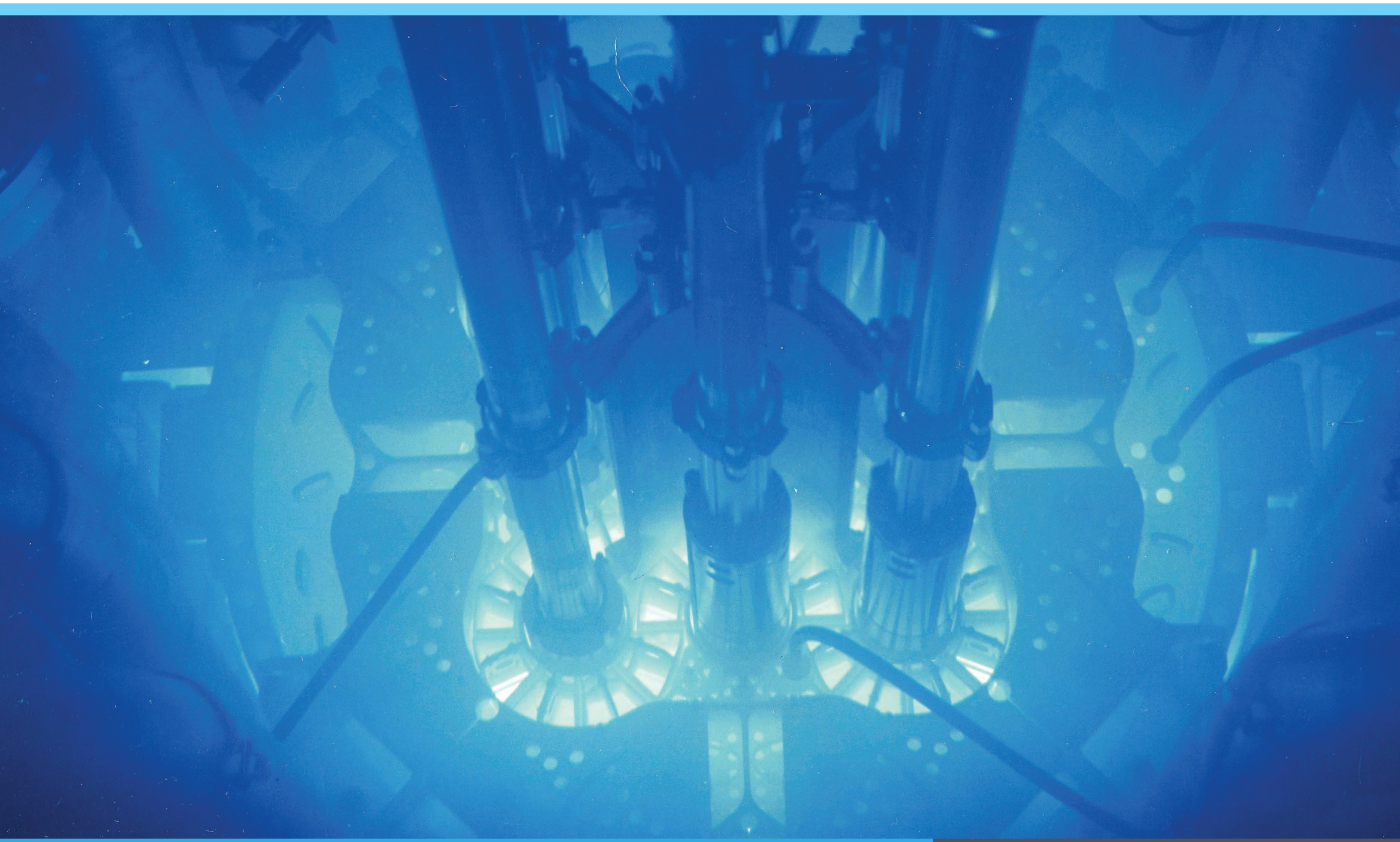
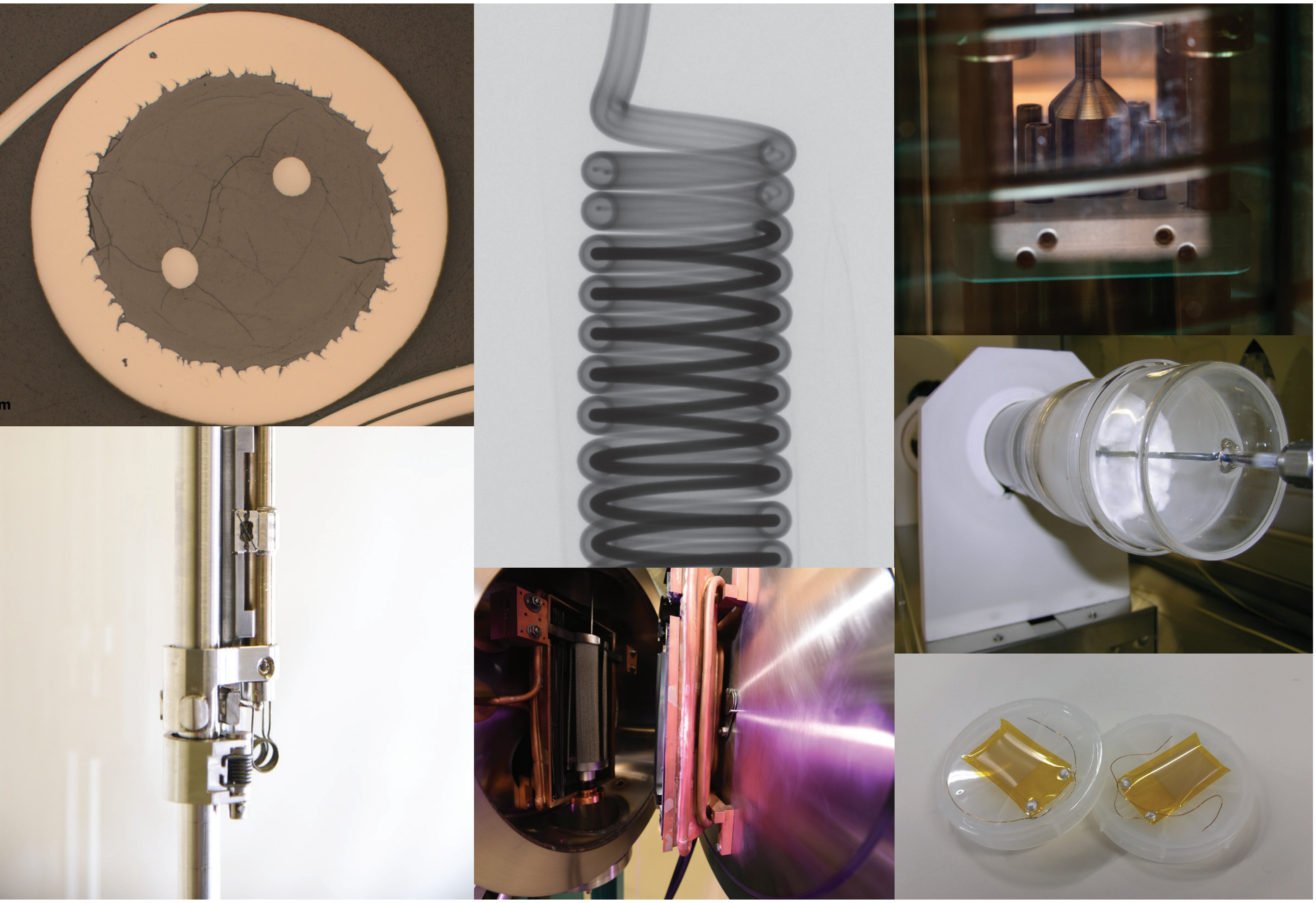


In-Pile Instrumentation (I2)

2018 Report

U.S. DEPARTMENT OF ENERGY
Nuclear Energy

Idaho National Laboratory



In-pile Instrumentation sensors developed in 2018

IN-PILE INSTRUMENTATION OVERVIEW (I2)

Energy demand is growing exponentially, renewing interest in nuclear technology as a reliable, carbon-free energy source. In alignment with the U.S. Department of Energy (DOE), Idaho National Laboratory's (INL's) primary mission is to discover, demonstrate and secure innovative nuclear energy solutions. The capability to monitor the conditions inside nuclear reactors core is considered essential to this development process. To enable such capability, the In-Pile Instrumentation (I2) program was conceived in 2017 as an additional element to DOE Crosscutting Technology Development activities under the Nuclear Energy Enabling Technology (NEET) program. This document reports on the first year of implementation of research activities.

Addressing instrumentation needs for DOE Nuclear Energy programs and the nuclear industry

Pattrick Calderoni

The I2 program was initially conceived at INL in response to weaknesses in developing instrumentation to support irradiation tests in operating Material Test Reactors (MTRs), with focus on the INL Advanced Test Reactor (ATR).

The main concern identified was the need to demonstrate the reliability and performance of sensors under the extreme environmental conditions of a nuclear reactor core, which provide a combination of temperature, pressure, and radiation that is unique to this application. Commercial sensors with certified performance for other high-tech industries repeatedly failed when integrated into ATR tests, sometimes even before the tests started. Similarly, innovative sensors with low technological maturity needed design optimization and screening before being accepted for deployment. "This made it risky to meet testing requirements and failing or faulty sensors can cause massively expensive delays," said Dr. Pattrick Calderoni.

Calderoni is manager of the INL Measurement Science Department and the In-Pile Instrumentation (I2) program. He came to the program because of his technical and leadership skills, consolidated during his five years deployed as project manager for ITER, a large-scale scientific experiment under construction in the south of France.

"There has been little innovation in instrumentation and control because it's an extremely high risk to use sensor technologies that haven't been through careful development and testing," said

Dr. Calderoni. "At the same time, the capability to test under conditions relevant to the operation of a nuclear reactor are extremely limited and the process too lengthy and costly to be undertaken by a single developer."

THE I2 PROGRAM SEEKS TO ESTABLISH THE CAPABILITY WITHIN DOE-NE LABORATORIES TO DESIGN, FABRICATE, TEST, AND QUALIFY SENSORS FOR MONITORING AND CONTROLLING EXISTING AND ADVANCED REACTORS AND SUPPORTING FUEL CYCLE DEVELOPMENT.

According to Dr. Calderoni, the I2 program seeks to fill the existing gap by establishing the capability within DOE-NE laboratories to design, fabricate, test and qualify sensors for nuclear operation. Testing is performed in neutron irradiation facilities, with INL test reactors, in particular ATR and Transient Reactor Test (TREAT) Facility, at the forefront. However, other irradiation facilities can be used during specific phases of the qualification process when deemed more accessible or effective. This is where efficient coordination with the Nuclear Science User Facilities (NSUF) program is crucial for identifying opportunities in an approach that opens up opportunities for researchers and students alike. In addition, the June 2018 decision to terminate the operation of the Halden Boiling Water Reactor in Norway has provided new urgency for a timely fulfillment of the I2 program mission since the Halden project was recognized worldwide for its leadership in instrumentation development and deployment for irradiation testing.

"But the I2 program is a lot more than a qualification program for existing or mature technologies under development," said Dr. Calderoni. "The integration of basic research capabilities in measurement science, material science, nuclear engineering, and modeling and simulation will enable a new generation of instruments, from the real time, distributed measurement of reactor parameters to the characterization of fuel and material properties and microstructure during irradiation. This will benefit all NEET stakeholders, from DOE programs to nuclear vendors, and help sustain the current operating fleet, and leverage the development of advanced reactor concepts."

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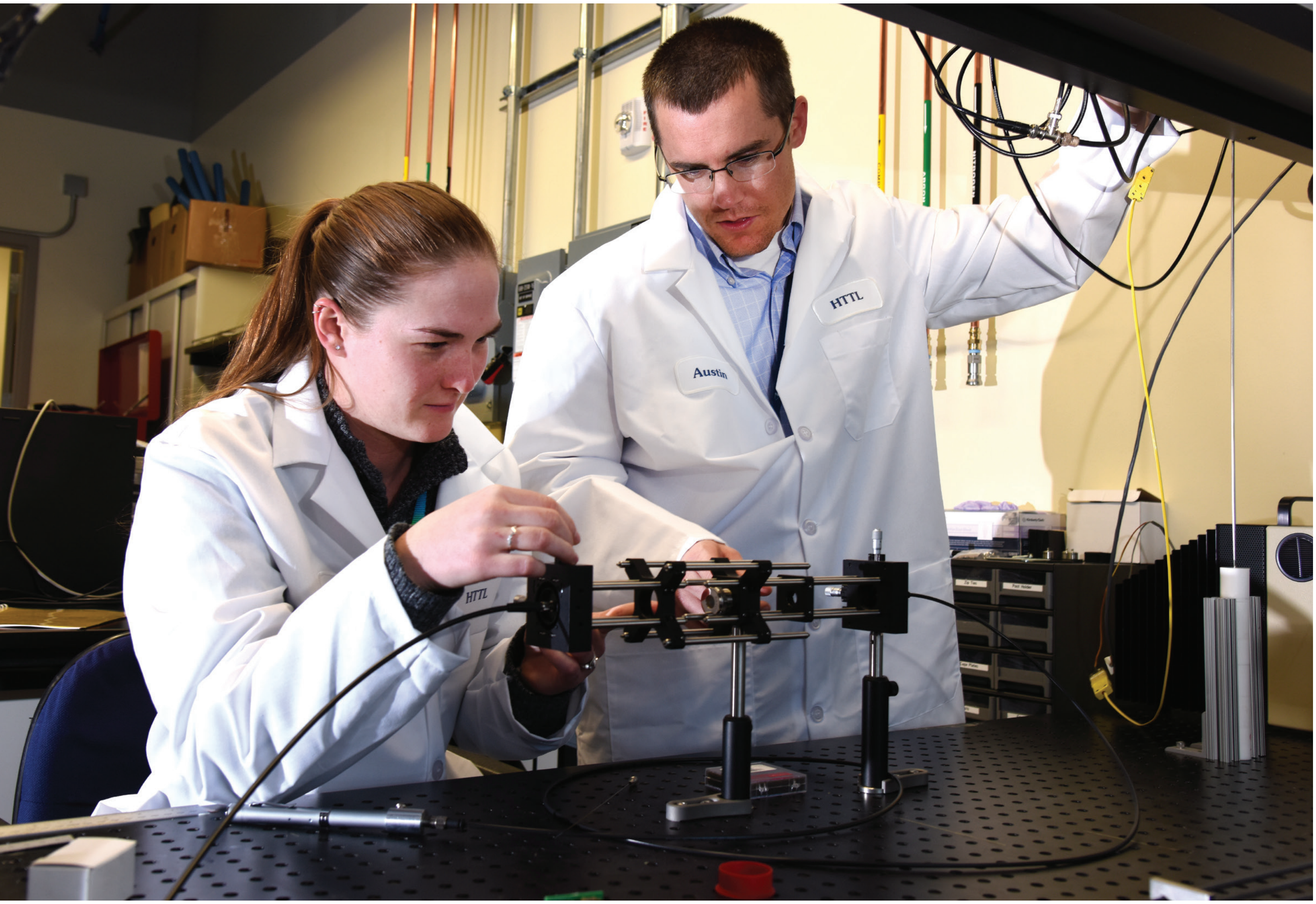


High Temperature Test Laboratory researchers working to solve complex instrumentation challenges.

