Nuclear Energy Research at PNNL

A Leadership Target for Safe, Secure, and Clean Nuclear Energy

Pacific Northwest NATIONAL LABORATORY

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Some use the word "renaissance;" others are more cautious in their optimism. Some critics have become supporters; others continue to pose tough questions. Perhaps more than any other industry, nuclear energy comes with a host of diverse and passionate perspectives—and a fate inseparably entwined with public opinion. However, our current moment in history has shed new light on an old debate: science and technology have revealed both the dire need to provide clean domestic sources of energy and promising ways to do so by harnessing the power of atoms.

More specifically, the current goal of doubling clean energy sources by 2035 and elimination of the country's reliance on foreign oil imports has made clear the need for new nuclear thinking. Along with conservation, renewables, a smart grid, and clean coal, nuclear power must provide clean base load electricity by responsibly expanding its segment of the nation's energy portfolio. So the question has become: what does "responsible" look like? For scientists at Pacific Northwest National Laboratory (PNNL), it looks like investing in the best expertise and technological resources available today in order to answer the nuclear energy challenges of tomorrow.

The challenges are distinct: an aging nuclear reactor fleet; substantial capital for new facilities and technologies; lengthy regulatory and licensing processes; fuels and fuel cycles in need of improvement to address the accumulation of used fuel; and ongoing complex concerns regarding safety, and weapons proliferation. In each area, there are technical gaps that must be filled in a timely manner in order for nuclear energy's expansion to have the intended impact on our world's climate and energy security crises.

PNNL recognizes the gaps and challenges, and has long been a recognized source of excellence in nuclear energy science. PNNL's nuclear résumé includes an infrastructure of two world-class facilities, each of which houses integrated, advanced instrumentation and expertise: the Environmental Molecular Sciences Laboratory (EMSL), a U.S. Department of Energy national scientific user facility located at PNNL, and the Radiochemical Processing Laboratory (RPL), a Hazard Category 2 non-reactor nuclear facility. State-of-the-art equipment is one thing; the ability to integrate the most relevant findings with next-generation modeling capabilities is another. The latter takes a holistic, strategic vision that can only come from decades of accomplishments ranging from the most fundamental understanding of nuclear materials to applied, market-deployed technologies. PNNL is poised to apply its longstanding expertise to this vision to help empower an industry at an important crossroads—to support the accelerated deployment of sustainable nuclear energy production.

PNNL is establishing new cross-cutting nuclear science concepts, including **Advanced Condition Monitoring (ACM)**, the science that integrates online nondestructive remote sensor measurements with interpretive and predictive modeling. The development of ACM will create, through various applications in the nuclear energy sector, a window of real-time and predictive performance measurement that offers industry, government, and regulatory bodies the ability to **Understand, Measure, Model, and Predict**.

Within, you'll find a tour of today's nuclear industry, with views of how PNNL's ACM breakthroughs will make an important impact at each stop along the way.

FUELS: STARTING AT THE CORE

In the world of nuclear power, the fuel that drives an industry—and churns out gigawatts of electricity—comes in many varieties, and is in need of innovation and improvement to address the challenges of today and tomorrow.

The development of higher burnup nuclear fuels would bring about many interrelated benefits: simply put, if more of the energy in nuclear fuels is utilized for power generation, there is less waste material for disposition, lower fuel costs, and fewer opportunities for misuse of harmful materials. If, for example, a nuclear fuel currently performs at 62 gigawatt-days per metric tonne, the goal would be to extend that burnup rate to 100 gigawatt-days—putting the fuel to better use.

However, at present, it can take years or even decades to develop a new fuel. In response to this challenge, PNNL's development and deployment of ACM would contribute to an accelerated fuel qualification process. Today's method of testing a fuel includes a long period within a nuclear reactor, followed by extensive post-reactor tests of the fuel's composition and characteristics. Through new sensor technologies that allow for in-reactor monitoring, not only would the regulatory process be faster, it would be more informative—truly the difference between observing a phenomenon as it is occurring and making assumptions about it after the fact. New data streams from sensory equipment, integrated with the ability to model these data, can open the door to a more streamlined regulatory process, as well as better insights for new fuel innovations.

