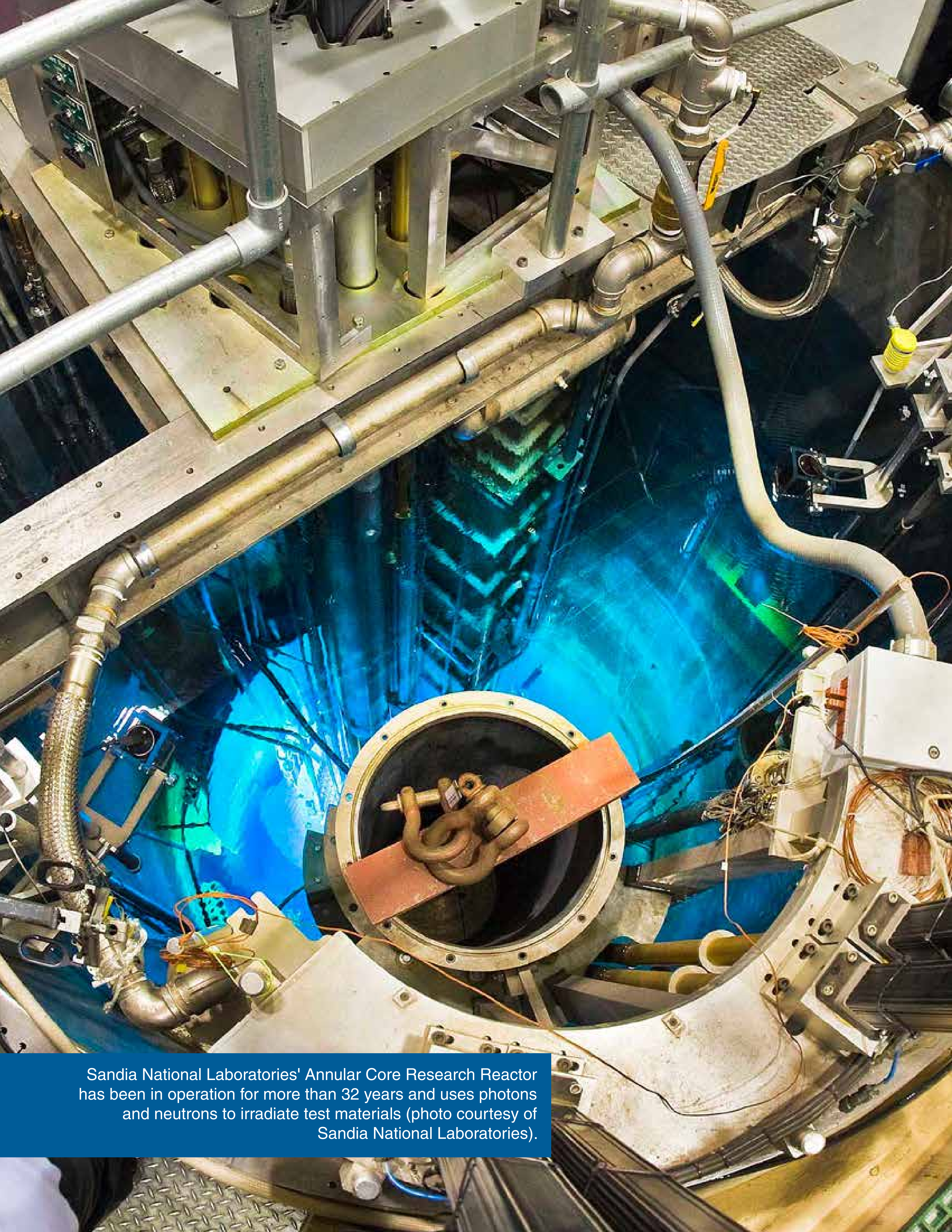
Call	Title	Principal Investigator	PI Organization	NSUF Facilities
FY 2019 RTE 2nd Call	*In-situ* TEM Study of the Irradiation Response of Pre-deformed Alloy 709	Xuan Zhang	Argonne National Laboratory	Argonne National Laboratory
FY 2019 RTE 2nd Call	Influence of Grain Boundary RIS on Dislocation Mobility in Irradiated Steels	Janelle Wharry	Purdue University	Center for Advanced Energy Studies
FY 2019 RTE 2nd Call	Investigation of the Mechanism Behind Irradiation-Decelerated Corrosion of Ni-20Cr in Molten Fluoride Salt	Weiyue Zhou	Massachusetts Institute of Technology	Idaho National Laboratory
FY 2019 RTE 2nd Call	Irradiation and TEM Characterization of Induced Defects in α-U and δ-UZr_{2+x} Crystals	Tiankai Yao	Idaho National Laboratory	Texas A&M University Idaho National Laboratory
FY 2019 RTE 2nd Call	Irradiation Response and Mechanical Properties of Cr Coated Zircaloy-4	Lin Shao	Texas A&M University	Texas A&M University Idaho National Laboratory
FY 2019 RTE 2nd Call	Microstructural Characterization of *in-situ* Ion Irradiated SiC Layer of TRISO Fuel	Subhashish Meher	Idaho National Laboratory	Idaho National Laboratory
FY 2019 RTE 2nd Call	Microstructural Characterizations of In-Core Molten Salt Irradiated TRISO Particles	Guiqiu Zheng	Massachusetts Institute of Technology	Idaho National Laboratory
FY 2019 RTE 2nd Call	Microstructure Characterization of Neutron-Irradiated Fe-Cr-C Model Alloys	James Stubbins	University of Illinois at Urbana-Champaign	Center for Advanced Energy Studies
FY 2019 RTE 2nd Call	Nano-precipitate Stability and α-Precipitation in ODS and Wrought FeCrAl Alloys	Caleb Massey	University of Tennessee	Center for Advanced Energy Studies
FY 2019 RTE 2nd Call	Nanoscale Analysis of Mn-Si-Ni Phase in Neutron Irradiated T91 at 320°C	Thomas Davis	University of Oxford	Center for Advanced Energy Studies
FY 2019 RTE 2nd Call	Neutron Powder Diffraction and Transmission in Graphite to Assess Impact of Microstructure on Neutron Thermalization	Ayman Hawari	North Carolina State University	North Carolina State University
FY 2019 RTE 2nd Call	Radiation Stability Study on Nuclear Waste Materials	Ming Tang	Los Alamos National Laboratory	Argonne National Laboratory

Call	Title	Principal Investigator	PI Organization	NSUF Facilities
FY 2019 RTE 2nd Call	Radiation Tolerance of Nanoporous Gadolinium Titanite	Jessica Krogstad	University of Illinois at Urbana-Champaign	Argonne National Laboratory
FY 2019 RTE 2nd Call	Role of Irradiation Damage Cascade Descriptors on ODS and Model ODS Nanocluster Evolution	Priyam Patki	Purdue University	Argonne National Laboratory
FY 2019 RTE 2nd Call	Scanning/Transmission Electron Microscopy Characterization of Irradiated Zr-1Nb-O During Thermal Treatments	Mahmut Cinbiz	Oak Ridge National Laboratory	Idaho National Laboratory
FY 2019 RTE 2nd Call	TEM Characterization of Neutron Irradiated $Nd_2Zr_2O_7$ and Its Thermal Recovery Behavior	Yachun Wang	Rensselaer Polytechnic Institute	Idaho National Laboratory
FY 2019 RTE 2nd Call	Temperature Shift Evaluation for G-Phase Nanocluster Evolution in Ferritic/Martensitic Alloys	Matthew Swenson	University of Idaho	Center for Advanced Energy Studies
FY 2019 RTE 2nd Call	The Impact of Grain Orientation on the Nucleation of Fission Gas Bubbles in U-Mo Fuel	Charlyne Smith	University of Florida	Idaho National Laboratory
FY 2019 RTE 2nd Call	The Microstructure Characterization of 21Cr32Ni Model Austenitic Alloy Irradiated at BOR60 Reactor	Muhammet Ayanoglu	Pennsylvania State University	Oak Ridge National Laboratory
FY 2019 RTE 2nd Call	Understand the Atomic Positions of the Metallic Fission Product in UCO Fuel Kernels and Determine the Exact Stoichiometry of UC, UO Phase of Irradiated TRISO Fuel Particles by Using Titan Themis 200 with EELS Characterization Capability	Zhenyu Fu	University of Florida	Idaho National Laboratory
FY 2019 RTE 3rd Call	Advanced Microstructural Characterization of Irradiation-Induced Phase Transformation in 304 steel	Andrew Hoffman	Missouri University of Science and Technology	Idaho National Laboratory
FY 2019 RTE 3rd Call	Alumina-stabilized Coatings Under Irradiations: Towards Future Generation Nuclear Systems	Fabio Di Fonzo	Italiano di Tecnologia	Argonne National Laboratory
FY 2019 RTE 3rd Call	Correlative Transmission Electron Microscopy and Atom Probe Tomography Study of Radiation Induced Segregation and Precipitation in Nanostructured SS304	Maalavan Arivu	Missouri University of Science and Technology	Center for Advanced Energy Studies

The Radiochemical Processing Laboratory at Pacific Northwest National Laboratory is an American Nuclear Society Nuclear Historic Landmark with the goal of studying and enhancing radiological material processes and nuclear energy initiatives (photo courtesy of Pacific Northwest National Laboratory).

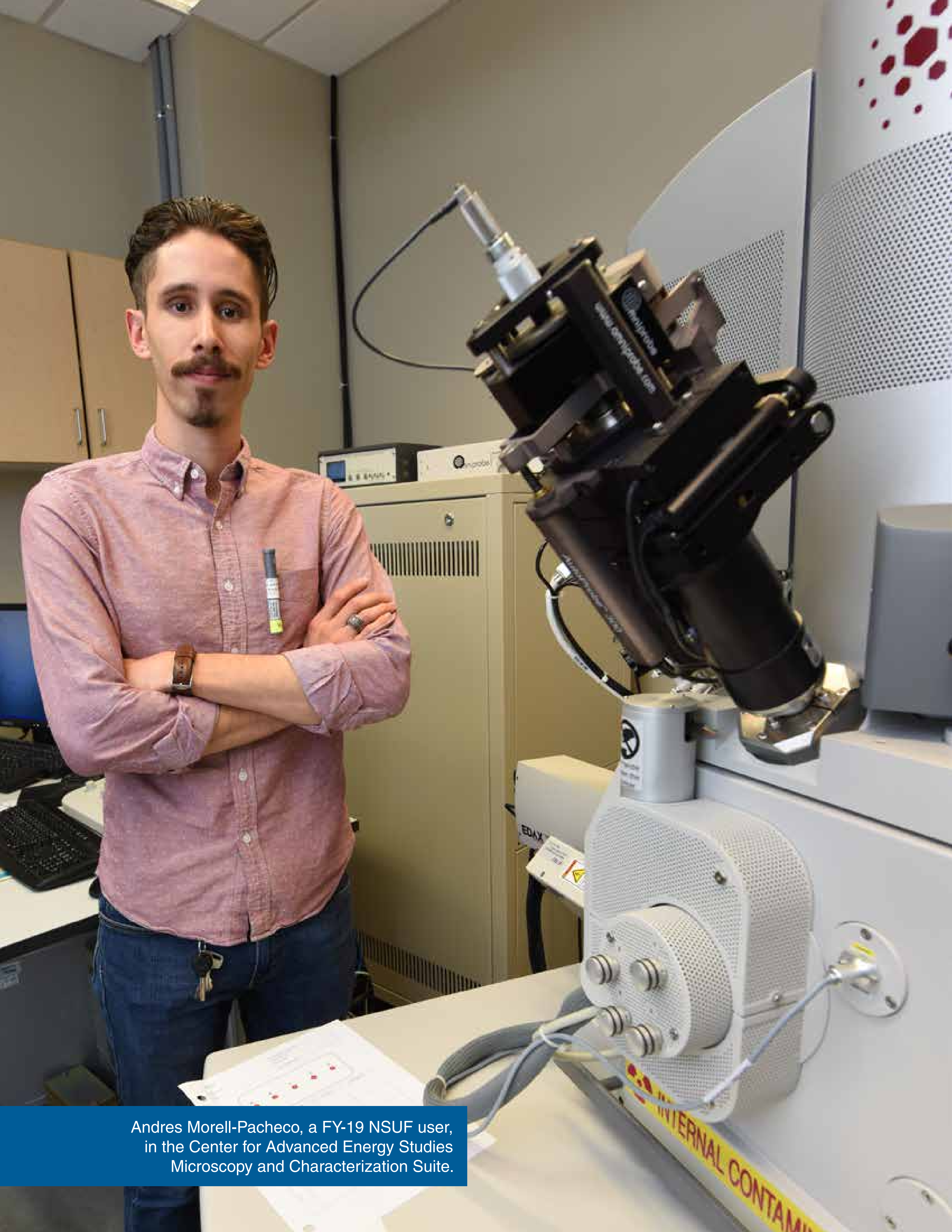
Call	Title	Principal Investigator	PI Organization	NSUF Facilities
FY 2019 RTE 3rd Call	Determination of Spatial and Chemical Relationship of Hydrogen and Helium in 316 SS PWR Flux Thimble Tube at 76 dpa for Extrapolation into Beyond-40-Year Operation	Kelvin Xie	Texas A&M University	Idaho National Laboratory
FY 2019 RTE 3rd Call	Dose Rate Effects on Irradiation-Enhanced Precipitation in FeCrAl Alloys	Samuel Briggs	Oregon State University	Center for Advanced Energy Studies
FY 2019 RTE 3rd Call	Dual Beam Irradiation Stability of Amorphous Silicon Oxycarbide (SiOC)	Qing Su	University of Nebraska	Texas A&M University Center for Advanced Energy Studies
FY 2019 RTE 3rd Call	Effect of Interstitial Elements on the Irradiation Response of HT9 Tempered Ferritic/Martensitic Steels	Eda Aydogan	Sabanci University	Argonne National Laboratory
FY 2019 RTE 3rd Call	Effects of Cold Rolling and Induction Casting on the Phase Decomposition and Distribution of Fission Gas Bubbles in U-10wt.%Mo alloys at Low Fluences	Gyuchul Park	Purdue University	Idaho National Laboratory
FY 2019 RTE 3rd Call	Examining Microstructural Evolution of HT9 under Neutron and Ion Irradiations from 370°C to 570°C	Li He	University of Wisconsin	Oak Ridge National Laboratory
FY 2019 RTE 3rd Call	High Resolution (S)TEM/EDS Characterization of Neutron Irradiated Commercial Zr-Nb Alloys	Zefeng Yu	University of Wisconsin	Idaho National Laboratory
FY 2019 RTE 3rd Call	Impact of Neutron Damage and Microstructure Changes on Hydrogen Retention in Nuclear Graphite	Kieran Dolan	Massachusetts Institute of Technology	Massachusetts Institute of Technology
FY 2019 RTE 3rd Call	*In-situ* Observation of Microstructural Stability Under Dual-Beam Irradiation in Interface/Microstructure-Manipulated Nickel Alloys	Jian Wang	University of Nebraska	Argonne National Laboratory
FY 2019 RTE 3rd Call	Investigation of Buffer Densification using TRISO Particles Irradiated in PYCASSO Project	Dong Liu	University of Bristol	Idaho National Laboratory
FY 2019 RTE 3rd Call	Investigation of Fission Gas Bubble Distribution, Phase Transformations, and Bubble Growth Kinetics in a FFTF-irradiated U-10Zr Fuel	Xiang Liu	Idaho National Laboratory	Idaho National Laboratory

