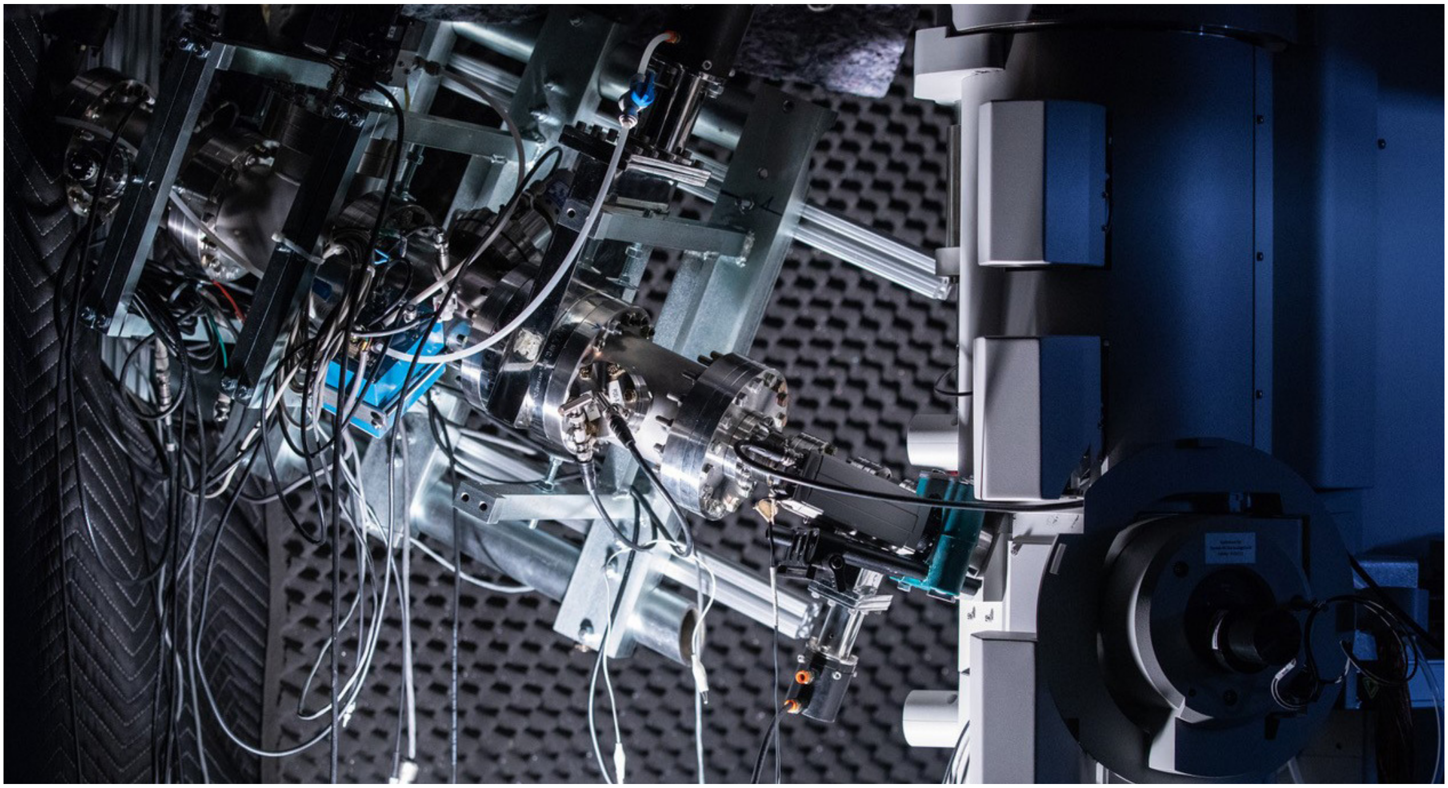


Ion beam - microscope interface for conducting in-situ dual ion irradiation in the transmission electron microscope (TEM).

Saving Time and Money: Ion Irradiation of Reactor Materials Offers Detailed Insight in Far Less Time

by Paul Menser for DOE's Nuclear Energy University Program

Suppose you could get done in three or four days what would normally take 10 years? For more than 30 years, this has been a dream of Professor Gary S. Was's, Director of the Michigan Ion Beam Laboratory (MIBL).

Since 1986, Was has been researching how to conduct ion irradiations from accelerators to simulate the neutron damage that happens to materials inside nuclear reactors. The idea faced headwinds for years, but an Integrated Research Project (IRP) supported by the U.S. Department of Energy's Nuclear Energy University Program is gradually making believers out of the skeptics.

"We're getting there, and this IRP has been a major factor," Was said. The research was detailed most recently in *Scientific Reports*, in an article titled, "Predicting structural material degradation in advanced nuclear reactors with ion irradiation."

"Ion irradiation offers the capability to shrink the irradiation time from many years in a reactor to days, using an accelerated damage rate to predict microstructural and mechanical property changes at lower cost," wrote Was and fellow researchers Stephen Taller, Gerrit VanCoevering, and Brian Wirth. "Therefore, ion irradiation is the only viable means to study many damaging degradation processes that could limit component lifetime, such as irradiation-induced swelling."