CAPABILITIES

A key objective of I2's development plan is to establish baseline capabilities in terms of out-of-pile characterization and testing equipment, build a standardized instrumentation testing rig and create the processes necessary to support the new instrument-development paradigm.

Researchers have begun the work of establishing the processes that will allow them to fabricate, calibrate and deploy baseline instrumentation while also supporting research to develop instruments based on innovative technology and fabrication methods.

In this section, we showcase the unique capabilities of the instrumentation development facilities that are home to the I2 program and some of the innovations being tested in a push to expand the state of the art in measurement science.

Troy Unruh

High Temperature Test Laboratory key to I2's in-pile instrumentation research

With renewed interest in nuclear energy in the United States and worldwide, a key effort is underway to design, develop and deploy new in-pile instrumentation technology and techniques, capable of providing real-time measurements of what happens to fuel and materials during irradiation. These measurements link advanced computational capabilities with innovative experimental research. Central to the In-Pile Instrumentation (I2) program's in-pile instrumentation work is the High Temperature Test Laboratory (HTTL), located in the Energy Innovation Laboratory (EIL) at INL, a unique facility equipped to meet the nation's needs and missions.

I2 researchers have been working for years to deploy real-time sensors for material test reactor irradiation experiments. Tasks have involved evaluating advanced technologies, such as fiber-optics-based length detection and ultrasonic thermometers. Specialized sensors for passive and real-time detection of experimental conditions have not only been provided to the INL's ATR and TREAT, but they are also being provided to several international test reactors.

In addition to widespread interest in nuclear energy as a dispatchable carbon-free source of energy, safety has also been a top industry concern since the Fukushima Daiichi accident of 2011. Industry and safety regulators have set ambitious goals for developing new materials and accident-tolerant fuels to keep accidents on such a scale from happening again.

In order to investigate the behaviors and characteristics of advanced fuels and materials, in-reactor instrumentation requires versatile capabilities: high fidelity, high resolution, real-time response, rapid transient response, and proven resistance to challenging reactor environments, which include high temperatures, high pressure and radiation fields. The HTTL is indispensable to developing, fabricating and performing laboratory demonstrations of proposed new in-core tools.

The HTTL has tripled in size in recent years; from a small dedicated laboratory within INL's Nuclear Science and Technology (NS&T) department to a fully staffed service center. The HTTL is maintained though fixed-rate charges that provide access to just-in-time fabrication and evaluation capabilities. Customer needs have led to focused investments of service center reserves to upgrade the 3-D computed tomography system to provide vastly improved imaging capabilities. Additional specialized equipment for instrumentation fabrication and evaluation available to service center customers include:

- Autoclaves for sensor testing
- Specialized mineral-insulated cable fabrication equipment
- Specialty laser welders for sensor fabrication
- A real-time x-ray imaging system and 3-D computed tomography system for non-destructive evaluations
- Mechanical testing equipment for optical fibers and strain sensors
- A laser flash thermal property analyzer
- A high-resolution laser for scanning small samples
- A differential scanning calorimetry system.

The lab offers basic capabilities including digital imaging of small samples, data acquisition, hand held x-ray fluorescence analysis, high temperature furnaces (tube and vacuum), and helium leak detectors.

The HTTL is looking ahead for seismic system, structure-health monitoring and early fault detection of the reactor structure, system and components beyond fuels and sensors. In recent years, the HTTL staff has attracted funding for high temperature material property testing and for in-pile instrumentation development and testing from a host of nuclear and non-nuclear programs.

The HTTL laboratory operates as a service center for the NS&T Directorate. This allows the directorate to recover part of the operation and maintenance costs from all programs utilizing equipment and personnel resources. In addition to directly contributing to INL infrastructure investment, the recovered costs have also resulted in a rapid expansion of capabilities in just a few years.

Research Programs and Sponsors for HTTL

- Nuclear Science User Facilities (NSUF) and Rapid Turnaround Experiments (RTEs)
- INL Laboratory Directed Research and Developments (LDRD)
- Nuclear Energy Enabling Technologies (NEET) Advanced Sensors and Instrumentation
- Accident Tolerant Fuels (ATF) program
- TREAT Instrumentation Development program
- DOE Technology Commercialization Fund
- Small Business Innovative Research partnership with Radiation Detector Technologies
- Advanced Gas-Cooled Reactor program (AGR 5/6/7)
- Various university-led collaborations and Nuclear Energy University Programs (NEUP), and TREAT integrated research projects.

Joshua Daw from INL and Brain Jacques from BSU at INL's High Temperature Test Laboratory.

Laser-based metrology laboratory

The Laser-Based Metrology Laboratory (LBML) is housed in the Department of Materials Science and Engineering within the Energy Environment, Science and Technology Directorate at INL.

The lab is managed by Dr. David Hurley, directorate fellow, and the technical lead for the structure/chemistry and materials science research thrusts within the I2 Program. Dr. Hurley's research background encompasses elements of physics, mechanical engineering and materials science. This middle ground between science and engineering has given him a unique perspective on many materials issues facing the nuclear industry.

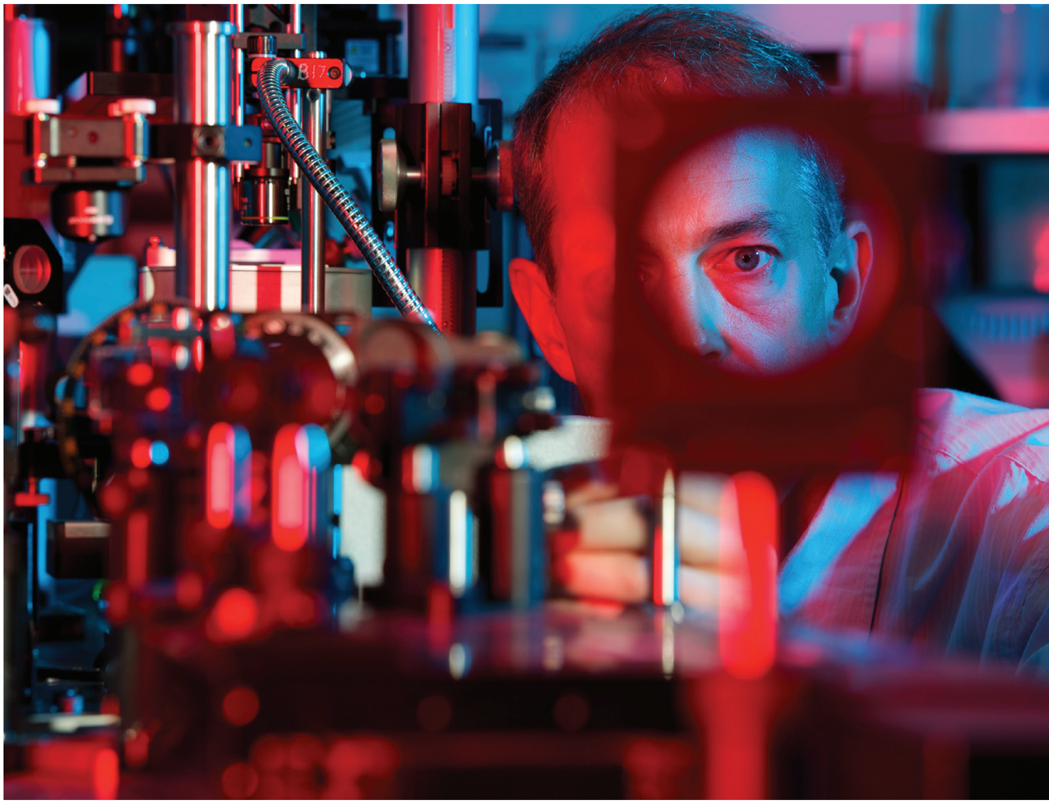
"Research conducted in LBML is focused on developing laser-based instruments to characterize aspects of nuclear materials," said Dr. Hurley. "Laser-based technologies are uniquely suited to investigating materials in extreme environments because they're, by nature, noncontact."

According to Dr. Hurley, applications include:

- Monitoring changes in mechanical texture using resonant ultrasound spectroscopy
- Measuring thermal properties of spent fuel on micron length scales
- Measuring bulk thermal conductivity of friable spent nuclear fuel
- Monitoring elastic properties at high temperatures
- Developing new techniques for process monitoring of additive manufacturing processes.

Several of these studies have direct applications to the I2 Program, including the development of a laser-based resonant ultrasound instrument to measure grain restructuring of nuclear fuel under irradiation, using zero-group-velocity plate waves to measure the dislocation contribution to acoustic attenuation, and development of a photothermal radiometry instrument to monitor in-pile changes in thermal conductivity.

The LBML also supports a wide array of optical spectroscopy including Raman, Brillouin, and photoluminescent spectroscopies and a range of surface characterization instruments including ellipsometry and optical profilometry.



Dave Hurley working in the Laser-Based Metrology Laboratory

Michael McMurtrey

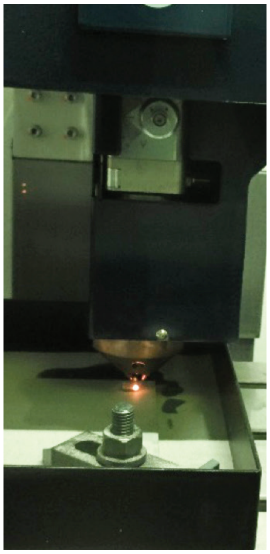
Additive Manufacturing Laboratory

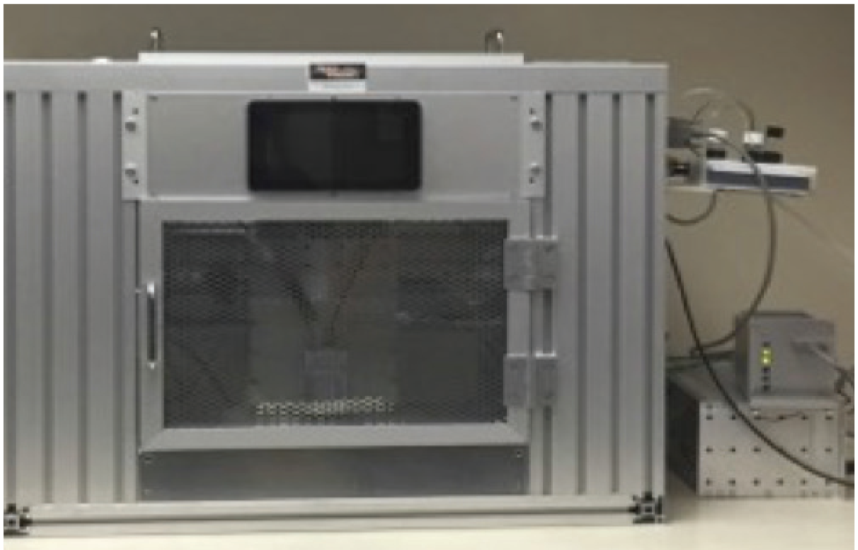
Advanced manufacturing contributes a significant role to novel sensor design and production. Additive techniques in particular are of interest for improving robustness, spatial resolution and opening up the design envelope to novel designs. Currently, in this non-radiological facility, there are two additive machines. A Plasma Jet Printer (PJP) from Space Foundry and a Laser Engineered Net Shaping (LENS) system from Optomec.

The PJP is designed to create thin wires and films directly on a substrate surface. It is a form of direct ink writing techniques, similar to aerosol jet printing. The printer uses an ink composed of a carrier liquid and nanoparticles of the material of interest to print. The ink is aerosolized and carried through feedlines to the print head. Inside the print head is a plasma generator which drives the carrier liquid, sintering the particles as it deposits them onto the substrate. In addition, the plasma acts as a built-in plasma cleaner to remove unwanted barriers to particle adhesion. The printer can use a wide variety of inks (metals, oxides/ceramics, organics and polymers) and a number of process variables can be controlled (power, gas mixtures, flow rates of inks and gas, plasma properties, etc.). It is ideal for thin films and wires and is able to print complex patterns with lines as narrow as 100 µm and hundreds of nanometers thick.