REACTORS: THE HARDWARE AND MATERIALS BEHIND CLEAN ENERGY

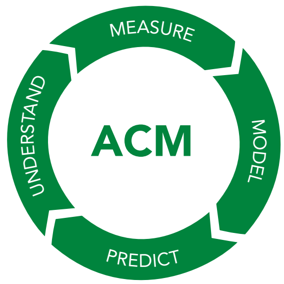
The United States produces more nuclear energy than any other nation—a sometimes forgotten fact because of the percentage of U.S. electricity attributable to nuclear power (approximately 20 percent). However, by quantity of energy produced, the U.S. is the world leader, generating about a quarter of the world's nuclear energy. This quantity is attributable to a large fleet of 104 operating nuclear reactors.

For nuclear power to make its contribution to a clean energy future over the next generation, extending the life of this generation's reactor fleet is very important. While the majority

Safe and secure expansion of nuclear power by knowing real-time performance

Fuels & Materials

- Accelerating development of advanced fuel concepts
- Enhancing small modular reactor designs
- Monitoring, prognostics of structural materials for life extension



PNNL leadership position in Advanced Condition Monitoring (ACM):

Integration of real-time monitoring, predictive and interpretative modeling, data integration and visualization, and diagnostics/prognostics.

of these facilities will have their licenses extended to a life of 60 years, safely keeping these established reactors online even longer is a high priority that may require significant technological breakthroughs. Through leadership in Advanced Condition Monitoring, PNNL is striving to deliver the science behind safety assurances within aging reactors.

For example, it is widely known that structural steels in harsh or stressed environments can eventually begin to crack. What isn't

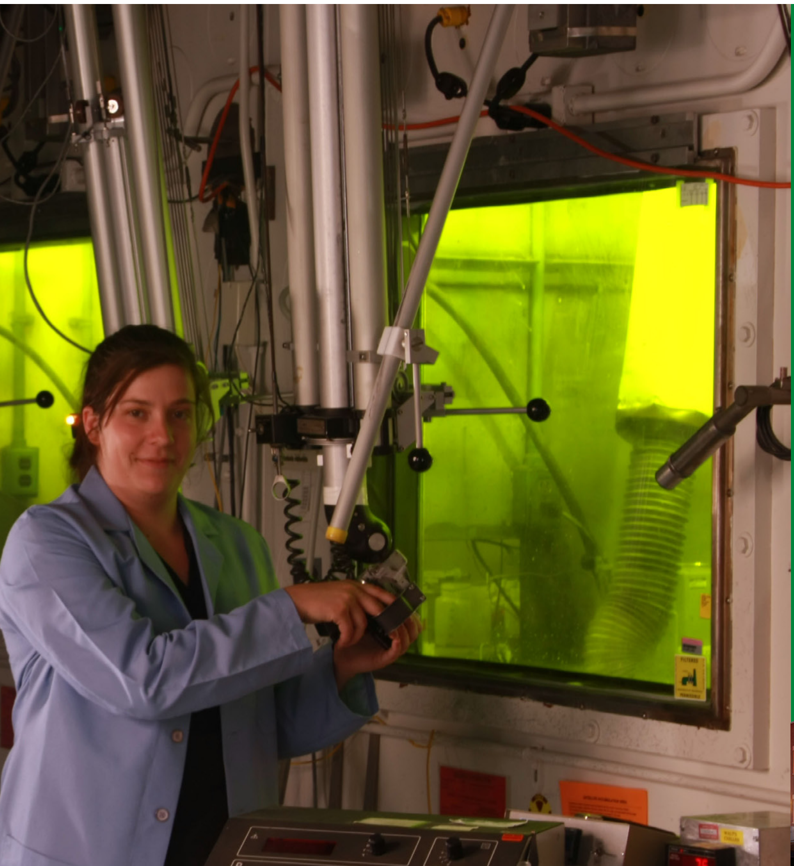
eparations Safeguards	Waste Forms
On-line real-time monitoring	Design, synthesis, and optimization
nometrics modeling	Waste process development
hanced reliability of safeguards	Testing/storage monitoring

widely known—and what PNNL scientists are beginning to better understand—is that there are slight microstructural changes that occur within and around a material long before a visible (or measurable) crack is formed. As PNNL gains new understanding of *material degradation precursors* within aging nuclear reactors, these indicating factors also become subject to the ACM method: advanced detection coupled with predictive modeling. By supplementing the work of visual inspections ACM would, in essence, offer something of a "crystal ball" capability to those who own, maintain, and regulate nuclear reactors. In addition, a deeper understanding of degradation precursors will offer insights into mitigating measures—actions that can be taken before the crack ever shows up. This sort of impact in the field is the goal of the ACM approach: getting better information sooner, and turning that information into action—this will yield important results in the safe extension of the existing reactor fleet, keeping clean energy on the grid.