Call	Title	Principal Investigator	PI Organization	NSUF Facilities
FY 2019 RTE 3rd Call	Investigation of Irradiation-assisted Stress Corrosion Cracking of Additively Manufactured Austenitic Stainless Steel	Jung-Kun Lee	University of Pittsburgh	University of Michigan
FY 2019 RTE 3rd Call	Investigation of the Irradiation Induced Porosity in Concrete Aggregates with X-Ray Computed Tomography and Helium Pycnometry	Jose Arregui-Mena	Oak Ridge National Laboratory	Oak Ridge National Laboratory
FY 2019 RTE 3rd Call	Ion-Irradiation and Microstructural Change Studies of Glassy Carbon	Junhua Jiang	Idaho National Laboratory	Texas A&M University Center for Advanced Energy Studies
FY 2019 RTE 3rd Call	Irradiation of Nb-93 targets for ASTM International Inter-Laboratory Study of E1297, "Standard Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Niobium"	Michael Reichenberger	Idaho National Laboratory	Idaho National Laboratory
FY 2019 RTE 3rd Call	Mechanical Characterization of Neutron Irradiated NF616 (T92) as a Function of Doses and Temperatures	Ramprashad Prabhakaran	Pacific Northwest National Laboratory	Pacific Northwest National Laboratory
FY 2019 RTE 3rd Call	Microstructural Investigation of Radiation Stability of Cold Spray Manufactured Oxide Dispersion Strengthened (ODS) Steel	Hwasung Yeom	University of Wisconsin	Idaho National Laboratory
FY 2019 RTE 3rd Call	Multi-Modal Serial Sectioning and Synchrotron Micro-Computed Tomography Analysis of High Burnup Nuclear Fuels	Alejandro Figueroa	Purdue University	Idaho National Laboratory
FY 2019 RTE 3rd Call	New Proposal: Irradiation of Structural Carbon Nanotubes for Nuclear Thermal Propulsion Application	Emilie Siochi	NASA Langley Research Center	Oak Ridge National Laboratory
FY 2019 RTE 3rd Call	New Proposal: Microstructure analysis of neutron irradiated Alloy 625	Emmanuelle Marquis	University of Michigan	Center for Advanced Energy Studies Los Alamos National Laboratory
FY 2019 RTE 3rd Call	Performance and Structural Damage Analysis of Chalcogenide Glass Phase Change Temperature Sensors Under Ion Irradiation	Al-Amin Ahmed Simon	Boise State University	University of Michigan Center for Advanced Energy Studies



Sandia National Laboratories' Annular Core Research Reactor has been in operation for more than 32 years and uses photons and neutrons to irradiate test materials (photo courtesy of Sandia National Laboratories).

Call	Title	Principal Investigator	PI Organization	NSUF Facilities
FY 2019 RTE 3rd Call	Predict the Mechanical Behavior of Irradiated Cast Stainless Steels Based on the Microstructures and Measured Properties from Nanoindentation	Yu Lu	University of Florida	Center for Advanced Energy Studies
FY 2019 RTE 3rd Call	Sink Strength Dependent Coherency Loss of Precipitates During *in-situ* Ion Irradiation of fcc-Structured Model Binary Alloys	Ling Wang	University of Tennessee	Argonne National Laboratory
FY 2019 RTE 3rd Call	Synergistic ODS Nanocluster Irradiation Evolution and Radiation-Induced Segregation	Janelle Wharry	Purdue University	Center for Advanced Energy Studies
FY 2019 RTE 3rd Call	The Influence of Proton Irradiation Damage on the Corrosion of Hastelloy N Exposed to FLiNaK Molten salt	Andres Morell-Pacheco	Texas A&M University	Texas A&M University Idaho National Laboratory
FY 2019 RTE 3rd Call	The Influence of Second Phase Precipitates on Hydride Reorientation in Spent Nuclear Fuel Cladding	Tyler Smith	University of Tennessee	Oak Ridge National Laboratory
FY 2019 RTE 3rd Call	Three-Dimensional Characterization of the Grey Phase in FBR MOX Fuel	Casey McKinney	University of Florida	Idaho National Laboratory
FY 2019 RTE 3rd Call	Understand the Fission Products Behavior in UCO Fuel Kernels of Safety Tested AGR2 TRISO Fuel Particles by Using Titan Themis 200 with ChemiSTEM Capability	Yong Yang	University of Florida	Idaho National Laboratory



Andres Morell-Pacheco, a FY-19 NSUF user, in the Center for Advanced Energy Studies Microscopy and Characterization Suite.

Select Project REPORTS

Through its RTE and CINR calls for proposals, NSUF grants access to its facilities for researchers to conduct their studies to further the understanding of the effects of irradiation on nuclear fuels and materials. The following reports document findings resulting from these NSUF projects.

Technical Report

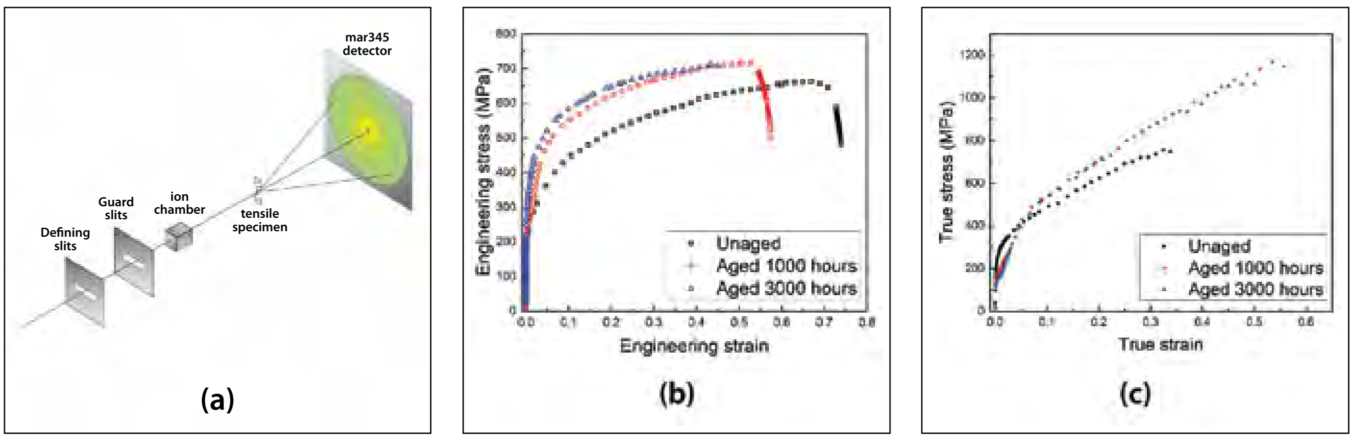
Understanding the Phase Transformation of Thermal Aged and Neutron Irradiated Duplex Stainless Steels Used in LWRs

Yong Yang – University of Florida – yongyang@ufl.edu

To understand the thermal-aging and neutron-irradiation effects on duplex stainless steels used in LWRs, *in-situ* testing with wide-angle X-ray scattering (WAXS) was used to quantify the mechanical response of individual phases under a tensile load. The X-ray experiments were complemented by microstructural characterizations using transmission electron microscopy (TEM) and atom probe tomography (APT). The aging effects were quantified in terms of (1) macroscopic tensile property, (2) lattice-strain evolutions of both the ferrite and austenite phases, and (3) dislocation-density evolution during plastic deformation. It was determined that thermal aging had a minimal effect on the austenite phase; however, thermal aging dramatically increased lattice strain and its yield strength in the ferrite phase. The increase of strength saturated at or before 1000 hours of thermal aging at 475°C. Pores that developed at the phase boundary were only observed for the 3000 hours aged specimen, with a significantly decreased ductility. The results also indicate that there is a load partition shift between ferrite and austenite phases upon thermal aging, as the ferrite phase becomes hardened. TEM and APT characterizations show that neutron irradiation introduced a similar microstructural change in the ferrite phase, including spinodal decomposition and G-phase precipitates.

Introduction

Extending the service lifetime of light-water reactors (LWRs) beyond 60 years requires a good understanding of the degradation mechanisms of materials and components in reactors. The lifetime of reactor components made of duplex stainless steels can be limited by embrittlement from thermal aging, neutron irradiation, or a synergistic effect of both. Previous studies showed that the spinodal decomposition in the delta ferrite phase is a primary embrittlement mechanism of the duplex structure stainless steels, while G-phase precipitates were also identified [1–2]. Most past studies focused on characterizations of fine-scale precipitates and phase decomposition using TEM and APT [3–5]. The fundamental mechanism and kinetics of elemental segregations occurring in the ferrite has not been fully understood. The exact



concurrent evolution mechanism of the solute clustering and spinodal decomposition are not clear. This knowledge gap has hindered the development of thermodynamic and kinetic modeling of microstructural evolution. It has also been speculated that cracks initiate in hardened ferrites and then propagate along the phase boundaries between ferrite and austenite. However, the fundamental mechanism of how the microstructural changes decrease the materials' fracture toughness has yet to be determined. This determination is needed to construct a physical model to predict the mechanical response to justify reactor lifetime extension.

In this research project, we use high-energy X-ray techniques, including X-ray diffraction (XRD), extended X-ray absorption fine-structure spectroscopy (EXAFS) and *in-situ* tensile testing with wide-angle X-ray scattering (WAXS) to probe the elemental segregations, phase precipitations and lattice-strain status under tensile load of different phases in selected cast stainless steels. The studies are complemented by advanced microstructural characterizations and conventional tensile testing. For the *in-situ* tensile experiments, only the pristine and thermally aged materials (sub-sized tensile specimens) were used due to

Figure 1. (a) In-situ tensile testing with WAXS, (b) engineering stress vs. stain curves, and (c) true stress vs. true strain curves.

