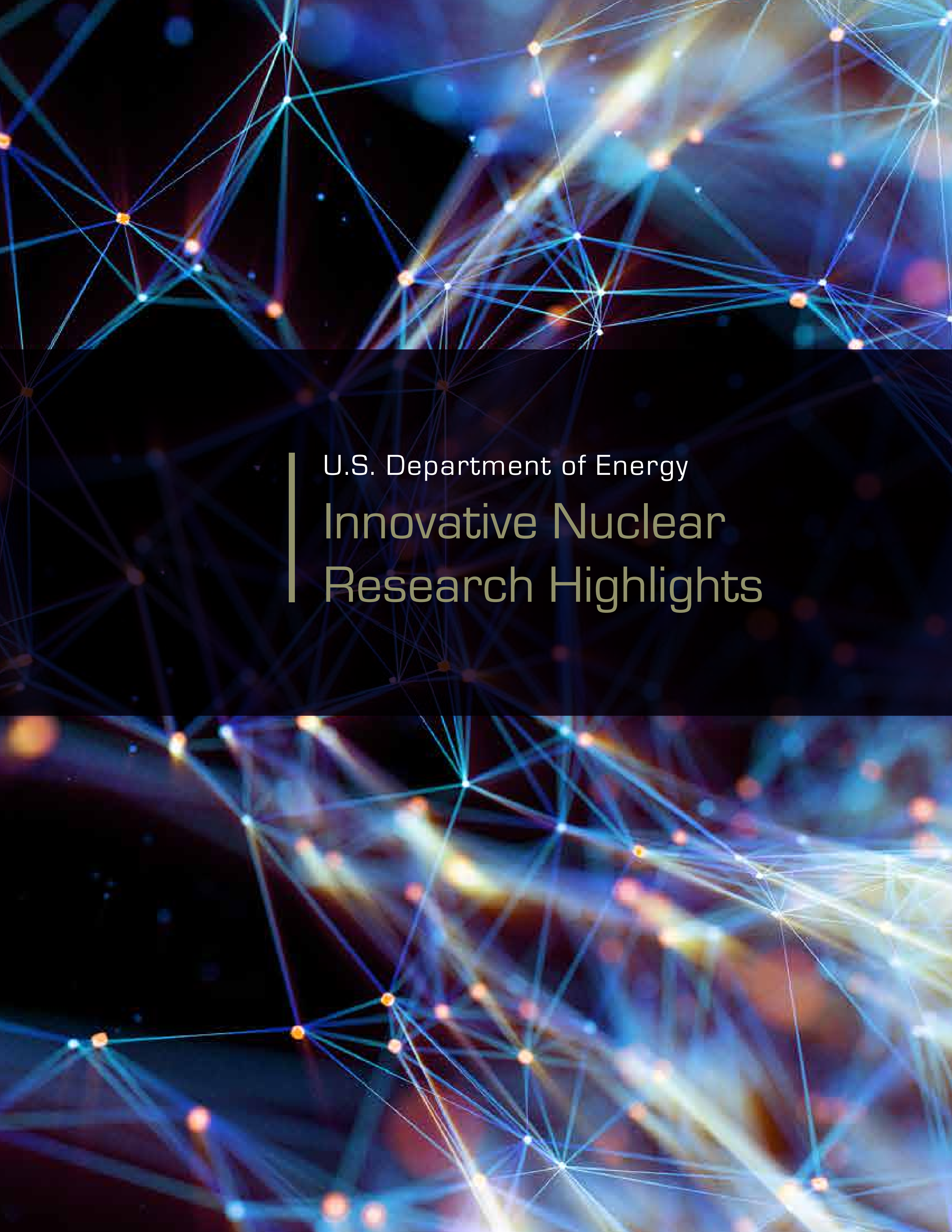
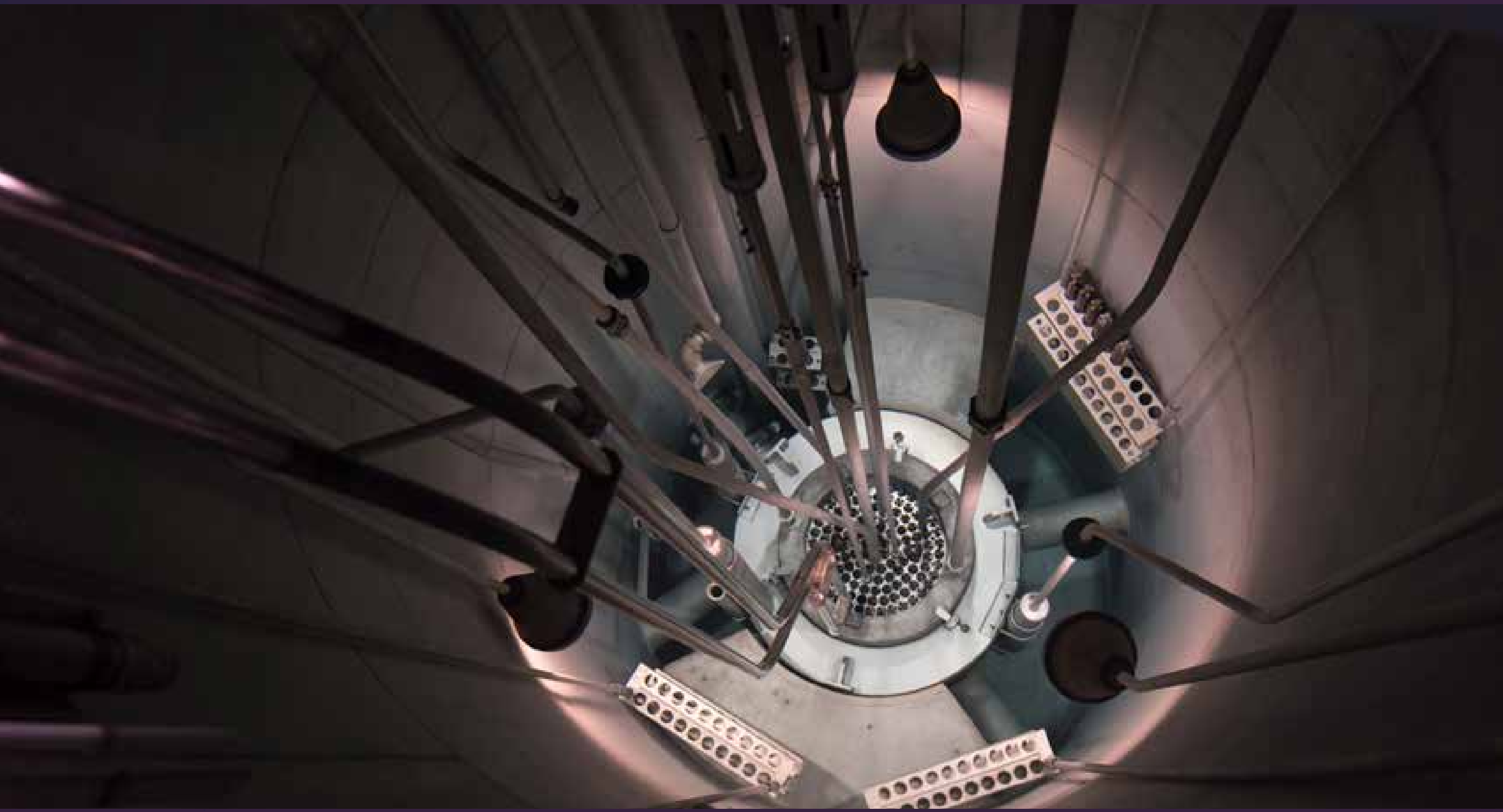


U.S. Department of Energy

Innovative Nuclear Research Highlights



The Oregon State University TRIGA reactor is a water cooled, pool type research reactor which uses uranium/zirconium hydride fuel elements in a circular grid array. The reactor is licensed by the U.S. Regulatory Commission to operate at a maximum stead state power of 1.1 MW and can also be pulsed up to a peak power of about 2,500 MW.

INNOVATIVE NUCLEAR RESEARCH

Overview

Innovative Nuclear Research (INR) houses the competitively funded programs administered by the U.S. Department of Energy, Office of Nuclear Energy (DOE-NE). INR provides a consolidated vision and peer review process to DOE-NE research and development programs and dedicates support to training the next generation of nuclear scientists through multiple student opportunities.

Through the Consolidated Innovative Nuclear Research Funding Opportunity Announcement, NE conducts crosscutting nuclear energy research and development (R&D) and associated infrastructure support activities to develop innovative technologies that offer the promise of dramatically improved performance for its mission needs, while maximizing the impact of DOE resources.

Through the Integrated University Program (IUP), DOE-NE ensures an adequate number of high-quality nuclear science and engineering (NS&E) students will (1) support the need for qualified personnel to develop and maintain the nation's nuclear power technology, (2) enhance educational institutions' capabilities to perform nuclear energy-related RD&D, and (3) meet DOE's and the national laboratories' needs for highly trained scientists and engineers in support of DOE-NE programs.

DOE-NE conducts Several programs fall under the INR umbrella:

Nuclear Energy University Program (NEUP) - University research integrated with overall DOE-NE program priorities

