The R&D Reshaping Nuclear Waste Management: 5 Focus Areas

As the global community, increasingly concerned about climate change, reframes its thinking about nuclear power, it faces a key question: What to do with the waste that nuclear reactors leave behind?

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Nuclear power has reached an historic juncture, as a growing consensus holds that nuclear power can, and must, play a significant role in mitigating climate change. Grasping the gravity of this crisis, the world has taken notice. The decades-long public antipathy for nuclear power has steadily begun to shift, ushering in a new age of open-mindedness to its potential benefits. Multiple European nations, including Belgium, Greece, and Sweden, as well as Asian countries such as South Korea and the Philippines, have signaled their intentions to either slow or halt the planned phaseout of their current nuclear plants or to begin exploring the construction of new ones.

But the reality of nuclear power is the conundrum presented by all that it leaves behind—that is, what should be done with nuclear waste. Currently, the United States' reliance on nuclear power is significant; per the U.S. Department of Energy (DOE), nuclear power is among our most reliable sources of energy and the largest source of our clean energy, representing roughly half of our carbon-free electricity and about a fifth of our total electricity. And as a result, every year, the U.S., which possesses the largest nuclear power fleet in the world, creates roughly 2,000 metric tons of spent nuclear fuel. We're not alone, of course: As of 2019, the world had amassed roughly 250,000 metric tons of nuclear waste. In the U.S., at least, this radioactive material is largely stored within water pools at reactor sites, with no real plan for a central repository for long-term storage.

As such, in this new era of revived enthusiasm for nuclear power, the safe and effective management of radioactive waste and spent fuel has become a subject of increasing interest. The DOE recently funded $48 million in research grants through the Advanced Research Projects Agency–Energy (ARPA-E)'s Optimizing Nuclear Waste and Advanced Reactor Disposal Systems (ONWARDS) program, specifically to develop technologies that can resolve the waste and storage challenges associated with advanced reactor (AR) fuel cycles.

While this is certainly positive news, it still leaves the question of what will happen to nuclear waste created by earlier-generation Light Water Reactors (LWR) that have been in use for decades.

Promisingly, it does seem that fresh new solutions to this long-vexing problem are in the works. The drive to develop new reactors is pushing the industry toward a spirit of problem-solving and innovation with regard to nuclear waste. Outside-the-box notions such as reusing spent fuel on a large scale, for example, or employing novel methods of storage, are cropping up with heartening regularity. And they're arriving just in the nick of time. While our existing means of decommissioning, disposing, and storing nuclear waste have been largely sufficient for decades, they simply can't scale effectively if and when more nuclear power is deployed to address the global climate crisis.

As Bill Gates, a proponent of and investor in nuclear power, recently told a German publication, not having a long-term waste management solution fully in place is no reason not to press on with expanding nuclear power—not when, as Gates contends, the risk of nuclear waste pales in comparison to the risk of climate collapse. In fact, Gates says, we owe it to ourselves and the planet to begin pursuing a growth in nuclear power *now*. To do so, the world's nations need faster, cheaper, safer, and more achievable solutions. Here are some of the most encouraging areas of inquiry thus far.

"The waste problems should not be a reason to not do nuclear. The amount of waste involved—that's not a reason not to do [it]. Say the U.S. was completely nuclear-powered. [That's] a few rooms worth of total waste...it's not a gigantic thing."

— Bill Gates, February 2023

1. SMALL MODULAR REACTORS

A Small Modular Reactor (SMR) is a nuclear reactor that can be created more quickly and on a far smaller scale than a traditional reactor, which can cost billions to build and can require extensive site-scouting and preparation. (A "small" reactor is defined as one that produces under 300 MWe. The largest reactor in the U.S., meanwhile, located in Arizona's Palo Verde plant, can produce around 3,900 MWe.) Because SMRs require less building time, they present a promising solution not only for large-scale use in highly populated areas, but also for low-electricity areas in need of more reliable power. Little wonder, then, that as the nimble nature of these small-footprint, less-expensive, quick-build, flexibly located reactors has become clearer, the SMR influence has continued to grow. And that trend will likely only continue: In 2020, the global SMR market was valued at $3.5 billion; by 2030, it's expected to reach $18.8 billion.

However, SMRs come with challenges, particularly regarding the waste they produce. Some studies have shown that these smaller designs experience far more neutron leakage—that is, radioactive neutrons escaping from the reactor core—than a conventional reactor, which threatens to both increase the amount and alter the constitution of the waste they produce. In fact, a joint study conducted last year by Stanford and the University of British Columbia found that SMRs may produce up to nine times more nuclear waste than traditional reactors, thanks not only to neutron leakage, but also to the researchers' estimation that the plutonium in spent SMR fuel may be up to 50% more radioactive in 10,000 years than that of traditional reactors.

Though many of these findings are contested by proponents of SMRs, the fact remains that this area of nuclear power generation is still relatively new—and, as such, ripe for further analysis, study, and technical refinement. That presents an enticing challenge for those in the field—and within the arena of SMRs, there are plenty of areas of inquiry to which engineers can and should devote their investigative talents.