The Optomec LENS is housed in the Energy Environment, Science and Technology Directorate and is available for use for programs throughout INL. It is a direct energy deposition system where a laser is used to create a melt pool and powdered material is fed through nozzles directly into the meltpool. The system uses a 1 kW laser and has three powder hoppers, allowing for three different materials to be mixed during the printing process. Atmosphere control in the build chamber reduces the oxygen and moisture content, allowing for a high purity argon gas environment to reduce oxidation during builds. It has a total possible build volume of 50 cm x 32 cm x 50cm, and is ideal for metallic structural components, such as a support rig surrounding a Linear Variable Differential Transformer (LVDT).

The Optomec LENS system is on the left, the Plasma Jet Printer is on the right.





Brenden Heidrich

Irradiation Facilities

To mature developmental sensor technologies, we must first demonstrate instrumentation performance through evaluations in relevant irradiation facilities. The I2 program has developed an irradiation strategy to leverage nuclear reactors throughout the United States to align instrumentation development needs with appropriate reactor facilities.

Nuclear reactors provide unique opportunities for researchers in all aspects of instrumentation development, from basic research to applied testing. Irradiation activities related to instrumentation development typically begin with simple passive material irradiations to understand radiation damage mechanisms and how these will be overcome for future instrumentation designs. As instrumentation designs mature from concept to reality, more complex experiments evaluate instrumentation performance in real-time against known irradiation conditions. These irradiation conditions each answer unique questions about instrumentation performance. A high-power transient irradiation will answer questions about fast response, short-term survivability and maximum power limitations. By contrast, a steady-state irradiation will answer questions about radiation-induced drift and long-term survivability.

As discussed below, each of the irradiation facilities offer unique capabilities for integration into the instrumentation development lifecycle. Access to these capabilities has leveraged many Department of Energy–Nuclear Energy programs that see the importance of instrumentation development irradiations. These programs include the Accident Tolerant Fuels (ATF) program, Advanced Gas-Cooled Reactors (AGR) program, and the Nuclear Science User Facilities competitive awards including Rapid Turnaround Experiments.

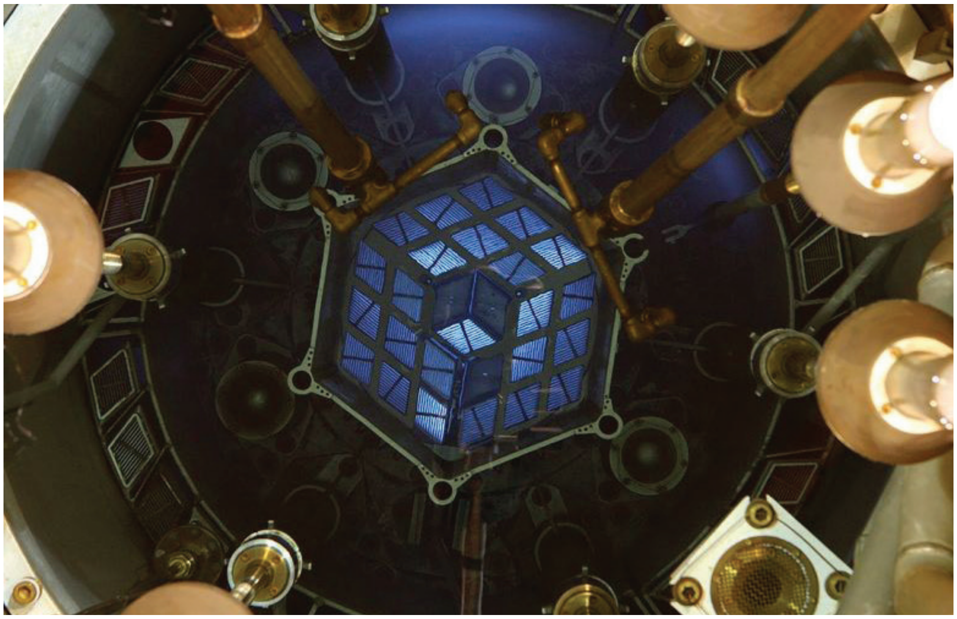
Advanced Test Reactor

INL Advanced Test Reactor

The ATR is a water-cooled, high-flux test reactor, with a unique serpentine design that allows large power variations among its flux traps. The reactor's curved fuel arrangement places fuel closer on all sides of the flux trap positions than is possible in a rectangular grid. The reactor has nine of these high-intensity neutron flux traps and 68 additional irradiation positions inside the reactor core reflector tank, each of which can contain multiple experiments. Experiment positions vary in size from 0.5" to 5.0" in diameter and all are 48" long. The peak thermal flux is 1x1015 n/cm2-sec and fast flux is 5x1014 n/cm2-sec when operating at full power of 250 MW. There is a hydraulic shuttle irradiation system, which allows experiments to be inserted and removed during reactor operation, and pressurized water reactor (PWR) loops, which enable tests to be performed at prototypical PWR operating conditions.

INL: Transient Reactor Test Facility

The INL's TREAT Facility provides transient testing of nuclear fuels. It is an air-cooled, thermal spectrum test facility specifically designed to evaluate the response of reactor fuels and structural materials to accident conditions ranging from mild upsets to severe accidents. The TREAT Facility is used to study fuel melting behavior, interactions between fuel and coolant, and the potential for propagation of failure to adjacent fuel pins. It has an open-core design that allows for ease of experiment instrumentation and real-time imaging of fuel motion during irradiation, which also makes TREAT Facility an ideal platform for understanding the irradiation response of materials and fuels on a fundamental level.



MITR (above) and TREAT Facility (below).

Massachusetts Institute of Technology Reactor

The MITR is a 6 MW tank-type research reactor. It has three positions available for in-core materials, fuel and instrumentation irradiation experiments over a wide range of conditions. Water loops at pressurized water reactor/boiling water reactor (PWR/BWR) conditions, static and lead-out capsule experiments in inert gas environment at temperatures up to 850 degrees C, custom-designed high-temperature irradiation facility up to 1400 degrees C and nuclear fuel irradiation experiments with fissile materials up to 100 gm U-235 or equivalent. A variety of instrumentation, support facilities, pneumatic tubes, beam ports, a neutron activation analysis laboratory, hot cells and non-destructive post-irradiation examination facilities are also available. Fast and thermal neutron fluxes are up to 1.2e14 and 6e13 n/cm2 s at 6 MW.

North Carolina State University PULSTAR Reactor

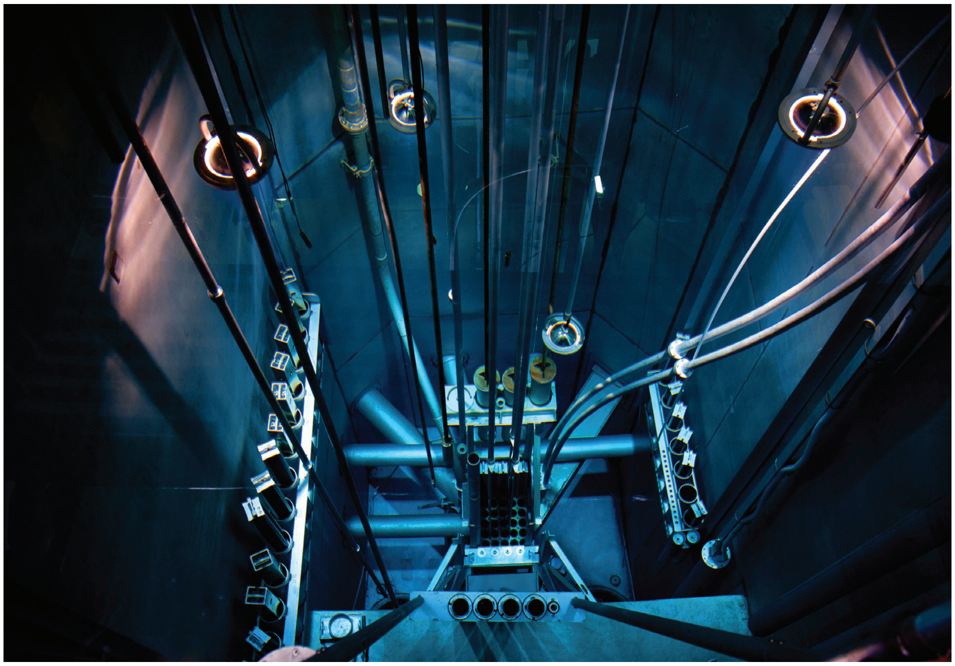
The PULSTAR reactor is a 1 MW pool-type nuclear research reactor located in NCSU's Burlington Engineering Laboratories. The reactor, one of two PULSTAR reactors built and the only one still in operation, uses 4 percent enriched, pin-type fuel consisting of uranium dioxide pellets in zircaloy cladding. The fuel provides response characteristics that are very similar to commercial light water power reactors. These characteristics allow teaching experiments to measure moderator temperature and power reactivity coefficients including Doppler feedback. In 2007, the PULSTAR reactor produced the most intense low-energy positron beam with the highest positron rate of any comparable facility worldwide.

The Ohio State University Nuclear Reactor Laboratory

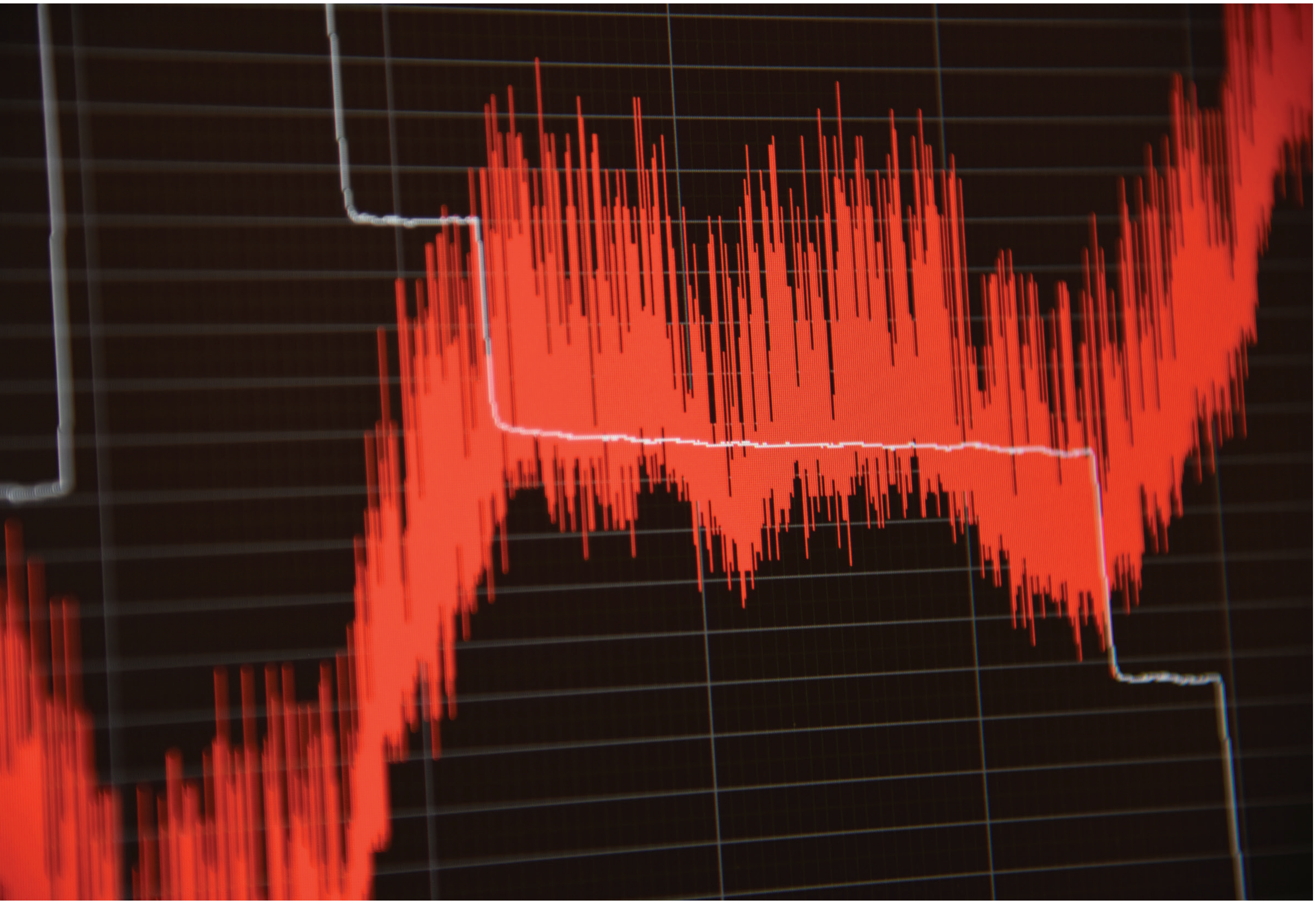
The Ohio State University Nuclear Reactor Laboratory (OSU-NRL) offers the unique capability of reactor irradiations in external large-experiment dry tubes for The OSU Research Reactor (OSURR). In the next-to-core position in which either a 6.5-in I.D. or a 9.5-in I.D. external dry tube can be located, irradiations can be performed in a neutron flux up to 1012 n/cm2/s. Among the possibilities for use are experiments involving instrumented, high-temperature irradiations of prototype instrumentation for next-generation reactors, sensors and sensor materials, and optical fibers designed for up to 1600 C. In addition to the external large-experiment dry tubes, the reactor also has two 2.5-in I.D. in-core dry tubes that support instrumented experiments, but at ambient temperature.