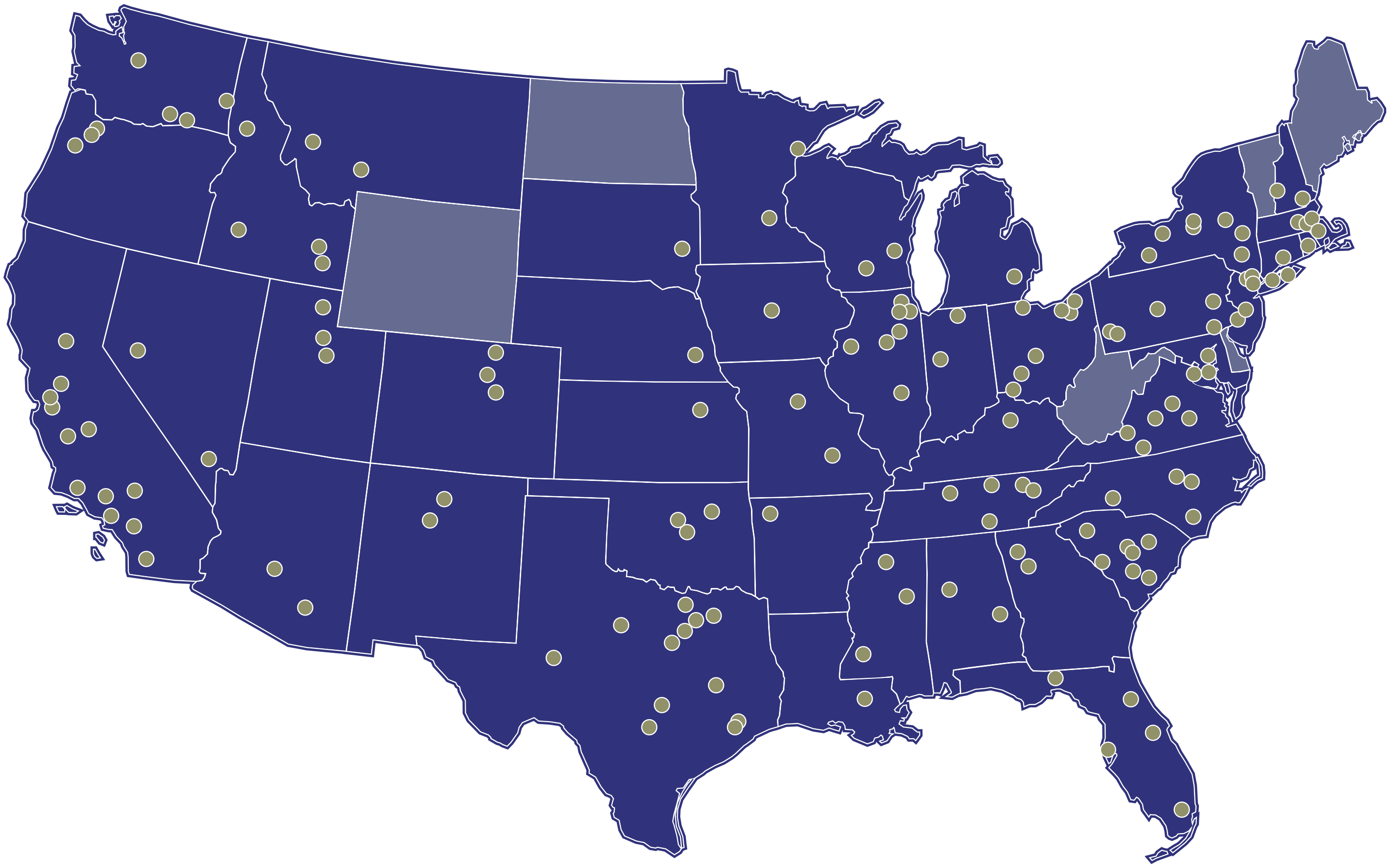
Integrated University Program (IUP) - Student educational support to train the next generation nuclear energy workforce

Nuclear Energy Enabling Technologies Crosscutting Technology Development (NEET-CTD) - Technology development focused on applicability to multiple reactor designs

Nuclear Science User Facilities (NSUF) - Unique capability access to enhance university and industry research projects

Award Recipients

Through the Consolidated Innovative Nuclear Research (CINR) Funding Opportunity Announcement (FOA) and the Integrated University Program (IUP), $729 million has been awarded to 125 U.S colleges and universities, 7 national laboratories, and 11 industry/utilities in 42 states and the District of Columbia.



$729,745,412

TOTAL AWARDED THROUGH CINR & IUP

Research & Development

677 Projects

531,286,612
Total R&D Funding

Integrated Research Projects

22 Projects

$89,009,625
Total IRP Funding

Infrastructure

241 Projects

$64,649,176
Total Infrastructure Funding

Integrated University Program

772 Projects

$44,799,999
Total IUP Funding

Nuclear Research & Development

The Consolidated Innovative Nuclear Research (CINR) Funding Opportunity Announcement (FOA) consists of three research and development (R&D) components that align with the U.S. Department of Energy's Office of Nuclear Energy (DOE-NE) mission and goals.

Michigan Ion Beam Laboratory member works on advancing the understanding of ion-solid interactions by providing unique and extensive facilities to support both research and development in the field. Photo courtesy: Joseph Xu, Michigan Engineering, Communications & Marketing.

The Nuclear Energy University Program (NEUP) awards competitively funded research and development opportunities in two main areas—fuel cycle and reactor concepts. The Nuclear Energy Enabling Technologies (NEET) Crosscutting Technology Development (CTD) program funds research that complements NEUP R&D. Programs partner with the Nuclear Science User Facilities (NSUF) program to provide R&D funds with access to one-of-a-kind facilities to enable research not typically available to university and industry researchers.

All applications undergo a rigorous multistage review process, including an independent peer review, to ensure projects are funded based on technical merit and relevance to DOE-NE's mission. Awardees are required to submit progress reports and meet specific milestones.

Nuclear Energy University Program: University research integrated with overall DOE-NE program priorities

Fuel Cycle: Evolving sustainable fuel cycle technologies that improve energy generation, enhance safety, limit proliferation risk, and reduce waste generation and resource consumption.

Reactor Concepts: Preserving the remaining commercial light water reactors as well as improving emerging advanced designs, such as small modular reactors, liquid-metal-cooled fast reactors, and gas- or liquid-salt-cooled high-temperature reactors.

Nuclear Energy Enabling Technologies: Technology development focused on applicability to multiple reactor designs

Advanced Manufacturing: Fabrication and repair techniques to increase viability of existing reactors or improve speed of manufacturing for new nuclear plants.

Advanced Sensors and Instrumentation: Demonstration of new sensor, instrumentation or controls technologies that enhance the operations of nuclear facilities.

Nuclear Science User Facilities: Unique capability access to enhance university and industry research projects

Joint R&D and NSUF research projects: NEUP and NEET project funds are combined with NSUF access to enhance research projects with one-of-a-kind testing capabilities.

NEUP	NEET	NSUF
562 Projects	72 Projects	43 Projects
97 Insitutions	30 Insitutions	26 Insitutions
45 Awards/year	9 Awards/year	5 Awards/year
$800K PROJECTS	$1M PROJECTS	$500K PROJECTS
Average # of pre-apps 570 Average # of full apps 225	3 TECHNICAL AREAS: Advanced Manufacturing, Sensors & Instrumentation, Materials	$10 million in NSUF facility access/year
$410.3M Total R&D Funding: 2009-2019	$72.6M Total R&D Funding: 2012-2019	$48.3M Total R&D Funding: 2016-2019

NSUF Access Only projects: Allows industry leads to access NSUF facilities for large ion irradiations, neutron irradiations or post-irradiation examination work to enhance industry-funded research projects.

Since 2009, the NEUP and CINR opportunities have received more than 6,500 pre-applications and over 2,900 full applications. From those applications, DOE-NE has awarded 658 research and development projects to 141 different academic, national laboratory and industry research institutions.

These projects have resulted in support for 2,133 students, over 1,200 scientific publications and over 10,000 citations in other scientific works.

PROGRAM HIGHLIGHT

Seawater Yields Yellowcake Uranium

by Kate Meehan for DOE's Nuclear Energy University Program

Chien Wai, principal investigator, displays the yellowcake uranium extracted using methods developed in NEUP-supported projects. Photo courtesy of LCW Supercritical Technologies.

Dipping a bundle of yarn into the ocean and pulling out uranium sounds easy enough. This method of extracting uranium from seawater, an effort led by Chien Wai, emeritus chemistry professor at the University of Idaho, has created quite a splash with its promising results. But while the process itself may be fairly straightforward, reaching this point of success has taken a significant amount of time and effort.

Uranium is a silvery-white metallic chemical element that occurs naturally in low concentrations in soil, rock and water. For many years, uranium was used primarily as a colorant for ceramic glazes and for tinting in early photography. Its radioactive properties were not recognized until 1866, and its potential for use as an energy source was not manifested until the mid-20th Century. Today, uranium is used to power commercial nuclear reactors that produce electricity and to produce isotopes used for medical, industrial and defense purposes around the world.

Traditionally, uranium has been mined the same way other heavy metals are extracted from the earth. In addition to environmental concerns, this method has a limited time span, as various agencies estimate that current methods of uranium mining will only provide around 100 more years of capacity for the world's nuclear power plants.

The potential for extracting uranium from seawater, by contrast, is almost limitless. Seawater contains approximately three parts per billion of uranium, a seemingly tiny amount. Yet with a total ocean volume of approximately 1.3x109 km^3, there are over 4 billion tons of uranium in seawater—about 1000 times the amount known to exist on land. Environmentally sustainable separation and recovery of uranium from seawater has been an ongoing research area supported by the Department of Energy's Office of Nuclear Energy (DOE-NE).

The low concentration of uranium in seawater (as well as its stable chemical form, uranyl tris-carbonato complex, or UO2(CO3)3) makes the extraction of uranium extraction extremely difficult. Scientists, mainly in Japan, have been tackling this challenge since the 1980s. These scientists determined that amidoxime-based polymer adsorbents have the greatest potential, thanks to their mechanical strength and high uranium loading capacities.

To continue this area of study, Wai applied for—and received—support from DOE's Nuclear Energy University Program (NEUP)back in 2011. This was in addition to ongoing support from DOE's Small Business Innovation Research (SBIR) program for LCW

Supercritical Technologies. Wai is CEO of LCW Supercritical Technologies, a company focused on bringing this new technology to market. Both avenues of funding from DOE have helped bring Wai's idea to fruition.

The first phase of his research was carried out over a two-year period and was then followed by a second, three-year NEUP research and development project. Over the course of these studies, Wai worked with both national laboratory partners and his home university. Oak Ridge National Laboratory (ORNL) developed an adsorbent and provided it to Wai, who then carried out most of the work at his lab at the University of Idaho. Uranium adsorption, elution and sorbent reuse tests were performed using a recirculating seawater flume system available at the Pacific Northwest National Laboratory (PNNL) Marine Sciences Laboratory located in Sequim, Washington.

ORNL's polymer adsorbent utilizes high-surface-area polyethylene fibers as the backbone material and shows very high uranium adsorption capacities. It is prepared through an intensive process of radiation-induced grafting and treatment with a strong potassium hydroxide (KOH) solution to make it effective for uranium adsorption in seawater. Hydrochloric acid has traditionally been used to elute uranium from the adsorbent, which must then be treated with KOH again to recondition the adsorbent. For his NEUP projects, Wai mainly used a variety of this adsorbent referred to as AF1.

In Wai's study, AF1 had an initial uranium adsorption capacity of about 3.7 g U/kg after 42 days of seawater exposure. After the acid elution and the KOH reconditioning process, the uranium adsorption capacity of the recycled adsorbent dropped drastically to about 0.5 g U/kg. Wai theorized that a combination of factors during the elution and reconditioning process causes physical and chemical changes to the material that reduce its uranium adsorption capacity. Spectroscopic techniques (FTIR and SEM) support this contention, as Wai observed a decrease in amidoxime groups as well as physical damage to the fiber structure of the material.

Wai's main objectives with his NEUP research included adsorption capacity, durability for reuse, and affordability, as these factors determine the economic feasibility for future commercial extraction of uranium from seawater. To this end, Wai aimed to develop a new, milder elution process that would result in minimal damage to the fiber adsorbent. During his five years of NEUP funding, Wai explored a number of different methods, including carbonate elution and supercritical fluid elution, before settling on a bicarbonate elution technique. Wai describes his new process, which uses sodium bicarbonate (baking soda), as "very effective" for removing uranium from the adsorbent.