"NSUF offers a great platform for conducting scientific research and training the next generation of work force."

– Yong Yang

the APS beamline dose limit, which excluded irradiated materials. For the microstructural studies, the samples included samples prepared from both aged and pristine *in-situ* tensile fractured specimens (TEM), and irradiated specimens with and without prior thermal aging (APT).

The research project is highly relevant to the DOE-NE Light Water Reactors Sustainability Program, and its outcome will significantly improve the scientific understanding of the degradation of duplex-structure stainless steels in LWRs and contribute to the construction of a physics-based model for predicting material performance for reactor license renewal and regulation.

Experimental or Technical Approach

As shown in Figure 1a, the *in-situ* WAXS tensile tests were conducted using the 10-ID-B beamline at the Advanced Photon Source (APS), Argonne National Laboratory (ANL). Two beamline experiments were conducted using two different control modes. For the first experiment, a monochromatic X-ray beam with an energy of about 64 keV ($\lambda = 0.1925$ Å) and a beam size about 600 µm × 600 µm was employed. The specimen was strained incrementally until fracture while operating in a displacement control mode. A displacement step of 0.001 mm in the elastic region and 0.05–0.10 mm in the plastic region was employed. X-ray-diffraction patterns were acquired after each displacement step using the mar345 image-plate X-ray detector. To maximize the signal-to-noise ratio without saturation, the exposure time was set to 30 seconds for diffraction pattern acquisition. To increase the data points recorded in the elastic deformation region, the second beamline experiment was conducted using a load-control mode. A load step of 10 N in the elastic region and 20–50 N in the plastic region were used. The monochromatic X-ray with energy about 52 keV ($\lambda = 0.2394$ Å) and beam size about 400 µm × 400 µm was used for the second experiment while the data acquisition process was the same as that used in the first experiment.

The dislocation density in the fractured tensile specimen was measured by TEM for both unaged and aged conditions. TEM lamellae were lifted from the gauge zone using a FEI HELIOS 600i focused ion beam (FIB). The dislocation density was measured using the scanning transmission electron microscopy (STEM) mode at selected zone axises. All TEM characterization was performed using a FEI Tecnai F30 S/TEM at the Microscopy and Characterization Suite (MaCS) of the Center for Advanced Energy Studies (CAES) in Idaho Falls, ID.

APT characterizations were conducted to quantify the spinodal decomposition and G-phase precipitates in the ferrite phase of neutron irradiated CF-8 cast stainless steel. Reconstructions and analyses were performed using Cameca's Integrated Visualization and Analysis software 3.8.0 (IVAS). Three-dimensional (3-D) reconstructions were conducted by following the standard procedure of Recon Wizard in the software, and SEM tip images were used to define tip profiles.

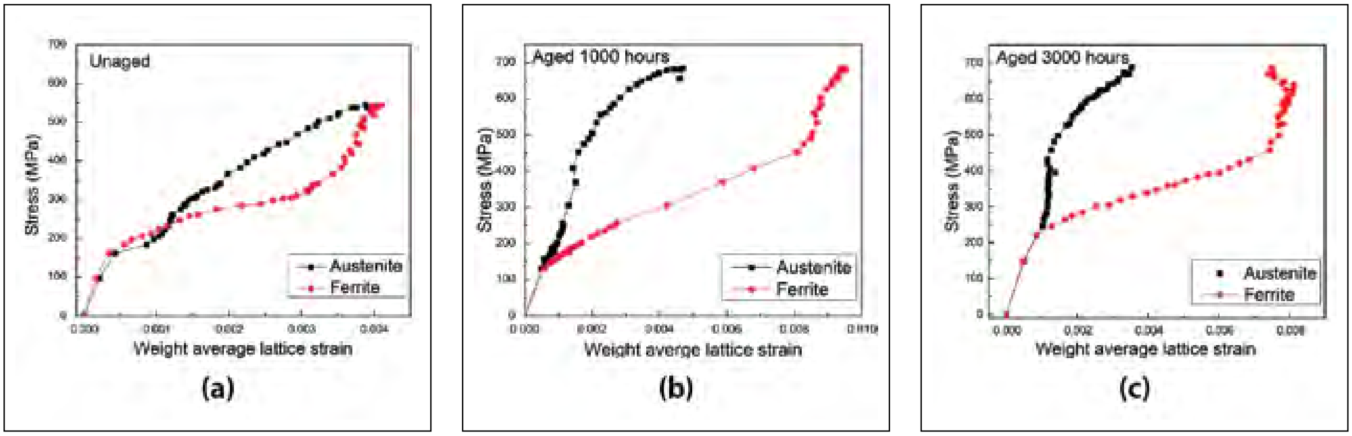


Figure 2. Stress vs. weight average lattice strain for unaged, 1000 hours aged and 3000 hours aged specimens, respectively.

Developing a mechanistic understanding of mechanical response of duplex stainless steel upon long-term reactor service is critical for component life evaluation and reactor license renewal.

Results

Figures 1b and 1c show the engineering strain vs. engineering stress and true strain vs. true stress curves, respectively, from the first beamline experiment using displacement control mode. It can be seen that thermal aging for 1000 hours greatly changes the mechanical behavior of the materials, which exhibit increased yield strength but reduced ductility. To better understand the load partition between the austenite and ferrite phase under different aging conditions, the weight average lattice strain was calculated. The average bulk lattice strain for austenite was derived from the lattice strains of the {111}, {200}, {220}, {311}, and {420} reflections while, for ferrite phase, it was derived from the lattice strains of the {110}, {200}, and {211} reflections. The weighted averaging algorithm was developed by Daymond [6]. The stress vs. weight average lattice strain for the first experiments are plotted in Figures 2a–c for the conditions of unaged, aged for 1000 hours, and aged for 3000 hours, respectively. The yield of austenite and ferrite phases were then determined based on ToMOTA's theory [7]. It clearly showed that the yield strength of the ferrite significantly increases from 315 up to 437 MPa upon thermal aging for 3000 hours, while the yield strength of austenite remains nearly unchanged at around 210 MPa.

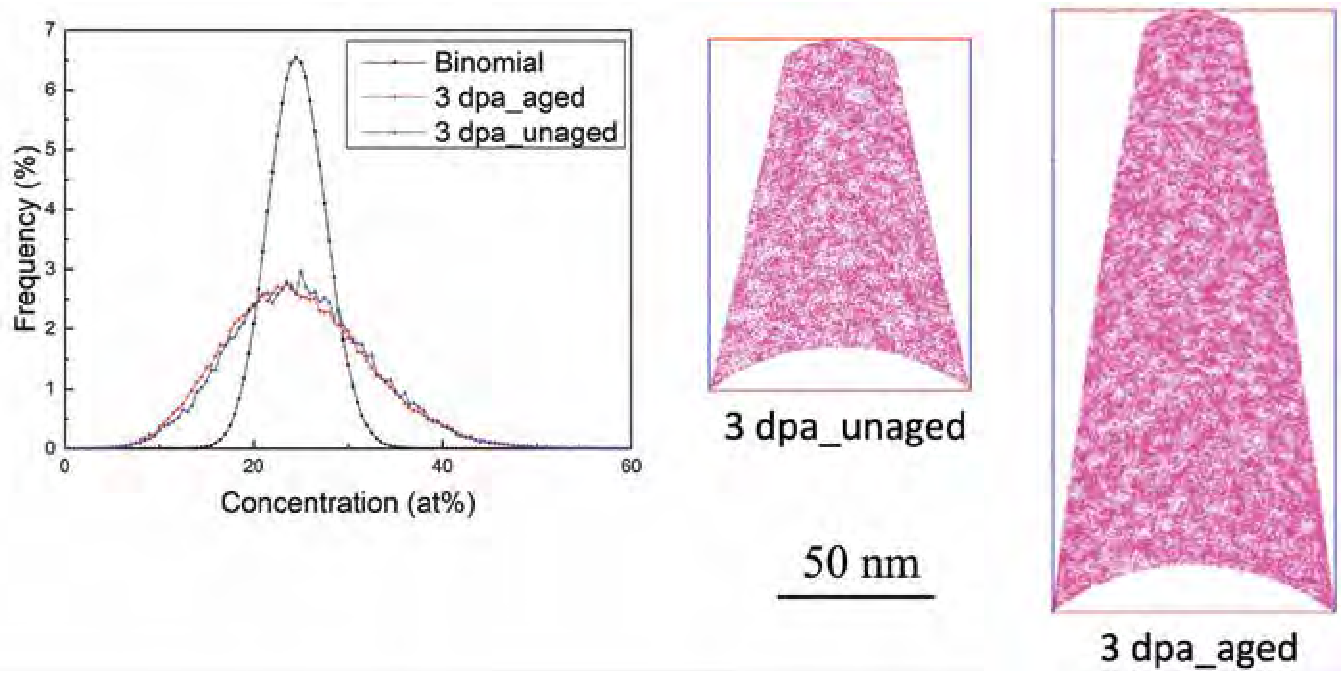


Figure 3. Atom probe tomography results (a) Cr elemental frequency distribution in ferrite phases and (b) spinodal decomposition of Cr in irradiated ferrite phases with or without prior thermal aging.

APT results show that neutron irradiation to 3 dpa induces significant spinodal decomposition and G-phase precipitation, as shown in Figures 3 and 4 for the materials without and with prior thermal aging. By using the Cr-Cr radial distribution function, the spinodal decomposition wavelength and amplitude were quantified as 13.2 nm/16.72 at.%, and 12.4 nm/16.99 at.% for the 3 dpa irradiated-unaged and 3 dpa irradiated-aged specimens, respectively. Thermal aging prior to neutron irradiation has nearly no impact on the level of spinodal decomposition in the ferrite beams completely overshadowed by neutron irradiation. This fact confirmed using the Cr elemental frequency distribution analysis, shown in Figure. 3a. The G-phase precipitates (Mn-Ni-Si clusters) were quantified using a widely accepted maximum-separation method (MSM) [8–9]. The measured number density and mean size are $(1.48 \pm 0.17) \times 10^{24}\ m^{-3}/1.06 \pm 0.05$ nm and $(1.44 \pm 0.06) \times 10^{24} m^{-3}/1.06 \pm 0.03$ nm for the 3 dpa irradiated unaged and 3 dpa irradiated aged conditions, respectively. The G-phase precipitates have a nearly identical volumetric fraction of around 0.75% in the ferrite phase in those two specimens.

Discussion

The *in-situ* X-ray tensile testing clearly showed the hardening of ferrite phase upon thermal aging, and it is anticipated that the ductility of

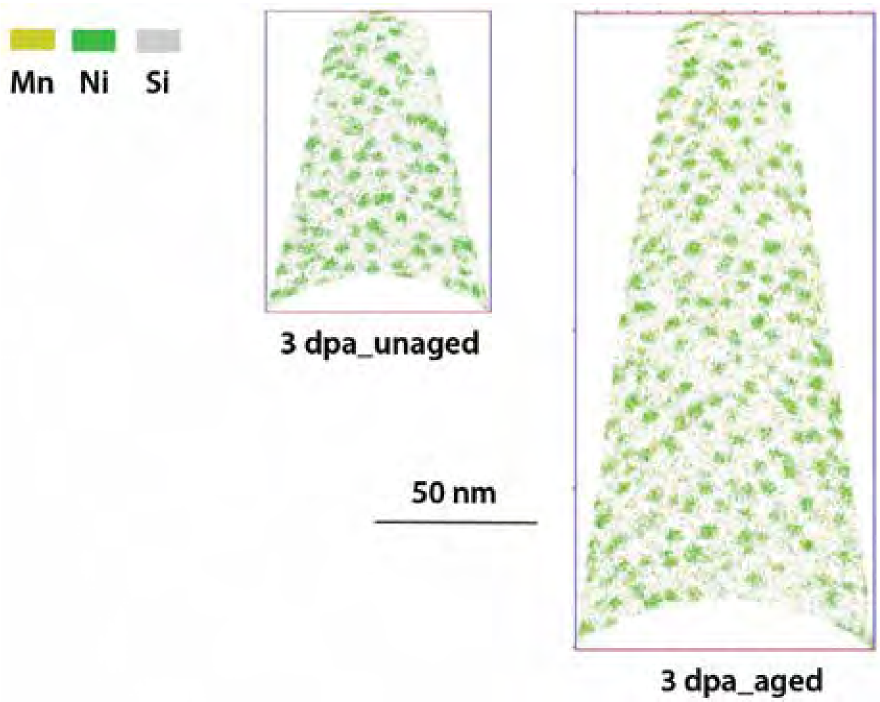


Figure 4. G-phase (Mn-Ni-Si) precipitates in irradiated ferrite phases.

ferrite would decrease subsequently. Limited study showed that the cracks initiate in hardened ferrite phase and propagate along the phase boundary, which reduce the overall fracture toughness of the material [10]. The APT microstructure characterization on the 3 dpa irradiated duplex stainless steel clearly displayed that the neutron irradiation introduced very similar phase evolutions in the ferrite phase as compared with thermal aging. With additional data collected from the samples irradiated at 5, 10, 20 and 40 dpa, it was found that neutron irradiation induced spinodal decomposition started to saturate at between 10 and 20 dpa. However, it is generally agreed that the decrease of bulk fracture toughness starts to saturate at 5 dpa. The discrepancy is attributed to the austenite phase becoming hardened and embrittled and essentially determining the bulk mechanical properties.