I2 Irradiation Tests Including I2 Instrumentation:

- ATF-2/SQT and AGR 5/6/7 at INL ATR facility
- MIMIC-N and MIMIC-RUSL in INL TREAT facility
- 4 NSUF irradiation tests at MITR (ULTRA 1/2, BSU-17-12527, PITT-17-13073, ND-18-14730)
- 1 NSUF irradiation test at NCSU PULSTAR (BSU-17-12527)
- 1 NSUF irradiation test at OSURR (OSU-18-14749)



NCSU PULSTAR



Data analysis is an important aspect of sensor development

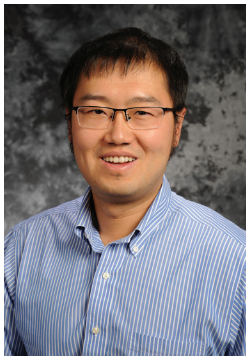
THE IN-PILE INSTRUMENTATION TEAM

The In-Pile Instrumentation program has access to a world class team of researchers from the INL Nuclear Science and Technology (NST) and Energy and Environment Science and Technology (EEST) directorate, with areas of expertise ranging from nuclear engineering to material science. The core of I2 personnel at INL is constituted by researchers and technicians affiliated with the NS&T Measurement Science Department, which was formed with the specific objective of of bringing together researchers with different backgrounds, but with a common focus on sensing applications. In addition, the program relies on supporting personnel from other INL Organizations, such as experiment designers and operators of the irradiation test facilities.

Table of INL researchers

Technical activities	Research team
Program oversight	Pattrick Calderoni, David Hurley, Kort Bowman
Technical activities coordinators	Troy Unruh, Brenden Heidrich, Mike McMurtry, Colby Jensen, Zilong Hua
Thermocouples	Richard Skifton, Joseph Palmer
SPND	Kevin Tsai, Troy Unruh
Passive monitors	Ahmad Al Rashdan, Kurt Davis
Miniature fission chamber	Troy Unruh
Ultrasonic Thermometer	Joshua Daw
Radiation tolerant fiber materials and sensors	Joshua Daw, Austin Fleming, Kelly McCary, James Smith
LVDTs	Kurt Davis, Anthony Crawford
Creep test rig	Malwina Wilding, Kurt Davis
Instrumentation irradiation vehicle for ATR	Joseph Palmer, Nate Oldham
Instrumentation irradiation vehicle for TREAT (MIMIC)	Nicolas Woolstenhulme, Kevin Tsai
Photo-thermal radiometry for thermal conductivity	David Hurley, Zilong Hua
Probe method for thermal conductivity	Austin Fleming
Mechanical properties	Anthony Crawford
Resonant ultrasound spectroscopy	Robert Schley
Electro-impedance spectroscopy (EIS) for hydride characterization	Hongqiang Hu
IR thermography for structure characterization	Zilong Hua
AM printing process control and sensors fabrication	Michael McMurtrey
Modeling	Larry Aagesen

New I2 Employees



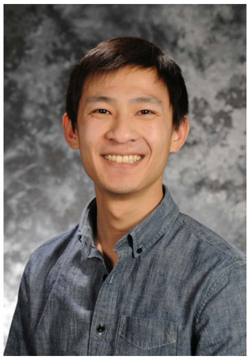
Zilong Hua
Research Scientist

What do you do in I2?

My primary work is on the photothermal radiometry.

What is your favorite part about working in I2?

My favorite part about working in I2 is the collaboration with university researchers. They provide different angles to understand the projects. It is also fun to communicate with other INL researchers from different departments. As a new employee, I am always happy to know more about other's research.



Kevin Tsai
Instrument Engineer

What do you do in I2?

My research focus under I2 is the development of Self-Powered Neutron Detectors (SPNDs) for localized in-pile, real-time, neutron flux measurements, and to bring this measurement capability to INL.

What is your favorite part about working in I2?

My favorite part about working in I2 is being able to participate in the forefront of research within my field of interest and collaborating with other great researchers.

Austin Fleming
Russell L. Heath Distinguished Postdoctoral Associate

What do you do in I2?

In the I2 program I am responsible for the development and deployment of a variety of sensors to measure temperature, thermal properties, and mechanical deformation. These sensor are based on a variety of cutting edge technologies including advanced fiber optic sensors and electrical impedance measurements. All of these sensors are being developed with an end goal of supporting in-pile experiments by expanding the available measurement capability and data quality.

What is your favorite part about working in I2?

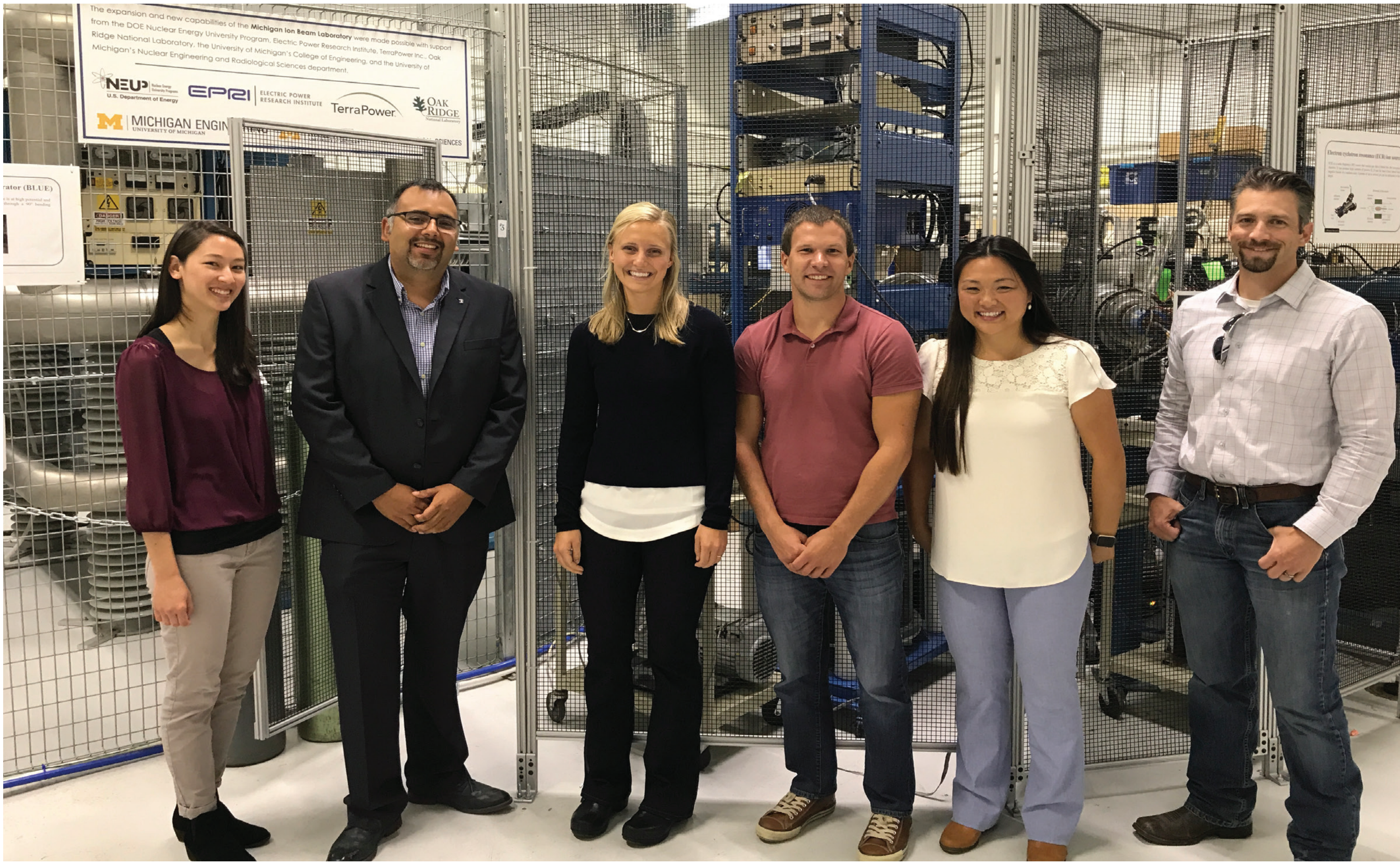
My favorite part of working in the I2 program is the variety of applications for the technology we are developing. Many of the sensors have applications ranging from qualifying nuclear fuel for the commercial industry to progressing fundamental scientific understanding. This diverse range of applications allows us to interact with a variety of customers and projects which makes the work more interesting.

Students

As with many INL programs, I2 has a strong emphasis on engaging students in its research activities in order to channel innovative thinking and ensure an adequate workforce pipeline.

INL's University Partnerships program plays an integral role in growing I2's impact by hosting interns, graduate fellows and postdoctoral researchers. This growth has expanded opportunities and strengthened collaboration with students, professors and researchers on various instrumentation development projects. These projects are strategically developed to leverage the strength of each individual and institution to form interdisciplinary teams that provide innovative solutions for the complex challenges associated with in-pile instrumentation. From computer-based research to hands-on laboratory experience, students engaged in I2 projects are mentored by experienced professionals to widen the research horizon for their futures.

Collaboration between BSU professors, BSU students and INL researchers plays a vital role for in-pile instrumentation development.



KELLY MCCARY

Graduate Fellow

In middle school, Kelly McCary asked her father, a retired naval supply corps officer, his advice about a career path.

He told her working as a “Navy nuke”—officers and enlisted personnel who take care of the nuclear reactors that power many of the Navy’s ships and submarines—might be a good job.

McCary took her father’s advice to heart and began to research nuclear engineering. “I liked the idea of it being a zero-carbon energy source,” she said. “Then I looked into it more and fell in love.”

Now, as a Ph.D. candidate in nuclear engineering at The Ohio State University (OSU), McCary is spending the next two years at INL as a Nuclear Engineering Graduate Fellow with a focus on sensors for high-temperature, high-radiation environments.

The INL Graduate Fellowship Program identifies outstanding students in research areas aligned with INL’s strategic agenda and provides them with mentoring and financial support.

McCary’s professor encouraged her to apply for and she received the Nuclear Energy University Partnerships fellowship that supported her first three years in graduate school at OSU. During that time, she also completed an internship at INL in 2017.

The experience prompted her to apply for the Graduate Fellowship at INL. For McCary, it was an easy decision. “I like the work here and I like the people,” she said. McCary was awarded an INL Graduate Fellowship in 2017 and began working at INL as a graduate fellow in August 2018.

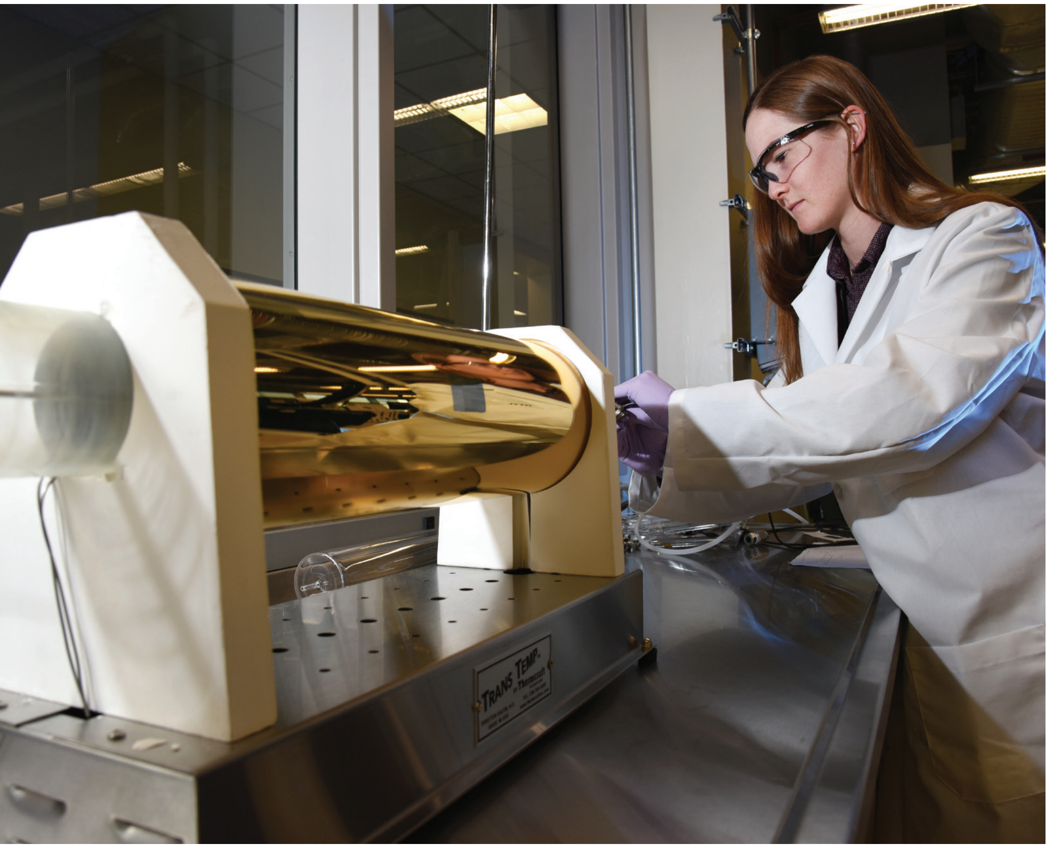
Her current work at INL continues McCary’s focus on sensors in high-temperature, high-radiation environments. Her laboratory experiments involve using fiber optic sensors made of both silica and sapphire.

“The silica fibers are similar to what is used in telecommunications,” she said. “They have an operational limit of around 1,000 degrees Celsius. Whereas, sapphire optical fibers have a melting point above 2,000 degrees Celsius.”

The fibers are inserted into a nuclear reactor or some high-temperature, high-radiation environment and interrogated with a laser. The laser reflects off defects or intentional etchings of the fiber, which creates backscatter that is measured with a detector.

