Capabilities in Support of
ADVANCED REACTOR DESIGN AND SAFETY ANALYSIS

Pacific Northwest
NATIONAL LABORATORY

U.S. DEPARTMENT OF
ENERGY

At Pacific Northwest National Laboratory (PNNL), we advance the designs of next-generation nuclear power reactors, safely extend the lives of the existing fleet, and develop processes for recycling, safe storage, transportation, and disposal of spent nuclear fuel. Our fundamental mission is to provide this broad range of basic and applied research capabilities to the U.S. Department of Energy (DOE), the U.S. Nuclear Regulatory Commission (NRC), and the nuclear industry to help meet the nation's continuing need for energy that is reliable, safe, and secure.

PNNL has experience in the design and safety analysis of nuclear systems, much of it gained in the commercial nuclear industry. Recent advances in non-light water reactor (non-LWR) technologies will pose novel challenges in reactor safety reviews under DOE's "Documented Safety Analysis" process and NRC's NUREG-0800, *Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants*.

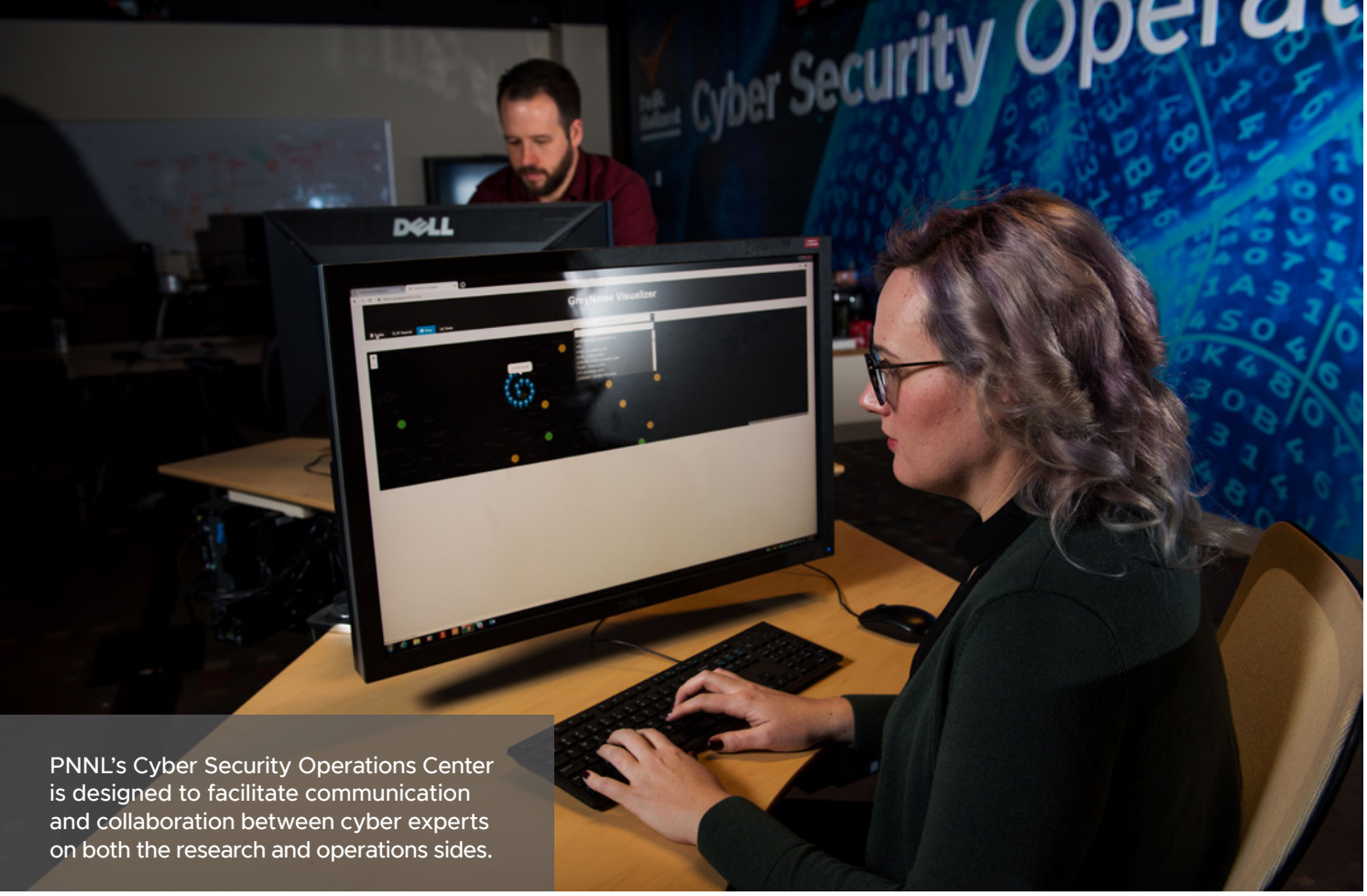
PNNL's experienced staff are uniquely qualified to understand these technical innovations and to apply our core nuclear capabilities in the following key technical disciplines.