The correlation between the microstructural changes and mechanical responses was established through the mechanistic understanding and finite element modeling developed in the project. Prediction can be made based on the microstructural data from small samples exposed to long-term thermal aging with or without neutron irradiation conditions, that normally poses significant challenges in experimental measurements due to the limit of surveillance samples. By simply characterizing the microstructures of the specimens extracted from reactor-surveillance samples or salvaged components, the related mechanical properties can be derived, and expected service life can be assessed. The research project directly contributes to the construction of a physics-based model for predicting material performance for reactor license renewal and regulation.

Conclusion

In-situ tensile testing using WAXS and post-tensile microstructural characterizations show that thermal aging induces a significant hardening effect on the ferrite phase and reduces overall ductility of the bulk material. Thermal aging shifts the load partition onto the ferrite phase, and the enhanced strain misfit introduces stress concentrations and promotes nucleation of pores at the phase boundary.

Future Activities

Further microstructural characterizations on the neutron irradiated spcimens and tensile fractured specimens using TEM and APT will provide a better interpretation of the results from the X-ray *in-situ* tensile testing. Ultimately, this data will help us to build a model to correlate the mechanical response with microstructural evolution in cast stainless steels.

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Distributed Partnership at a Glance	
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Short Communications

Characterization of Grain Boundaries of Alloy X-750 and SS 304 Irradiated in Experimental Breeder Reactor-II

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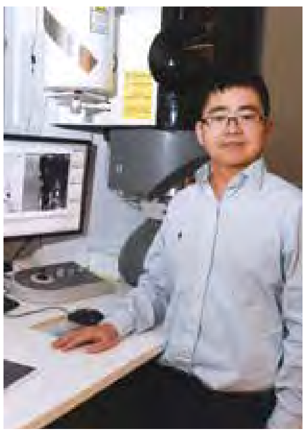

This project investigates the dose rate effect on the microstructural evolution of stainless steels, which is currently not well understood. Moreover, this project also tries to characterize the elemental segregation behavior at different types of grain boundaries and establish the possible relationship between elemental segregation and grain boundary strength as part of an Idaho National Laboratory (INL) Laboratory-Directed Research and Development project. The grain boundary strength will be measured using similar setup as previous studies [1,2]. The specimens were chosen from the NSUF library [3]. For both unirradiated and irradiated specimens, focused ion beam (FIB) was used to prepare site-specific lamellae for characterization by transmission electron microscopy (TEM). The Titan Scanning TEM (STEM) at the Irradiated Materials Characterization Laboratory (IMCL), equipped with ChemiSTEM technology was used to quantify radiation-induced defects (i.e., dislocation loops, voids, and precipitates) and the segregation at defect sinks (dislocations and grain boundaries). Electron backscatter diffraction (EBSD) was carried out to distinguish different types of grain boundaries. Atom probe tomography (APT) measurement of the segregation at the selected grain boundary was conducted on a LEAP 4000X HR at the Center for Advanced Energy Studies (CAES) Microscopy and Characterization Suite (MaCS). STEM, TEM, and APT data were then combined to achieve better understanding of the irradiated microstructure and microchemistry.

Results

STEM data on the irradiated microstructure, including the size and number density of voids, Frank loops, and gamma-prime precipitates were gathered as well as APT data. APT data on microchemistry at different types of grain boundaries. The irradiated microstructures of stainless steel (SS) 304 and nickel-base alloy X-750 were compared to existing data in literature of similar alloys irradiated at different dose rates.

Our results show [4] that dose rate has a significant effect on the loop size and density in SS 304 i.e., lower dose rate leads to larger loop size but lower loop density. Besides dislocation loops, voids were also found in SS 304 [4]. Ni and Si segregation was identified at the void-matrix interface, and (Ni,Si)-rich clusters were also identified. The HyperSpy non-negative matrix factorization (NMF) multivariate statistical analysis (MVSA) was used to better quantify the Ni and Si content in the (Ni,Si)-rich clusters.

Conclusion

The results of this project provide new insights and advanced microstructure data on neutron-irradiated SS 304 and nickel-base alloy X-750. It also provides specific segregation behavior of different types of grain boundaries, both before and after irradiation. These data are being incorporated into molecular dynamics (MD) and density functional theory (DFT) simulations of corresponding alloys.

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Distributed Partnership at a Glance	
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Collaborators	
Idaho National Laboratory	Lingfeng He (principal investigator), Mukesh Bachhav (co-principal investigator), Sebastien Teysseyre (co-principal investigator), Xiang Liu (collaborator)

Characterization of Neutron-Irradiated Zr-1Nb-O Using Scanning Transmission Electron Microscopy

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Modern zirconium alloys show excellent water-side corrosion resistance, low hydrogen pickup, and exceptional irradiation-resistance during light-water reactor (LWR) operation as compared to Zircaloys [1]. Improved operational performance of these alloys boosted activities to increase current burnup limits for nuclear fuel rods from ~60 to ~70 GWd/t for LWRs. Burnup extension faces many design challenges from the licensing viewpoint, primarily related to high-burnup structure (HBS) formation as well as mitigation of pellet/cladding chemical and mechanical interaction during reactor transients. In order to succeed, a detailed description of nuclear fuel is needed. This description needs to be robust and accurate enough that computational models can be developed, modeling from nanoscale to engineering scale. State-of-the-art characterization techniques, such as analytical transmission electron microscopy (TEM), can elucidate evolved microstructure and local chemistry at the pellet/cladding interface (PCI) for the development of further experimental investigations and computational efforts. Thus, this study investigated the microstructural characterization of high-burnup nuclear fuel at the PCI with the presence of HBS using analytical TEM. Several TEM samples were prepared from a high-burnup nuclear fuel using focused ion beam milling. Phases present were identified via electron-diffraction patterns, and the local chemistry was investigated by energy-dispersive x-ray spectroscopy (EDS). Findings will be informative for the development of materials computational models, especially for mesoscale approaches.

Results

Characterization of the PCI region revealed the presence of monoclinic and tetragonal zirconium oxide phases formed at the fuel/cladding interface. Monoclinic phase is formed at the zirconium side of the PCI region, and the tetragonal phase was formed at the fuel side. This suggests monoclinic phase was formed prior to the formation of the tetragonal phase. Elemental maps, as shown in Figure 1, showed that no single-phase uranium-zirconium-oxygen compound was detected in the PCI region, but interlocked separate zirconium oxide and uranium oxide phases were observed. Both zirconium and uranium oxides exhibited nanograin structure. Monoclinic grains were elongated while tetragonal grains were equiaxed. A notable observation, shown in Figure 1, was that zirconium oxide encapsulated fuel into small pockets, suggesting the diffusion of zirconium was the main driving force. Mo-Tc-Ru-Rh-Pd precipitates were found not only in the UO_2 fuel region, but also in the zirconium oxide region. The Mo-Tc-Ru-Rh-Pd precipitates are known as five metal precipitates in irradiated UO_2 fuels [2]. Measurement of a large Mo-Tc-Ru-Rh-Pd precipitate enabled the determination of the composition, such as 37 at% Mo, 8.6 at% Tc, 29 at% Ru, 1.4 at% Rh, and 14 at% Pd. It should be noted that almost all the Mo-Tc-Ru-Rh-Pd precipitates were associated with pores.

Conclusion

This study characterized the PCI region of a high-burnup fuel from an LWR using analytical TEM. Results revealed that the PCI region is a complex structure where zirconium oxide diffuses into oxide fuel. At high burnup, the pellet/cladding gap is completely closed by forming an interlocked diffusion layer (see Figure 1). This implies that thermal energy would be transported throughout PCI layer, and the gap thermal uncertainty would be null. Modeling tools must incorporate this effect by including the thermal properties of zirconium oxide phases. However, the thermal conductivity of zirconium oxide phases must be incorporated to heat-transfer models. This study offers a clear description of the PCI layer that can easily be included in mesoscale computation. In addition to that, the nanograined microstructure of the PCI shows the feasibility of applying micromechanical test methods to investigate the mechanical properties of fuel.

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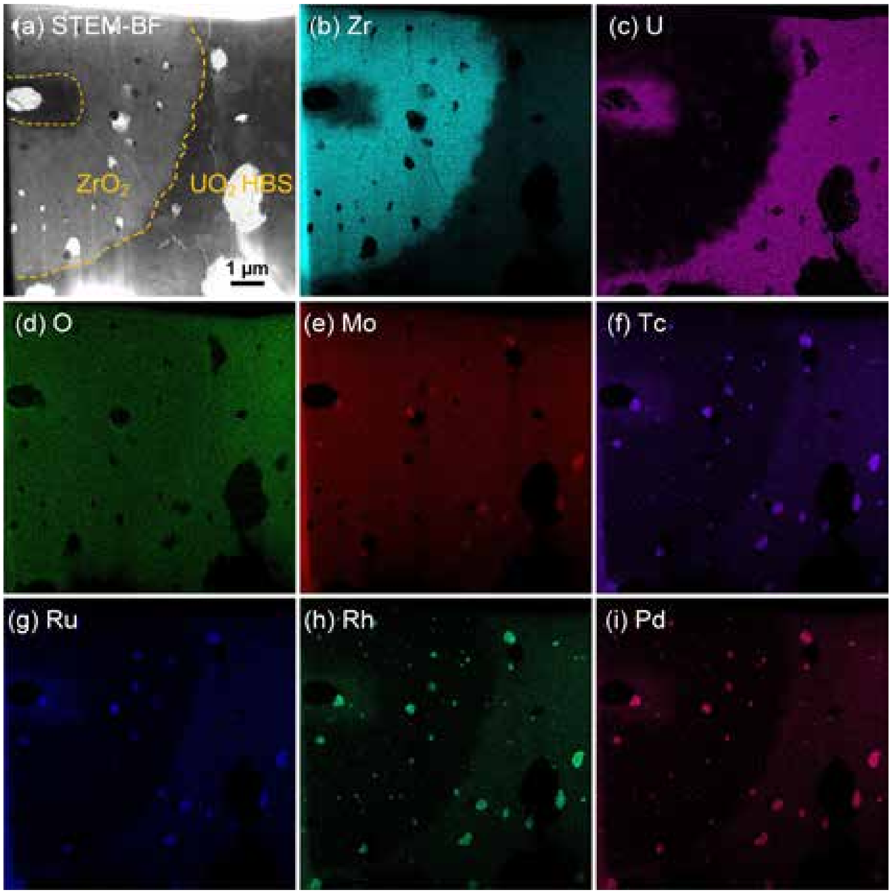

Figure 1. STEM-EDS results of the PCI-UO_2 fuel interface: (a) STEM bright-field image showing the ZrO_2 region and the UO_2 region; both regions contain pores. (b) to (i) Elemental maps of Zr, U, O, Mo, Tc, Ru, Rh, and Pd, respectively.