As the reactor heats up the fiber, the fiber expands and the temperature is determined by correlating the time it takes for the backscatter to return to the sensor. “You can get a bunch of temperature readings off one optical fiber,” McCary explained.

As for the future, McCary hopes to complete her Ph.D. and then continue with her research. “I would love to continue my career at INL and expand into other high temperature radiation sensors,” she said.



Kelly McCary

KIYO FUJIMOTO

Graduate Fellow

Boise State University student Kiyo Fujimoto, an Idaho native, is finishing her three-year fellowship from the Department of Energy's Nuclear Energy University Program (NEUP) and will relocate to Idaho Falls in July to start her two-year Graduate Fellowship at INL for her doctorate in materials science and engineering. She earned a degree in chemistry from BSU in 2016.

Fujimoto is part of Dr. David Estrada's Advanced Nanomaterials and Manufacturing Laboratory team and is mentored by INL's Troy Unruh of the High Temperature Test Laboratory.

With a focus on additive manufacturing, Fujimoto is researching techniques, using microscale 3D printers, to print advanced sensors for use in test reactors. This work is part of the INL-led I2 program to help characterize reactor environments to gain a better understanding of the response of reactor materials.

If this printing concept proves viable, the goal is to fabricate sensors for use in nuclear reactors to collect real-time data and ultimately improve safety and efficiency. Fujimoto said there is currently a technology gap that researchers like her are trying to close.

"This helps us characterize the materials so we can have a really good understanding of how they react," Fujimoto said. "If we can understand that relationship, we can know the limits of the materials."

Her focus in 2018 was the in-house development of nuclear-relevant ink to use in the 3D printer. These inks aren't available commercially, so Fujimoto is attempting to find a workable recipe using chemical elements such as molybdenum, niobium, iron, platinum, cobalt, titanium and alumina. This is an example of a mutually beneficial collaboration between I2 and BSU. The university lab has unique instrumentation and equipment for the ink development, Fujimoto said.

Her research project was recently awarded a Nuclear Science User Faculty Rapid Turnaround Experiment to irradiate her sensor samples. This information will help develop a list of materials suitable for additive manufacturing with a focus on nuclear applications.

Fujimoto, a wife and mother of two, is excited to finish her classwork and start her residency at INL's High Temperature Test Laboratory where she will continue her hands-on research with advanced sensors and increasing the feasibility of additive manufacturing while collaborating with like-minded researchers.

"We want to make future nuclear reactors safer than they are currently," she said.

The INL fellowship pays her tuition during these two years, plus a $60,000 annual salary.

Kiyo Fujimoto

INL, Boise State jointly seek to develop instrumentation expertise

Idaho National Laboratory's High Temperature Test Laboratory (HTTL) can point at least in part to a growing relationship with Boise State University (BSU) and its Micron School of Materials Science and Engineering for the groundbreaking in-pile instrumentation work in 2018.

Guided by five faculty members – Drs. Nirmala Kandadai, Harish Subbaraman, Brian Jaques, Dave Estrada and Lan Li – BSU students contributed vital research on a wide range of projects, on the BSU campus and at HTTL, in the INL Energy Innovation Laboratory (EIL) in Idaho Falls.

Ember Sikorsksi

Ember Sikorski

A doctoral candidate in materials science, Ember Sikorski came to INL for an internship in summer 2018 to learn more about computational modeling. What she didn't know was that actual experiments in the HTTL would broaden her scope considerably. "I had a basic idea of how a thermocouple works," she said. "Now I really understand what I'm modeling. You can only understand so much from reading papers."

With the split focus, Sikorski had two mentors, Dr. Larry Aagesen on the computational modeling side and Dr. Richard Skifton in the HTTL. Using the INL-developed Multiphysics Object-Oriented Simulation Environment (MOOSE), Sikorski modeled grain evolution and material fracture. Then, with the modeling completed, she turned her attention to processing (heat treatment), then performance (voltage measurement). On a poster displayed at the Aug. 9 INL Intern Expo, she offered this observation:

"Collaboration between experiment and computation can accelerate the development of materials. Experimental results can be used as input parameters for computation to improve the model's accuracy. The model can then be used to screen a variety of variables to predict what will yield the best performance, reducing experimental time and cost."

"The best thing is she has come from the modeling side," Skifton said. "This internship has given her hands-on experience. You always get pretty pictures in computational models – nice smooth curves – but anything can happen, and the experiment helps us solidify what's happening in real life."

Sohel Rana

Sohel Rana, a doctoral student in the BSU Department of Electrical and Computer Engineering, has been awarded a two-year INL fellowship to continue his sensor research. A native of Bangladesh, India, Rana is focused on designing and fabricating fiber optic sensors to monitor high temperatures in nuclear reactor cores. His fellowship is scheduled to begin in summer 2020, covering his last two years of tuition at Boise State and providing a living stipend.

Rana's work at BSU has been done at the newly created Fiber-Optics, Lasers and Integrated-Photonics Research (FLAIR) lab, co-directed by Dr. Nirmala Kandadai,

Sohel Rana

an assistant research professor in the Department of Electrical Engineering, and Dr. Harish Subbaraman, an assistant professor of electrical engineering. Rana and other researchers working in the FLAIR lab have hoped to develop and deploy radiation-hard, fiber-optic sensors to allow them to monitor temperatures inside reactors in real time.

At INL, he will be working directly under the supervision of Joshua Daw, a research scientist and engineer at the High Temperature Test Laboratory.

"I was impressed with Sohel after meeting him, listening to him present his research," Daw said. "This will help INL rapidly build capabilities in an area with the potential for tremendous benefit." It also helps establish and strengthen a talent pipeline between Boise State and INL. "We are always looking for the next generation of researchers," Daw said. "And for Sohel, he will experience the research culture of a national lab, which is not quite like either academic or corporate/industrial environments."

Courtney Hollar

Courtney Hollar joined Boise State's Nanoscale Materials and Device Group and the Mullner Group in 2010. As a graduate student at Boise State and graduate research assistant at University of Idaho, she has studied the harnessing of waste heat. In 2015, she was one of three BSU recipients of a graduate research fellowship from the National Science Foundation.

Her research is focused on measuring the thermal conductivity of nuclear fuels. The thermal conductivity of UO2 nuclear fuel is of high interest because of its impact on fuel temperature and the resulting reactor performance and safety considerations. The thermal conductivity of UO2 undergoes significant changes with irradiation, and as a result is a strong function of burnup. Additionally, accurate fuel thermal conductivity measurements are of interest to aid in the development and validation of simulation codes used to predict the thermophysical properties of UO2 under various conditions.

Current thermal conductivity measurements utilize a post-irradiation examination steady state approach, which is time-consuming and expensive. By nature of a post-irradiation measurement, the thermal conductivity can only be measured at one burnup state. By utilizing an in-pile thermal conductivity measurement, thermal conductivity can be determined under prototypic conditions over a range of burnup.

In her latest project, Hollar has utilized a line heat source (i.e., needle probe) for transient analysis of thermal conductivity of nuclear fuels for in-pile measurements. A transient, multilayer analytic model was developed to describe the thermal interactions between the measurement device and the sample. This model was developed using the quadrupoles method. The analytic results generated by the model have been compared to experiments she performed at the HTTL using stainless steel 304 and Teflon of varying diameters and shown good agreement.

Courtney Hollar

International Collaborations

INL and CEA have been collaborating on the development of innovative instrumentation for experiments in Material Testing Reactors (MTRs) for several years. The goal of this continuing and growing international partnership is to promote technical exchanges between CEA and INL to improve the scope and the quality of the in-pile instrumentation in Research Reactors in the U.S. and in France, particularly in the Advanced Test Reactor and in the Jules Horowitz Reactor.

INL and CEA researchers performing fission chamber evaluations at the MINERVA reactor in Cadarache, France.

Ultimately, the international nuclear energy community hopes this collaboration will take mutual advantage of the experience acquired by CEA and INL in the field of in-pile instrumentation. Joint programs between CEA and INL will test and benchmark measurement techniques dedicated to Research Reactor characterization, benefitting nuclear energy technology as a whole.

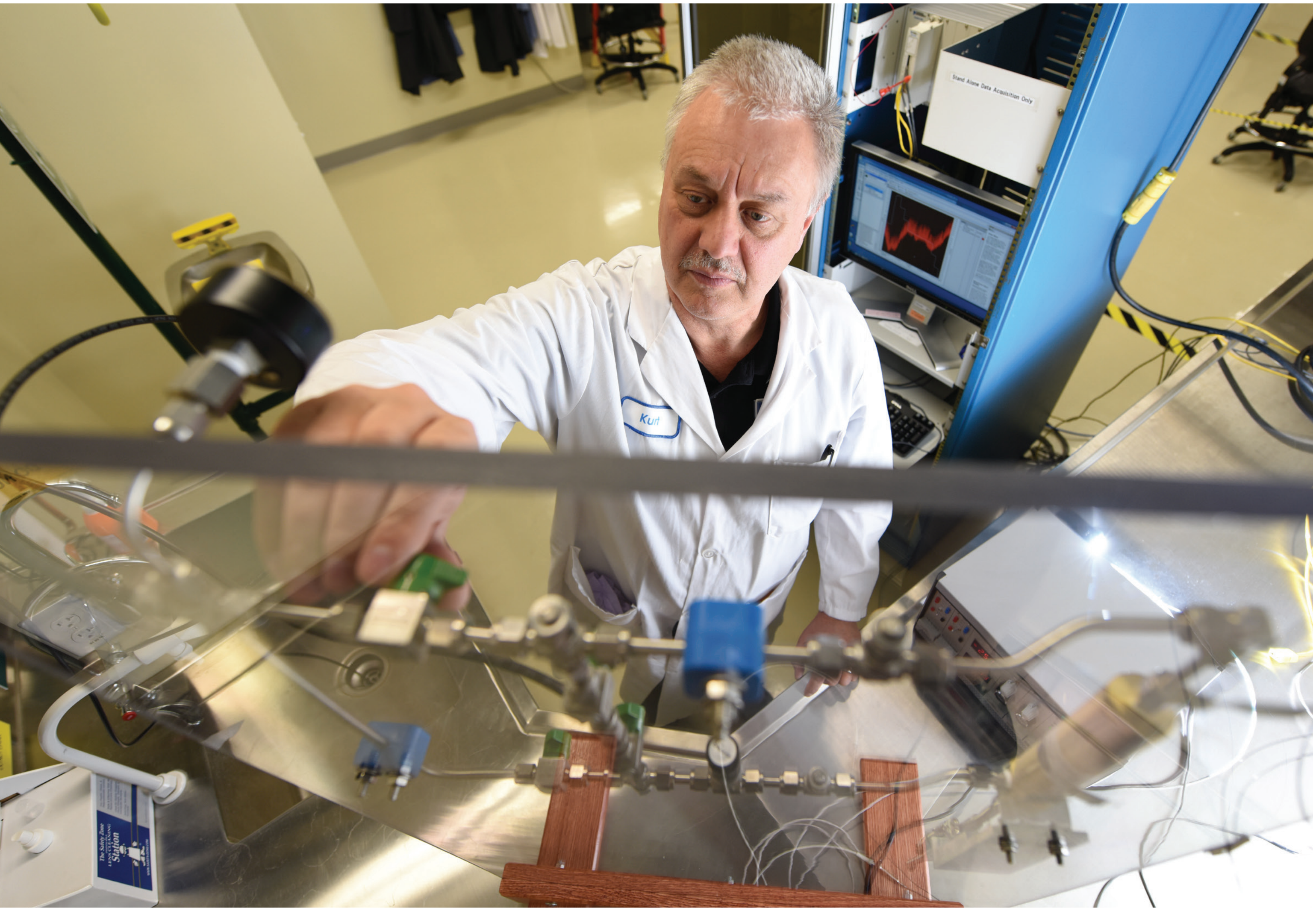
Cooperation under this collaboration includes:

1. Neutron and gamma flux measurement evaluation
2. Temperature profile measurement evaluation
3. Elongation sensor evaluation
4. Gas analysis sensor evaluation
5. Instrumentation development status reports
6. Personnel and student exchange.

INL and CEA have maintained their own R&D projects on this topic, and it is of mutual benefit to collaborate on the evaluation of new sensors for on-line monitoring of experiments.

I2 Collaborators in 2018

Partner	Project Title	PI	Students	Notable features or outcomes
BSU	High Temperature Irradiation Resistant thermocouples: materials optimization	Brian Jaques / Lan Li	Ember Sikorski, Scott Riley, Beck Perrine	Develop models that predict thermocouple performance in high temperatures and validate these models with mechanical and electrical performance testing
BSU	Ultrasonic Thermometers	Brian Jaques / Dave Estrada	Katie Livingstone	Develop methods to print components for advanced manufactured ultrasonic thermometers and test performance
BSU	Radiation tolerant fibers: materials assessment	Nirmala Kandadai, Harish Subbaraman, Lan Li	Sohel Rana (INL graduate fellow), Austin Biaggne	Develop models that predict optical fiber performance in irradiations and use in conjunction with laboratory evaluations to rapidly down-select materials for radiation resilient optical fibers
U Pitt	Radiation tolerant fibers: sensor performance	Kevin Chen	Mohamed Zaghloul	Perform laboratory evaluations of radiation hardened optical fibers that are under development for in-pile applications
BSU	Advanced manufacturing processes for sensor fabrication	Dave Estrada/Lan Li/Eric Jankowski	Kiyo Fujimoto (INL graduate fellow)	Perform laboratory evaluations of radiation hardened optical fibers that are under development for in-pile applications
BSU	Line source method: characterization of time domain response	Dave Estrada	Courtney Hollar	Develop and test alternative operational modes for measurement of thermal conductivity using the transient hot wire needle probe
BSU	Sample preparation for Resonant Ultrasound Spectroscopy test	Brian Jaques		Fabricate surrogate samples to be used to develop characterization techniques for the application of resonant ultrasound spectroscopy sensor demonstrations
TOSU	Thermography modeling of microstructural changes	Marat Khafizov		Develop models to validate thermography based measurement systems for microstructureal changes
BSU	Electrochemical measurement of fuel cladding properties	Mike Hurley / Claire Xiong		Develop and test methods to determine fuel cladding properties using electrochemical impedance spectroscopy
BSU	Thermography for imaging of large scale structure	Harrish / Brian Jaques		Develop and test methods to image microstructural changes using IR thermography in fuel surrogates
Notre Dame	Combinatorial Materials Science for sensor materials	Yanliang Zhang		Application of combinatorial material science to research new materials to support in-pile sensor fabrication
BSU	Mechanical Sensors	David Estrada	Kiyo Fujimoto (INL graduate fellow)	Develop Advanced Manufactured Strain Gauges and compare with traditiational strain gauges
BSU	Neutron Detectors	Brian Jaques		Install Neutron Generators at BSU and characterize fission chamber fissle deposits.



