A fresh set of eyes on next-generation nuclear reactors

June 26 2024, by Kristen Mally Dean

Credit: Pixabay/CC0 Public Domain

Decarbonization requires radical transformation of the U.S. energy sector, and nuclear energy could be at the center of that transformation. It already provides a fifth of the nation's electricity, and new designs suggest it can generate even more. Essential to achieving U.S. climate goals, nuclear energy is one of the key contributors to a low-carbon energy system.

At the U.S. Department of Energy's (DOE) Argonne National Laboratory, experienced and fresh eyes alike are turned toward five key areas of research and development: advanced reactor design and safety analysis; nuclear materials management and nonproliferation; reactor and fuel cycle physics; nuclear engineering modeling and simulation; and sensors, instruments and diagnostics.

Meet five early and mid-career engineers and scientists who are finding ways to apply modern tools and technologies to study the next generation of nuclear reactors and to sustain and improve the 93 legacy reactors that currently provide half of the nation's carbon-free electricity. Their work just might transform the American nuclear industry.

"I can't solve it all at once, but I can solve a little bit. Every small bit I do will contribute to the overall goal," said Tingzhou Fei, Argonne principal nuclear engineer

Advanced reactor design and safety analysis

Scientists observing the first self-sustained nuclear chain reaction experiment used zero radiation shielding. In Chicago during December 1942, they likely wore ordinary wool clothes as they stood less than 25 feet from natural uranium as nuclear fission began. Protection from such an experiment couldn't be more different today.

According to Tingzhou Fei, Argonne principal nuclear engineer in advanced reactor design and safety analysis, shielding can account for at least 10 times the mass of any active agent powering a reactor's core. Picture a large fluted nuclear reactor cooling tower. The vast majority of the structure is there to protect the people who work there.

"If we can optimize and reduce the shielding configuration of advanced reactors, we can save a lot of space and make them smaller," Fei said.

This kind of economical, compact design is of interest to people in remote areas, the military, universities and even those interested in roadside reactors for electric long-haul trucking fleets.

Fei used to focus on designing advanced reactor core concepts to meet energy demand. Those core designs, he said, "almost never got off the paper." He finds his current work satisfying because shielding optimization is a complex issue several degrees closer to nuclear industry projects that might actually get built.

"My piece is just one part of an entire system and I have to be sure it's safe and it doesn't interfere with other components," Fei said. He works with materials science experts, mechanical design teams and other kinds of engineers to study the same problem from varied but equally important angles. "I can't solve it all at once, but I can solve a little bit. Every small bit I do will contribute to the overall goal."

Nuclear materials management and nonproliferation

In addition to nuclear reactor safety, researchers at Argonne focus on the security of nuclear material, which relies upon the responsible use of nuclear materials and facilities both domestically and internationally. They carefully consider material on its way into a nuclear process or system and on its way out. Everything must be accounted for.

"Our collective mission is to ensure that any pursuit of nuclear is peaceful and for the benefit of all or many, as opposed to the benefit of a few," said Claudio Gariazzo, group lead for nonproliferation innovation in nonproliferation research, analysis and engagement.

"We work with international partners such as the International Atomic Energy Agency (IAEA) to help safeguard nuclear materials and secure the use of nuclear facilities and technologies."

The IAEA is the oversight organization that inspects facilities worldwide to ensure nuclear facilities are not being misused and that all civilian-use nuclear material is accounted for, down to the tiniest amount.

Strict IAEA reporting requirements drive designers, facility operators and the international community to work with experts like Gariazzo and his colleagues to be sure nonproliferation efforts and accurate, precise materials management are part of any existing operation or new reactor design.

"When a country chooses to use nuclear energy and builds a fuel fabrication facility, they have an obligation to report their material quantities with high fidelity to the international community," Gariazzo said.

He adds that it feels good knowing that he works in a community doing something that betters global society. "It is critical to ensure we can reap the benefits of nuclear energy without increasing the risk of nuclear proliferation."

Reactor and fuel cycle physics

Ten years ago, U.S. scientists conducted a large study to determine which fuel cycle and reactor technologies were the most promising when it came to the future development of nuclear energy. The answers they arrived at relied on advanced reactors.