Some SMR enhancements are already being explored. For the issue of higher rates of neutron leakage, one proposed fix is to encase the reactor core in materials like steel and graphite that can deflect or reduce the speed of the neutrons rattling inside. Of course, once these materials are thoroughly bombarded with neutrons, they too will become radioactive, presenting a new disposal and handling problem for engineers to ponder. Another approach to mitigating neutron leakage is the use of fuel that's been more highly enriched with Uranium-235, offering up a greater number of atoms for those neutrons to split, potentially diverting them from leaking from the core. But with a greater concentration of atoms, researchers estimate that these reactors will wind up with higher volumes of spent fuel.

The final summation? SMRs are brimming with potential—and they'll likely be the site of major scientific breakthroughs in years to come.

"It cannot be emphasized enough: decarbonization is a global movement that requires cross-collaboration...[we need to] advance global decarbonization and accelerate the deployment of solutions to meet the growing need for clean energy and energy security."

— John Hopkins, President and CEO, NuScale (a leading builder of SMRs)

2. AI AND MACHINE LEARNING

As in countless industries, artificial intelligence (AI) and machine learning (ML) are upending the ways in which complex tasks are conducted in the nuclear waste arena. AI, for example, is enabling researchers to improve complex waste management procedures and improve safety. The applications for both are nearly endless. AI and ML can be used to do everything from optimizing waste travel routes between reactor to repository to perfecting reactor design.

Meanwhile, by trawling vast troves of data—satellite imagery, environmental sampling, gamma ray spectroscopy, and video surveillance—ML can be used to predict contamination levels without the hazards of in-person detection. It can also be used to model probable outcomes, and direct reactor workers to respond accordingly.

At the Orano La Hague nuclear material recycling plant in France, for example, a project team used ML-fueled algorithms trained over five years of nuclear waste simulations to categorize the magnesium levels within different waste-storage areas of the plant. The algorithm then suggested to plant workers ways to distribute the material evenly between its storage silos, maintaining magnesium levels at safe thresholds within each.

The use of AI to reduce the costs associated with nuclear energy—including constant monitoring and maintenance—and to increase its safety and sustainability, also has the potential to make it a much more valuable modern energy source.

3. AUTONOMOUS ROBOTS

Among the countless fields being reimagined via the use of robotics, the nuclear industry may be the most intuitive realm for non-human engagement given the extraordinarily hazardous materials involved. The industry is increasingly deploying robots to carry out the repetitive, dangerous tasks associated with nuclear waste categorization, and to make decommissioning projects safer and more efficient.

However, the use of robots introduces new questions that nuclear waste management professionals are working to address. For example, if a robot deployed at a nuclear site becomes contaminated, it too becomes nuclear waste—raising a new problem of disposal logistics. But at present, the positive potential of robotics within the nuclear industry far outweighs the negative. The Virtual Remote Robotics (VIRERO) project, funded by the German Federal Ministry of Education and Research and expected to be completed in 2023, for one, is working to create technologies to help decommission highly radioactive materials, as well as to handle, store, and dispose these materials.

Meanwhile, in the United Kingdom, Dounreay Site Restoration Ltd. (DSRL) is working with the Robotics and Artificial Intelligence in Nuclear (RAIN) Hub to perfect their Lyra robot—a camera-equipped probe outfitted with radiation meters, whose job is to take samples and measurements to map radiation levels along its path. Early this year, Lyra, named one of Time magazine's Best Inventions of 2022, surveyed a duct beneath two plant laboratories, collecting samples that will aid enormously in the eventual decommissioning of the site.

Also in the U.K., the nuclear services firm Jacobs Energy has created a robot to help survey the defunct Fukushima Daiichi reactor in Japan, site of the 2011 nuclear accident brought on by a cataclysmic earthquake and resulting tsunami. Decommissioning processes have been underway at Fukushima's damaged plant since the disaster, but the presence of a highly skilled robot will make this painstaking safer and faster. The thoroughly tested prototype is small (allowing it to access hard-to-reach areas) and phenomenally precise (with the ability to retrieve objects as small as 10mm).

Finally, an innovative collaboration between the Australian government, the Hungarian robotics company Datastart, and the International Atomic Energy Agency has yielded the Robotised Chernkov Viewing Device, a self-propelled floating robot designed to monitor and safeguard used nuclear fuel stored in water pools. When deployed within a used fuel storage pond, the device makes its way across the surface, creating a video map (via its camera) of the location and status of the fuel rods, detecting whether any fuel has moved or changed since the previous inspection.

"This is a prime example of how we are combining innovative engineering and deep nuclear knowledge to help decommissioning agencies meet the challenge of transforming legacy sites into a safe end state."