Testing of LVDT-based instrumentation for In-Pile experiments.

IMPACT & RESEARCH HIGHLIGHTS

In-Pile Instrumentation program structure

The I2 program mission is to develop instrumentation that can provide real-time, accurate, spatially-resolved information regarding test conditions and the performance of fuels and materials in nuclear reactors. The structure of the program is designed to implement its core mission, a comprehensive approach to R&D activities, which: (1) ensures the availability of a qualified set of baseline instrumentation, (2) complements it with the development of innovative sensors with disruptive potential in terms of performance and (3) integrated measurement systems that address specific material science issues (4) and provides the capabilities to qualify and maintain the aforementioned technologies.

Baseline capability: qualify instrumentation for integration in standardized irradiation rigs — TRL 5-6 Technology demonstration

- Self-powered detectors (SPD) to measure neutron or gamma flux
- Thermocouples and passive monitors to measure local temperature
- LVDTs to measure deformation and pressure

Innovative Sensors: demonstrate disruptive potential for in-pile application — TRL 3-4 Technology development

- Electrical sensors/Ultrasonic sensors/Fiber optics/Advanced Manufactured sensors

Single effect test: investigate in real time material science issues in-pile — TRL 2-6 Research to feasibility

- Thermal properties/Mechanical properties/Chemistry/Microstructure

Enabling capabilities

- Irradiation vehicles for instruments performance demonstration (TREAT, ATR, MITR, VTR)
- Out-of-pile system to enable re-instrumentation of irradiated fuel assemblies
- Expanded out-of-pile testing capabilities (HTTL, including flowing autoclave for PWR conditions)

The concept of technology readiness assessment is helpful for the classification of instrumentation technology as part of the program strategy. Instruments and integrated measurement systems developed under the In-Pile Instrumentation program target material test reactor (MTR) experiments. Therefore, the program objective is to mature the technology to TRL 6, which is the "demonstration of the technology in relevant environments." Several paths exist within DOE to extend the maturity beyond TRL 6 through GAIN, technology commercialization funding and small-business programs leading, for example to the integration of sensors for the operation of advanced reactors prototypes or direct commercialization. However, as a general case, the activities needed for such extension fall outside of the scope of the program. On the opposite end of the scale, one of the In-Pile Instrumentation program's main objectives is to demonstrate the applicability of technologies with proven feasibility for irradiation testing; hence, starting from TRL 3 (proof of concept completed), the coordination with other DOE-sponsored activities (e.g., Basic Energy Sciences programs or Nuclear Energy Enabling Technology Advanced Sensor and Instrumentation [ASI] projects) is considered specifically to screen for low maturity technologies to be included in the program structure.

Joe Palmer

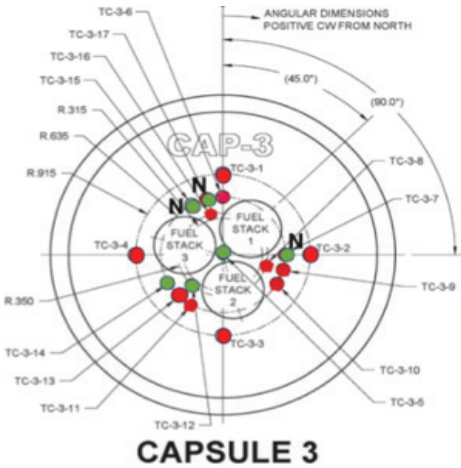
Richard Skifton

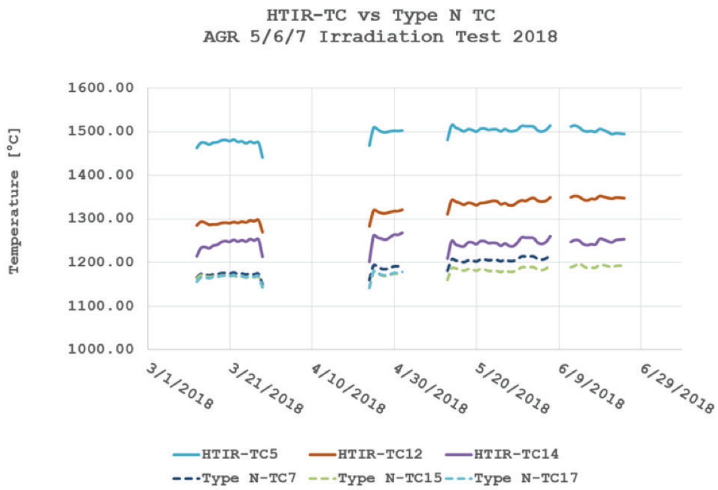
Performance of HTIR thermocouples in the AGR-5/6/7 experiment

Measuring high temperatures in reactor experiments is difficult. Typical thermocouples used in commercial power plants work very well for measurements of less than 600 ^{0}C. Others, namely the standard Type N thermocouple, have been developed, pushing the state-of-the art to temperature measurements up to 1050 °C. But even these are subject to rapid decalibration, called drift, because their alloying elements transmute into other elements with different electromotive properties.

Recognizing the limitations of existing thermometry to measure such high temperatures, the sponsor of the AGR-5/6/7 test supported a development and testing program for thermocouples capable of low-drift operation at temperatures above 1100 °C for approximately 10,000 hours. In the experiment, researchers tested the standard Type N along with the INL's High Temperature Irradiation Resistant thermocouple (HTIR-TC) which was developed and tested during this four-year effort. In parallel to this effort, a new Type N thermocouple from the University of Cambridge was also under consideration. The HTIR-TC is a Molybdenum/Niobium-based thermocouple system. The promise of this thermocouple was based on the high melting temperatures of Mo and Nb, and the low thermal-neutron absorption cross-sections of both elements.

With the thermocouples in place, irradiation tests of the AGR-5/6/7 experiment began in February 2018. The thermometry of the AGR-5/6/7 fuels test shattered the previous threshold of 1050 ^{0}C thanks to the performance of the HTIR-TC. All other comparable temperature probes degrade at this temperature in the harsh environment of a nuclear reactor. The highest-temperature HTIR-TC operated at ~1480 °C - for ~3,000+ hours; this is the highest-sustained temperature ever recorded inside a nuclear reactor. Further, the TCs went through multiple thermocycles as the reactor was shut down and restarted.



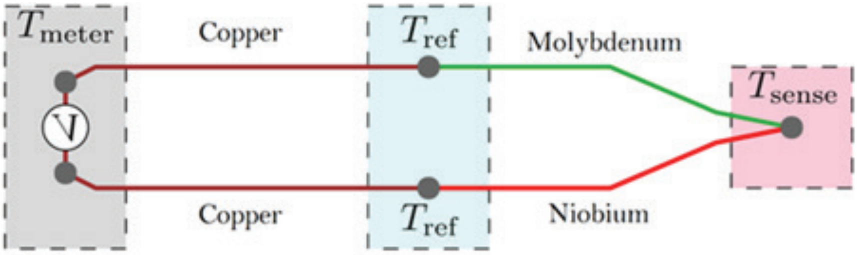


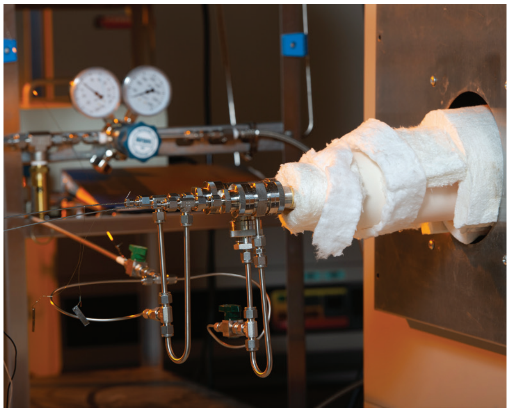
The HTIR-TC performance data

The highlighted results included:

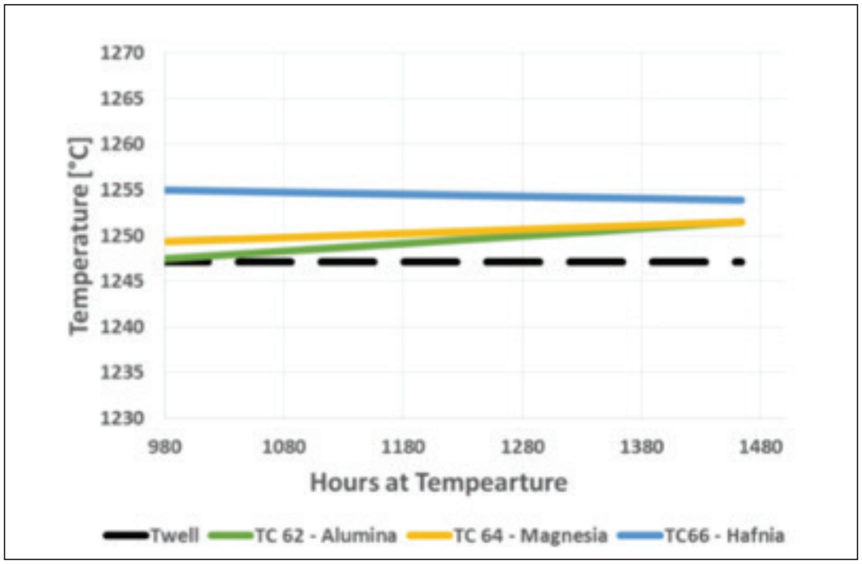
- The highest, sustained temperature every recorded in the nuclear reactor was recorded by the HTIR-TC operating at ~1480 °C - for ~3,000+ hours
- The highest-temperature Cambridge Type N TC at ~1200 °C
- In contrast, the highest standard Type N at 915 °C
- The robust build of the TC using refractory metals withstood multiple thermo cycles of close to ΔT = 1450 °C each cycle
- The HTIR-TC's new calibration procedure allows for a much larger range of 0 °C up to 1500°C or higher.

Under the I2 Program, the High Temperature Irradiation Resistant thermocouple (HTIR-TC) has gone from a benchtop prototype, to a fully-commercialized, "off-the-shelf" sensor. Changes in the heat-treating and calibration procedures for the HTIR-TCs resulted in substantial improvements in accuracy and drift compared to previous efforts in the AGR-1 irradiation, completed in 2009. Further, INL worked closely with Boise State University's (BSU) Micron School of Materials Science and Engineering to develop simulations in crack growth and atomic diffusion as well as to perform experimental studies on thermocouple material interactions and sheath ductility. Recently an international collaboration between INL and the University of Cambridge was awarded by the U.S.-EURATOM International Nuclear Energy Research Initiative (INERI) on the topic of applying the HTIR-TC to Gen IV reactor verification processes.





HTIR-TC calibration in the tube furnace and the following long duration out-of-pile furnace testing.

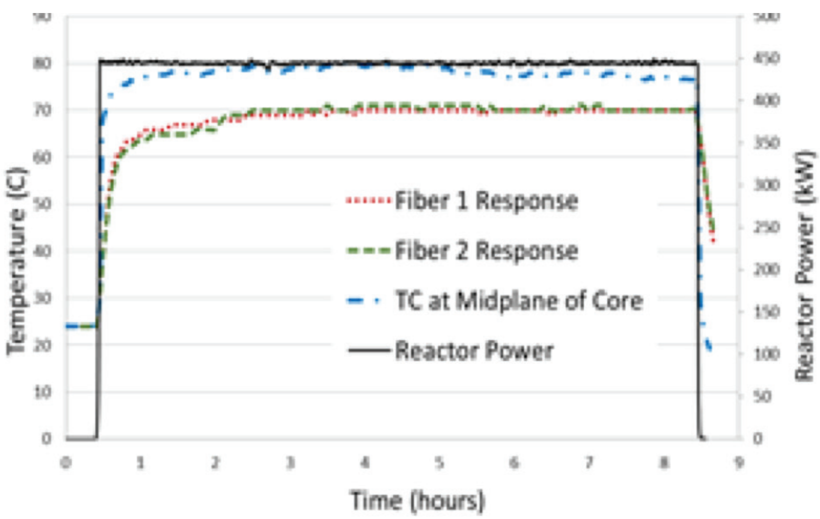


Joshua Daw

Radiation Tolerant Optical Fibers and Fiber Sensors

Measurement techniques based on optical fibers have been identified as a high risk, high reward component of the I2 program. Fiber optic sensors based on standard fused-silica have demonstrated the capability to provide multi-sensing (measuring different operational parameters within a single sensor configuration, such as temperature, pressure and strain) and multiplexing (communicating data collected at multiple locations through a single line) instrumentation. They are intrinsically immune to electromagnetic interference, electrically passive, compatible with a number of different sensing methodologies, and widely available at reasonable cost.

