US-UK: Drawing on International Expertise

by Kate Meehan for DOE's Nuclear Energy University Program

Nuclear energy and nuclear waste cleanup are international industries; however, research and development in these fields has historically been rather isolated. Funding tends to come from governmental organizations that focus on local concerns and support researchers in their own countries.

The U.S. Department of Energy Office of Nuclear Energy (DOE-NE) has sought to change this paradigm by placing increased emphasis on coordinating with equivalent agencies in other countries. The intent is to draw on nuclear energy expertise from around the world. In 2012, the Nuclear Energy University Program (NEUP) joined with The Research Councils United Kingdom (RCUK) to provide collaborative opportunities to benefit both countries. Through its Engineering and Physical Sciences Research Council (EPSRC), the UK partnered with DOE-NE to provide funding to support NEUP projects using DOE-NE's existing review framework. In the UK, EPSRC is the main funding body for engineering and the physical sciences. RCUK is the public body which coordinates public policy in the UK. DOE and RCUK targeted NEUP's relatively new Integrated Research Project (IRP) initiative for these initial collaborations. IRPs are three-year awards for projects that address specific research issues and capability gaps identified and defined by the NE research and development programs. These projects are multidisciplinary and comprise at least two university partners. They can include non-university partners as well (e.g., industry, national laboratory, and international).

Beginning in 2012 and continuing in alternating years since, several successful NEUP proposals have also received funding from EPSRC to facilitate cross-border collaborations. During the 2012 award cycle, over $13 million in U.S. funding was allocated for IRPs. The EPSRC then allocated an additional £2.1 million ($3.7 million) to UK researchers who collaborated on successful applications. In this way, over $16 million was channeled into new research, significantly increasing the value of each country's investment. Since 2015, the EPSRC has targeted traditional NEUP projects through this funding mechanism, allowing the UK to participate in a much broader set of U.S. projects.

"EPSRC's priority for international engagement is to enable 'best-with-best' collaborations," says Jim Fleming, head of EPSRC's energy theme. "The ability to enable UK researchers to work with leading U.S. groups through participation in DOE's NEUP program has provided a unique opportunity to empower world-leading research."

DOE-NE's Mike Worley, associate deputy assistant secretary for reactor fleet and advanced reactor deployment, echoes the value of the U.S./UK collaboration, saying, "The strong partnership between the U.S. and UK has made available to both parties significant and diverse research capabilities to address the most urgent issues facing the industry today, through innovative and transformative techniques that will help strengthen the quality of university-based research."


Dr. Afsaneh Rabiei using the in situ scanning electron microscope (SEM) machine acquired to perform the unique high throughput experimental method (HTEM) developed to lower the extended time needed to study the creep and creep fatigue of advanced material and the extreme environment of nuclear structures, which also lowered the amount of material needed.

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To date, this successful partnership has resulted in 18 total projects involving 26 U.S. and 10 UK institutions.

Materials Science and Fuel Cycle Technologies

Two of the main work scopes supported by NEUP are nuclear reactor technologies, including advanced structural materials, and fuel cycle research. The Reactor Concepts program aims to develop new and advanced reactor designs and technologies by addressing technical, cost, safety, and security issues. The Fuel Cycle program works to enable used nuclear fuel management strategies by improving resource utilization, reducing waste generation, enhancing safety, and limiting proliferation. This includes research into cladding materials that can improve accident tolerance as well as waste management.

Alloy 709

In 2015, DOE announced that Alloy 709, a stainless-steel alloy, had been identified as a promising cladding material that needed further evaluation. An interdisciplinary team, led by Dr. Afsaneh Rabiei at North Carolina State University, responded to this call with a project studying creep and creep-fatigue crack growth mechanisms in this alloy.

Rabiei is a professor of mechanical engineering who has studied stainless steel for decades. She explained that Alloy 709 is a new type of stainless steel with alloy elements that can withstand high temperatures, is corrosion resistant, and weldable. These attributes make it a promising material for construction of new nuclear reactors, particularly molten salt reactors.