Distributed Partnership at a Glance	
NSUF and Partners	Facilities and Capabilities
Idaho National Laboratory	Irradiated Materials Characterization Laboratory
Collaborators	
Idaho National Laboratory	Daniel Jädernäs (collaborator), M Nedim Cinbiz (principal investigator), Lingfeng He (collaborator), Xiang Liu (collaborator)

Study of Nb Redistribution in ZrNb Alloys Following Proton Irradiation by Transmission Electron Microscopy with Energy Dispersive X-ray Spectrometry

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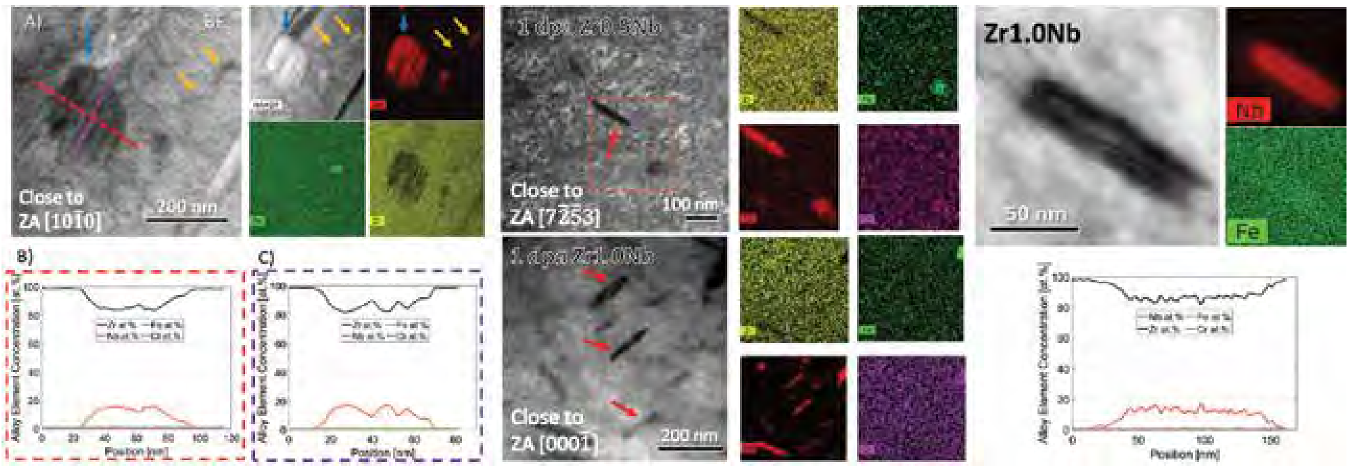
This rapid-turnaround experiment (RTE) proposed to study the effect of irradiation on Nb redistribution in ZrNb alloys, providing knowledge on Nb redistribution and to quantify Nb concentration in both precipitates and matrix after irradiation. The overall research program aimed at precisely characterizing the microstructure and microchemistry of proton-irradiated ZrNb alloys with different Nb contents below and above the theoretical solid solubility limit to better understand in-reactor corrosion behavior of ZrNb alloys [1]. Proton-irradiated samples prepared by focused ion beam (FIB) lift out technique were studied utilizing the Titan Themis 200 transmission electron microscope (with transmission electron microscopy [TEM] and scanning transmission electron microscopy [STEM]) with super-X energy dispersive spectroscopy (EDS) at the Irradiated Materials Characterization Laboratory (IMCL). The state-of-the-art Titan provides high resolution to reveal nanostructures, and super EDS can effectively map Nb-rich precipitates in the matrix and quantify alloying-element concentrations. From analyzing the compositions of precipitates in the matrix, this study revealed the effect of irradiation on distribution of Nb atoms.

Results

The samples used in this study were Zr-xNb (x = 0.2, 0.4, 0.5 and 1.0 wt.%) binary model alloys, each irradiated up to 1 dpa at 350°C at the University of Wisconsin, Madison's Ion Beam Laboratory. The microstructure and microchemistry characterization primarily focus on native precipitates and irradiation-induced platelets (IIPs) [1]. The blue arrows in Figure 1 show native precipitates in the Zr matrix of the ZrNb alloy in the irradiated samples. Before irradiation, the precipitates usually contain less than 80 at.% Nb. After irradiation, native precipitates contain about 40–60 at.% Nb. IIPs were only found in Zr-0.5Nb and Zr-1.0Nb alloys. These IIPs (highlighted with red arrows in the figure) were about 100 nm long and about 20 nm wide. Because of the matrix effect, EDS sometimes shows



less than 20 at.% Nb in IIPs. However, the maximum Nb concentration in IIPs has been detected to be about 40 at.% Nb.

Conclusion

This RTE confirms that proton irradiation can redistribute Nb atoms in the Zr matrix of ZrNb alloys. This redistribution is hypothesized as the primary reason for the relatively low in-reactor corrosion kinetics experienced by ZrNb alloys even at large burnups.

This overall hypothesis is being tested through an ongoing research program at the Couet group, and this RTE has brought critical data for its validation. This information will allow reevaluation of current fuel-cladding design to maximize safety and burnup for the use in current generation of nuclear reactors through the Mechanistic Understanding of Zirconium Corrosion (MUZIC) consortium.

Figure 1. (S)TEM/EDS characterization on native precipitates (blue arrows), IIPs in Zr-0.5Nb (red arrows), and IIPs in Zr-1.0Nb (yellow arrows) [1].

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Distributed Partnership at a Glance	
NSUF and Partners	Facilities and Capabilities
Idaho National Laboratory	Irradiated Materials Characterization Laboratory
Collaborators	
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University of Wisconsin, Madison	Adrien Couet (co-principal investigator), Zefeng Yu (principal investigator)

Radiation Damage in High-Entropy Alloys

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Materials in fast reactors are expected to withstand high temperatures, damaging radiation levels, and corrosive environments for extended periods of time. They must be resistant to void swelling up to several hundreds of dpa, maintain adequate creep strength up to 650°C, fracture toughness at 320°C, and exhibit high levels of corrosion resistance in liquid-sodium or liquid-lead-alloy coolants. Therefore, the deployment of sodium fast reactors (SFRs) is, in part, limited by the development of materials that can sustain these conditions [1]. High-entropy alloys (HEAs) are composed of four or more metallic elements mixed in equimolar (or near to equimolar) ratio to favor single-phase solid-solution formation [2]. FCC HEAs based on 3d transition metals are characterized by low stacking-fault energy; thus, they deform by twinning, which increases their dislocation-storage capacity and, hence, their ductility [3]. On the other hand, HEAs based on light refractory metals exhibit high strength and limited softening up to very high temperatures [4]. These properties make them potentially attractive candidates for investigations as cladding alloys in the extreme SFR conditions. The goal of this study is to understand the microstructural changes in proposed HEAs under heavy ion irradiation to evaluate its radiation damage to enhance our fundamental understanding of irradiation effects in these multi-component alloys and to assess their potential applications in future SFRs.

Results

Two high entropy alloys, $Cr_{18.1}Fe_{27.3}Mn_{27.3}Ni_{27.3}$, and $Cr_{15}Fe_{35}Mn_{15}Ni_{35}$, along with reference materials (model Alloy 709, Ni, and V) were irradiated at 500 °C with 3.7 MeV self-ions Ni^{2+} to 50 dpa. The irradiations of FCC materials resulted in the formation of perfect dislocation loops against a dislocation network. The average size of all loops is quite similar, ranging from approximately 13 to 20 nm in the longest dimension. Voids (shown in Figure 1) were also found in $Cr_{15}Fe_{35}Mn_{15}Ni_{35}$, but not in $Cr_{18.1}Fe_{27.3}Mn_{27.3}Ni_{27.3}$ beyond the damage peak predicted by the Stopping and Range of Ions in Matter (SRIM), which supports the idea that interstitial loops are generally less mobile with increased compositional complexity.

Conclusion

The mobility of interstitial loops depends on the compositional complexity of the material, decreasing as the complexity increases. In an isotropic neutron-irradiation environment, the formation of dislocations, which are immobile even after unfaulting, may increase the sink strength and reduce the time needed to form a supersaturation of vacancies and for voids to grow to larger sizes.

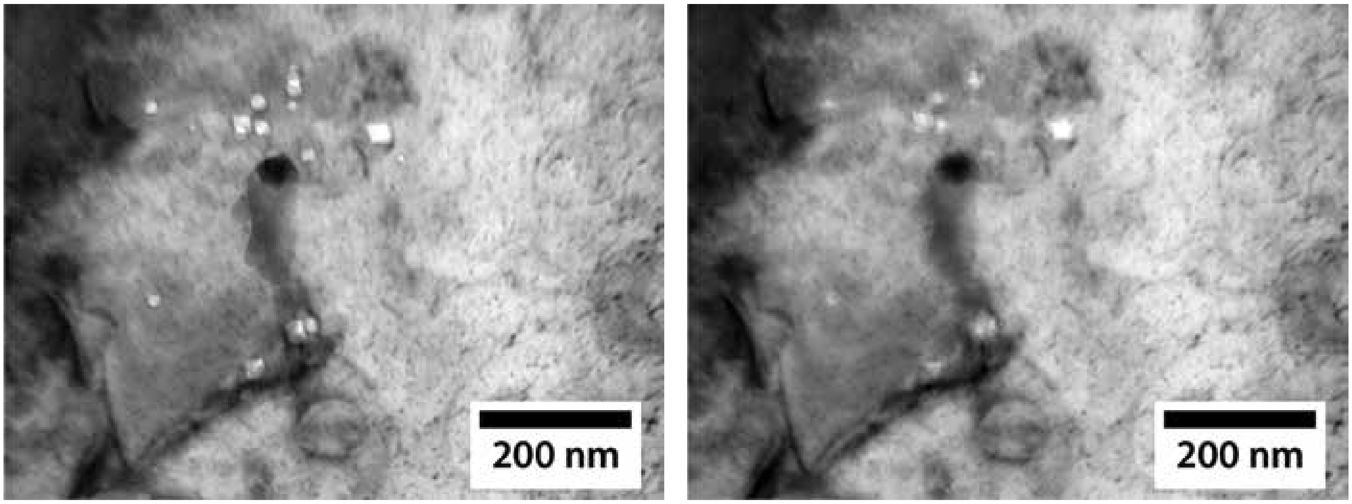

Figure 1. Micrographs of voids seen in $Cr_{15}Fe_{35}Mn_{15}Ni_{35}$ irradiated at 500°C. Left is under focused, and right is over focused to show the features are in fact voids.

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Distributed Partnership at a Glance	
NSUF and Partners	Facilities and Capabilities
University of Wisconsin	Ion Beam Laboratory
Collaborators	
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Characterization and Modeling of Secondary Phase Evolution in an Irradiated Zr-1.0Nb Alloy

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The objective of this study is to characterize the evolution of Nb-rich clustering and solute migration in a Zr-1.0%Nb alloy irradiated with either neutrons or Kr^{2+} ions to otherwise similar conditions (5 dpa at 310°C), enabling isolation of the dose-rate effects. Zirconium-based alloys are commonly used as cladding materials in existing reactor applications because of their low thermal-neutron absorption cross section, good corrosion resistance at high temperature, and high resistance to irradiation-induced swelling and creep. More recent development of Zr-based alloys with small amounts of niobium has also demonstrated improvement in corrosion resistance and the ability to minimize irradiation-induced linear growth. In this study, an RXA Zr-1.0%Nb alloy was irradiated with Kr^{2+} or neutrons to a common dose of ~5 dpa (each at 310°C). Atom-probe tomography is used to quantify any solute-cluster morphology and the solute concentrations in the matrix, clusters, and preexisting β-Nb precipitates before and after each irradiation. This approach enables systematic characterization of the Nb-solute migration as a result of irradiation, along with an evaluation of dose rate effects and the ability for Kr^{2+} ions to emulate neutron irradiation at low dose.

Results

In this study, atom-probe tomography (APT) is used to systematically quantify the migration of Nb solutes due to each irradiation. Prior to irradiation, only β-Nb precipitates are observed, with a surrounding matrix containing 0.59 at% Nb, which is close to the solubility limit for Nb [1,2]. Following both irradiations, nanoscale Nb-rich clusters are found within the matrix, consistent with prior observations [1,3,4], and are likely elongated or needle-shaped, with an average aspect ratio of ~2:1 measured using APT. The irradiation-induced clustering coincides with a reduction in matrix composition of Nb to 0.36 at% and 0.49 at% following Kr^{2+} ion or neutron irradiation, respectively. This evidence suggests the solutes migrate from the matrix to irradiation-induced clusters. The size of the Nb clusters are 4.51 ±1.09 nm and 4.17 ±2.23 nm following Kr^{2+} and neutron irradiation, respectively, while number density of the Nb clusters are 379 × 10^{21} m^{-3} and 253 × 10^{21} m^{-3} following the same irradiation conditions. Therefore, Kr^{2+} irradiations have resulted in higher volume fraction of Nb clustering at the same dose and temperature as neutron irradiation.