Advanced Nuclear Fuels: We design and develop fabrication processes for new and innovative fuels and cladding materials. Our hot cells, mechanical test frames, and microscopy assets allow the testing of new fuels and clad, as well as nano-level evaluation of materials performance. PNNL is assisting the NRC in preparing for anticipated license applications and commercial use of accident tolerant fuel for light water reactors. We also develop advanced extrusion techniques for both uranium-molybdenum and uranium-zirconium alloys and perform both extrusion and pilgering process development for oxide dispersion cladding and other innovative cladding concepts.

Post irradiation examination of high burnup fuel rods is conducted in hot cells inside PNNL's Radiochemical Processing Laboratory, a Hazard Category II non-reactor nuclear research facility.

PNNL has multiple test systems dedicated to evaluating stress corrosion crack initiation of legacy and next generation materials that are exposed to light water reactor core cooling water. The ability to perform *in situ* detection of crack initiation provides the most accurate data on stress corrosion crack initiation behavior, enabling more informed regulatory actions and improved scientific modelling. These outcomes can allow the existing U.S. nuclear power reactor fleet to operate to extended lifetimes and help with the development of advanced light water reactors.

Component Integrity: Our materials scientists are improving our understanding of the mechanisms by which materials degrade, thereby helping ensure that the life of our existing fleet can be safely extended. This research also leads to advanced alloys and materials for use in the harsh environment of next generation of reactors. PNNL has expert staff familiar with the unique reactor coolant systems anticipated in non-LWR designs, including molten salt, high-temperature gas, and liquid metal. Our capabilities in these areas include evaluation and testing of reactor vessel materials and coolant system components, application of applicable ASME codes and standards, and evaluation of steam generator and other primary and secondary system components. We maintain expertise in the simulation of material interactions in extreme environments, from the density functional theory level to finite element methodology.



PNNL's Cyber Security Operations Center is designed to facilitate communication and collaboration between cyber experts on both the research and operations sides.

Cyber Security: We support DOE, the U.S. Department of Defense (DoD), and the NRC in developing risk-based cybersecurity programs to protect energy generating facilities (i.e., nuclear power plants, photovoltaic solar arrays, wind power, marine renewable energy, hydropower plants) from potential cyberattacks. Cybersecurity programs utilize industry developed risk management frameworks to identify security controls and protect digital assets, processes, and operators needed to maintain safe operation of facilities, to implement safe shutdown of nuclear reactors, and to support emergency response plans. Risk-based methods incorporate threat modeling, vulnerability assessments, and consequence analyses to determine appropriate security controls to protect assets from a cyberattack.

External Hazards: We steward extensive flood hazard assessment capabilities. These capabilities include the full range of hydrologic (local, watershed, and regional scale rainfall/snowmelt modeling and simulation), hydraulic (one, two, and three-dimensional modeling and simulation), and hydrodynamic (nearshore and oceanic modeling and simulation) assessments.

We are currently developing procedures for systematically conducting probabilistic flood hazard assessments for critical infrastructure from low-frequency, high-impact hydrometeorological events that can be used to assess risks, to both the infrastructure and to human health and safety.

We have key technical expertise in probabilistic and deterministic seismic hazard analysis helping to provide end-to-end evaluations. With more than 30 years of professional seismic expertise and 15 years of industry experience related to the evaluation of sites and structures, we are uniquely positioned to advance the state-of-the art and provide trusted solutions.

Our team of nuclear engineers and radiological specialists performs environmental surveys of buildings and surrounding areas in support of the deactivation and decommissioning of old facilities.

Human Factors Engineering: We support the NRC in addressing issues related to human performance, human safety, human reliability, learning, and training. Our researchers have developed methods to explore the effects of human factors on training and qualification on manual ultrasonic nondestructive examination in the nuclear industry, provided ongoing support in human reliability analysis to support safe and reliable nuclear operations, examined environmental factors' impact on operator action in emergency response at nuclear power plants, and leveraged the latest scientific discoveries in human health and performance to inform nuclear regulatory analysis. In addition, our growing capabilities in human factors enable more expansive technical support in human- machine teaming and cognitive systems engineering that could help modernize operations and decision making in the nuclear domain.