Rabiei teamed with Paul Bowen, a professor at the School of Metallurgy and Materials at the University of Birmingham, to pioneer an innovative approach to studying Alloy 709. Rabiei and Bowen have known each other for many years, with Bowen's team in the UK having extensive experience studying on nickel alloys in high-temperature aerospace applications.

The researchers received samples of Alloy 709 from Argonne National Laboratory, and each studied the material in unique ways. Rabiei's team in the U.S. focused on heating, loading, and looking at the microstructure of the material to see how cracks propagate. They did this using a unique SEM to study real-time crack growth in samples only 1mm thick at temperatures of up to 1,000ºC. Bowen's team was able to study larger samples, thanks to their existing mechanical testing facilities. Together, researchers were able to study the performance of Alloy 709 in various extreme conditions of loading and heating and compare their results to other types of stainless steels, such as 316H (a stainless steel that is well known for high-temperature application in nuclear structures). In the end, researchers concluded that Alloy 709 outperformed other types of high-temperature stainless steels in extreme temperatures and would allow a greater design margin (temperature and stress) and/or component life in future nuclear power structures.

Rabiei described significant benefits from collaborating with Bowen. They interacted mainly through monthly online meetings and videoconferencing, with the only major challenge being the time difference. Each team has different experimental tools available, making collaboration essential. "We cannot have everything under the same roof," explained Rabiei.

Rabiei described their collaboration as basically "buy one, get one free." She felt this was a "win-win situation" for the researchers, as well as DOE, because they had one streamlined project but double the team.

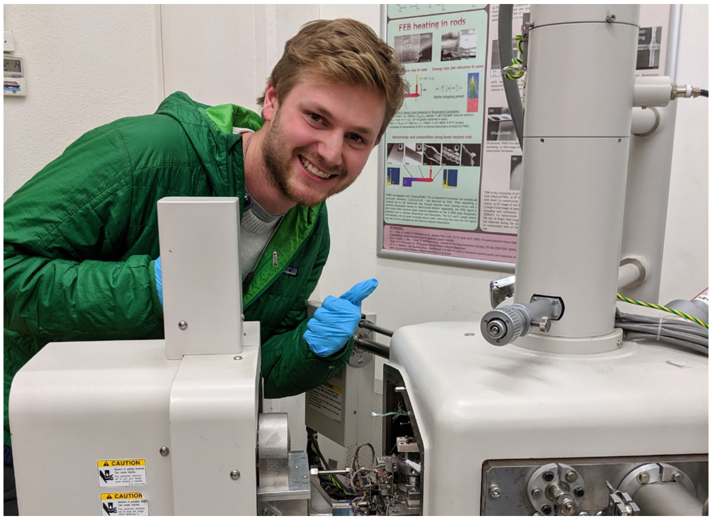
Silicon Carbide Fuel Cladding

Also in 2015, a team led by Dr. Peter Hosemann at the University of California (UC)-Berkeley responded to a call on fuel cycle research and development with a project studying silicon carbide's use in accident-tolerant fuel cladding applications. Prompted by the accident at Fukushima, DOE started to emphasize accident-tolerant fuel (ATF) concepts. Hosemann's team proposed a study of silicon carbide as a fuel cladding material that could replace a zirconium alloy, the current material used for this purpose.

Hosemann started with the vision of wanting to understand the mechanics and thermal properties of silicon carbide and silicon carbide fiber composite. Then he built a team of researchers who could complete the study.

Hosemann began with an industry partner—General Atomics—based in San Diego, California. Hosemann had worked with General Atomics previously, and he described it as the only company that could make this material. The company produced several silicon carbide samples for Hosemann's team to study, with a range of different composite parameters.