Understanding degradation of materials

Developing new materials for advanced nuclear energy systems will depend greatly on understanding how radiation degrades the materials that serve as the structural components in reactor cores. Stress corrosion cracking caused by irradiation is one of the biggest problems in light water reactors (LWRs), even more so in supercritical water reactors—LWRs that operate at supercritical pressure, offering a high thermal efficiency and simpler design. In high-dose fission concepts, such as the sodium fast reactor, structural materials must survive up to 200 displacements per atom (dpa) at temperatures in excess of 400°C. In the traveling wave reactor the damage level can reach 600 dpa.

The dpa represents the number of times, on average, an atom is displaced from its lattice site as a result of energetic particle bombardment. Traditionally, research into radiation-induced changes in materials has been conducted with experiments in test reactors, followed by comprehensive post-irradiation examination. This is a very time-consuming and expensive process because of the low damage rates that even the highest flux reactors exhibit and activation of the samples under neutron irradiation. Moreover, the number of test reactors is shrinking and space in the remaining reactors is in limited supply worldwide.

Michigan Ion Beam Laboratory's origins

The Michigan Ion Beam Laboratory for Surface Modification and Analysis got its start in 1986 when it acquired its first major instrument, the Maize 1.7 MV Tandem particle accelerator. This allowed researchers to examine ion-solid interactions, observe changing microstructures, and perform experiments on ion-implanted samples. Things took a leap forward in 2007 with the acquisition of an open air 400 KV ion implanter made by the National Electrostatics Corporation. "That opened up a number of new experiments," Was said.

This was also when the Gen-IV Reactor program started yielding new reactor concepts, many of them requiring structural alloys capable of enduring much higher neutron doses than materials used in conventional LWRs. Around the same time, the Advanced Test Reactor (ATR) at Idaho National Laboratory was opened up as a user facility, quickly becoming the centerpiece of the Nuclear Science User Facilities, a nationwide network of labs and universities equipped with radiation capabilities. University of Michigan joined in 2010.

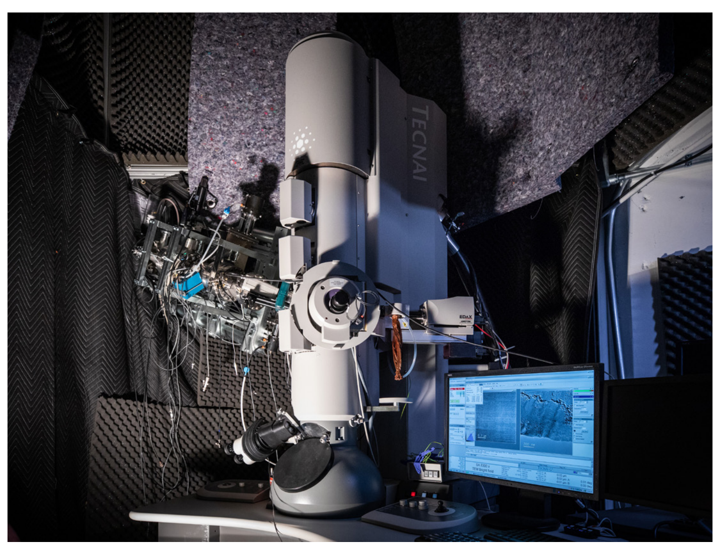
Integrated Research Project begins

The irradiation experiments under the current IRP started in 2014, the same year MIBL acquired Wolverine, its 3 MV Tandem particle accelerator. The accelerator operates on a relatively simple principle. Negative ion beams are injected into the

Of the 48 projects conducted at MIBL in 2019, 8 were funded through NSUF. Overall, the lab conducted 156 irradiations, accounting for 5,910 hours of instrument usage. In addition to University of Michigan researchers, participation came from corporate research laboratories, private companies, government laboratories, and other universities across the United States. Experiments included Rutherford backscattering spectrometry, elastic recoil spectroscopy, nuclear reaction analysis, direct ion implantation, ion beam mixing, ion beam assisted deposition and radiation damage by proton irradiation, self-ion irradiation, dual ion irradiation, triple beam irradiation, and single and dual beam in-situ irradiation in the TEM.

Dr. David Woodley inspecting the high voltage stack on the 400 kV ion implanter.

Multi-beam chamber for conducting dual and triple beam irradiations.



The 300 kV FEI Tecnai G2 F30 TEM with image stabilization and high accuracy temperature control for in-situ irradiation.

accelerator's low energy tube. Once inside the terminal (the portion between the low energy and high energy tubes), the negative ions enter an area rich in nitrogen where the extra electrons are stripped off, generating positive ions; these ions are accelerated through the high energy tube to be delivered at the exit of the accelerator.

Linking the three accelerators together in a common target chamber was a major step forward. "It was our first opportunity to tackle, on a large scale, this question we posed many, many years before," Was said.