— Karen Wiemelt, Security & Technology Senior Vice President, Jacobs Energy

4. DEEP BOREHOLE DISPOSAL

A startling fact: No permanent repository for nuclear waste has ever been built on earth. The famous Yucca Mountain site in the Nevada desert is still undeveloped, and the U.S. stores much of its nuclear waste at reactor sites and in a temporary location outside Carlsbad, New Mexico. (The latter site, known as the Waste Isolation Pilot Plant, or WIPP, is licensed to store nuclear waste for only 10,000 years—not the millennia required to outlive the stored materials' radioactivity.) However, that's all about to change. Finland is close to completing Onkalo, a deep repository that will entomb a cache of spent fuel rods for the accepted scientific interval of 100,000 years. This form of storage is known as a geological disposal facility (GDC), and for generations it's been the conventional wisdom that GDC is the optimal answer—if not the actual practice—for nuclear waste disposal.

But a modified version of this solution has come to the fore, and R&D around Deep Borehole Disposal (DBD) is now gaining significant traction. With DBD, extremely deep holes—roughly three miles deep, in fact—are drilled into the ground before canisters of waste are sent down to live out their period of radioactivity far below the earth's surface. (Most schematics indicate that radioactive material would fill only the bottom third or so of the borehole.) This methodology dramatically expands both the kind and the number of locations that could serve as repositories, and because DBD allows for horizontal storage, rather than merely vertical, it also mitigates the compression risk of stacked canisters. That fact alone creates more storage options at a given repository location, limiting the need to truck waste to far-flung locations. (Though it should be stated that nuclear waste trucking is far safer than it may seem—waste material is shielded from both the workers transporting it and the public by steel encasements anywhere between five and 15 inches thick, and there are firm regulations on allowable radioactivity levels for transported matter.)

Enthusiasm for and interest in DBD has grown among the global nuclear community in recent years. Earlier this year, the U.K. Department for Energy Security and Net Zero awarded the California start-up Deep Isolation a sizable grant to fund the development of a canister able to house spent fuel rods at 3 km below the earth's surface—without corroding, buckling, or proving permeable to the elements. Testing will take place at the planned Deep Borehole Demonstration Centre, to be located in the United States. And participants in a recent study by Deep Isolation cited major advantages as increased site flexibility, cost savings, and bolstered safety for disposing of radioactive waste.

"Challenges are opportunities. We are doing something that has never been done before. And that's much of what makes it so rewarding."

— Elizabeth Muller, Founder and CEO, Deep Isolation

5. RECYCLING SPENT FUEL

A layperson likely hears "spent fuel" and imagines something inert, used up, no longer possessed of its catalyzing powers. In the case of nuclear spent fuel, this couldn't be further from the truth. In fact, more than 90% of a fuel rod's potential energy remains within it once it's removed from a reactor. Recycling nuclear waste focuses on extracting plutonium and uranium, which can subsequently be mixed with fresh uranium and made into new fuel rods that can continue producing energy.

In theory, this method, known as reprocessing, could eliminate the global presence of nuclear waste; in reality, we face a problem of capacity. Though more than 88,000 tons of nuclear waste is generated each year, we possess the global infrastructure to reprocess only 2,400 tons of it. Were that to change, the problem of nuclear waste disposal could look very different indeed.

But until that day comes, researchers are busy finding novel ways to turn nuclear waste into usable products. The Washington D.C.-based nuclear innovation start-up Curio recently developed a chemical process to turn nuclear waste into isotopes that can be used to produce power sources for space missions and batteries. Another D.C. startup, Zeno Power Systems, is developing a radioisotope power system that converts the heat from recycled nuclear waste into electricity. The U.S. government-funded Argonne National Laboratory and California electric power company Oklo are working on a project to commercialize a technique called pyroprocessing, which can recover and recycle nuclear materials from used nuclear fuel. Argonne, Oklo, and Deep Isolation—leaders of the deep borehole research project mentioned above—are also working to improve a process that converts used nuclear fuel into a metal that can then become the material for advanced reactor fuel.

CONCLUSION

At present, some of these areas of research may seem untested, still in the zygote stage. Yet the technology that undergirds each of these novel approaches could have a lasting influence on this complex industry, propelling new thinking, inspiring fresh solutions, and generating innovative ideas that may well revolutionize the nuclear field. To make that happen, of course, the industry will need a steady stream of new and eager talent, filling its ranks—and enlivening its discourse and development—in the crucial years to come. If nuclear power is to be one of the silver bullets in the fight against climate change, there is much work to be done—and many people needed to do it.

But beyond the required people-power, new theories need testing. Projects need funding. And engineers interested in this awesome and singular field need cultivating, to ensure that they become the visionaries of tomorrow, able to navigate not only the enormous logistical challenges of nuclear waste management but also to continue to do their work amid a tumultuous political landscape, ever-shifting regulatory concerns, and the roller coaster of public opinion.

It's impossible to predict how the future will unfold with regard to nuclear power, and by extension, to nuclear waste. But one thing is certain: This is an area with enormous scientific and engineering potential, as well as tremendous human stakes. And if these pioneering new projects are any indication, we're well on our way to a tomorrow rife with innovation.