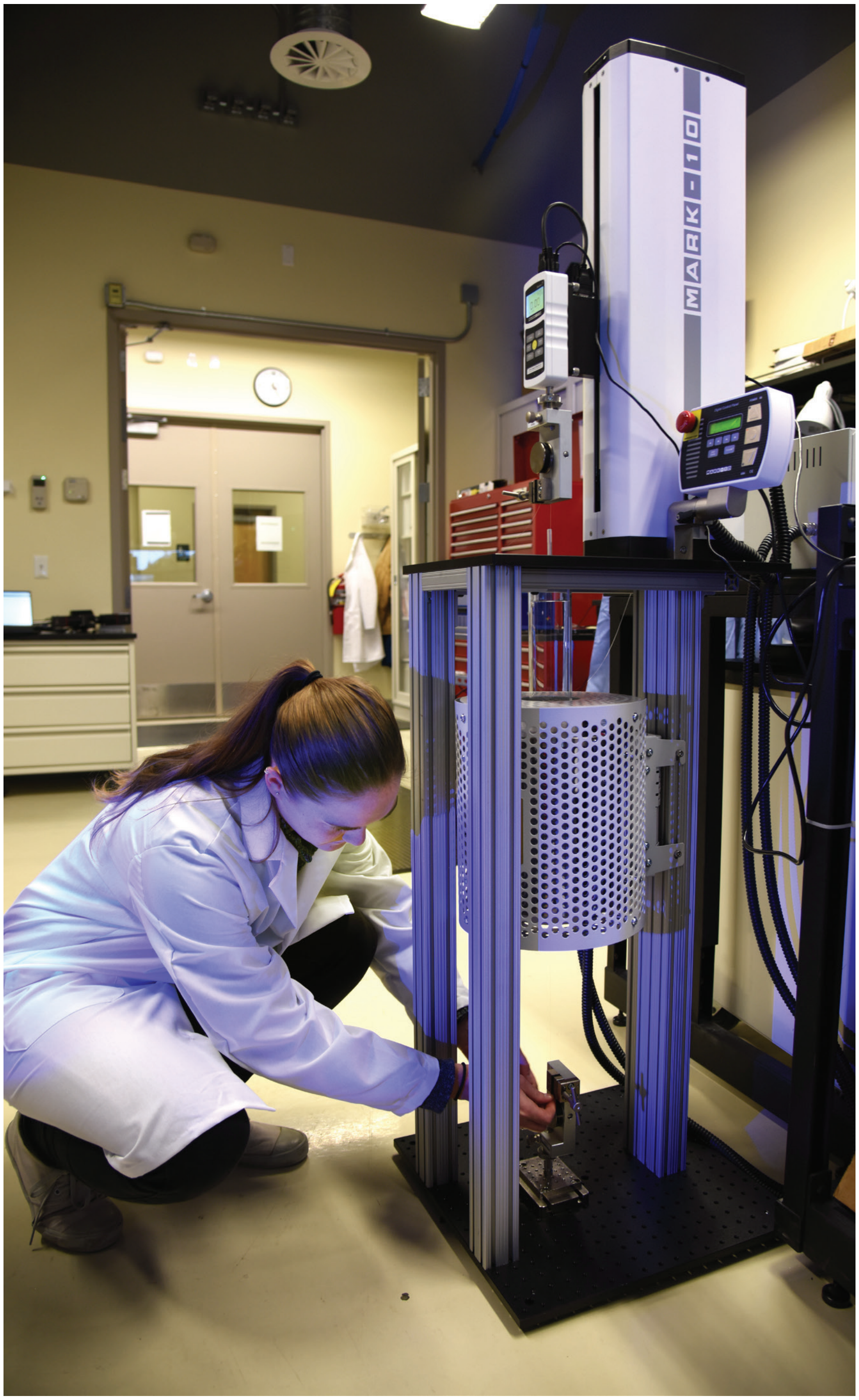
In addition to the widespread use for telecommunication applications, instruments based on silica fibers are deployed in industrial applications at temperatures approaching 300–400 ^{0}C for applications such as distributed temperature sensing in oil and gas recovery. Ongoing research is testing the limits of amorphous silica as fiber material with respect to operational temperature. . At temperatures above 500 ^{0}C, conventional silica fibers can suffer from instabilities caused by interactions with various environmental species (especially hydrogen and/or water). While the application of protective coatings can alleviate environmental concerns, the amorphous structure of fused silica implies inherent instability when approaching the so-called 'annealing' temperature (1000–1100 ^{0}C) at which the silica network will begin to relax internal strain (recrystallization). Sapphire (α- Al2O3) fibers are recognized as a high-temperature alternative to amorphous silica due to the high melting temperature (about 2054 °C), outstanding chemical resistance, and mechanical strength of their crystalline network. In summary, while the use of optical fiber in high temperature environments remains challenging, advanced technologies are available for applications relevant to nuclear applications.



Calibrated response of fs-FBG in sapphire fiber under low temperature irradiation tests at OSURR.

The amorphous structure of fused silica is also strongly impacted by radiation. Three mechanisms are responsible at the macroscopic scale for the degradation of the fiber performance: Radiation Induced Attenuation (RIA), which increases light adsorption in the material (darkening); Radiation-Induced Emission (RIE), which generates unwanted light (optical noise); and Radiation-Induced Compaction (RIC), which causes variations in the density of the fiber material resulting in changes of optical properties. Various dopants such as fluorine, chlorine, hydrogen and OH have been tested to improve the defects caused by irradiation. The dopants improve RIA of the fiber at certain wavelengths but worsens it at the other. For instance, Fluorine-doped fibers perform better at infrared wavelength, but have higher attenuation in the visible regime. Overall, pure silica and Fluorine-doped silica have shown the highest promise at 1550nm and are the reference material for optical fiber sensors under investigation for nuclear applications.

The near-term application of optical fibers to in-pile instrumentation enabling Infrared (IR) pyrometry in transient tests performed in TREAT. In this application, optical fibers are used simply as light guides, allowing real-time, remote characterization of the light emitted by nuclear fuel cladding surfaces during operation. Beyond the use as a light guide, several types of optical sensors and related measurement techniques have been considered for nuclear applications. In order of increasing complexity in terms of development, they include: extrinsic sensors based on Fabry-Perot interferometry; Fiber Bragg Gratings (FBG); and distributed optical-sensing techniques (Rayleigh, Brillouin, Raman), or more specifically, Optical Frequency Domain Reflectometry (OFDR). Current I2 activities focus on FBG sensors due to their maturity in other industrial applications, demonstrated potential for high temperature operation, multiplexing capability and ease of deployment.



Fiber optic thermo-mechanical testing facility.

Austin Fleming

Thermoconductivity Probe Method

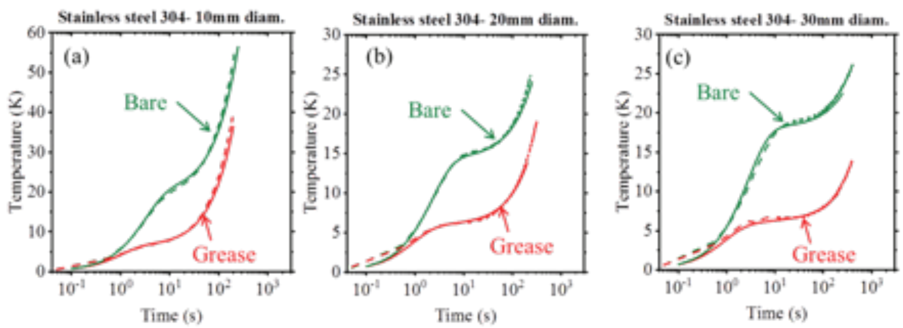
During irradiation, nuclear fuels undergo significant microstructural changes which impacts the bulk thermal properties. The nuclear fuel thermal conductivity plays an important role in removing heat from the fuel and significantly impacts the operating temperature in a nuclear reactor. Researchers from the In-Pile Instrumentation (I2) program at INL have developed a thermal conductivity needle probe to perform high-temperature in-pile thermal conductivity measurements in nuclear reactors.

The thermal conductivity needle probe uses the standard line-source technique to extract the thermal properties. This standard technique requires large sample sizes to perform an accurate thermal conductivity measurement, which is not always feasible for in-pile applications.

Through the I2 program, an analytic model has been developed which allows for more flexibility in the measurement, specifically smaller samples which are more prototypic. This advanced model also takes into account the influence of the needle probe properties and the thermal contact resistance between the probe and sample.

Benchtop testing of the needle probe has been conducted using a variety of samples ranging in both geometry and thermal properties. The analytic model was used for thermal contact resistance and thermal property determination using the experimentally measured data. The experimental and analytic results for three samples of Stainless steel 304 are presented below. Good agreement between the analytic model and experimental results is observed for all three sample diameters including the cases with and without the use of thermal grease.

Through this laboratory testing the model has demonstrated its effectiveness at extracting accurate thermal properties over a range of samples. The model development and laboratory-based testing has been documented and submitted as a journal publication to the International Journal of Thermal Sciences. This work builds on previous research to develop and qualify a thermal conductivity needle probe capable of performing in-pile thermal conductivity measurement on materials, specifically uranium oxide. Prior to deployment for in-pile experiments, the next challenges to be researched include resolving cross-talk between heating wire and thermocouple at elevated temperatures and addressing sample size requirements for the technique.



Experimental measured data (solid lines) and analytic model (dashed lines) for stainless steel 304 samples of three different radii. As indicated, one data set thermal grease was used between the probe and sample to reduce the thermal contact resistance.

Single Effect

Larry Aagesen

Rob Schley

Measuring Changes in Grain Microstructure and Recrystallization of Nuclear Fuels and Structural Materials

Microstructure evolution due to irradiation in a nuclear reactor can have a dramatic effect on material properties. Researchers need a better understanding of this evolution to develop improved nuclear fuels and materials. The ability to measure such changes in real time is extremely limited due to the harsh conditions, high radiation fields and limited access of the reactor environment.

One activity of the I2 program is to develop instrumentation and techniques to measure the evolution of material microstructure under irradiation, including the recrystallization of nuclear fuels and structural materials.

To aid in designing in-pile experiments and interpreting their results, INL staff and researchers from Purdue University are collaborating to develop a new model for recrystallization based on the phase-field method.

Work is currently underway to directly import experimentally-observed microstructures into a model using INL's Multiphysics Object-Oriented Simulation Environment (MOOSE), a finite element method-based framework for solving coupled partial differential equations. The model includes a realistic representation of the physical structure of the dislocation network formed within grains during heavy deformation.

Recrystallized grains (blue) growing into deformed matrix (red). The recrystallization front exhibits protrusions and retrusions, in agreement with past experimental evidence.

Data from this model will allow researchers to better understand the microstructural evolution so they can predict under different conditions the response of a Laser Resonant Ultrasound Spectroscopy-based characterization experiment.

Researchers have developed an instrument to monitor grain microstructural changes during irradiation. Their measurement approach involves exciting and measuring the resonant frequency of a thin cantilever beam. Excitation and detection of the flexural vibrations of the beam are accomplished using optical methods which require only an optical fiber connection between the instrumentation and the sample. Recrystallization is the formation of a new, undeformed grain structure from within a heavily-deformed material.

Through these experiments, measurement of elastic properties can be tied directly to microstructure. An important finding of the work thus far is that the simulated morphology of the recrystallization front exhibits protrusions and retrusions, in agreement with the experiment.

This technique has been demonstrated in a laboratory setting to monitor the recrystallization of highly-textured copper during high-temperature annealing. A test capsule incorporating this technique has been developed for in-reactor testing. The capsule has been designed to be compatible with a reusable test module which allows simplified insertion in the TREAT reactor at INL.

Irradiation in the TREAT reactor to monitor the recrystallization transition of a pure metal is planned for 2019.

Colby Jensen

Halden reactor shutdown puts INL front and center

The 2018 shutdown of the nearly 60-year-old Halden Boiling Water Reactor (HBWR) test reactor at Halden, Norway, has offered both challenges and opportunities for the U.S. nuclear research and development (R&D) community. The long history of successful operation of HBWR for irradiation testing of nuclear fuels and materials for light water reactor R&D is based on mastering of state-of-the-art technology and engineering processes, including those related to the deployment of nuclear instrumentation.

The reactor was shut down in March, and in June it was announced there were no plans to seek relicensing in 2020. The Halden Reactor Project (HRP) – still in operation even as the reactor has been retired – is renowned for its success in online measurements of irradiation parameters and fuel rod performance under prototypic light water reactor (LWR) conditions. Instruments used in the HBWR have included thermocouples for temperature measurement, LVDT-based sensors for dimensional measurements, Self-Powered Detectors (SPDs) for neutron and gamma flux measurements, and sensors for monitoring chemical potential and corrosion.

Though having broad international scope and execution, much of HRP's work has been in collaboration with the U.S. Department of Energy and Idaho National Laboratory. The announced closure of the HBWR has provided a renewed interest and focus on existing R&D activities for advanced sensor development within the US DOE Nuclear Energy programs portfolio, in particular the In-Pile Instrumentation (I2) program. At INL this has been reflected in the creation of the Measurement Science Department as part of the Nuclear Science and Technology (NS&T) division.

To assess the impact of HBWR closure DOE organized a two-day Halden Capability Gap Assessment Workshop at INL in July 2018 where participants – INL, nuclear vendors, representatives from American and European research universities and agencies – agreed that no single facility can replicate what Halden has done. There was consensus, however, that some of Halden's capabilities exist or may be replicated elsewhere, and others might be covered by separate effects testing and planned integral testing capability.

