Research explores safer fuel for nuclear reactors

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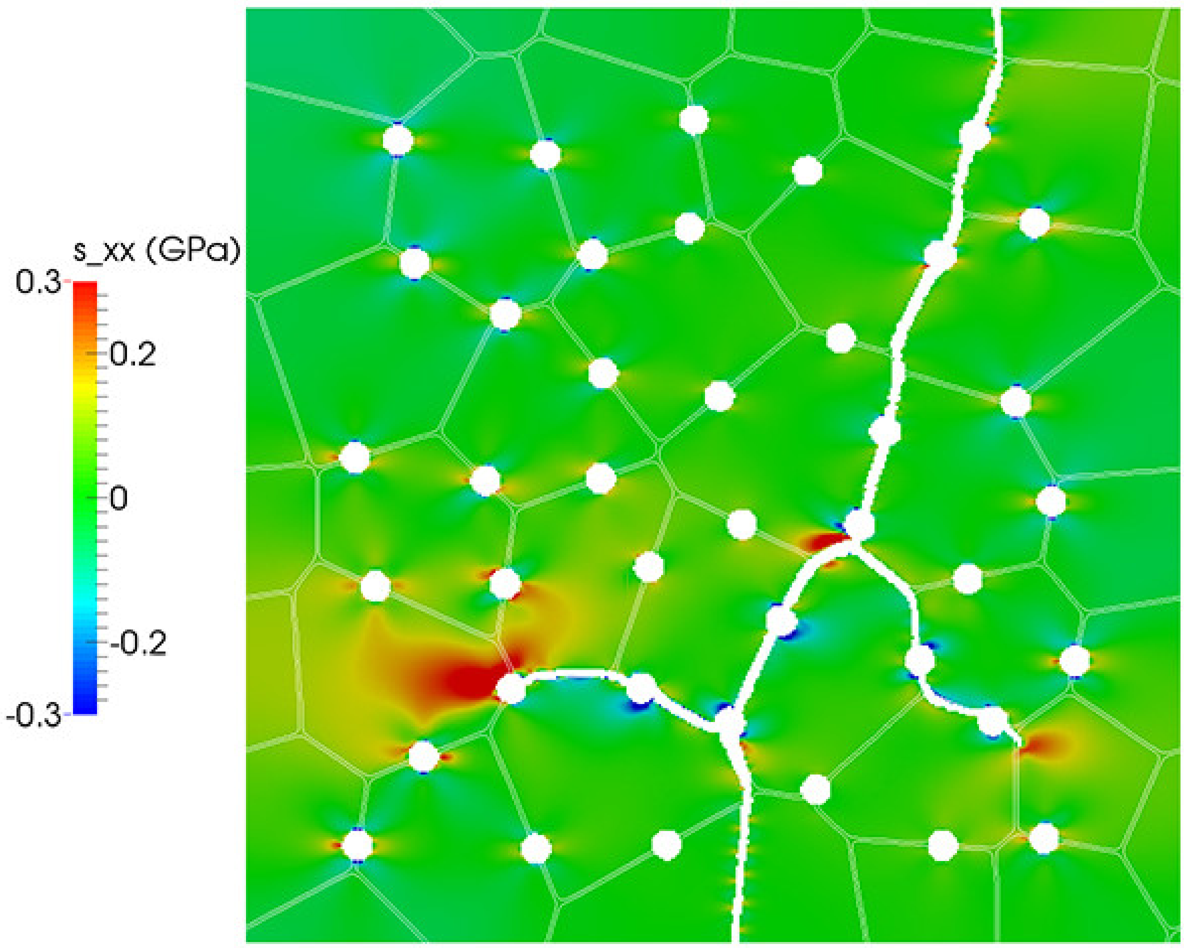

Image shows a mesoscale simulation used to predict the impact of fission gas bubbles on uranium dioxide fracture strength. Similar simulations will be used to investigate microcracking in silicon carbide composite cladding. Credit: Michael Tonks

Nuclear power is an important energy source in the U.S. and around the world and its use is seen by proponents as essential to reducing carbon emissions from fossil fuels. However, many people feel the risk of nuclear accidents does not outweigh the benefits associated with nuclear energy.

Michael Tonks, assistant professor of mechanical and nuclear engineering at Penn State and director of the Microstructure Science and Engineering Laboratory at Penn State, is involved with three projects through the Department of Energy's Nuclear Energy University Program (NEUP). These projects are exploring new materials for nuclear fuel, which could make current light water reactors (LWRs) safer.

