

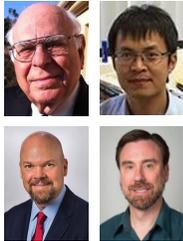
INDUSTRY



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MIT's accident-tolerant fuel IRP team included four universities, two industry partners, and one national laboratory (INL).

Nuclear Energy University Program IRP Results Lead to Important Recommendations for the Nuclear Industry

by Eric Williams for DOE's Nuclear Energy University Program

Koroush Shirvan isn't a zoologist, but he's well acquainted with moose, bison, cobras, and falcons, to name a few.

Like anyone working in the world of advanced research on nuclear power, this assistant professor in the Massachusetts Institute of Technology's (MIT) Nuclear Science & Engineering department deals daily in initialisms and acronyms, which for Shirvan include MOOSE, BISON, COBRA, FALCON, and dozens more.

One of Shirvan's areas of expertise is accident-tolerant fuels (ATF), and he served as the executive director of an Integrated Research Project (IRP) titled, *Development of Accident Tolerant Fuel Options For Near-Term Applications*. The multi-institution project was funded by the Department of Energy's Nuclear Energy University Program (NEUP).

At the outset, the project was framed with a clear understanding that it wasn't intended to find one magical answer about which ATF concept was the best. Rather,

the objective was to take the necessary, practical step of understanding the different ATF concepts, develop computational tools, and set out a pathway that leads to a down-select process.

"In 2015 when we started, the (broader) ATF program had really been expanded to all countries with major nuclear programs," Shirvan recalled. "So, we had a very good foundation to draw on. We decided to focus on near-term concepts that would see commercializing sooner ... we were really focused on finding an economic benefit."

When Shirvan says "we," he means it. The IRP team included experts from Texas A&M University, the University of Florida (UF), and the University of Wisconsin at Madison (UW) as well as Idaho National Laboratory (INL) and private industry representatives with Structural Integrity Associates, Inc. and Framatome. Also high on Shirvan's "we" list is Frank Goldner, the longest-tenured employee at the Department of Energy, and the one who provided Federal oversight for the project.

Goldner, in turn, has high praise for Shirvan, the “powerhouse” universities on the team, and Framatome’s role in providing the base material for coatings. “If you are looking for a poster child of something that has worked well, this one is it,” Goldner said.

Indeed, Framatome’s involvement was vital and required high levels of trust and cooperation in navigating the process, technical and legal considerations. This excerpt from the report exemplifies how creativity overcame the interwoven complexities:

The feasibility of modeling the chromia doped fuel behavior under normal operation in BISON [the nuclear fuel performance code] was confirmed based on Halden [Norway research reactor] data ... The available validation data from Halden did not include power ramps, the key benefit of doped fuel and the FRAMATOME power ramp database is proprietary. Therefore, a unique collaboration mechanism was arranged. MIT, in collaboration with INL, optimized the BISON settings for simulation of doped fuel. Then MIT turned in the BISON input files to FRAMATOME which has the BISON license through the CASL program. FRAMATOME then modified the input file with their proprietary boundary conditions for 3 different tests involving a power ramp. The result indicated a 15% underestimation of FGR by BISON, which is within the uncertainty of the code. In such way, we gained confidence in code prediction and capability for use in future projects while FRAMATOME kept the intellectual rights of its data.

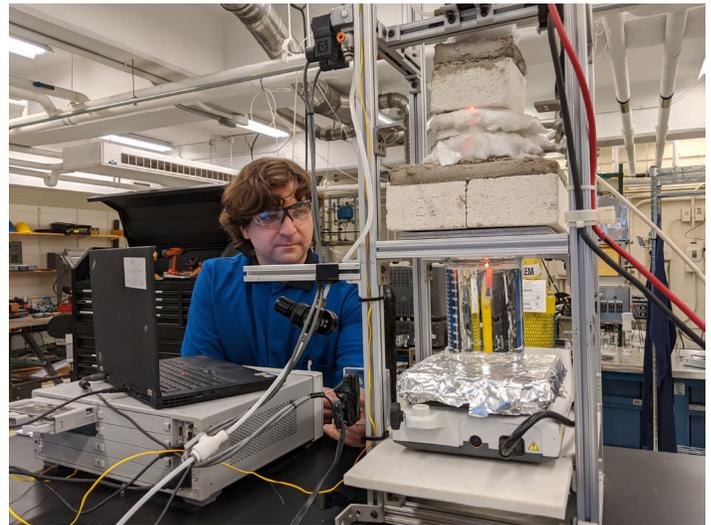
Notably, the project overcame the untimely deaths of two key team members, Principal Investigator Mujid Kazimi and Collaborator Thomas McKrell, both of MIT and both leaders in nuclear research and mentoring. Also integral to the project’s success, Goldner noted, was the appropriate level of cooperation the IRP team had with the Nuclear Regulatory Commission (NRC). In simple terms, the project deployed models the NRC was using – including, specifically, the TRAC/RELAP Advanced Computational Engine (TRACE) and the integrated safety analysis code known as MELCOR.