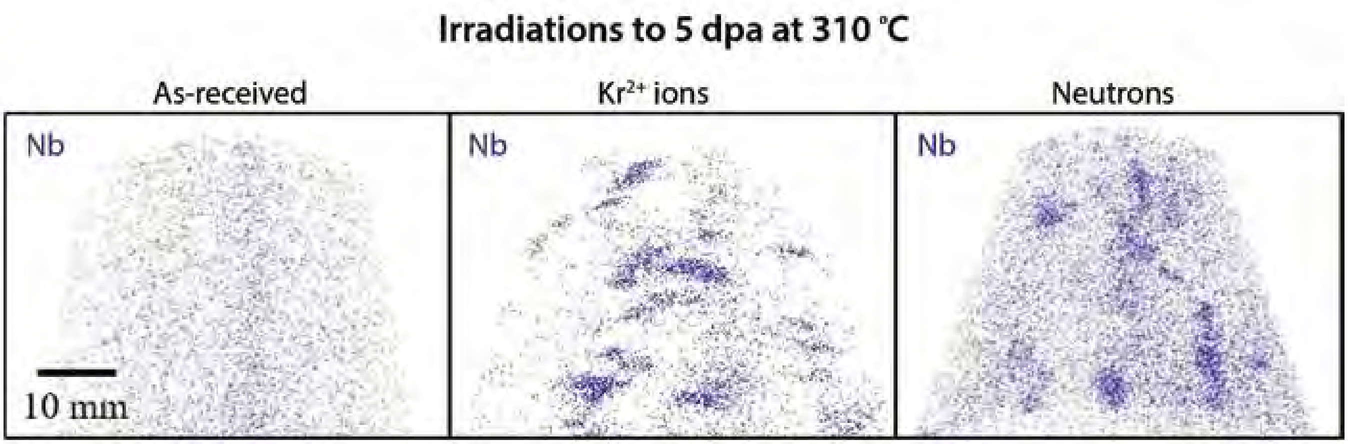

Figure 1. Atom Probe concentration maps for Nb in Zr-1.0%Nb matrix. Following each irradiation, small Nb-rich nanoclusters are observed, with comparable size and number density.

Conclusion

Irradiation with either Kr^{2+} ions or neutrons to 5 dpa at 310°C have each led to the development of Nb-rich nanoclusters in a Zr-1.0%Nb alloy. Nanoclusters rich in Nb are expected to impede the growth of <c> loops in Zr-based alloys, likely reducing the effects of irradiation-induced linear growth [5,6]. The Nb clustering also lowers the amount of Nb in solid solution within the matrix, likely improving the corrosion resistance of the alloy [1]. The Kr^{2+} ion irradiation appears to be a reasonable emulation of neutron-irradiation effects on Nb solute migration, but some key differences are noted.

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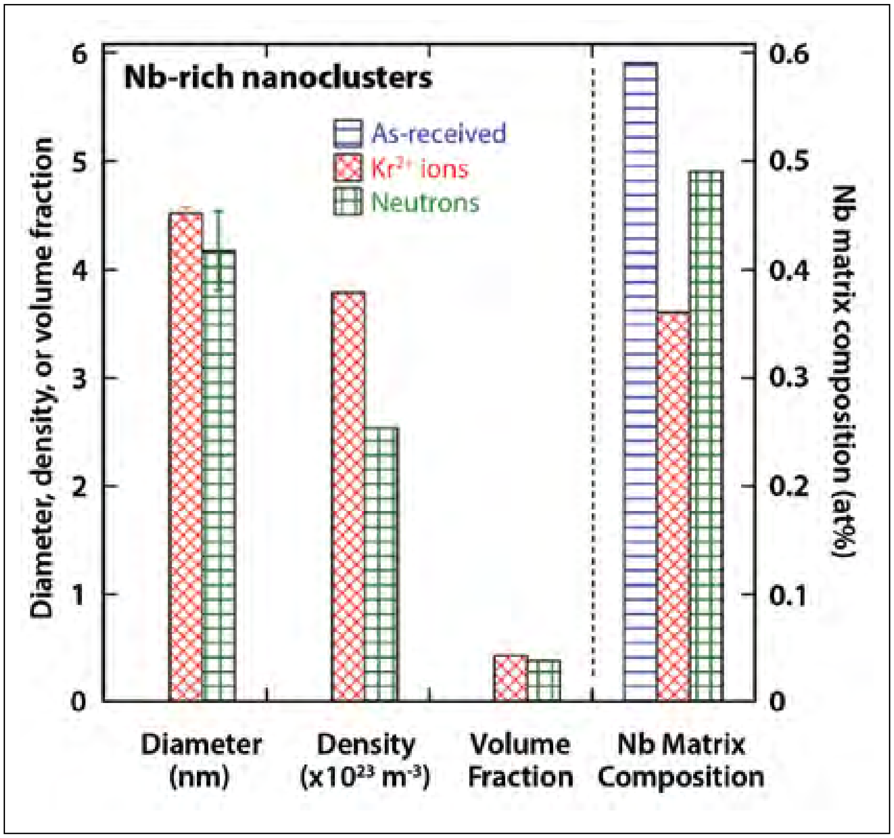

Figure 2. Summary of Nb-rich cluster morphology follow each irradiation and the resulting evolution in the matrix composition of Nb in at%. Error bars for diameter represent the standard deviation of the mean.

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Distributed Partnership at a Glance	
NSUF and Partners	Facilities and Capabilities
Center for Advanced Energy Studies	Microscopy and Characterization Suite
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Active Irradiation Testing of Temperature Sensing Capability of Clad Sapphire Optical Fibers With Type 2 Bragg Gratings Using Optical Backscatter Reflectometry

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This work investigated the temperature-sensing capabilities of Type II fiber Bragg gratings (FBGs) inscribed in sapphire optical fiber in The Ohio State University Research Reactor (OSURR) (Figure 1). A Luna Innovations 4600 optical backscatter reflectometer (OBR) was used to interrogate FBGs in three sapphire optical fibers with an internal cladding that was developed by Ohio State [1]. The sapphire fibers were fusion-spliced to silica lead fibers. In addition to the sapphire fibers, two silica fibers with the same Type II FBGs were included in the experiment as a reference. The fiber-based sensors were irradiated in the Central Irradiation Facility (CIF) of the OSURR for a total of 40 hours over five days at a reactor power of 450 kW, resulting in a total neutron fluence of approximately 2.5×10^{18} n/cm^2 and a gamma dose of approximately 3.48 Grad. Two K-type thermocouples were included within the rig: one at the core centerline and the other 12 inches above the top of the core. The temperature was not actively controlled, but the thermocouples were used to provide a reference to which the fiber-based temperature measurements could be compared.

Results

The FBGs located closest to the silica-to-sapphire fiber splices generally performed much better than the FBGs located further from the splice. All measurements for FBGs located more than ~5−10 cm from the silica-to-sapphire splice either failed or showed prohibitive noise, perhaps indicating that the cladding of the sapphire fiber was not effective in achieving single-mode operation. However, for two of the three sapphire fibers, the FBG located closest to the silica-to-sapphire splice performed well, with the magnitude and time response of the fiber-optic measurements generally matching those of the thermocouples for all five days of irradiation (Figure 2). Some of the observed differences between the various sapphire fibers could be attributed to pre-irradiation heat treatment. The two sapphire fibers that showed better performance were heat treated at >1300°C prior to irradiation while the remaining fiber was heat-treated at 1000°C. The thermal annealing of the clad optical fiber may have a significant effect on transmission in the fiber, due to the creation of nanovoids [2]. The FBGs inscribed in the silica fibers showed no significant noise or signal drift over five days of irradiation, indicating that the Type II gratings themselves perform well under irradiation.

Conclusion

This work showed that temperature sensing using FBGs in sapphire optical fiber is possible given that at least one FBG in two of the three sapphire fibers survived and gave reliable readings up to a total neutron fluence of approximately 2.5×10^{18} n/cm^2. There is still a need to reduce the modal volume and the intrinsic attenuation in the sapphire fibers. However, if these challenges can be overcome, the high melting temperature of sapphire (>2000°C) makes sapphire optical-fiber sensors a potential candidate for monitoring of centerline temperatures during irradiation testing of advanced fuels for high-temperature

Figure 1. Experiment installed in the central irradiation facility of The Ohio State University Research Reactor.

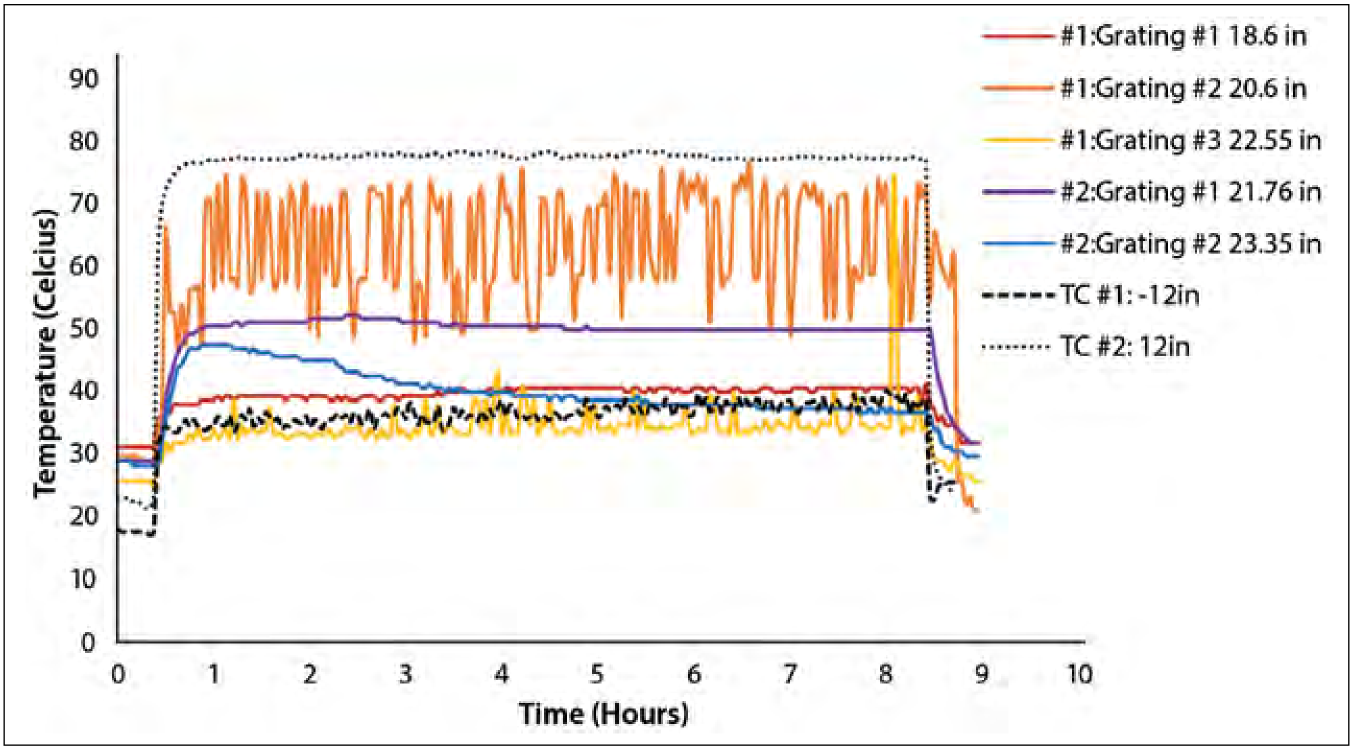

Figure 2. Temperatures measured by FBGs in sapphire Fibers 1 and 2, as well as thermocouples as a function of time on the fifth day of irradiation. Measurements were made at various distances below the top of the OSURR core, with the reactor midplane located 12 inches below the top of the core.

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Distributed Partnership at a Glance	
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Oak Ridge National Laboratory	Christian M. Petrie (principal investigator)
The Ohio State University	Brandon Wilson (collaborator), Kelly McCary (collaborator), Thomas Blue (co-principal investigator)

In-situ Small-Scale Mechanical Testing of Fast Reactor Mixed Oxide Pins

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The sample investigated in these experiments belongs to a mixed oxide (MOX) legacy pin, available in a hot cell at the Hot Fuels Examination Facility of Idaho National Laboratory. The pin was irradiated in the Fast Flux Test Facility between 1985 and 1992. From the sample, four blocks of size approximately 70 µm × 70 µm × 30 µm were cut from the original sample using the FEI Helios plasma focus ion beam installed at the Irradiated Materials Characterization Laboratory. Blocks 1 and 2 were cut close to the central hole of the fuel pellet, and Blocks 3 and 4 were cut close to the fuel periphery. The blocks were embedded within precut pockets and welded with Pt in a stainless steel disk of 5 mm diameter that could be mounted in the mechanical testing equipment. The blocks were tested with a Hysitron PI 88 scanning electron microscope pico indenter to measure both elastic modulus and hardness. Prior to mechanical testing, electron backscattered diffraction (EBSD) data were collected on the MOX blocks at the Electron Microscopy Laboratory. Nanoindentation was conducted at room temperature in displacement-control mode to 200 nm on the blocks, all under vacuum.