Building on that research, the DOE's Office of Nuclear Energy invests today in the Advanced Reactor Demonstration Program to support demonstration of advanced reactors through cost-shared partnerships with U.S. industry.

That investment includes enlisting experts at the national labs in order to get advanced designs beyond the drafting stage and into U.S. infrastructure by set deadlines.

For example, several private industry designs seek to use proliferation-resistant high-assay low-enriched uranium (HALEU). That approach raises questions, such as, can the U.S. ramp up its enrichment facilities to produce enough HALEU? How much HALEU does the U.S. actually need, and how much waste would proposed fuel cycles generate? On the economic side, how expensive would transition to HALEU-fueled reactors be, and how much government support would be needed before private industry took over?

Scott Richards, an Argonne principal nuclear engineer, works to answer these complex questions and more. His goal is to provide unbiased information to policy makers so they are well informed on the paths needed to achieve goals set for 2030, 2050, 2100 and beyond.

"Currently, we are not making judgments about what's best and what's not best," Richards explained. "We look at what it would take to have successful commercial deployment. "If you want to do this, then here is what it would take.'"

Modeling the complex systems to answer these questions is high priority for Richards. He earned his doctorate studying how to model the important physics of how isotopes change under different conditions using nuclear codes that do not sacrifice computational efficiency. He said he is impressed by the level and immediacy of current support for nuclear energy.

"It makes me pretty optimistic for the future of nuclear in general," he said. "I think we have a shot at meeting net-zero goals."

Nuclear engineering modeling and simulation

There is no crystal ball in nuclear engineering, so Argonne principal nuclear engineer Shikhar Kumar uses advanced computer modeling and simulation to try to predict what will happen inside a nuclear reactor's core.

His computer screen looks like lines of code most of the time. Some of it he develops, some of it is developed by others. Those lines of code are used to generate a 3D model of a reactor core and what's happening inside. Kumar can zoom in on a certain area and see what's happening.

"You can see power production and, in areas that have high power, those areas tend to have higher heat," he explained. "We want to extract that heat from the core itself to a coolant that will transfer that heat into electrical power. The first step of seeing where the power is being used is a visual cue to where we expect power to be localized."

Kumar joined Argonne in March 2021 after earning his doctoral degree in nuclear engineering. Raised in Japan, he speaks Japanese and works with fellow scientists from the island country to exchange data sets and compare analysis tools.

"With the tools available, like low-level algorithms, we try to figure out the inventory of materials inside a core so we know how radioactive things are, how effective we are at producing power over time and how much fuel is left," he said.

Experimentation with smaller, more modular new reactor types affect predictions about what is happening inside the core, and that makes Kumar's work challenging. But looking at large data sets, he finds he can not only predict what is going on in the core, but also validate the data.

"The energy densities associated with nuclear is something that I've been interested in and something that I think the country is realizing it needs to invest in," he said. "It's how we'll move toward a clean energy future."

Sensors, instruments and diagnostics

Just as he does when training for one of his marathons, Tim Nguyen brings the highly practical skills of preparation, training and planning to his role as principal nuclear engineer. His work focuses on developing sensors, instruments and diagnostics that can be used to detect and address flaws in a system before they become major reasons for repair.

These tools help facility operators optimize maintenance plans on a planned schedule instead of dealing with costly component failures or the shutdown of a facility in order to complete a major fix.

"One of the major challenges facing nuclear power is its high operation and maintenance costs," Nguyen said. He joined Argonne in early 2020. "I work on the development and commercialization of computer codes for cost reduction applications in nuclear power plants so that nuclear energy is an economically competitive choice when compared with other energy sources."

Nguyen helped Argonne develop a patented fault detection and diagnosis code. The code uses physics-based models to gather detailed knowledge of the current state of the physical system and diagnose component faults and sensors that are out of calibration or failed. The result is presented as a ranked list of candidate faults, from greatest risk of failure to least probable. This aids plant operators in decision making.

"I like seeing the value of my work in practical applications," said Nguyen. "People talk about climate change and renewable energy, and nuclear energy is an important part of that. I believe my work can help improve the viability of nuclear power in the energy market. It can make a difference in a meaningful way."

Provided by Argonne National Laboratory