In real seawater experiments carried out at PNNL, the fiber attracted heavy metals as well as natural organic matter, which was not removed by the bicarbonate elution. Wai added a dilute base (0.5M NaOH) soaking step to the process, which removed organic matter as well as some of the transition metals. After this process, the initial uranium adsorption capacity of the recycled adsorbent remained

"I went to Goodwill and picked up a sweater and a pair of gloves that were 100% acrylic. We can convert waste into a magical material."

Just Add Seawater

Tests at Pacific Northwest National Laboratory's Marine Sciences Laboratory have focused on recreating actual ocean conditions. The purpose is to better understand environmental factors that can degrade acrylic yarn as well as provide accurate estimates of uranium adsorption. The adsorbent is added by attaching it to a flume where raw sea water is circulated for approximately one month (photo: top right). At that time, the yarn is removed from the system, measured and packaged to be sent to Wai's lab in Moscow, Idaho (photo: bottom right).

Wai emphasizes that this research is in the preliminary stages. To increase production for large-scale industrial application, which would be needed to supply U.S. nuclear reactors, the system would have a large footprint. Wai estimates that several square miles would be needed to deploy enough yarn to collect the necessary levels of uranium.

The adsorbent is added by attaching it to a flume where raw sea water is circulated for approximately one month (photo: top right). At that time, the yarn is removed from the system, measured and packaged to be sent to Wai's lab in Moscow, Idaho (photo: bottom right).

virtually unchanged; however, uranium adsorption started to decrease with subsequent reuse. Wai theorized that the fiber material is probably not stable over long-term exposure to seawater.

To combat this, during the first phase of his DOE SBIR award, Wai developed his own highly efficient polymer adsorbent (LCW fiber) derived from acrylic yarn. The material is inexpensive, according to Wai, both to purchase and modify. Wai can start with any acrylic fiber, which can readily be found in craft stores in the form of yarn, or even in clothing stores already made into apparel.

“I went to Goodwill and picked up a sweater and a pair of gloves that were 100% acrylic,” said Wai. “We can convert waste into a magical material.”

In fact, if Wai could find a large enough volume of recycled fiber, he would not need to use any newly created material. The fiber is also reusable (though its life span is still under investigation), making this a truly green technology.

Once he has the acrylic fiber, Wai performs a simple chemical process to prepare it for uranium adsorption. The overall procedure is significantly cheaper than the process of radiation-induced grafting required to create fibers like AF1.

During the second phase his DOE SBIR grant, Wai’s experiments yielded over 5 grams of yellowcake uranium (uranium oxide), a bit more than the size of a U.S. nickel. Yellowcake is the material used in the preparation of fuel for nuclear reactors. Right now, Wai only has the capacity for small-scale production at his lab in Moscow, Idaho, but he is looking to scale up.

Future experiments seek to test LCW fiber in an actual ocean installation. Thanks to an ongoing grant from the DOE SBIR program, Wai has continued his partnership with PNNL. In 2019, the team will begin testing in the warm waters of the Gulf of Mexico. Since the material performs better in warmer water, Wai expects higher removal rates of uranium from the region than have been found at PNNL’s home in the Pacific Northwest.

Looking forward, Wai envisions a bright future for his new technology. While uranium remains the focus, LCW fiber is also effective at removing heavy metals like lead from water. Wai sees the potential for LCW fiber to be used in a variety of ways to help with heavy metal cleanup, from a large mining site to the water filter in your kitchen. In fact, his company is currently comparing its technology to commercially available filters for drinking water.

Might we find LCW fiber on the shelf any time soon? Wai says the company is still in the testing phase. So far, experiments have established the fiber as nontoxic, but some questions still need to be answered, such as how often the fiber can be recycled and how to properly dispose of it once it has reached the end of its usefulness. Wai’s company is currently looking for private investment to continue to develop and prove the efficacy of its technology, particularly in the field of industrial wastewater treatment.

With an impressive amount of success already under its belt, LCW fiber is well on its way to becoming a novel, green technology capable of providing both waste cleanup and uranium extraction in the years to come.

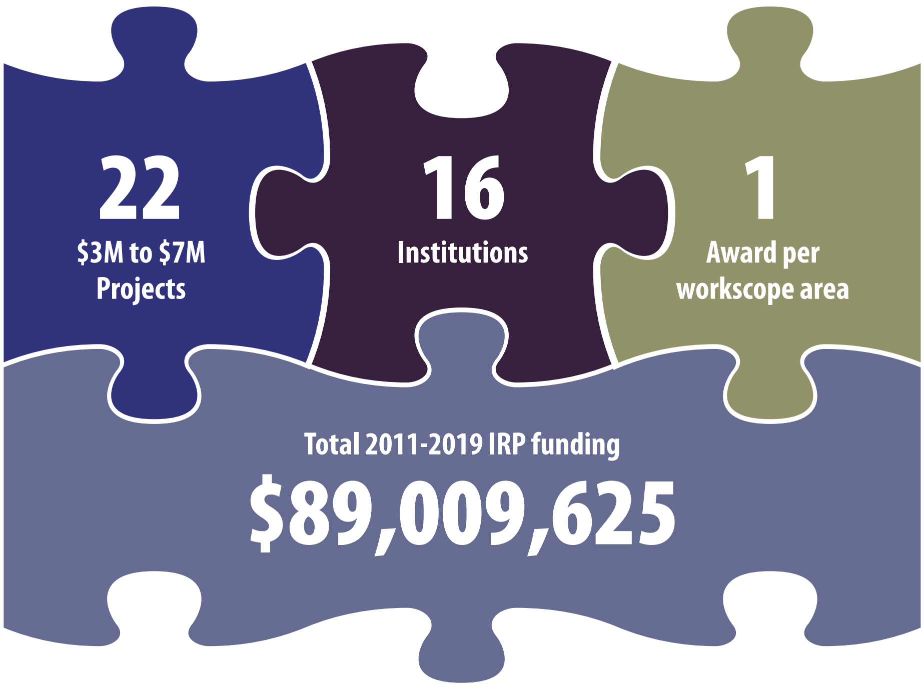
Integrated Research Projects

Integrated Research Projects (IRPs) comprise a significant element of the Department of Energy's (DOE) innovative nuclear research objectives and represent the Program Directed (PD) component of the Office of Nuclear Energy (NE) strategy to provide research and development (R&D) solutions most directly relevant to the near-term, significant needs of the NE R&D programs.

Dr. Travis Knight, University of South Carolina, lifts an interchangeable experimental rod from a fuel storage canister.

IRPs are significant projects within specific research areas. IRPs are intended to develop a capability within each area to address specific needs, problems, or capability gaps identified and defined by NE. These projects are multidisciplinary and require multi-institutional partners. IRPs may include a combination of evaluation capability development, research program development, experimental work, and computer simulations. Past areas include:

- Advanced reactor design;
- Used fuel disposal and transportation;
- Accident tolerant fuel development;
- Materials irradiation techniques;
- Transient test reactor instrumentation and fuel testing;
- Used fuel cask inspection and repair techniques;
- Compact heat exchangers development; and
- Modeling and simulation.



IRPs are intended to integrate several disciplinary skills in order to present solutions to complex systems design problems that cannot be addressed by a less comprehensive team.

Although a proposing team must be led by a university principal investigator and include at least one additional university collaborator, the proposed project team may include multiple universities and non-university partners (e.g., industry/utility, minority-serving institution, national laboratory, underrepresented group, and international).

PROGRAM HIGHLIGHT

Kairos Power: DOE-NE Integrated Research Project to Nuclear Startup

by Paul Menser for DOE's Nuclear Energy University Program

Gus Merwin, test engineer at Kairos Power, supervising a salt material compatibility test in the Kairos Power laboratory at corporate headquarters in Alameda, California.

Kairos Power, a California-based company aiming to transform the energy landscape in the United States by combining existing technologies in new and exciting ways, is modernizing fluoride-salt-cooled high-temperature reactor (FHR) technology for an emerging stage of commercialization. Although the concept itself is not new, novel developments in associated technology have made the reactor a viable power production and heat processing option. This is important to the economy as other energy sources continue to become more expensive in the United States.

Additionally, the technology has the potential to provide a reliable and steady foundation of energy to the other renewable sources on the grid, which have intermittent power sources.

Based on research funded through the Department of Energy's (DOE) Nuclear Energy University Program

(NEUP), Kairos is using past data to create current solutions.

Advances made in understanding and predicting the performance of passive safety systems have created new and unexpected opportunities for decades-old ideas.

The idea of an FHR dates back to 2001, when the Generation IV forum chose molten salt reactors as one of six concepts to pursue. In 2004, DOE's Office of Nuclear Energy (DOE-NE) started supporting FHR development on a small scale through its laboratories and university research programs. In 2010, DOE-NE endorsed FHRs as a potential means for achieving the administration's research and development (R&D) goals for nuclear energy.

FHRs rely upon technology that was not available during the earlier molten salt reactor (MSR) era back in the 1950s. Still, by the time the government's MSR program was cancelled in the 1970s, substantial technical progress had been made on other reactor classes and technologies that support FHRs. For example, data collected in the mid-1980s at Argonne National Laboratory's Idaho Experimental Breeder Reactor-II indicated that decay heat from low-pressure, liquid-cooled reactors could be passively rejected to the local air without fuel damage. Similarly, the ongoing advanced gas reactor fuel testing program demonstrated ceramic-coated-particle fuel could be mechanically robust and manufactured at an acceptable price.

Today, nearly 20 years later, Kairos's founding officers—CEO Mike Laufer, Chief Technology Officer Ed Blandford and Chief Nuclear Officer Per Peterson—plan to have a demonstration reactor in operation before 2030.