Results

Qualitative inverse pole figures were acquired to evaluate the crystallinity of the cfuel samples. The main phase is composed of a solid solution of $(U,Pu)O_2$. The small inclusions present with different crystal orientation have either a cubic structure compatible with $(Ba,Zr)O_3$ phases or hexagonal structure typical of Mo-Ru-Rh-Tc-Pd noble metal precipitates [1]. The measured reduced modulus E_r (GPa) was converted to elastic modulus E (GPa) using Equation 1:

$$\frac{1}{E_r} = \left(\frac{1-v_s^2}{E_s} + \frac{1-v_i^2}{E_i}\right)$$

where E_i (GPa) is the indenter Young's modulus and, v_s and v_i the sample and indenter Poisson's ratios, respectively. A Berkovich diamond tip was used for the present tests. The Young's modulus and Poisson's ratios are 1140 GPa and 0.07, respectively. Regarding the MOX Poisson's ratio, the recommended formula by Martin [2] was used:

$$v = 0.326(1 + 0.11x)$$

where x is the sample deviation from stoichiometry, which was assumed to be the as-fabricated value.

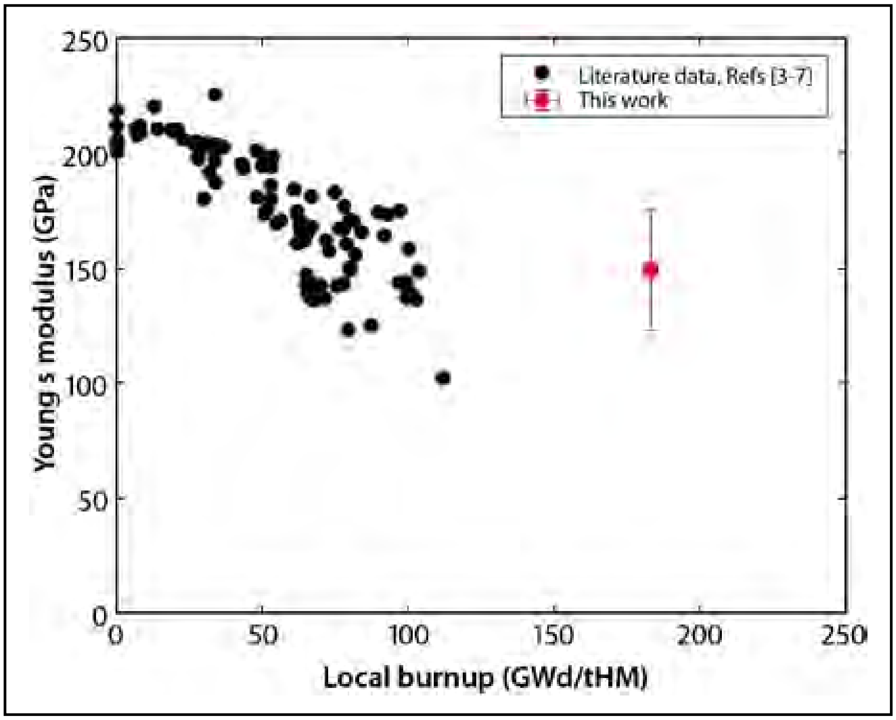

Figure 1. Measured Young's modulus versus burnup. Red square represents the average of the six indentations from this work. Black circles represents published data on irradiated ceramic fuels. [3–7]

The hardness value was calculated according to Equation 3:

$$H = \frac{F_{max}}{A_c}$$

where H (Pa) is the sample hardness, F_{max} (N) is the maximum load, and A_c (m^2) is the indentation area.

As the PI 88 stage holds the sample surface parallel to the electron beam, the indentation imprint could be checked only once the PI 88 is removed from the scanning electron microscopy chamber at the end of the measurement campaign. Secondary electron images were collected with the FEI Quanta following indentation tests to evaluate the imprints. The measured elastic modulus of the nanoindentation work can be seen in Figure 1, compared with available literature data.

Conclusion

The present work represents a pioneering study in the application of advanced techniques to measure micromechanical properties of highly radioactive advanced nuclear fuels. First data of Young's modulus and hardness of fast reactor MOX at burnup exceeding 150 GWd/tHM have been obtained. Despite the challenges encountered in the current work, the experimental approach sought in this work has been proved successful in obtaining new data of high relevance for fuel performance on a system with high Pu content and high radiotoxicity with extremely limited exposure to personnel. Further experiments will be conducted in the future based on the present approach, leveraging the experience gained in this project.

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Distributed Partnership at a Glance

NSUF and Partners	Facilities and Capabilities
Idaho National Laboratory	Electron Microscopy Laboratory, Irradiated Materials Characterization Laboratory
Collaborators	
Idaho National Laboratory	Brandon Miller (collaborator), Daniel Murray (collaborator), Fabiola Cappia (co-principal investigator)
Los Alamos National Laboratory	David Frazer (principal investigator)
Oak Ridge National Laboratory	Jason Harp (collaborator)

High Fluence Irradiation Testing of Fiber Optic Material Transmission

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This work leveraged a recently completed irradiation of capsules assembled and inserted into the High Flux Isotope Reactor (HFIR) in FY 2017. NSUF funding allowed for post-irradiation measurements by Dr. Petrie of the contents of the rabbit capsules. Each capsule contained 12 fiber-optic-material slab specimens, split equally between: 1) low-OH fused silica, 2) high-OH fused silica, and 3) single crystal-sapphire materials. The nominal sample dimensions were 16 mm long × 5 mm wide × 0.85 mm thick. The rabbit capsules were irradiated for approximately one 24 day HFIR cycle. Each capsule was designed to achieve a unique temperature that is typical of light-water reactors or some high-temperature advanced reactors.

The pre- and post-irradiation transmission and density measurements were made at Oak Ridge National Laboratory (ORNL) at the Low Activation Materials Development and Analysis (LAMDA) Facility. Optical transmission was measured through the sample thickness, using a broadband optical-transmission system, which allowed for the measurement of radiation-induced attenuation (RIA) in the specimens over a wavelength range from approximately 200–1700 nm.

Results

Measurements of RIA and radiation-induced dimensional changes were made in a-SiO_2 samples that were subjected to high-dose neutron irradiation at temperatures of 95, 298, and 688°C (based on dilatometry, using passive SiC temperature monitors) (Figure 1). These temperatures are higher than those of previous work. Results show that RIA may be approaching saturation for the range of photon energies that were tested and that the hydroxyl content has a significant impact on RIA when the irradiation temperature is increased to 688°C. For 1550 nm operation, however, the observed increase in RIA does not preclude interference-based measurements of fiber temperature. A model was developed for predicting radiation-induced compaction, and the resulting impact on signal drift and RIA for Bragg grating sensors as a function of neutron fluence and temperature. The data were well fit by a simple model. The sapphire samples showed significant RIA that increased with increasing temperature. However, the samples may have suffered from diffusion of impurities from the surrounding capsule materials at high temperatures. Additional characterization is being planned to confirm whether impurities were introduced.

Conclusion

The primary concern for implementing a-SiO_2 fiber-optic sensors in a nuclear environment is the RIA of the light signal due to the formation of radiation-induced color centers. In addition, Bragg-grating sensors drift under irradiation due to radiation-induced compaction of the a-SiO_2 structure. Our work provides new data regarding RIA and radiation-induced compaction of a-SiO_2 samples irradi-

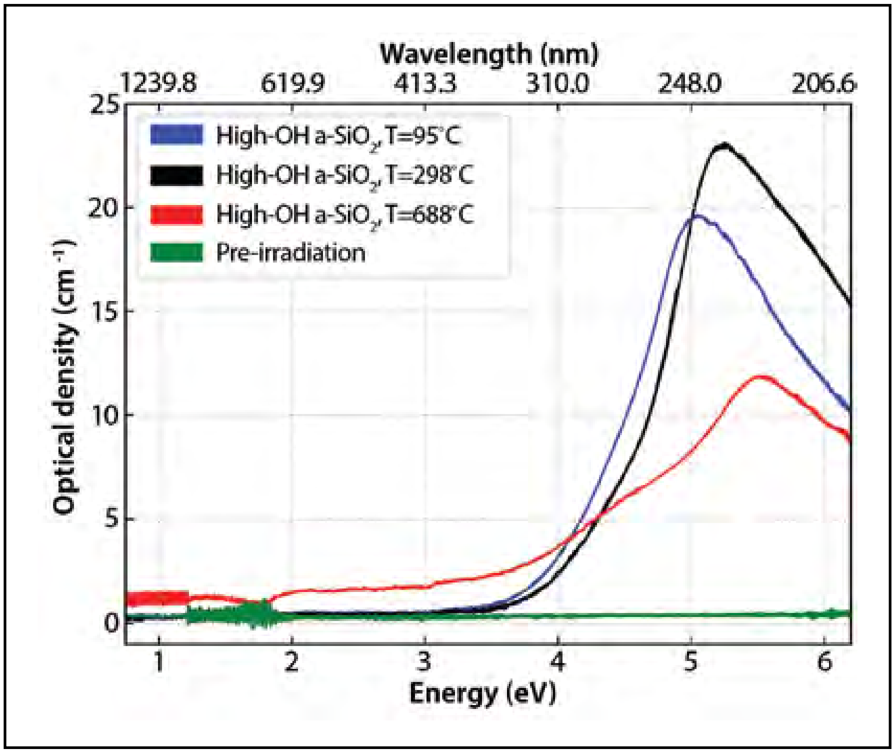

Figure 1. Optical density vs. photon energy and wavelength with irradiation temperature (T) as a parameter for the high-OH a-SiO_2 samples.

ated to a fast neutron fluence of 2.4×10^{21} n/cm^2 at temperatures of 95, 298, and 688°C. The observed increase in RIA does not preclude interference-based measurements of fiber temperature. However, the effects of drift can be significant and may require compensation.

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Distributed Partnership at a Glance	
NSUF and Partners	Facilities and Capabilities
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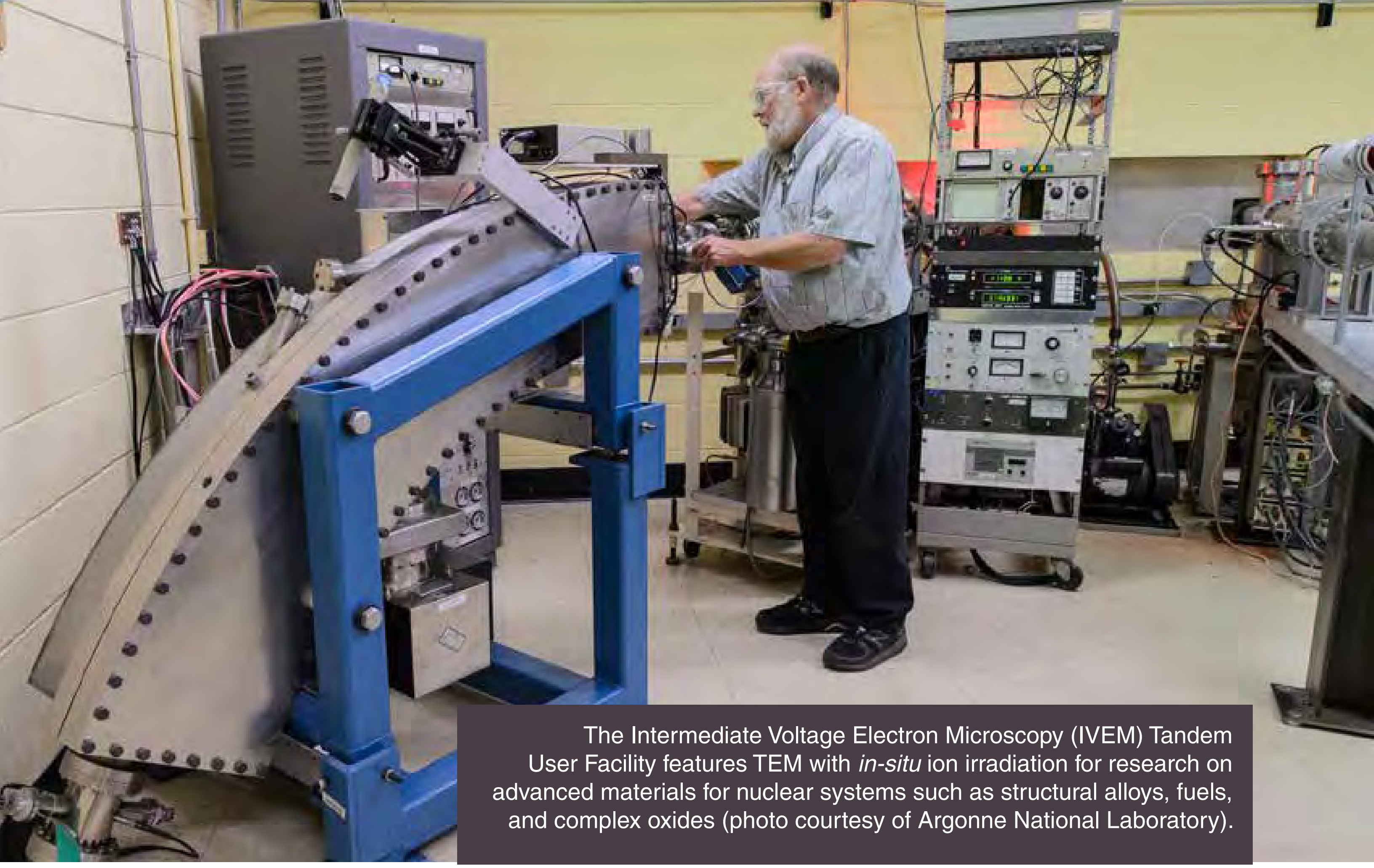
Ohio State University	Dr. Thomas E. Blue (principal investigator)