Instrumentation and Controls: We have been at the forefront of research, development, and deployment in the area of advanced sensors, instrumentation, and control for monitoring processes, systems, structures and components in light water reactors, small modular reactors, and advanced reactors. We support advanced instrumentations and controls development, including the functions necessary to operate the nuclear power plant safely under normal conditions and under accident conditions. We maintain expertise in reactor control and safe shutdown systems, information systems important to safety, and conformance with Institute of Electrical and Electronics Engineers standards.

PNNL partnered with the NRC and U.S. Army Corps of Engineers to complete—in record time—an environmental impact statement for the nation's first small modular nuclear reactor, to be sited at Clinch River, TN. The PNNL team gathered at Clinch River for the environmental impact statement audit.

Mechanical Engineering: Our familiarity with the design and engineering of structures, components, and equipment is directly applicable to non-LWR designs. These capabilities include application of ASME codes to non-LWR plant components, seismic qualification and wind loadings, design of containment structures and foundations, fracture mechanics, leak-before-break, fitness for service, seismic fragility analysis, and structural mechanics.

Quality Assurance: If required, our NQA-1-compliant Nuclear Quality Assurance Program ensures the work is performed by trained and qualified staff members and documentation is complete, correct, practical, satisfies the applicable requirements, and includes the appropriate quality control requirements.

Radiation Protection and Dose Assessment: Our staff are familiar with evaluating radiation sources in a nuclear power plant during both normal operations and accident conditions.

PNNL has developed and maintains several nationally and internationally known health physics codes used for radiological environmental monitoring and emergency response, including the RASCAL Emergency Response Code and the GENII Environmental Dosimetry System. We have decades of experience in the field of health physics and the use of health physic codes in the expert assessment of difficult radiological protection issues for the NRC, DOE, and other national and international agencies. We led the development of Chapter 12 of the *Design-Specific Review Standard for the mPower™ Design*.

Reactor Chemistry: We steward radiochemistry capabilities and facilities focused on designing materials, sensors, and systems that will perform in the extreme environments expected in the next generation of reactors. For example, we are developing approaches to controlling materials corrosion in molten salt reactors by

developing real-time spectroscopic sensing tools. Combining spectroscopic and electrochemical methods to probe speciation and redox states of uranium and fission products in a molten salt reactor will enable the monitoring and control of materials corrosion. This work is conducted in laboratories and test beds in our Radiochemical Processing Laboratory, a Hazard Category II non-reactor nuclear research facility housing hot cells and glove boxes to support bench- and pilot-scale testing of chemical systems.

Reactor Physics, Neutronics, and Nuclear Design: Our capabilities in the design of fuel assemblies, control systems, and advanced reactor cores include expertise in criticality safety, shielding, fuel system design, thermal hydraulics, and reactor internal and core support structural materials. We are proficient with a number of nuclear design codes, including the SCALE simulation suite, Monte Carlo tools, including MCNP, Serpent, and Keno, the fuel performance codes FRAPCON/FRAPTRAN and FAST, and Westinghouse and Studsvik core design software.

Safety Analysis: Extensive knowledge of NRC regulations and performing reviews—in accordance with NUREG-800—includes reviewing portions of construction permit or operating license applications under 10 CFR Part 50 and early site permit, design certification, combined license, standard design approval, or manufacturing license applications under 10 CFR Part 52. Additionally, PNNL has reviewed numerous Final Safety Analysis Report chapters and underlying methodology documentation for operating and design applications, including documentation associated with fuel and thermal-hydraulic design, neutronics design, and nuclear safety analysis.

A PNNL researcher works in a glove box to prepare a spectro-electrochemical experiment with a chloride-based eutectic containing plutonium. This experiment marked a significant accomplishment in demonstrating capabilities to characterize fundamental behavior of actinides in molten salts.

Site Characteristics and Site Parameters: Our meteorology, geology, and hydrology capabilities apply to the unique evaluations of site parameters required in a non-LWR design certification. We are the lead laboratory assisting NRC with the development of the Advanced Reactor Generic Environmental Impact Statement. We assisted NRC with the development of COL/ESP-ISG-027 "Specific Environmental Guidance for Light Water Small Modular Reactor Reviews." We led the development of Chapter 2 of the *Design-Specific Review Standard for the mPower™ and NuScale Small Modular Reactor Designs,* and our team recently led the "Environmental Impact Statement" for siting a small modular reactor at the Clinch River site in Tennessee.

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On the cover: PNNL materials scientist Ramprashad Prabhakaran evaluates the mechanical properties of nuclear materials using an Instron tensile tester with an atmosphere-controlled high-temperature Centorr furnace.

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