In some respects, HBWR's closure represents an opportunity for the materials and fuels testing community to turn the page, said Daniel Iracane, deputy director-general and chief nuclear officer of the Paris-based Nuclear Energy Agency, an arm of the Organisation for Economic Co-operation and Development (OECD).

"For 50 years, the Halden Reactor Project demonstrated the value of international shared fuel and material testing activities," he said. In the wake of its reactor shutdown, the community dynamic, data, expertise and research are assets that can be spread worldwide through a coordinated approach, implementing key experiments at multiple facilities.

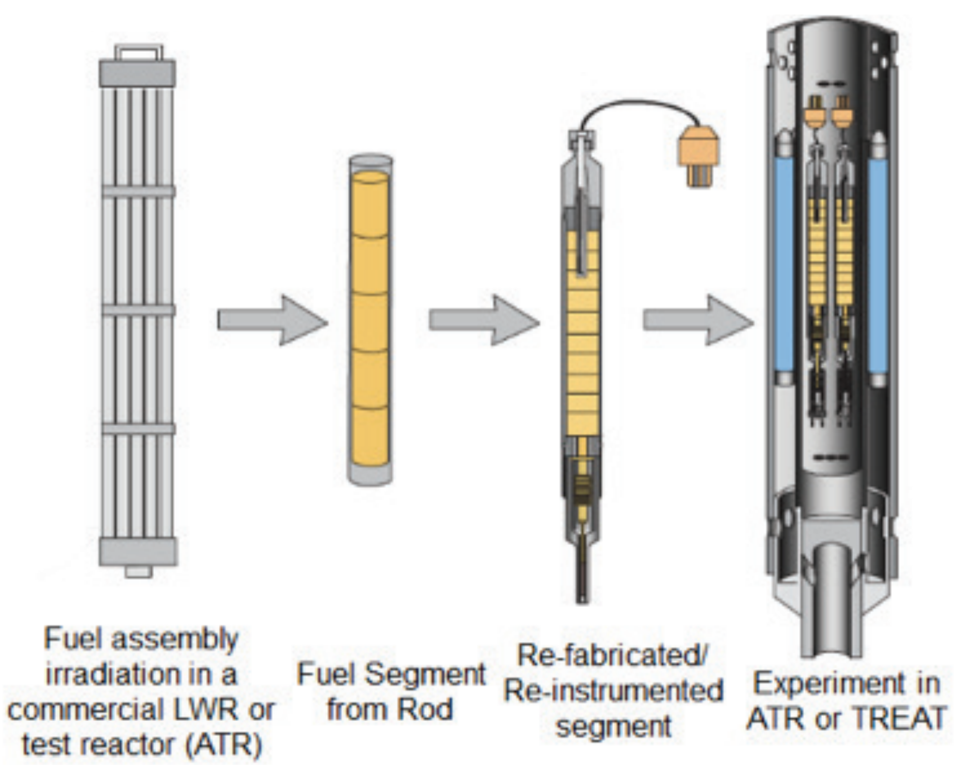
"The challenge is not technical, but in the way that we behave," Iracane said. "Creating confidence is a very important part."

In December 2018 INL's Colby Jensen summarized the gap assessment in his report titled "Post-Halden Reactor Irradiation Testing for ATF: Final Recommendations". The fourth recommendation in the report was for reliable in-pile instrumentation to complement in-pile testing facilities. As Jensen wrote, "Key to its success is making the HRP instrumentation strategy central to all irradiation testing capabilities, from ex-reactor testing to in-reactor testing and experimental devices to interim exams, and hot cell re-fabrication".

A review of all available in-pile instrumentation used at facilities around the world reveals that the variety of instrumentation considered widely mature, successful and diversely applicable is relatively small. They include thermocouples, LVDT-based sensors, and SPDs. "The primary gap in DOE facilities exists in experienced integration of instrumentation into fuel rods (re-fabrication), test devices, and specific reactor facilities and related instrument qualification," the report said.

The primary measurement approaches developed by HRP will likely continue to develop, but without the HBWR it will be DOE's responsibility, at INL and Oak Ridge National Laboratory, to prioritize and support in-pile instrumentation R&D and qualification. The report calls for "a pointed effort" to move Halden LVDT technologies to INL. Also, DOE should leverage Halden experience with water loop instrumentation to support development and operation of new water loops at ATR.

"In all cases, the Halden experience should be cited as much as possible to facilitate efficient maturation of these capabilities," Jensen said in the report. This need has been addressed by appointing Jensen as the technical lead for the instrumentation development and deployment for material test reactor experiments to mitigate the loss of the Halden Reactor Capabilities as part of the I2 program.



The capability to replace instrumentation in between successive phases of irradiation experiments is key to the success of the Halden test process.

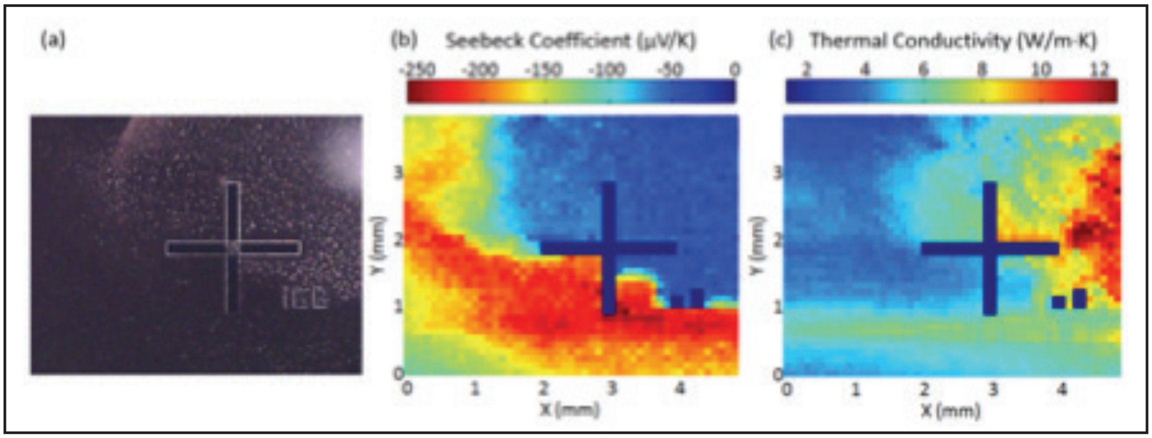
Yanliang Zhang

INL and Notre Dame pursue combinatorial materials science for sensor development

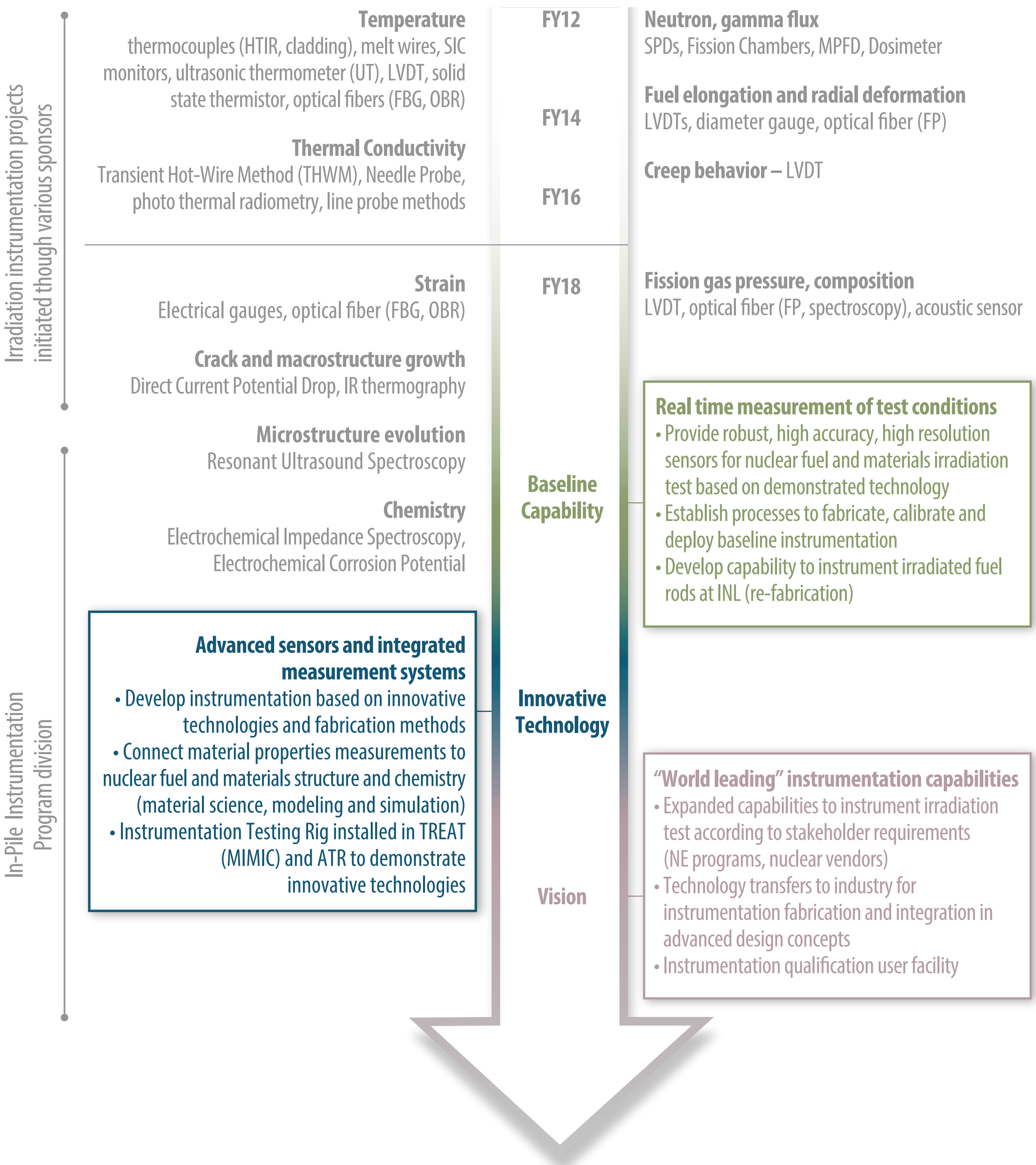
A necessary step in improved and novel sensor design is material selection. In-pile instrumentation must remain accurate in the extreme environments of the nuclear test reactors. Proper material selection can improve the function and robustness of sensors during irradiation, however, experiments to test the irradiation properties are expensive in both cost and time. INL, with Professor Yanliang Zhang at the University of Notre Dame, are exploring combinatorial materials science as a method for rapid testing of sensor materials. Combinatorial materials science refers to the testing of materials with graded properties, such as a graded composition. High-throughput combinatorial materials fabrication and screening process enable us to identify the optimal sensor materials composition and processing conditions that yield both desired sensing/transduction properties and required irradiation resistance in the most efficient and economic manner. This task is divided in to two primary goals: Developing methods for localized measurement of properties of interest and creation of materials with the desired gradient in properties.

The focus of the initial portion of this collaboration has been on pursuing methods for localized measurements. Without the ability to take measurements localized at a specific location within the gradient of the material and create property maps, combinatorial materials science loses its significance. Current thrusts in this area have led to the development of a microprobe at Notre Dame University that is capable of measuring thermal conductivity, Seebeck's coefficient and electrical conductivity at a resolution of ~1 μm2. These three properties play important roles in many sensor materials.

Initial efforts will focus on films with gradient compositions. Test films with varied compositions of Ti, Ni and Sn have been created using deposition processes. Future efforts in this area will use printing processes to create the gradients in composition, as well as creating films with constant compositions but varied process parameters of the printer.



(a) Optical image of a Ti-Ni-Sn combinatorial film with (b) Seebeck coefficient and (c) thermal conductivity maps.


Irradiation instrumentation projects initiated though various sponsors
In-Pile Instrumentation Program division
Temperature
thermocouples (HTIR, cladding), melt wires, SIC monitors, ultrasonic thermometer (UT), LVDT, solid state thermistor, optical fibers (FBG, OBR)
Thermal Conductivity
Transient Hot-Wire Method (THWM), Needle Probe, photo thermal radiometry, line probe methods
Strain
Electrical gauges, optical fiber (FBG, OBR)
Crack and macrostructure growth
Direct Current Potential Drop, IR thermography
Microstructure evolution
Resonant Ultrasound Spectroscopy
Chemistry
Electrochemical Impedance Spectroscopy, Electrochemical Corrosion Potential
Advanced sensors and integrated measurement systems
• Develop instrumentation based on innovative technologies and fabrication methods
• Connect material properties measurements to nuclear fuel and materials structure and chemistry (material science, modeling and simulation)
• Instrumentation Testing Rig installed in TREAT (MIMIC) and ATR to demonstrate innovative technologies
FY12
FY14
FY16
FY18
Baseline Capability
Innovative Technology
Vision
Neutron, gamma flux
SPDs, Fission Chambers, MPFD, Dosimeter
Fuel elongation and radial deformation
LVDTs, diameter gauge, optical fiber (FP)
Creep behavior – LVDT
Fission gas pressure, composition
LVDT, optical fiber (FP, spectroscopy), acoustic sensor
Real time measurement of test conditions
• Provide robust, high accuracy, high resolution sensors for nuclear fuel and materials irradiation test based on demonstrated technology
• Establish processes to fabricate, calibrate and deploy baseline instrumentation
• Develop capability to instrument irradiated fuel rods at INL (re-fabrication)
"World leading" instrumentation capabilities
• Expanded capabilities to instrument irradiation test according to stakeholder requirements (NE programs, nuclear vendors)
• Technology transfers to industry for instrumentation fabrication and integration in advanced design concepts
• Instrumentation qualification user facility

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