The FHR concept combines three elements:

1. Li2BeF4, a lithium-beryllium-fluoride salt known as Flibe;

2. Tri-structural isotropic (TRISO)-coated particle fuel embedded in small graphite pebbles, originally developed for high-temperature gas-cooled reactors (HTGRs); and

3. Low-pressure, High temperature, thin walled vellel and piping originally developed for sodium cooled fast reactors.

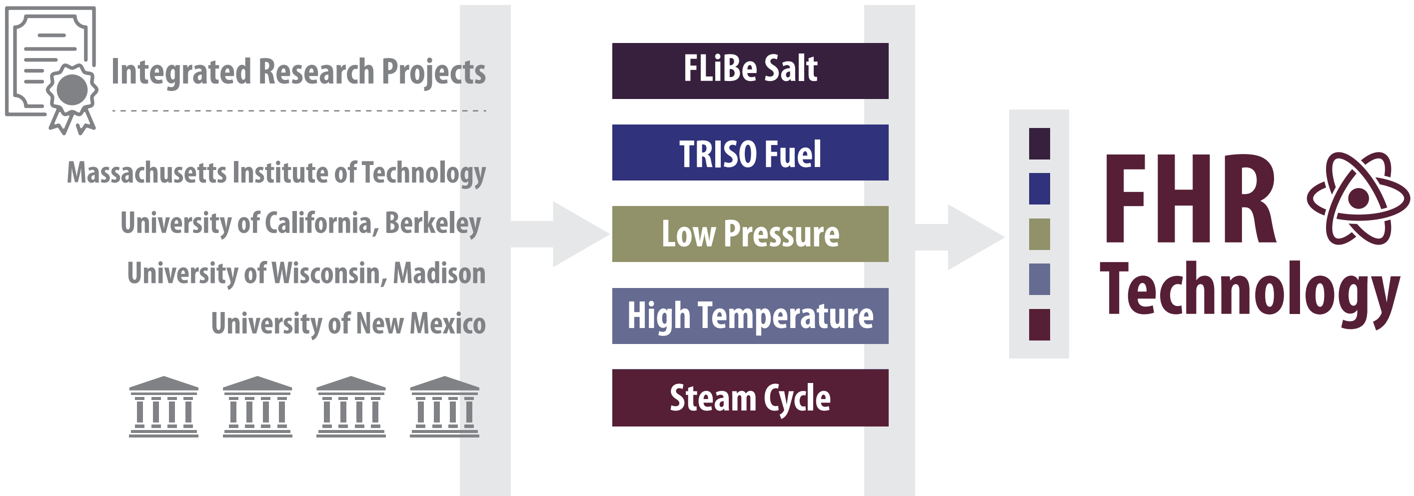
With the cancellation of DOE's molten salt reactor program in the 1970s, expertise in the technology was no longer a priority for national laboratory or university projects. Subsequently Flibe was studied for use as a coolant in fusion systems, but capabilities to work with Flibe experimentally were lost.

Although the company wasn't incorporated until 2016, Kairos's story actually began in 2011. Through NEUP, a three-year Integrated Research Project (IRP) was awarded to MIT and its partners at the University of California, Berkeley (UCB) and the University of Wisconsin, Madison (UW). The proposal opened with this statement:

"(The objective) is to develop a path forward to a commercially viable salt-cooled solid-fuel high-temperature reactor with superior economic, safety, waste, non-proliferation, and physical security characteristics compared to light-water reactors."

"This was the first project that used Flibe salt as a coolant for solid fuel in a reactor," said Todd Allen, the materials testing lead on the 2011 IRP project.

Students pose on the Compact Integral Effects (CIET) Test facility, a scaled thermal hydraulics facility that provides data on salt cooling behavior in FHRs. The CIET team included now Kairos CEO, Dr. Michael Laufer (front, second from right) and Dr. Per Peterson, Kairos Chief Nuclear Officer (front, fourth from right).



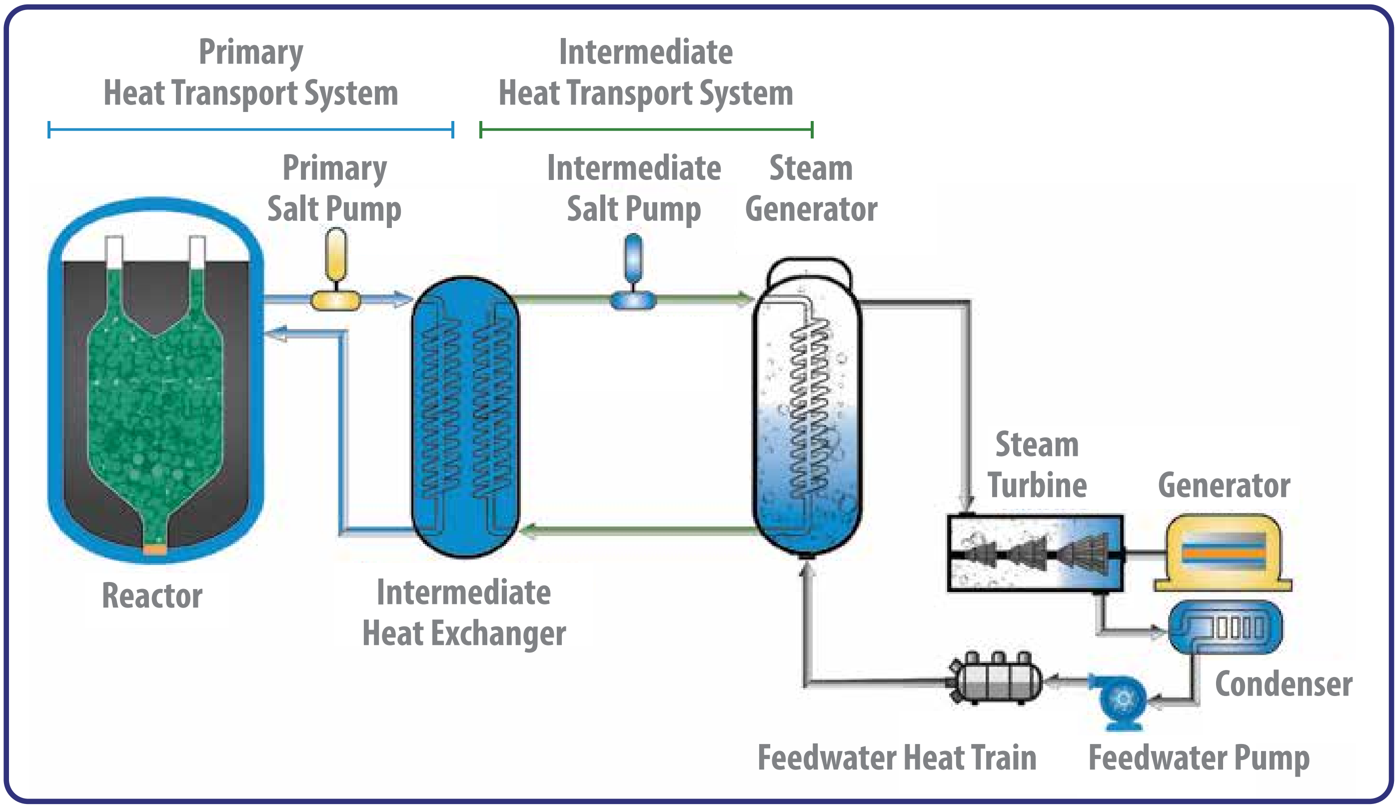
What followed were workshops in 2012 involving graduate students from all three institutions. Their involvement—the questions they asked, the discoveries they made and the perspectives they offered—gave the IRP a different kind of energy. "These were the first students in a generation that worked on developing a molten salt reactor."

During the IRP workshops, retired Oak Ridge National Laboratory personnel in their late 70s and 80s provided guidance on technical direction, insight and discussion of pertinent issues; this allowed for knowledge transfer to graduate students working on the projects.

As a result of these collective IRP projects, dozens of graduate students have now graduated and are contributing in this area as university professors and national laboratory or industry staff.

IRPs represent the program-directed component of NEUP by providing research and development (R&D) solutions most directly relevant to the near-term, significant needs of the NE R&D programs. IRPs complement the other NEUP components, which include program supporting and mission supporting university-based R&D, university reactor and research equipment infrastructure upgrades, and Integrated University Program student fellowship and scholarship grants. They are significant three-year awards for projects that address specific research issues and capability gaps identified and defined by the NE R&D programs. They are intended to develop a capability within each

"These were the first students in a generation that worked on developing a molten salt reactor."



The Kairos Power FHR (KP-FHR) is a novel advanced reactor technology that leverages TRISO fuel in pebble form combined with a low-pressure fluoride salt coolant. The technology uses an efficient and flexible steam cycle to convert heat from fission into electricity and to complement renewable energy sources.

specified area. These projects are multidisciplinary and require multi-institutional partners.

In the case of FHR, each university involved had unique features to contribute:

- Materials irradiations: MIT students developed, built and operated test capsules with prototypical materials in 700°C salt in the MIT reactor under prototypical temperature and irradiation conditions expected in the FHR. Identical tests were conducted outside the reactor at UW to understand and separate out the effects of salt corrosion and irradiation on materials.
- Materials testing: UW has built and now operates systems to purify the fluoride salts required for the FHR. Students used these salts in 700°C corrosion tests to evaluate different potential materials for the FHR.
- Thermal hydraulic tests: UCB has built large-scale thermal-hydraulic test loops that use an organic simulant, in which students conducted experiments to provide required experimental data for reactor design.

This 2011 IRP project provided a renewed DOE investment in molten salt reactor technology, which now has a dedicated work scope area in DOE's Consolidated Innovative Nuclear Research funding opportunity. This is supported by research at Oak Ridge National Laboratory.

By the end of the project, the IRP had produced four white papers and more than 100 technical reports and papers summarizing the three activities and associated experimental work. A subsequent IRP was then funded in 2014, with University of New Mexico joining the original partner universities.

All of this has helped develop a workforce for the FHR project. By December 2018, Kairos had hired 26 researchers who had done graduate work on the IRP.

Nicolas Zweibaum, Ph.D., Manager of Engineering Testing at Kairos Power (left) and Trevor Beck, Engineering Technician operating a heat transfer test in the Rapid Lab at the Kairos Power headquarters in Alameda, California.

Meanwhile, a second FHR-focused IRP was awarded in 2014, involving Georgia Institute of Technology, The Ohio State University, Texas A&M University at College Station, Texas A&M University at Kingsville, and several other national and international partners.

"It presented them with a real interesting and advanced learning experience," said Regis Matzie, a retired Westinghouse chief technical officer who chaired the original IRP advisory panel. As they explored the FHR concept, they came to the conclusion that it took the best aspects from several forms of power generation. For example:

- Gas-cooled reactors: TRISO fuel, structural ceramics, and high-temperature power conversion;
- Molten salt reactors: fluoride salt coolant, a structural alloy and hydraulic components;
- Liquid metal reactors: passive decay heat removal, low-pressure design and hot refueling;
- Light water reactors: high heat capacity coolant and transparent coolant; and
- Advanced coal plants: a supercritical water-power cycle and structural alloys.

Joel Hughes, a former DOE-NE IUP Fellow at University of New Mexico and current Kairos Power employee, preps an experiment at Kairos Headquarters in Alameda, California.

FHRs afford lower power costs (due to a low-pressure primary system enabling functional containment) and thermal efficiency at least 12 percent higher than light water reactors (due to high temperature delivery of heat). Also, with low water consumption and no need for a grid connection for process heat, they seem to be more easily siteable.