Here’s how the team’s report described the situation this IRP addresses:

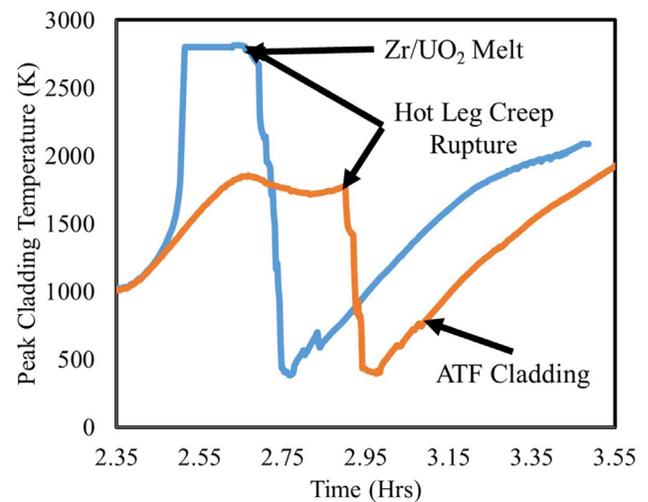
Following the Fukushima disaster in 2011, US congress mandated the Department of Energy to start an R&D program on accident-tolerant fuel (ATF) concepts for the existing light water reactor fleet. By 2015, the start date of this IRP, several ATF concepts were being pursued by various entities. In general, the ATF concepts were divided into two categories: near-term and long-term. The near-term concepts included coated Zircaloy clad, fuels with additives and dopants, and FeCrAl/steel-based claddings. The long-term concepts included SiC composite cladding, high density fuels (U3Si2, UN), and TRISO type fuel forms (e.g., FCM).

This particular NEUP project focused on those near-term concepts; it made specific recommendations in ten areas:

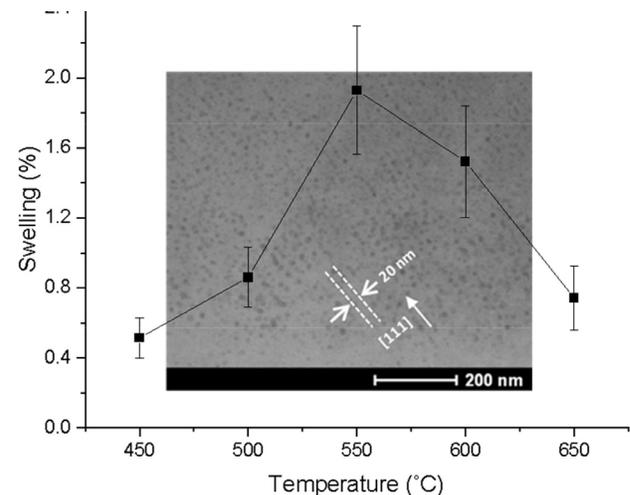
- Mo/FeCrAl coating testing outcome
- Cr coating testing outcome
- Ion irradiation testing outcome



Research scientist Dr. Bren Philips performing high temperature quench experiments on coated cladding concept to understand mechanical and thermal-hydraulic performance.



UW utilized MELCOR and MIT used Enhanced TRACE (results shown) to perform PWR Station Blackout Analysis for Zircaloy and ATF claddings. Analysis results showed ATF cladding can prolong time to fuel melt by a noticeable but modest length of time.



TAMU performed ion irradiation of Chromium to investigate its radiation stability. The graph shows the void swelling of pure Cr irradiated to 50 peak dpa, as a function of irradiation temperature and TEM image of a grain in <111> orientation, showing development of void alignment.