Once they received the samples, Hosemann's group at UC-Berkeley conducted micro-scale testing using techniques such as fiber push-out tests, micro-pillar interface testing, micro-cantilever testing, micro-tensile tests on single fiber tow and



Joey Kabel, a senior Ph.D. student, is about to load a SiC/SiC sample in an SEM to perform micromechanical tests on the SiC/SiC composites. This picture was taken during Kabel's visit at Swiss Federal Laboratories for Materials Science and Technology (EMPA) in Switzerland.

nanoindentation testing on the silicon carbide composite. These micromechanical tests allow to sample the properties of individual features in the composite such as the fiber/matrix interface, matrix fracture property, fiber integrity, etc. The micromechanical properties obtained from the localized tests used combined with composite micro structural input (including void sizes, shapes and distributions) as well as the overall cladding design input (e.g., joints and fiber weave structures) were used to produce a component model which assess performance of the full cladding structure.

Research partners at the University of Illinois, Urbana-Champaign conducted measurements of thermal conductivity, picosecond acoustics as received and ion beam irradiated samples to quantify the change in thermal properties associated with radiation damage. Their colleagues at Oregon State University led the computational effort to combine all these properties to describe and predict the component behaviour.

It was the collaborators at Oxford University around Prof David Armstrong in the UK who really led this team to become what Hosemann described as "a fully integrated effort."

According to Hosemann, the resources at Oxford really let the team "punch above our weight." These resources are not available anywhere in the U.S., and they allowed higher-temperature nanomechanical testing. They conducted hundreds of mechanical tests and took on extra statistics work that led to a truly successful study. As a result of this study and the collaboration, the team was able to quantify the detailed fiber/matrix interaction via different methods and enhance the confidence in the data due to the statistical work.

The collaborative process with all these different teams turned out to be extremely fruitful resulting in several publications. The researchers visited each other's institutions but mainly saw each other at conferences, particularly the annual Minerals, Metals & Materials Society (TMS) conference.

All the collaborators continue to research this field and are looking for a broader understanding of the fiber matrix in the material.

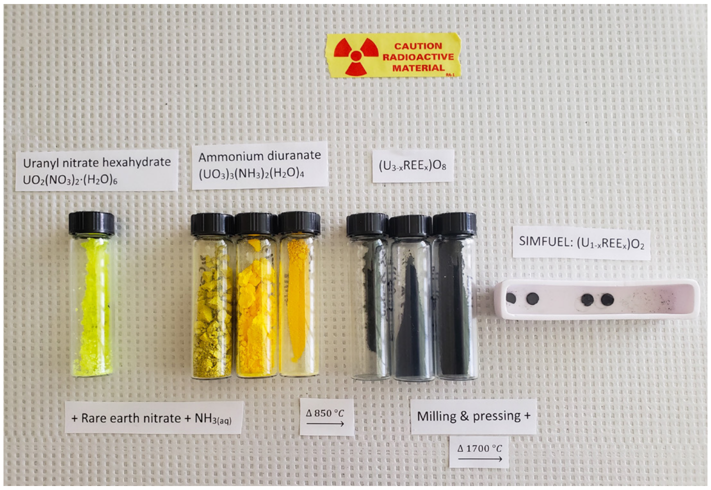
Waste Forms

In recent years, DOE has expressed a need for improved understanding of the composition and stability of waste glasses to be used for commercial high-level waste forms. Safe encapsulation of nuclear waste is one of the most pressing challenges facing the nuclear energy industry, and DOE has prioritized the search for a stable and reliable material ("waste form") to encapsulate radioactive ions and keep them safely contained. Ongoing studies have looked at novel glass, ceramic, and glass-ceramic compositions to serve as waste forms.

Glass-Ceramic Nuclear Waste Forms

In August 2014, Dr. Neil Hyatt of the University of Sheffield contacted Dr. John McCloy at Washington State University (WSU) to gauge his interest in collaborating on a research project. What began as a single proposal on glass-ceramics for nuclear waste forms has evolved into a significant effort.