The project has enlisted a wide range of collaborators, including national laboratories (Argonne, Idaho, Los Alamos, Lawrence Livermore, and Oak Ridge), academia (University of Tennessee, Pennsylvania State University, University of Wisconsin, University of California - Berkeley and Santa Barbara, and University of South Carolina), industry (TerraPower and the Electric Power Research Institute) and major international programs and organizations (University of Manchester, University of Oxford, Queen's University, AREVA, CEA, UKAEA, and ANSTO). In addition to the Nuclear Energy University Program, the International Nuclear Energy Research Initiative (I-NERI) is involved, as is the Engineering and Physical Sciences Research Council of the United Kingdom.

Irradiation in BOR-60

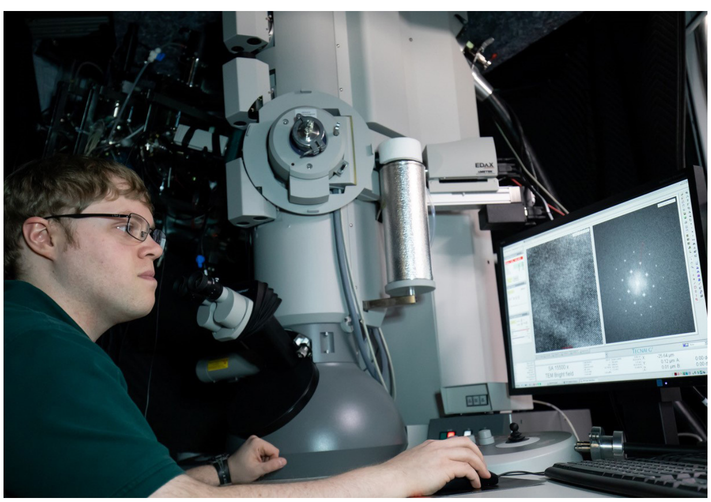
For purposes of comparison, capsules have been irradiated in BOR-60, the sodium-cooled fast reactor in Dimitrovgrad, Russia. BOR-60 can irradiate materials at about 15 dpa a year and, with their samples currently at 35 dpa, the MIBL team is looking forward to samples from BOR-60 taken to the 100 dpa damage level.

These samples will be essential to conducting dual- and triple-ion irradiations that capture the key elements of the BOR-60 reactor neutron spectrum. By engaging the worldwide radiation effects community through workshops and working groups, a unified consensus on addressing ion irradiation techniques and analyzing defects in irradiated microstructures will emerge. Crosscutting activities will help unify these major thrusts.

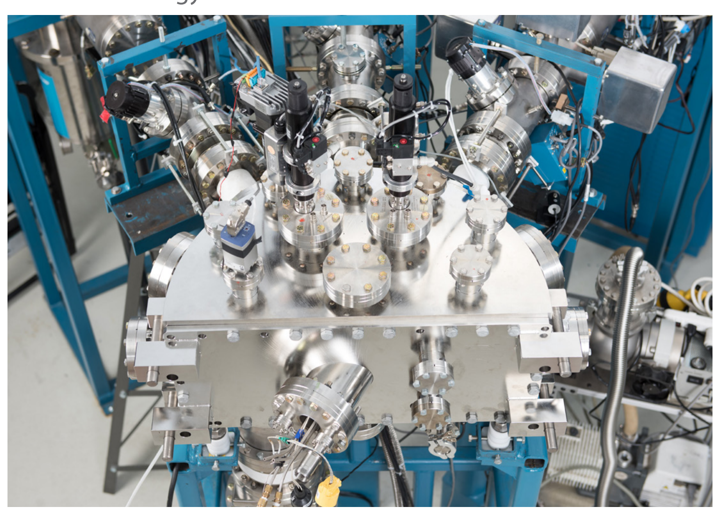
Measurements of temperature, damage rate, and damage levels are difficult to acquire in a reactor, resulting in a reliance on calculations. Ion irradiations have been developed to the point where temperature is extremely well controlled and monitored. Damage rate and total damage are also measured continuously and accurately throughout the irradiation. Because there is little activation with ion irradiation, samples are not radioactive, and post irradiation examination can be conducted immediately after irradiation without additional precautions.

In addition to BOR-60, this project utilizes national user facilities like the ATR for sample characterization through grants that have already been awarded. It employs a coordinated ion and neutron irradiation program out to 100 dpa on identical alloy heats as well as incorporates existing neutron data. It engages the worldwide radiation effects community in a truly global effort to develop ion irradiation as a tool to serve as a surrogate for neutron irradiation.

In the end, the irradiated research project's findings are expected to provide a much quicker path for materials qualification at high doses with significantly lower costs, with improved safety and performance in the existing LWR fleet and emerging advanced reactor designs. As materials degradation due to irradiation is both a life-limiting and a concept-validating phenomenon, a solution to the radiation damage problem is truly the grand challenge for the growth and vitality of nuclear energy worldwide.



Oak Ridge National Laboratory Alvin M. Weinberg Fellow, Dr. Stephen Taller, on the Tecnai TEM, manufactured by FEI Company, located in the MIBL.



Multi-beam chamber with beamlines from Maize, Blue, and Wolverine.