- Quench heat transfer behavior testing outcome
- Reactor physics simulation
- Thermal-hydraulic system modeling and simulation
- Normal and AOO fuel-performance simulations of near-term ATFs
- Transient and accident fuel performance simulations of near-term ATFs
- Economics and cost analysis
- Time-to-fuel-failure analysis

A key objective of the ATF research, of course, is to buy time; when things don't go as planned and operators need to make adjustments, minutes are precious. Both Goldner and Shirvan are optimists, and both were somewhat disappointed in the research findings. According to the report:

In this IRP, the system code TRACE predicts up to 20 minutes added coping time while MELCOR simulations predict up to 2 hours for station blackout type scenarios. In either case, the capacity to provide additional core cooling as an alternative severe accident mitigation strategy is deemed to be more effective for existing plants.

Shirvan explained that "some analysis was being done that said, if you employ these cladding concepts, you can gain several hours" before the core's integrity becomes problematic. There were even predictions that the cladding concepts could provide a cushion of a few days, but the research determined that's not the case. As the research continues, "we initially found it to be five minutes, and now it's up to forty minutes," he said.



Pressure Tube Sample



Steam Oxidation Sample (Tested)



CRUD Ring Sample



Hydraulic Quench Sample



4-Point Bend Fatigue Sample

Fabricated Cold-Spray Cr coating sample-types for testing; a unique approach of the IRP was to start with test samples that can cover a large set of separate-effect test conditions to decipher coated clad failure modes as opposed to initially testing small coupons.

Recommended NEUP Direction on ATF

Part and parcel of the final report (*Development of Accident Tolerant Fuel Options For Near-Term Applications*) were recommendations for future work. The recommendations are presented in three areas:

NEUP Areas Bucketed in Industrial ATF Concepts:

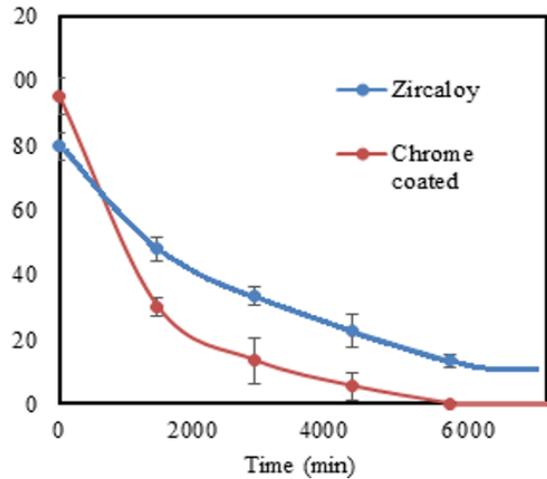
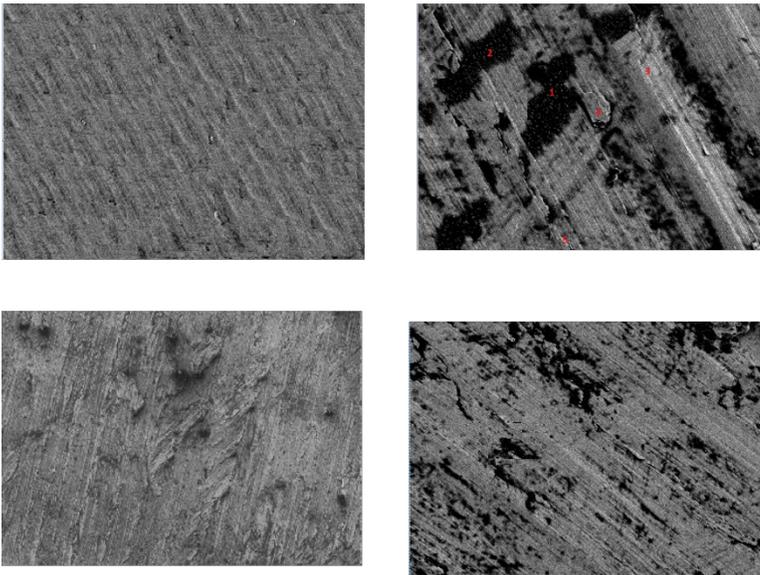
- Coated cladding
- Doped fuel
- Silicon carbide fiber in silicon carbide (SiC/SiC) matrix composites
- High-density fuels
- Fuel performance for beyond design basis
- Post-critical heat flux (CHF) and fuel rod survival after CHF