In addition to the technical aspects of the project, a significant amount of the IRP work has been focused on the regulatory aspects of getting an FHR licensed by the U.S. Nuclear Regulatory Commission. In fact, the first series of workshops was aimed at addressing the best way to go about licensing this technology. As a result, Kairos has leapfrogged to newer safety codes developed by DOE.

"If we had not done that work in advance, it would have been a much more daunting prospect," Peterson said. "It is remarkable, the quality of the work and how much has been documented."

The data collected in experiments done decades before and advancements in current reactor technology, along with the NEUP funding, have provided a unique story and a prime moment to commercialize remarkable technology that potentially offers a viable energy solution.

Kairos Power Continues Partnership with DOE-NE on Reactor Development

Kairos Power was recently awarded two project partnerships through DOE-NE's U.S. Industry Opportunities for Advanced Reactor Development funding opportunity, which funds advanced reactor technology that will be deployed in the mid- to late-2020s. Two projects, totaling over $11 million ($5.5 million in DOE funds, $5.8 million in Kairos Power cost share), will support development and licensing activities to accelerate development of the Kairos Power FHR (KP-FHR).

- **Development of Modeling and Simulation Pathways to Accelerate KP-FHR Licensing**

  This project advances the schedule in critical advanced modeling and simulation capabilities needed for the FHR's license application. The team consists of NEAMS developers at Idaho National Laboratory, Argonne National Laboratory and Los Alamos National Laboratory. They will develop modeling tools that will be useful to both Kairos Power and other molten salt and fluoride high-temperature reactor development programs.

- **Technology Pre-application Licensing Report on the Development of a Mechanistic Source Term Methodology for the KP-FHR.**

  This project will develop a mechanistic source term for the KP-FHR design, including consideration of radionuclides generated and transported in the fuel particle and the barriers to release for licensing basis event analyses.

Infrastructure

Through the Nuclear Energy University Program (NEUP), NE integrates university-led innovation into its technical missions by way of a competitive grant process. Established in 2009, NEUP funds two types of grants: Research and Development (R&D) and Infrastructure. Infrastructure grants have been integral in strengthening the nuclear energy research capabilities of universities across the country.

This support is often in the form of laboratory equipment. DOE funds two types of NEUP Infrastructure grants: General Scientific Infrastructure (GSI) support and research reactor upgrades. The typical amount awarded by the government for a GSI grant is $250,000 (may include cost match). Universities can receive up to $1.5 million for reactor upgrades.

To date, the Department of Energy (DOE) has funded 234 Infrastructure grants at 60 institutions at a value of more than $61 million. Split between two focus areas, GSI and Reactor Upgrades, DOE has funded projects such as a nuclear power plant simulator at The Ohio State University and the replacement of cooling system components at Oregon State University's TRIGA reactor. All 25 university research reactors in the United States have been supported through NE Infrastructure grants,

Melinda Krahenbuhl is a recipient of two Infrastructure grants to improve the reliability and enhance the research capabilities of the Reed Research Reactor. The Reed Research Reactor, established in 1968, is the only reactor operated primarily by undergraduates. Photo by Leah Nash, courtesy of Reed College.

$61,346,210*

in NEUP infrastructure grants since 2009

General Scientific Infrastructure	**150** awards	**58** different universities
Reactor Upgrade	**84** awards	**24** universities (out of 24 eligible institutions)

boosting universities' capabilities for cutting-edge research and for educating the next generation of the nuclear workforce.

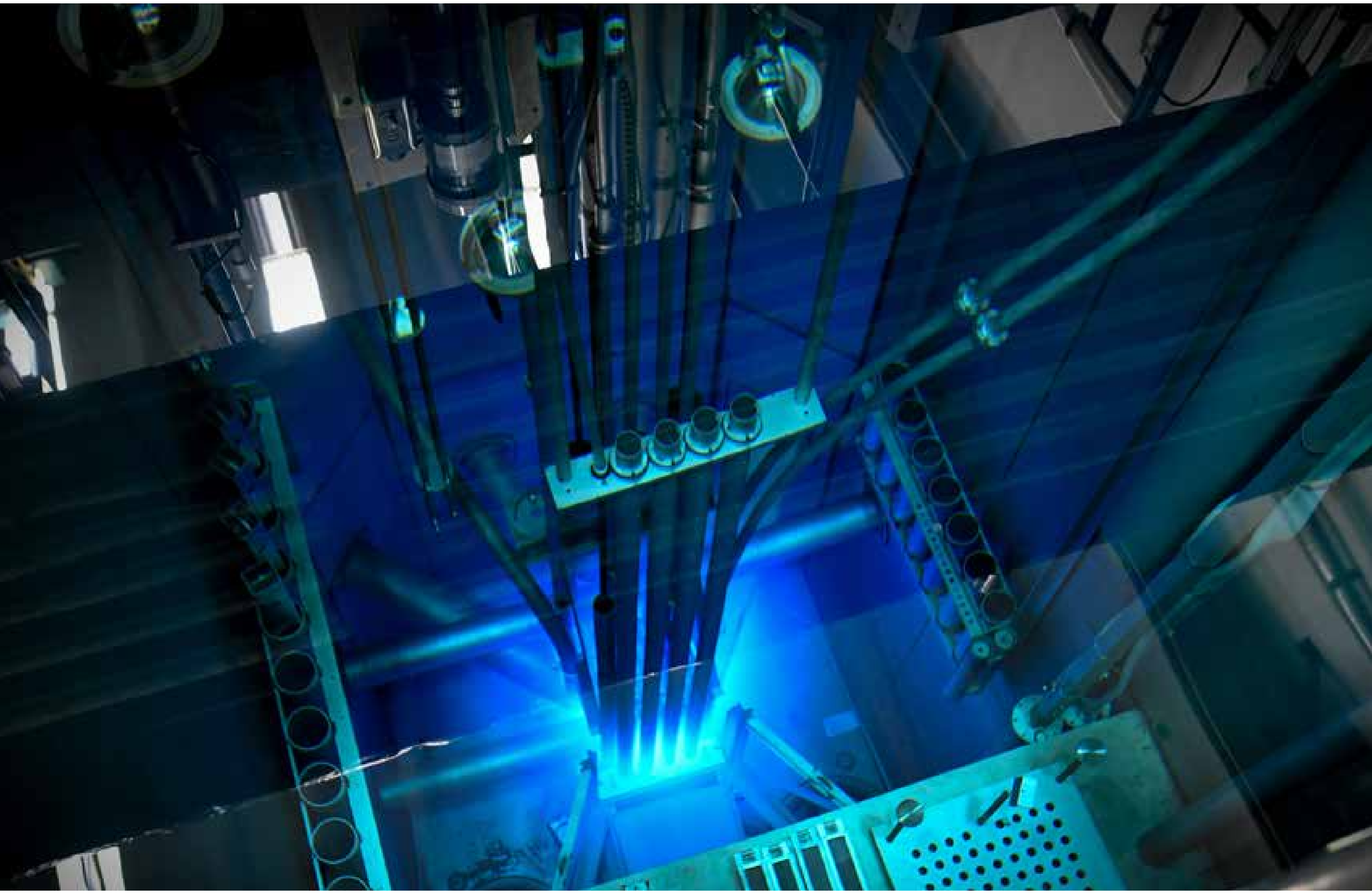
Infrastructure upgrades often develop or strengthen a unique capability beneficial to researchers from more than just the university at which the capability resides. Historically managed by NEUP, the Infrastructure grant process now resides with the Nuclear Science User Facilities (NSUF). NSUF, another program housed under NE, offers free access to NSUF facilities found at universities and national laboratories around the world. Through NSUF's separate competitive peer-reviewed processes, researchers can gain access to NSUF facilities for zero cost. These include the partner facilities found at universities enhanced through NEUP grants.

* $64,649,176 including 7 NEET national laboratory infrastructure projects (2014-2016)

PROGRAM HIGHLIGHT

PULSTAR Reactor – a Research Reactor for the 21st Century

by Kate Meehan for DOE's Nuclear Energy University Program

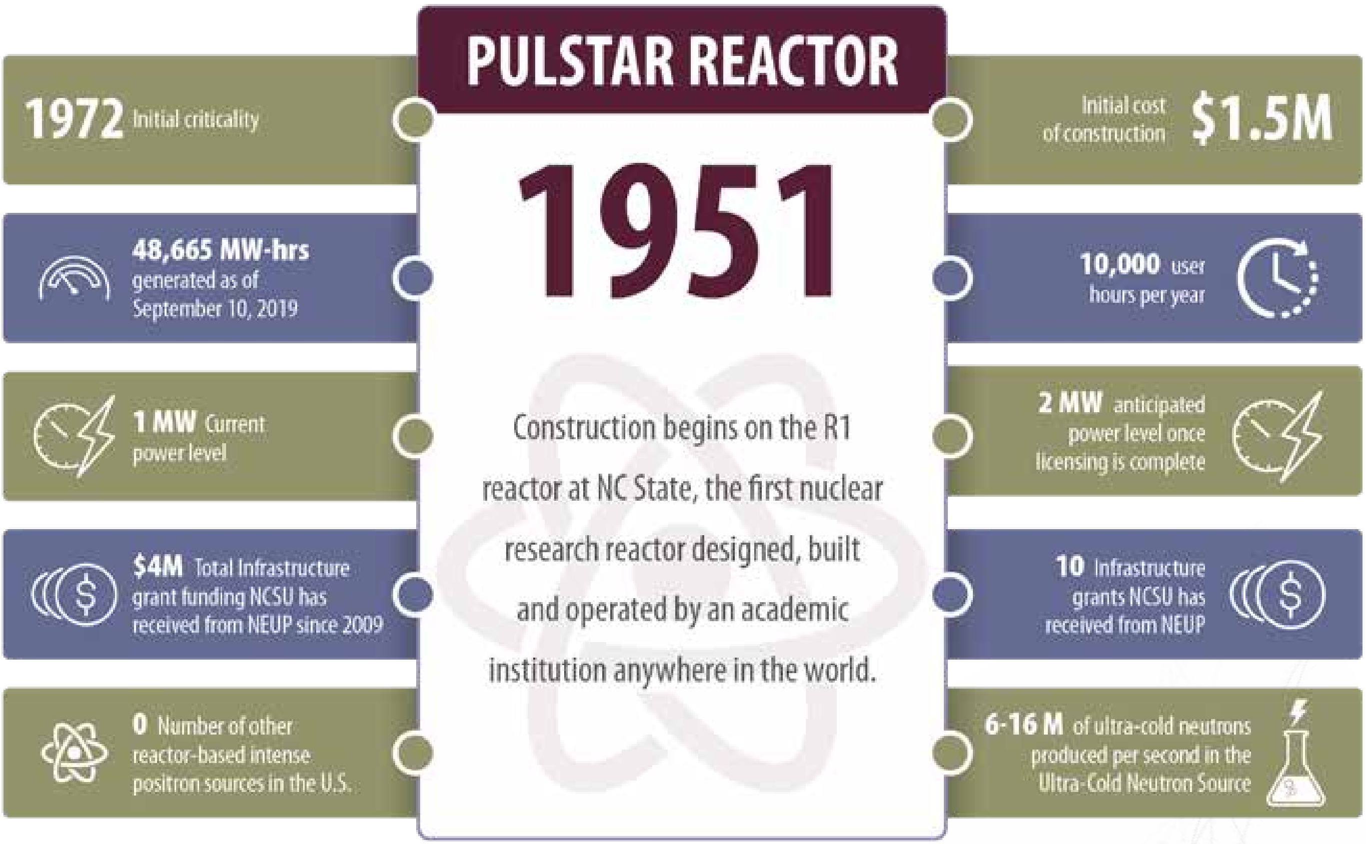


The conduct of irradiation tests in North Carolina State University's PULSTAR reactor pool in support of the Nuclear Reactor Program.