Joey Kabel and Rujie Shao, both Ph.D. students, on a Focused Ion Beam (FIB)/SEM at University of California, Berkeley, manufacturing microcompression samples on SiC/SiC materials.



Steps for making doped uranium oxide (UO_2) sintered ceramic at WSU.

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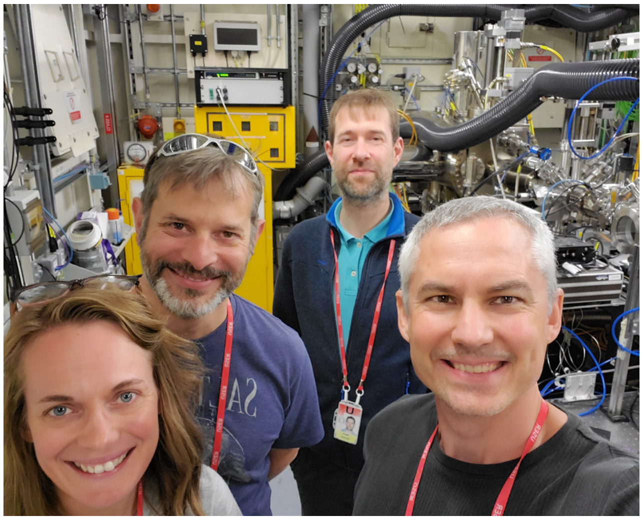
NEA-NEST Collaborations

Beginning in FY 2020, researchers applying for NEUP funding in the Mission Supporting Grand Challenge work scope are also able to apply for funding through the Organization for Economic Cooperation and Development (OECD) Nuclear Energy Agency (NEA) Nuclear Education, Skills and Technology (NEST) program. NEST was launched to help address important gaps in nuclear skill capacity building, knowledge transfer, and technical innovation in an international context. NEST ties together university research projects across multiple countries to provide students a fuller professional experience as they pursue their degrees. NEST funds are provided to allow travel for students to interact with colleagues in other NEST countries, including:

- Belgium
- Canada
- France
- Germany
- Italy
- Japan
- Korea
- Russia
- Switzerland
- United States



Synchrotron X-ray Absorption team at the Diamond Light Source facility in the UK, 2019. This was part of McCloy's sabbatical at Sheffield as a Fulbright Scholar. Left to right: Dr. Claire Corkhill (Sheffield), Professor Neil Hyatt (Sheffield), Dr. Martin Stennett (Sheffield), and Professor John McCloy (WSU).

The pair's first proposal, "Understanding Influence of Thermal History and Glass Chemistry on Kinetics of Phase Separation and Crystallization in Borosilicate Glass-Ceramic Waste Forms for Aqueous Reprocessed High Level Waste," was funded in 2015, thanks to the NEUP funding opportunity announcement that asked for projects that studied glass ceramic waste forms incorporating specific elements and minerals. This initial team comprised nine researchers at five institutions in the U.S. and UK.

McCloy already had longstanding relationships with the researchers in the U.S., based at Pacific Northwest National Laboratory (PNNL) and Rutgers University. McCloy's project relied on glass-ceramic samples created at PNNL, which has a renowned glass science group capable of producing innovative materials used in waste forms. McCloy originally planned to apply for the NEUP grant with this three-pronged team—until Dr. Hyatt approached him about working together. Thanks to Hyatt, the team expanded to include a large team from the University of Sheffield, as well as the University of Warwick.

This international team studied crystallization in glass ceramics for radioactive waste immobilization. In particular, the researchers worked to develop a fundamental understanding of the phase transitions and crystallization mechanisms in complex glass-ceramic high-level waste forms.

Before this project, McCloy and Hyatt had never worked together, but they found their working relationship to be extremely productive. The whole team held quarterly teleconferences bolstered by annual meetings centered around professional conferences. Hyatt also proposed that he and McCloy take formal appointments at each other's institutions. Now McCloy is a visiting professor at the University of Sheffield, and Hyatt is an adjunct professor at WSU. They also heavily involved graduate students in the collaborative process, sending students from each of their home universities abroad to facilitate the partnership.