NSUF LIST OF ACRONYMS

AI .... artificial intelligence
AML .... Activated Materials Laboratory
ANS .... American Nuclear Society
APT .... atom probe tomography
ATR .... Advanced Test Reactor
BEIS .... Business, Energy, and Industrial Strategy
BNL .... Brookhaven National Laboratory
C3 .... Collaborative Computing Center
CAES .... Center for Advanced Energy Studies
CINR .... Consolidated Innovative Nuclear Research
CIR .... Central Irradiation Facility
CNL .... Canadian Nuclear Laboratories
CoMET .... Combined Materials Experiment Toolkit
DFT .... density functional theory
DISECT .... Disc Irradiation for Separate Effects testing with Control of Temperature
DOE .... Department of Energy
DOE-NE .... Department of Energy Office of Nuclear Energy
dpa .... displacements per atom
EBR-II .... Experimental Breeder Reactor II
EBSD .... electron backscatter diffraction
EDS .... energy dispersive spectroscopy
EELS .... electron energy loss spectroscopy
EXAFS .... extended X-ray absorption fine-structure spectroscopy
FASB .... Fuels and Applied Science Building
FBG .... fiber Bragg grating
FCCI .... Fuel Cladding Chemical Interaction
FFTF .... Fast Flux Test Facility
FIB .... focused ion beam
FOA .... Funding Opportunity Announcement
GAIN .... Gateway for Accelerated Innovation in Nuclear
HEA .... high-entropy alloy
HFIR .... High-Flux Isotope Reactor
HPC .... high performance computing
IASCC .... Irradiation Assisted Stress Corrosion Cracking
IIP .... irradiation-induced platelets
IMCL .... Irradiated Materials Characterization Laboratory
INL .... Idaho National Laboratory
IVAS .... Integrated Visualization and Analysis Software
LAMDA .... Low Activation Materials Design and Analysis Laboratory
LANL .... Los Alamos National Laboratory
LWR .... light water reactor
MaCS .... Microscopy and Characterization Suite
MD .... molecular dynamics
MFC .... Materials and Fuels Complex
MOX .... mixed oxide
MRE .... Materials in a Radiation Environment
MUZIC .... Mechanistic Understanding of Zirconium Corrosion
NADM .... Nuclear Academics Discussion Meeting



The Intermediate Voltage Electron Microscopy (IVEM) Tandem User Facility features TEM with *in-situ* ion irradiation for research on advanced materials for nuclear systems such as structural alloys, fuels, and complex oxides (photo courtesy of Argonne National Laboratory).

NEID........................ Nuclear Energy Infrastructure Database

NFML .... Nuclear Fuels and Materials Library

NMDQi.......................................Nuclear Materials Discovery and Qualification Initiative

NNUF..................................... National Nuclear User Facility

NSUF.......................................Nuclear Science User Facilities

OBR......................................optical backscatter reflectometer

ODS ....oxide dispersion strengthened

ORNL .... Oak Ridge National Laboratory

OSURR ....Ohio State University Research Reactor

PI ....principal investigator

PWR .... pressurized water reactor

RIA ....radiation induced attenuation

RIS.. radiation induced segregation

RPV..reactor pressure vessel

RTE ....Rapid Turnaround Experiment

SEM ....scanning electron microscope

SFR .... sodium fast reactor

SMR.. small modular reactor

TEM .... transmission electron microscope

TREAT ....Transient Reactor Test

WAXS .... wide-angle X-ray scattering

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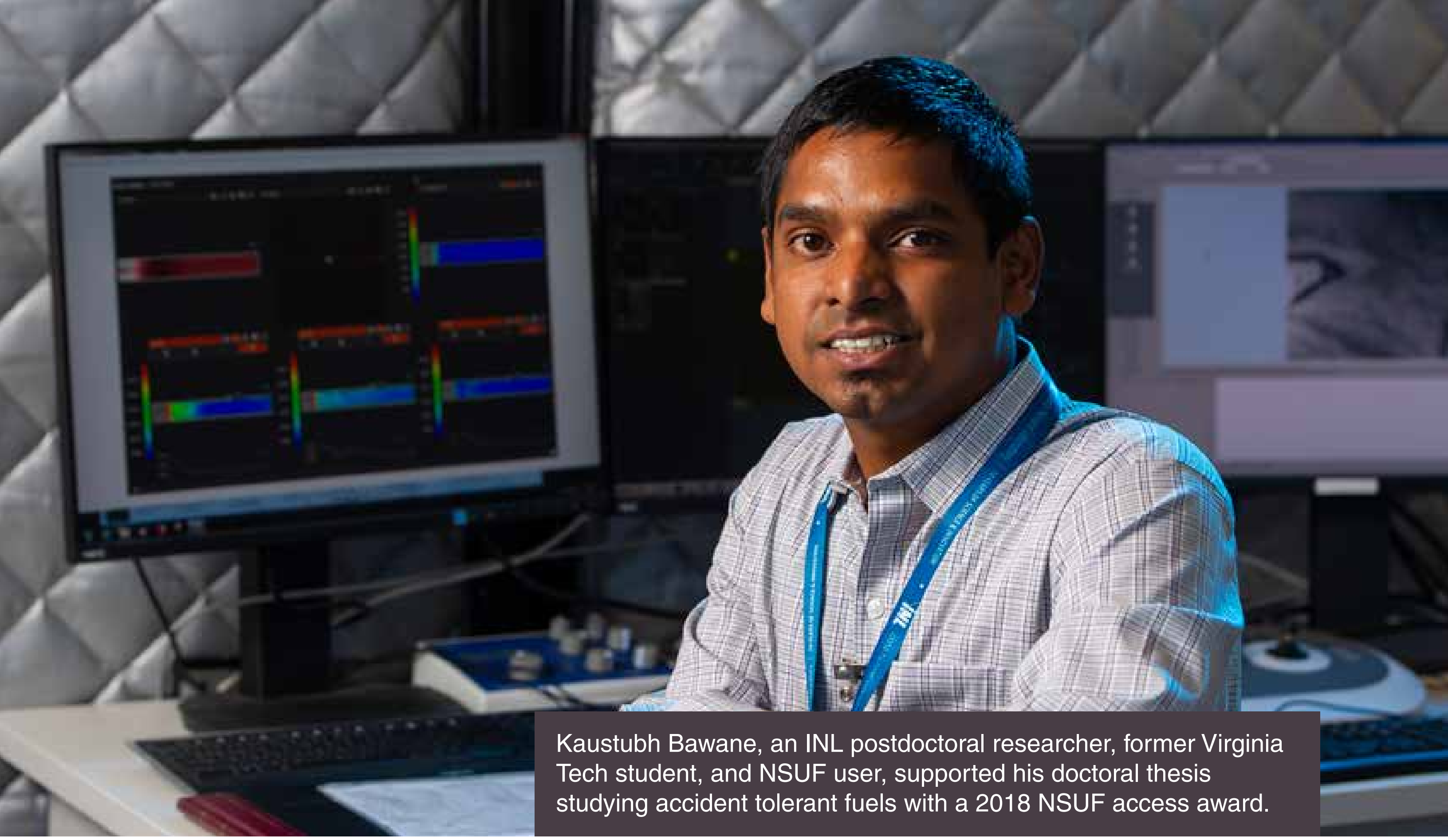
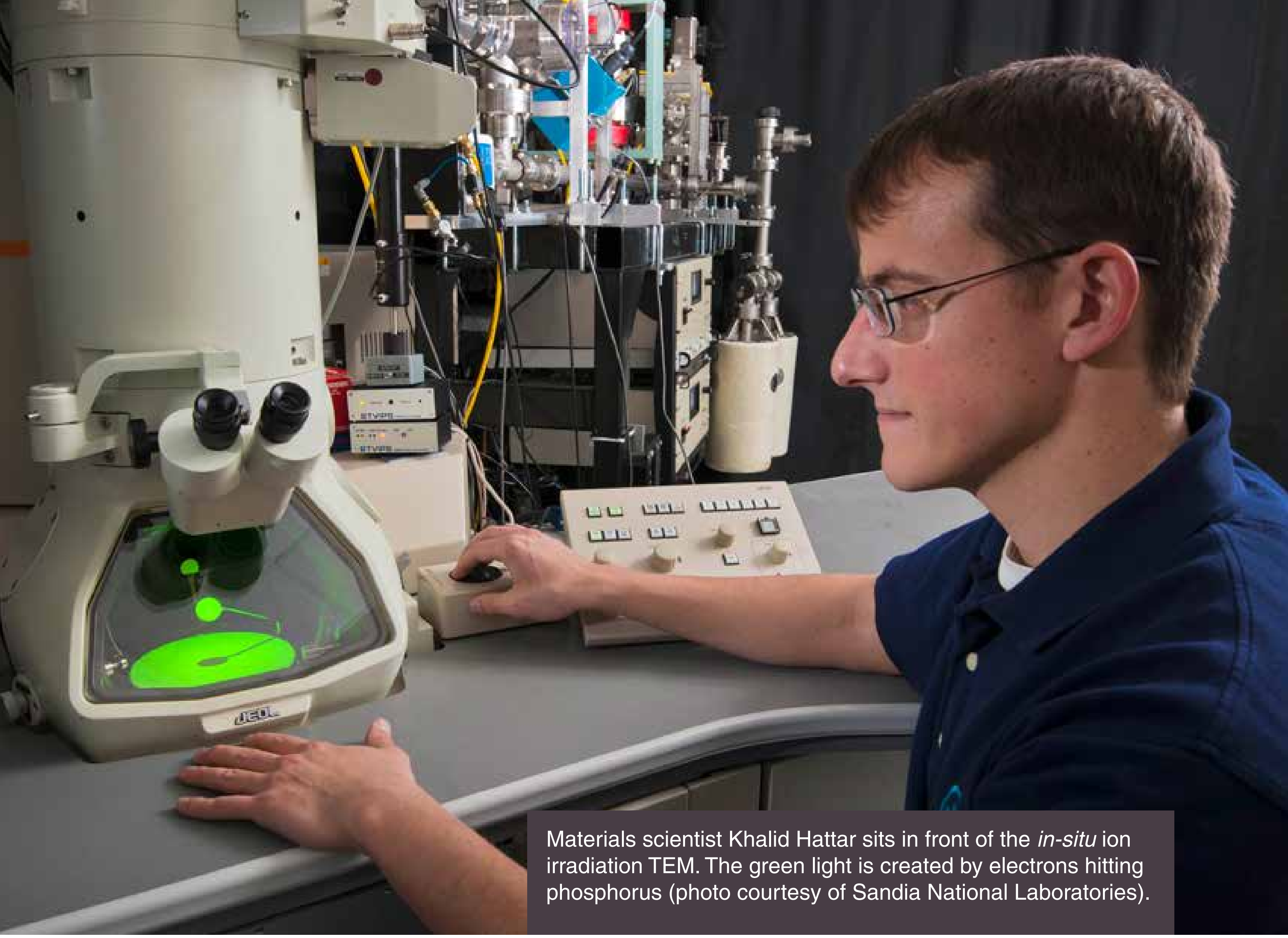


Kaustubh Bawane, an INL postdoctoral researcher, former Virginia Tech student, and NSUF user, supported his doctoral thesis studying accident tolerant fuels with a 2018 NSUF access award.



Materials scientist Khalid Hattar sits in front of the *in-situ* ion irradiation TEM. The green light is created by electrons hitting phosphorus (photo courtesy of Sandia National Laboratories).

NSUF Nuclear Science User Facilities

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