Other Recommended Future Work:

- Coated cladding experimental testing
- Improvement in ATF value proposition including application to high burnup
- Improvement of the NEAMS fuel performance tool BISON for Transients and Design Basis Accidents
- Improvement of the TRACE severe accident simulations

Recommended Work Not Accomplished by the IRP:

- Fuel performance during a severe accident, specifically through a structural mechanics framework
- Atomistic and mesoscale modeling of the corrosion and interlayer interaction for coated cladding
- Pairing Nuclear Energy Advanced Modeling and Simulation (NEAMS) Multiphysics Object Oriented Simulation Environment (MOOSE) tools to perform the multiphysics analysis of concepts
- Pursuit of new MAX-phase (layered material system) alloys as a coating
- Code-to-code comparison of Fuel Analysis and Licensing Code such as FALCON to BISON for near-term ATF concepts



Mechanism of surface induced hydrophilicity (lowering of contact angle) due to gamma irradiation was found to be due to formation of surface oxides as shown in black (top middle photo) after sample gamma irradiation. The surface undergoes hydrophobic recovery due to surface contamination of the formed oxide as shown in SEM after 24 hours of irradiation (bottom left photo) but the contamination is removed upon heating (bottom middle photo) and the benefits of increase in hydrophilicity due to gamma radiation is present during accident conditions.

Along with being optimists, Shirvan and Goldner are also realists. As Goldner put it, “the results didn’t give me my dream answers, but they did give the system some additional time, when minutes are crucial.” They agreed that it’s far better to know the answers rather than relying on overly enthusiastic estimates and to subscribe to the adage put forth by America’s greatest inventor: “Negative results are just what I want,” Thomas Edison said. “They’re just as valuable to me as positive results. I can never find the thing that does the job best until I find the ones that don’t.”

Moreover, like many ATF researchers, Shirvan’s team is also on the lookout for other attributes the advanced fuels can provide.

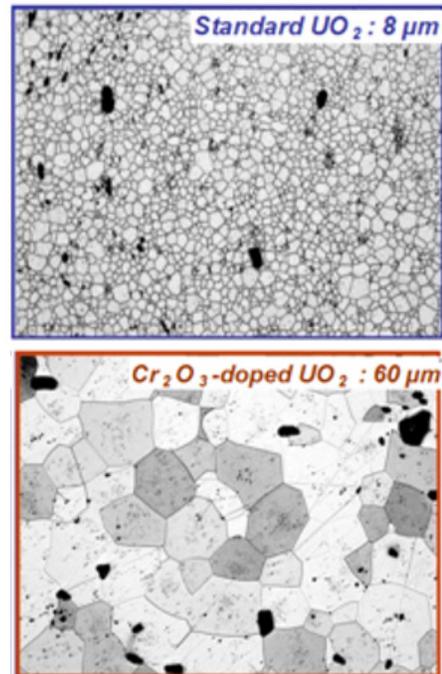
As explained in the report:

However, outside of their modest coping time improvements, ATFs do present other safety and economic opportunities in [the] form of more resilient fuel for normal operation and design basis accidents and have potential to enable higher fuel burnups. In order to realize such benefits, significant R&D is needed to address new failure modes and build the safety and commercial case. These challenges can be overcome through a public-private partnership between the DOE and industry.

“The most important thing is that nuclear is a blessing. That is my elevator speech,” Goldner said.

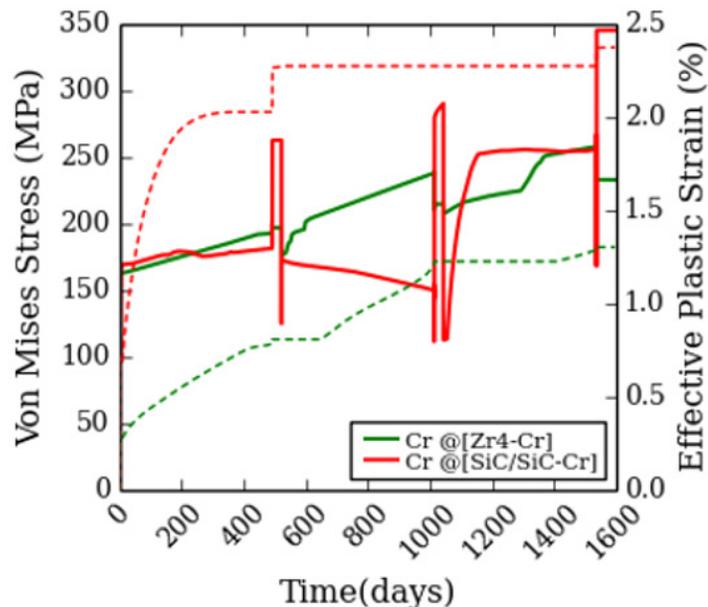
And, he added, “we’re trying to make sure a Fukushima doesn’t happen again. We’re working to enhance the safety of nuclear reactor[s] and at the same time ensure they’re economically competitive.”