While lending retroactive support for older reactors, ACM can also be proactively "built in" to new reactors. If sensors are deployed from the start in new generations of reactors, and in new reactor types such as small modular reactors, this will not only support a larger database of trends in material degradation precursors, but will enhance the licensing process by helping measure a new reactor's performance and durability. This becomes particularly important to build confidence that a new reactor will perform well even in its most vulnerable and high-stress regions, such as welds of dissimilar materials and the areas exposed to the most extreme radiation and environmental conditions.

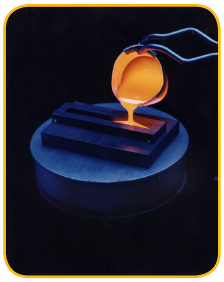
FUEL CYCLES AND SAFEGUARDS: MORE INFORMATION, MORE STREAMLINED

In any complex system, improvements are gained through direct observations not only of input and output, but of the intricate workings of each step along the way. For example, in another area of PNNL's energy leadership, scientists are making major efforts to collect data from sensory equipment currently being installed throughout the North American electric grid. These data



At the Pacific Northwest National Laboratory's **Radiochemical Processing Laboratory (RPL)**, researchers conduct analytical research on nuclear materials using hot cells that shield the researcher from the radiation. The RPL, with its state-of-the-art equipment and instrumentation, is a cornerstone of PNNL capabilities that facilitates cutting-edge science with nuclear materials.

The Environmental Molecular Sciences Laboratory (EMSL), a DOE national scientific user facility at PNNL, provides integrated experimental and computational resources for discovery and technological innovation in the environmental molecular sciences to support the needs of DOE and the nation.



unlock something very important: the ability to optimize the system by monitoring performance in real time, to predict and avoid problems. The same is true for the radiochemical processes that occur within the nuclear fuel cycle. After fuels are used, the task becomes processing these materials in a safe and sustainable manner. Today, performance is measured using traditional sampling and analysis techniques, which require solutions to be held for sampling in a considerable progression of tanks. ACM's vision is to provide real-time monitoring and chemometric models to predict performance directly in the process piping or unit operation, thereby improving the chemical processes themselves, bolstering the confidence of those who invest in and regulate them, and ultimately reducing the tankage and associated facility footprint required to safely process spent fuel.

Aside from cost, ACM also addresses the other major hurdle to closing the fuel cycle: ongoing weapons proliferation concerns that arise from the separation of nuclear materials. Increasing safeguards means increasing the precision of detection mechanisms, which ACM could enable. Separated materials that are more precisely measured, detected, and tracked, are less likely to slip through the cracks—or into the wrong hands.

WASTE FORMS: DISPOSAL WITH CONFIDENCE

Environmental and political concerns related to waste make up much of the hesitation regarding the expansion of nuclear power. The ultimate goal in the world of nuclear waste is to know with confidence that all non-recyclable fission products are prepared in waste forms that lead to safe, effective disposal in a permanent repository. Thus, knowing the short- and long-term performance of these waste forms is vital to moving forward. Once waste goes into a repository, it is both difficult and expensive to get it out, and new repository designs are far more costly if they include retrievability features.

ACM's integration of sensors and modeling will allow costs and risks to be lowered by measuring the real-time performance of a waste form and predicting its behavior—both within specific repository structures or in research environments that qualify it for disposal. By generating validated waste form performance models, ACM can enable improvements in design as well as confidence industry-wide, helping address certain risks and costs associated with disposing of nuclear waste.

Across the nuclear industry, there must be a paradigm shift—from reactivity (wait, observe, analyze, fix) to proactivity (understand, measure, model, predict). Through continued ACM development and deployment, PNNL will lead this shift, enabling new innovations within industry and regulation.

PREDICTIVE MODELING: CROSS-CUTTING ADVANCEMENTS

Each of ACM's various applications requires predictive modeling, a field in which PNNL envisions new breakthroughs to support nuclear energy. First, new semi-statistical (e.g., chemometric) and novel comprehensive (e.g., combined chemometric/computational) modeling techniques are being developed at PNNL to yield rapid data processing, prediction of material properties, and displays. This will lead to improved understanding and new designs of nuclear energy systems, structures, and components. Second, the integration of models and data must also come with the development of an *uncertainty pipeline*. This novel uncertainty and sensitivity analysis pipeline will integrate inspection to show which areas most need to be monitored based on physical or statistical importance. Through these actions, PNNL is rethinking modeling techniques in order to tailor their use in the nuclear power industry.

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