The tree-lined, red brick campus of North Carolina State University houses an unlikely facility: a PULSTAR reactor, the only reactor of its type still in operation. This unique reactor operates at a steady state power of 1MW. The reactor provides the opportunity for researchers from around the world to conduct a wide variety of experiments, thanks to its intense source of neutrons.

Over the past decade, the Nuclear Reactor Program (NRP) at NC State has received substantial infrastructure investments from the Department of Energy's (DOE) Nuclear Energy University Program (NEUP), as well as from other agencies, allowing for a significantly increased research capability. DOE's Office of Nuclear Energy created NEUP in 2009 to consolidate its university support under one program. NEUP funds nuclear energy research and equipment upgrades at U.S. colleges and universities and provides students with educational support.

NC State has been awarded 10 NEUP grants for research reactor and infrastructure improvements totaling over $4 million. These grants



have allowed the NRP to add state-of-the-art equipment, including two facilities that are the only ones of their kinds in the United States – an intense positron beam and an ultra-cold neutron source. These grants have also funded upgraded power of the PULSTAR reactor, the establishment of a hot cell capability, new reactor control console instrumentation and monitoring equipment, and other improvements that allow for greater research capabilities.

Dr. Ayman Hawari, distinguished professor of nuclear engineering and director of the NRP, began working at NC State in 2002. At the time, the PULSTAR reactor was an aging artifact that had been operating for 30 years with little change.

“We were not equipped, from the perspective of operational infrastructure or technical and scientific infrastructure, to fulfill mission objectives as a research reactor,” said Hawari.

Hawari spearheaded a campaign to upgrade the reactor to meet the needs of 21st-century scientists. The NRP initially received funding from Innovations in Nuclear Infrastructure and Education (INIE) – the predecessor of NEUP. This program aimed to set up university reactors as effective tools of science and education.

Thanks to the ongoing cycle of grant funding from NEUP, Hawari has seen the PULSTAR become a sought-after, well-used modern reactor.

DOUBLING POWER

One of the first NEUP grants that NC State received for the PULSTAR was also its largest: $1.4 million to double the reactor’s operating power from 1 MW to 2 MW. This funding allowed the NRP to refurbish the whole reactor with new equipment, including the primary and secondary cooling systems.

"This almost gave us a brand-new reactor," said Hawari. "Only the core is not brand new."

NC State received the funding in 2010 and has gone through an extensive process to prepare the reactor for this power upgrade. The initial phase required the university to work with vendors, complete a safety analysis, and evaluate the core and the effect on fuel needs. The second and final phase is now nearing completion and will result in a license for the PULSTAR to operate at the new 2 MW power level.

Hawari gives two reasons for wanting to double the reactor's power: first, the increased power will enable more utilization opportunities for years to come; second, doubling the power means doubling the efficiency of neutron creation.

"We will double what we used to do in one day," explains Hawari.

A neutron image of jet turbine airfoils acquired using the PULSTAR reactor's Neutron Imaging Facility.

One obstacle emerged during this power upgrade: the constant need for fuel. This is not a new issue, but it is one that becomes more urgent as the power upgrade comes online. A more powerful reactor is a hungrier reactor, consuming more fuel during its daily operations.

The search for fuel led NRP to Buffalo, NY. The University at Buffalo has a decommissioned PULSTAR reactor, the only other reactor of this type ever built. The pin-type fuel for these PULSTAR reactors is unique; the reactor in Buffalo uses fuel enriched to 6%, whereas NC State uses fuel enriched to 4%. The NRP received funding from DOE to ship the pins from Buffalo to North Carolina, and a license was obtained to feed the reactor a mix of 4% and 6% enriched fuel. For a modest amount of money, this process gave NC State a large infusion of fuel. That fuel has now been feeding the reactor for about two years.

Hawari estimates that at current usage rates, the PULSTAR has enough fuel to run for another 8-10 years. However, with the coming power upgrade, this will lessen the run time allowed by the available fuel to nearly 5 more years, leaving the NRP in search of yet another fuel source for the future.

INTENSE POSITRON SOURCE

One of the most extraordinary facilities in the PULSTAR reactor is its Intense Positron Source (IPS), which has been supported by multiple grants. The IPS creates large numbers of positrons, which are the antiparticle of electrons; they have the same properties as electrons but with a positive charge instead of negative. Positrons are useful for their ability to identify defects in materials at sizes as small as a single atom.

The IPS is a unique facility in the United States that Hawari describes as "a world-class user facility," attracting researchers from all over the world.

NEUTRON DIFFRACTION AND IMAGING

Multiple facilities at the PULSTAR reactor allow researchers to perform nondestructive examination techniques. The Neutron Powder Diffraction and Neutron Imaging Facilities direct the neutrons produced by the PULSTAR reactor toward an object in order to form an image or a diffraction pattern for that object. This capability has been supported by NEUP, particularly by a 2012 grant that established high-resolution digital neutron imaging using a digital image plate system. This capability is currently evolving to support dynamic imaging and capture phenomena in motion.

These neutron facilities provide a complementary function to the IPS. Testing materials both ways produces positive and negative "images" of the same material, which is like having both a photograph and its negative.

MOVING FORWARD

The PULSTAR reactor has benefited tremendously from its funding from NEUP, which has allowed for the construction of the facilities described above, as well as additional capacities like the ultra-cold neutron source and the coming addition of a hot cell capability.

"I feel that infrastructure funding is key to our success," said Hawari. "It has allowed us to adapt with the times to ensure this nuclear facility is a tool of 21st-century science and education."

Over the past decade, with the support of NEUP Infrastructure grants, the NC State Nuclear Reactor Program has also become a partner institution of the Nuclear Science User Facilities (NSUF).

"This allows us to tap into the reservoir of users NSUF created," explained Hawari. "NSUF has been great to us."

Hawari described how users come to the PULSTAR reactor through NSUF programs and then keep returning for further experiments. During his time at NC State, Hawari has seen annual user hours increase by an order of magnitude, from around 800-1,000 user hours in 2002 to 10,000 today. He expects the popularity of the reactor to further increase as it keeps growing and improving.

In the next year or two, Hawari expects the reactor to receive its license to operate at 2 MW, add a hot cell capability (allowing for isotope production) as well as a fuel testing facility, and increase material characterization capabilities. The productive relationship among NC State, NEUP and NSUF will continue to enhance this world-class reactor.

Related NEUP Projects:
Infrastructure Reactor Upgrades: 10-9971, 12-9830, 13-6063, 16-10958, and 18-18471.Izzy10

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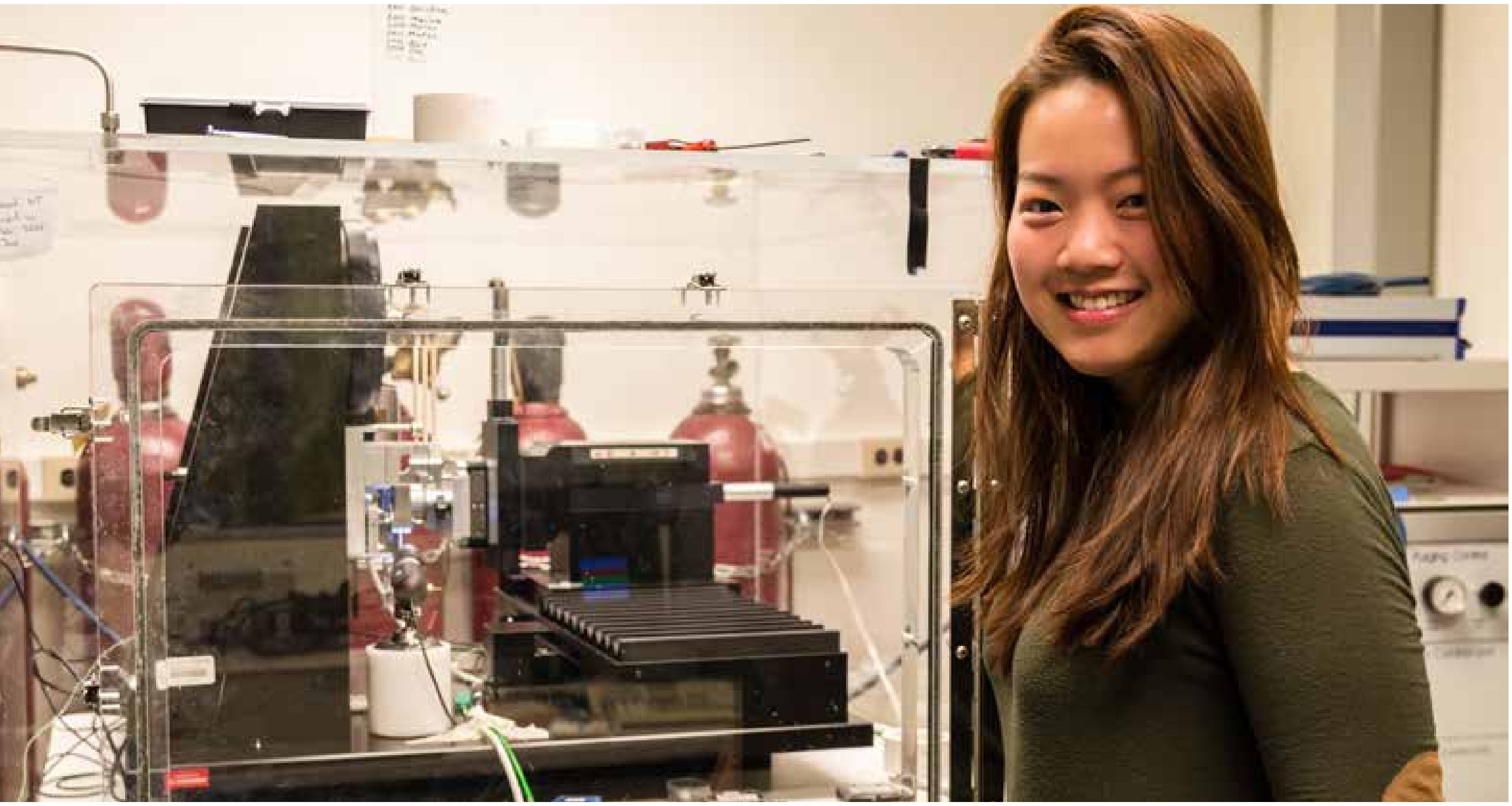
PROGRAM HIGHLIGHT

University Infrastructure Upgrades: Bolstering Nuclear Energy for the Nation

by Tiffany Adams for DOE's Nuclear Energy University Program



Student uses the micro-materials nanoindenter in the University of California, Berkeley's Nuclear Materials Laboratory.