Completing a project of this scope, in a university environment and in the compressed three-year timeframe allowed by the IRP program, is full of potential pitfalls. Despite those challenges,



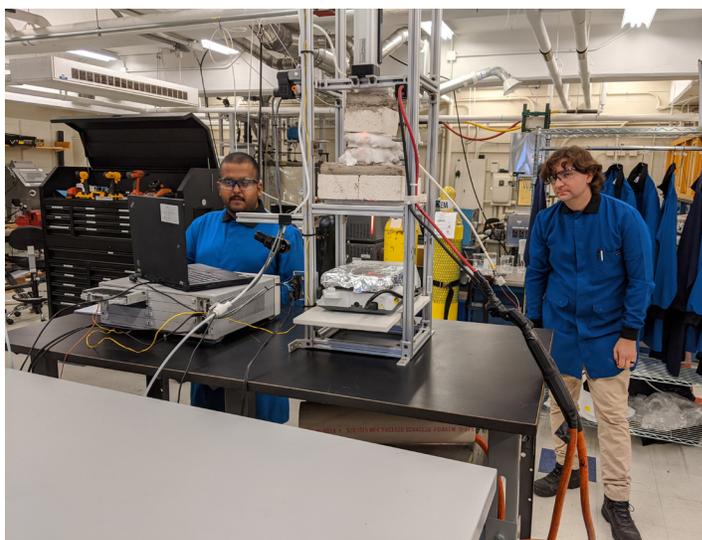
Unique team structure was formed to investigate the fission gas release of doped UO₂ fuel within the IRP. MIT performed model development with guidance of INL and INL’s HPC resources. Then the model in BISON was transmitted to Framatome to be used for validation purposes. On average, the predicted fission gas release for doped UO₂ after a power ramp was less than 20% compared to Framatome’s proprietary database. The findings were also used to confirm LANL diffusivity calculations after the IRP. Photo courtesy of Framatome.

by using an integrated modeling and testing approach Shirvan and the team not only solidified the understanding of the additional time that ATFs provide in crucial moments, they also provided much-needed clarity to inform the next steps in research.



Exposure of three coated pressure tubes to 1200°C steam for 90 minutes and two new severe accident failure modes identified: Cr coating survived in all three tests, zipping due to presence of manufacturing coating defect took place in top two figures (top fresh, middle post-creep), ductile bending or buckling due to lack of thick oxide layer took place in bottom figure.

IRP for first time modeled Cr coating for Zircaloy and SiC cladding with MOOSE/BISON during normal operation, power ramps, load following, and loss of coolant and rod ejection accidents. Figure above shows while Cr coating is compatible with Zircaloy and SiC, some plasticity (dotted lines) is expected to occur even during normal operation.



Team members graduate student Arunkumar Seshadri and research scientist Dr. Bren Philips performing high temperature quench experiments on coated cladding concept to understand mechanical and thermal-hydraulic performance.

Nuclear Energy Advanced Modeling and Simulation Software:

MOOSE - A Multiphysics Object Oriented Simulation Environment that allows nuclear fuels and materials scientists to develop numerous applications that predict the behavior of fuels and materials under operating and accident conditions.

BISON - A Finite Element-Based Nuclear Fuel Performance code applicable to a variety of fuel forms including light water reactor fuel rods, TRISO particle fuel, and metallic rod and plate fuel.

COBRA - Class of code systems for thermal-hydraulic transient analysis of light water reactor fuel assemblies and core. One class, CTF has been adopted for use in the CASL VERA toolset.

MARMOT - Mesoscale fuel performance code with the purpose to predict the coevolution of microstructure and material properties of nuclear fuels and claddings due to stress, temperature, and irradiation damage.