Following this initial collaborative success, McCloy has teamed with Dr. Clair Corkhill from the University of Sheffield in response to a 2017 NEUP call with a proposal entitled, "Simulated Used Nuclear Fuel Dissolution as a Function of Fuel Chemistry and Near Field Conditions." Corkhill participated in the original collaboration and now works as the lead of the UK team for the current project. As part of this project, McCloy spent the fall semester of 2019 on sabbatical as a Fulbright Scholar working with Corkhill and her colleagues at the University of Sheffield studying international issues in nuclear waste management.

This continuing project focuses on developing an understanding of the various effects of simulated nuclear fuel microstructure on its dissolution in geologic repository conditions. The researchers are studying used nuclear fuel models under different potential repository conditions to achieve a desirable long-term performance.

McCloy describes these joint projects as "the best research experiences I have had as a professor." He is eager for funding to continue to support long-term collaborations to make their international teamwork more permanent. "We cannot solve these problems alone," explained McCloy.

Melt-Derived Nuclear Waste Forms

Dr. Maik Lang responded to a funding opportunity announcement in 2017 with a team comprising six different researchers from four institutions. The project, entitled, "The Thermodynamics of Crystallization and Phase-Separation in Melt-Derived Nuclear Waste Forms," aims to give a fundamental understanding of the stability of glass waste forms to be used for safe and reliable encapsulation of nuclear waste.

Currently, borosilicate glass is the most commonly used waste form for immobilizing nuclear waste streams, but there are limits to the concentrations of waste constituents that can be immobilized in glass. Demonstrating the applicability of waste forms with some crystallinity, however, could enable the more efficient disposal of nuclear waste at significantly higher waste loadings than those attainable in a pure glass waste form. Lang's team is studying several different formulations of glass and glass-ceramic to see which ones may provide the best long-term stability when used as nuclear waste forms.

Glass samples for the study have been designed and prepared at PNNL by teams led by Dr. Joseph Ryan and Jarrod Crum. Lang estimates that by the time the study is completed, the researchers will have analyzed between 50 and 100 samples from PNNL.

Researchers at Arizona State University, led by Dr. Alexandra Navrotsky, measure the thermodynamic data using calorimetry techniques. Meanwhile, Lang's team at the University of Tennessee does the structural characterization using total neutron scattering experiments at Oak Ridge National Laboratory. The results of these two different types of testing are compared to molecular dynamics computer models developed by the UK team led by Dr. Kostya Trachenko and Dr. Martin Dove at Queen Mary University in London. Their simulations are crucial both to understanding the experimental results for these tests, as well as for the future design of novel waste form materials.

This multidisciplinary team collaborates largely through conference calls, but Dr. Navrotsky also organized a lecture series to bring the researchers together in person at UC-Davis. They are still working together on this project, with completion expected in 2020.

Future Collaborations

DOE-NE continually looks to expand its research and development portfolio and will continue to pursue further opportunities to collaborate with international entities. NEUP and EPSRC continue to work together on additional funding for U.S./UK collaborative projects, with both sides eager to keep up the momentum.

"We look forward to continuing this fruitful relationship with DOE and the excellent research collaborations it inspires," says Fleming. "This has been a unique opportunity to make significant headway on such important areas to both countries."

NEUP/EPSRC COLLABORATIONS

Joint NEUP/EPSRC Projects 2012-2019

18 Number of projects

$29.2M NEUP Contributions

£8.9 M=$11.7 M EPSRC Contributions

Research Areas

- Accident-tolerant fuels
- Ion irradiation effects
- Fuel cladding
- Glass and ceramic waste forms
- Nuclear materials alloy development
- Fission products
- Liquid-metal-cooled fast reactors
- High-temperature gas reactors
- Alloy development for molten salt reactors

Number of **Institutions Involved**

26 United States

10 United Kingdom