University of California, Berkeley

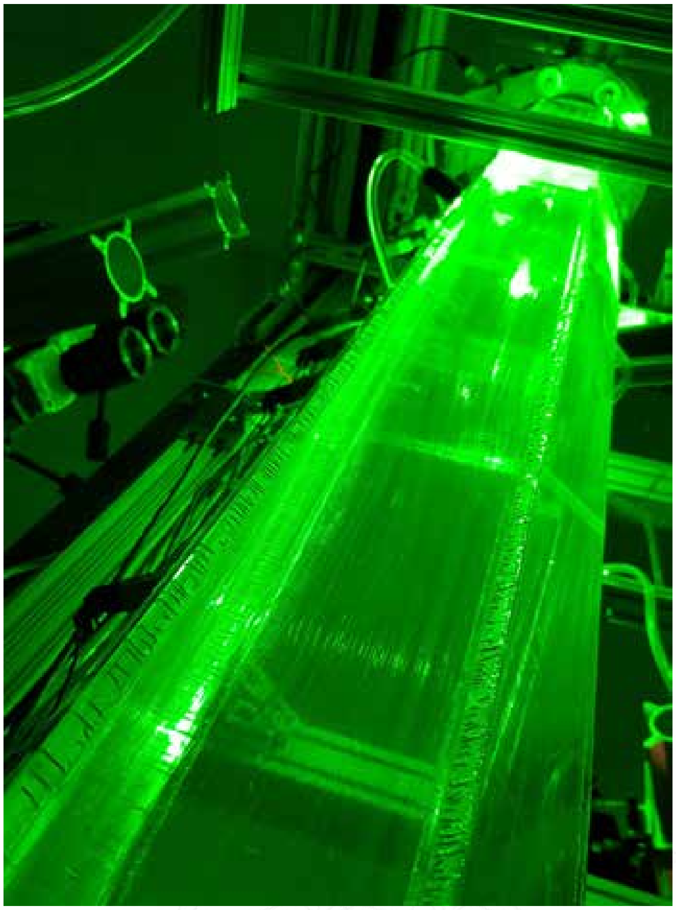
For the Nuclear Materials Laboratory (NML) at University of California, Berkeley (UCB), Infrastructure grants have been critical to development and success. "Without this funding agency, there would be no way to provide state-of-the-art infrastructure for research and teaching," said Peter Hosemann, professor and chair of the Department of Nuclear Engineering. To date, UCB has received five Infrastructure grants for approximately $1.26 million, much of which has been used to establish and enhance the NML. This laboratory was the first to start small-scale mechanical testing on nuclear materials. Now an NSUF partner facility, the NML can be used by researchers from across the country, free of charge. "NSUF is a cornerstone for the nation's nuclear infrastructure and is essential to research and training in the area of nuclear energy," Hosemann said.

Of the NML's many capabilities, NEUP funds were used to acquire items to perform mechanical testing from nanometer to centimeter from -140°C to +800°C on irradiated and unirradiated materials in different environments. Items like a high temperature furnace (<1200°C) for the existing MTS criterion model 43 tensile test frame with a maximum load capacity of 30kN. The temperatures covered include a range important for LWR accident scenarios and important for advanced reactor concepts like high-temperature gas reactors. The Bruker PI88 insitu nanoindenter capable of measuring mechanical properties up to 800°C at the nano scale probing properties of protective coatings for ATF concepts or sampling highly irradiated and radioactive materials.

Texas A&M Thermal-Hydraulic Research Laboratory

NEUP Infrastructure grants and research awards have been instrumental in developing Texas A&M's Thermal Hydraulic Research Laboratory. The laboratory, hosted at the Texas Engineering Experiment Station, is a 14,000-square-foot laboratory with a variety of thermal hydraulic setups, including flow visualization loops and state-of-the-art instrumentation for flow measurements. The work focuses on single- and two-phase flow and multiphase flow phenomena in light water reactors, advanced reactors and high-temperature gas-cooled reactors. NEUP Infrastructure grants in 2009 and 2010 bolstered the laboratory with new flow measurement equipment to support a state-of-the-art three-dimensional particle image velocimetry (PIV) measurement technique using tomographic PIV. PIV was used successfully in three funded 2009 NEUP projects focused on different thermal

Texas A&M's advanced high-temperature reactor (AHTR) concept leverages a particle-based fuel format consisting of discrete spherical graphite pebbles arrayed in a packed bed architecture. Thermal regulation achieved via flow of gas (e.g., helium) or liquid (e.g., molten salt) coolants through the void spaces between pebbles in the bed (characteristic pebble diameters: ~ 6 cm, gas cooled; ~ 3 cm, liquid cooled).



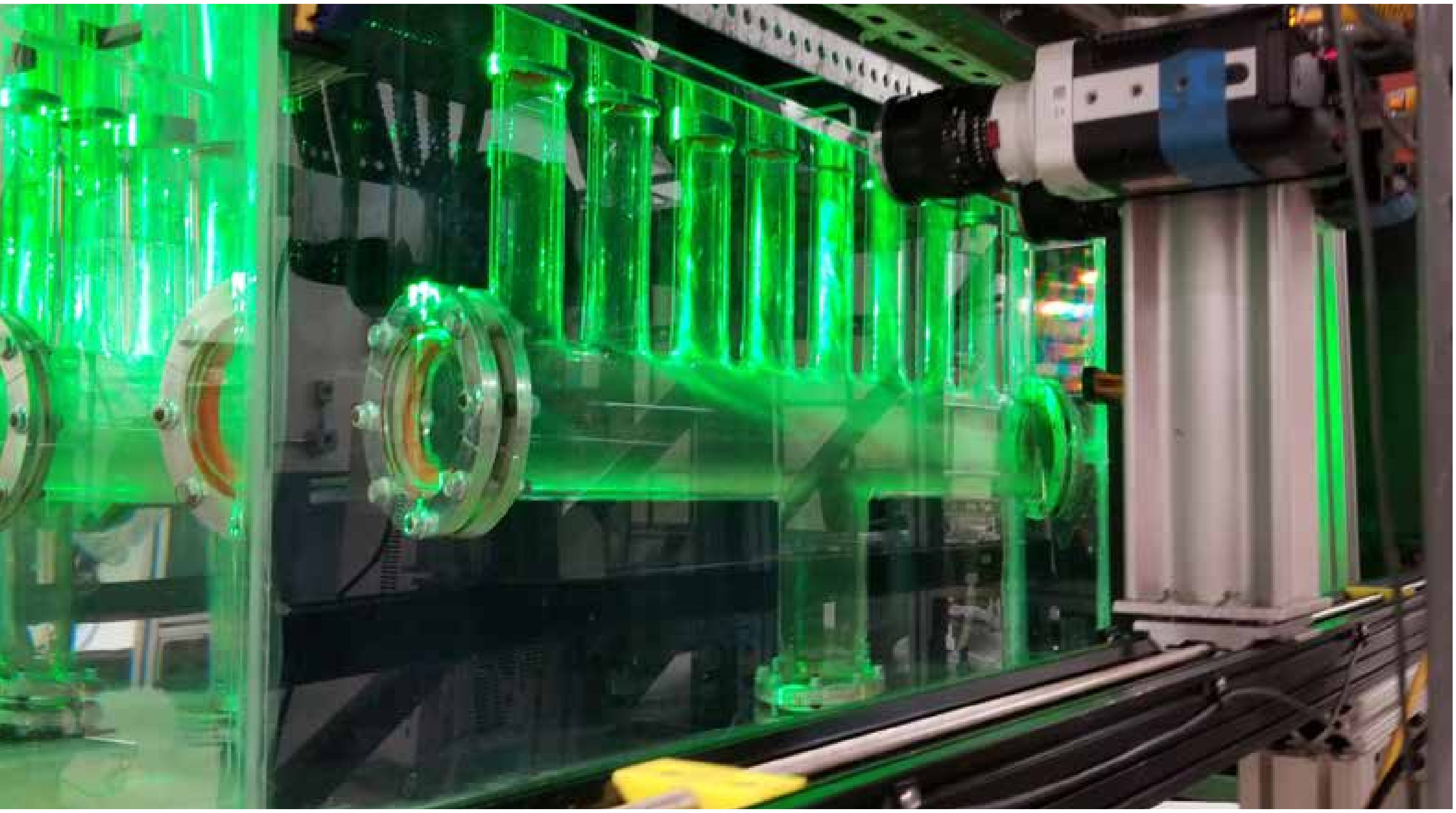
The Texas A&M experiment is using the largest transparent test fuel assembly of its kind to date. In the facility, measurements of hydraulic parameters and validation of computational tools are done, just like in reactor testing and design.

hydraulic measurements associated with high-temperature gas-cooled reactors and very-high-temperature reactors. The Infrastructure grant, along with the experimental setups established by these three projects, provided the foundation for verification and validation of thermal hydraulic phenomena in HTGRs, which is still ongoing today.

"The initial $100,000 investment in flow measurement equipment has resulted in additional investment by DOE-NE and industry," said Dr. Yassin Hassan, the lab's technical lead. "The lab continues to support impactful work on university, industry and national laboratory projects."

Various projects funded through NEUP have used these facilities and capabilities, including seven NEUP projects at Texas A&M. The projects have focused on wire-wrapped fuel assemblies, water-based reactor cavity cooling systems, plenum mixing, pebble bed thermal hydraulics and air ingress accidents in high-temperature gas-cooled reactors.

Recently, the laboratory collaborated with South Texas Project (STP), utilizing the laboratory-developed measurement techniques in resolving the Generic Safety Issue (GSI-191), which has been the subject of enormous efforts within the industry for more than 20 years. The GSI-191 issue is based on a loss-of-coolant scenario in a nuclear reactor, which can generate debris and potentially affect the performance of the safety system. This project was completed successfully and saved the pilot STP power plant approximately $43 million.