These projects all involve accident-tolerant fuels, or fuels with enhanced tolerance to withstand loss of coolant during a nuclear accident for considerably longer than traditional fuels. The extra time gives reactor operators a chance to resolve problems before there are large consequences. Accident tolerant fuels also need to have similar or improved performance compared to current fuels and be cost effective.

"The issues with the Fukushima Daiichi nuclear reactor accident were actually direct issues with the choice of material for the fuel and cladding," Tonks said. "And so the idea is that maybe we can change the fuel material or the cladding material, but keep everything else in the reactor the same."

Cladding is the metal that surrounds a stack of fuel pellets and separates the fuel from the coolant inside the reactor.

Altering the fuel and cladding is a more cost-effective and near-term solution than replacing existing nuclear reactors with newly designed reactors, and it could drastically change the future of nuclear energy.

The nuclear fuel used in all LWRs in this country is uranium dioxide and the cladding material used in these LWRs is a zirconium alloy. These materials have properties that make them very good choices for use in nuclear reactors and they continue to perform well. However, they also have issues that keep them from holding up well in accident conditions.

Uranium dioxide has very low thermal conductivity, which means it traps heat inside the fuel pellet. Not only is the low thermal conductivity counterproductive to a nuclear reactor's goal to generate heat, but it can also cause the fuel pellets to overheat and even melt when a reactor loses coolant.

The zirconium alloy cladding is highly reactive with water, especially the steam that can be produced if coolant water heats up under accident conditions. The steam causes it to oxidize and release hydrogen gas, which is highly combustible.

The main focus of Tonk's work is to understand how the microstructure of a material impacts that material's behavior. For these projects, he is looking at how the small-scale structures of potential new fuel and cladding materials will behave when exposed to reactor conditions, especially radiation.

"It's well understood that the microstructure has a direct impact on the properties of the material, but my research focuses on harsh environments, where, because of the environment, the microstructure doesn't stay static, but actually changes with time," said Tonks. "It's not enough just to design a microstructure that's going to give you the behavior you want. You have to make sure that even as the microstructure evolves, it doesn't ever result in behavior that's going to cause your part or your reactor to fail."

To understand these microstructures, Tonks uses computational models to create simulations on scales ranging from 1 to 10 microns, which is much smaller than a strand of hair. These simulations predict a material's behavior under a variety of conditions.

Tonks and his research team are using these simulations to explore possible alternatives for a safer reactor fuel. In regards to the cladding, the simplest solution they are looking into is layering other materials over the zirconium alloy cladding. By creating layers of materials, researchers hope to get the strengths of the different metals and eliminate the weaknesses. The layered material would protect the cladding from reacting with steam and producing hydrogen. However, the layers could be more prone to radiation damage. Tonks is using modeling to simulate reactor conditions and understand the changes these materials experience.

The group is also exploring the feasibility of completely changing the cladding material to a silicon carbide composite. Silicon carbide has a lot of the same benefits of zirconium alloy and has been used in many non-nuclear applications. It has the added benefit of not reacting with coolant water, so it would not degrade and produce hydrogen inside the reactor. Unfortunately, the composite is hard to fabricate and it has the potential to crack. Tonks is using fracture simulations under normal and accident conditions to determine how radiation induces cracking and whether those microcracks would allow fission products to escape.

To address the thermal conductivity issues with reactor fuel, the research team is simulating various fuel additives to raise the thermal conductivity of the uranium dioxide. Tonks is focusing on determining the possible side effects of the various additives when used in a harsh reactor environment.

"Our role is developing the models for these systems," Tonks said. "No one has ever done this before so there are no models. We are developing the models from scratch and then using them to help evaluate whether these concepts are viable or not."

Specifically the researchers are looking for potentially damaging interactions between the new materials and radiation in normal and accident operating conditions.

"We are hoping to be able to apply the tools that we have developed for understanding uranium dioxide and zirconium alloy, but now extend them to look at these new materials."

One of the main tools that Tonks is using for these projects is a mesoscale fuel performance tool called MARMOT, which is being developed by the U.S. Nuclear Energy Advanced Modeling and Simulation Program. Tonks was the lead developer for MARMOT while at the Idaho National Laboratory.

The work by Tonks and his research team will help evaluate accident tolerant fuels faster than if researchers were using experimental data alone. Modeling provides data less expensively and more easily than running full nuclear tests. The simulations will guide the experimental work being completed by collaborators by pinpointing the fuels that are most likely to be viable so researchers can prioritize the experimental work.

Provided by Pennsylvania State University

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