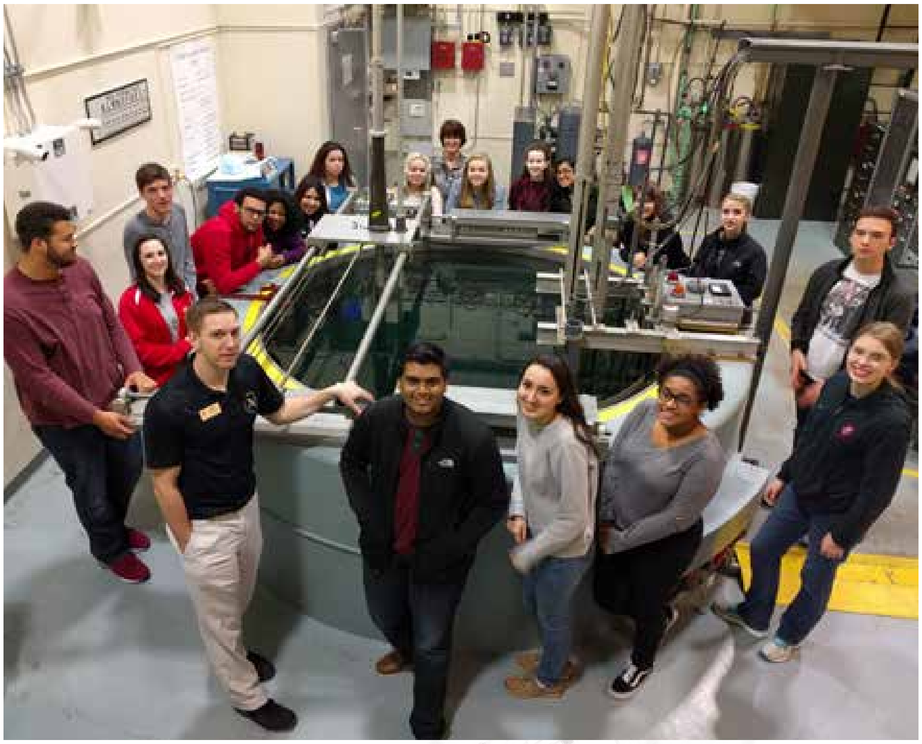
PIV, laser-doppler velocimetry (LDV) and distributed temperature sensor (DTS) measurement techniques are being applied.

Purdue University

DOE's Infrastructure grant gave new life to Purdue University's research reactor. "We had reached a point with our equipment where we had more downtime than uptime," said Robert Bean, director of Radiation Laboratories. Completed in 1962, the instrumentation and control systems were all original, making quality replacement parts nearly impossible to find. Bean explained that, unlike a commercial reactor, test reactors don't have duplicate systems, so if the system must be paused for repairs, all research stops.

Using their $1.2 million in funding beginning in 2012, Purdue upgraded their reactor control systems and reactor safety system from analog to digital. From alarm beacons to fission chamber detectors, the reactor systems were completely overhauled. "It was effectively everything," Bean said. Purdue has just been granted license approval by the Nuclear Regulatory Commission. They hope to become an NSUF partner facility, filling the void for a facility that can be used as a proof-of-concept testing ground. "It is a smaller facility, and the power level will allow more flexibility for researchers to verify their idea, that their equipment works and that their students know how to gather data," Bean said. "They can demonstrate their ideas for less."

PUR-1's first-of-a-kind all-digital instrumentation and control systems upgrade.



Clive Townsend, PUR-1 Reactor Supervisor (front left in black shirt), leads high school students on a tour of the facility.

Student Support

The Office of Nuclear Energy's (NE) Integrated University Program (IUP) funds undergraduate scholarship and graduate fellowships as part of the U.S. Department of Energy's (DOE) ongoing commitment to educating the next generation of nuclear scientists and engineers. NEUP research projects also support research roles for students ranging from undergraduates to post-doctoral researchers.

Sarah Stevenson, two-time IUP Scholar out of Kansas State University and current IUP Fellow, is currently pursuing her Ph.D. in nuclear engineering at the University of California, Berkeley. Photo by John La Barge.

Graduate Fellowships: $161,000 over 3 years

Applicants must be:

- U.S. citizens or legal permanent residents
- Entering their first or second year of overall graduate study
- Enrolled in an IUP-accepted college or university
- Studying nuclear science or engineering, or a related field
- A student with a cumulative GPA of 3.5 or higher at both the undergraduate and graduate levels

Undergraduate Scholarships: $7,500, 1-year

Applicants must be:

- U.S. citizens or legal permanent residents
- At least a sophomore in college when the award begins
- Enrolled in an IUP-accepted college or university

2,133

NEUP Supported Students

720	696	451	266
Ph.D.	Masters	Undergrad	Post-docs

772

IUP Scholarship & Fellowship Recipients

276	496
Fellows	Scholars

50%

Of all Nuclear Engineering PhDs were supported with DOE-NE IUP or NEUP funds from 2010-2018

- Studying nuclear science or engineering, or a related field
- A student with a cumulative GPA of 3.25 or higher

IUP and NEUP have supported more than 2,400 undergraduate and graduate level students in obtaining science, technology, engineering or math (STEM) degrees.

Of those students pursuing nuclear engineering degrees between 2011-2018, NEUP supported 331 Ph.D., 339 master's and 127 undergraduate students. IUP supported 162 nuclear engineering graduate degrees. Undergraduate data for the IUP program is currently unavailable. According to a 2018 Oak Ridge Institute for Science and Education report, 1,334 Ph.D.'s were awarded by nuclear engineering programs in the United States1,2 between 2010 and 2018. DOE-NE has directly supported more than 50% of nuclear engineering Ph.D. degrees obtained in the United States.

The vast majority of IUP Fellows have gone on to start their own companies, work in industry, become faculty members at distinguished universities or researchers at national laboratories. Students funded by NEUP on research and development (R&D) projects are not tracked past graduation, but many of these students are active in the nuclear academic, national laboratory and industry communities.

PROGRAM HIGHLIGHT

Colby Jensen: IUP Fellow Pays It Forward

by Kate Meehan for DOE's Nuclear Energy University Program

Colby Jensen, Idaho National Laboratory (INL) research scientist and former Office of Nuclear Energy (NE) Integrated University Program (IUP) Fellow.

Dr. Colby Jensen grew up on a farm outside the small town of Preston, Idaho, physically close to Idaho National Laboratory (INL) and yet a world apart in many ways. He had no ambition to one day work as a researcher at the lab; in fact, he had little knowledge of the lab despite living just a few hours away. But after going away for college and eventually earning his Ph.D., Jensen realized that INL was exactly where he wanted to work.

Jensen began his career as an undergraduate studying mechanical engineering at Utah State University (USU). He had always found that math came naturally to him, so engineering was a logical choice, though he had no particular career in mind. While at USU, Jensen took a class with Dr. Heng Ban, a professor of mechanical and aerospace engineering and founding director of the Center for Thermohydraulics and Material Properties. Ban saw potential in Jensen and took him under his wing, beginning a strong mentoring relationship that Jensen highly values.

Ban brought Jensen with him on a visit to INL in 2008, while Jensen was still finishing his bachelor's degree, to work on a direct-funded Next Generation Nuclear Plant project. This was Jensen's first visit to the lab, and the quality of interesting research being done there made a strong impression on him. Jensen went on to graduate as valedictorian of the USU College of Engineering and decided to stay at the university to pursue an advanced degree and continue his research on thermal conductivity in Ban's lab.

The project that first brought Jensen to INL eventually became the focus of his master's thesis: "TRISO Fuel Compact Thermal Conductivity Measurement Instrument Development." After completing his master's, Jensen received a fellowship from the Department of Energy's Integrated University Program (IUP) to continue his graduate work. Jensen stayed at USU and continued working with Ban, studying ion irradiation on thermal transport in zirconium carbide.

Jensen credits both Ban and the IUP fellowship for making his research path possible. Ban provided mentorship which, according to Jensen, "...makes all the difference in the world." The IUP Fellowship made the Ph.D. financially viable for Jensen, providing support so he could continue to focus on his research.

While working on his Ph.D., Jensen actively sought out opportunities and pursued everything available to him. This mindset led him to France, where he spent a year researching, pioneering a joint Ph.D. in energy engineering from the Université de Reims Champagne-Ardenne and mechanical engineering from USU. His dissertation was titled "Bridging the Nano and Macro Worlds: Thermal

Property Measurement using Scanning Thermal Microscopy and Photothermal Radiometry – Application to Particle-Irradiation Damage Profile in ZrC."

After he completed graduate school, Jensen was drawn back to INL. He initially considered careers in academia or at other national labs but says he realized that "the opportunity I was looking for was here." From 2014 to 2016 he worked as a thermal analyst for experimental safety and performance evaluations at the Advanced Test Reactor (ATR) and Transient Reactor Test (TREAT) Facility. He then became the separate effects testing lead for irradiation experiments in the Fuel Performance and Design Department. In his present position, Jensen is deputy technical lead for development of advanced reactor fuels. He leads in-pile instrumentation development for transient irradiation testing, leads development of in-pile thermal properties measurement and is a principal investigator for transient testing of light water reactor and advanced reactor fuels.

Jensen has been involved in designing some of the first experiments in the reopened TREAT Facility, which provides transient testing of nuclear fuels and materials. Its unique design offers real-time monitoring of the fuel's or material's behavior under postulated reactor accident conditions, allowing scientists to determine the appropriate safe limits for the fuels and materials in nuclear power reactors.

As part of his current role, Jensen has a lot of direct involvement as a technical point of contact and collaborator with other researchers who are coming to use the facility. Many of them work under awards received from DOE's Nuclear Energy University Program (NEUP). One of these researchers, in fact, is Heng Ban. Ban currently holds an award for an Integrated Research Project (IRP) conducting experiments at TREAT, with Jensen as one of his collaborators on a portion of the project studying transient boiling behavior. In this way, Jensen has come full circle, from an undergraduate just learning about nuclear energy to a subject-matter expert advising experienced researchers, including his own mentor.

When asked about his greatest successes, Jensen repeatedly returned to the importance of teamwork, collaboration and mentorship. He credits Ban in particular with providing excellent mentorship. As a leader himself now, Jensen emphasizes that "mentorship is key." He has made providing that leadership to younger scientists one of his main responsibilities. Jensen's efforts in this capacity have been recognized by his coworkers, as he won the 2018 INL Mentor of the Year Award.

Jensen complimented the teams he works with at INL and the researchers who visit the lab from all over the world. Jensen puts great value on working with dedicated people, and he advises his interns and young colleagues to always prioritize the team they are working with rather than the technical aspects when choosing a project.

Throughout his career, Jensen has "focused on what needs to be done" even when it has led him in unexpected directions. He has always looked for opportunities and taken leaps of faith, from his initial decision to pursue a Ph.D. (thanks to his IUP Fellowship) to earning a joint degree between French and American universities to his current testing work in TREAT. According to Jensen, forging new paths is not always easy, but it is certainly interesting.

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