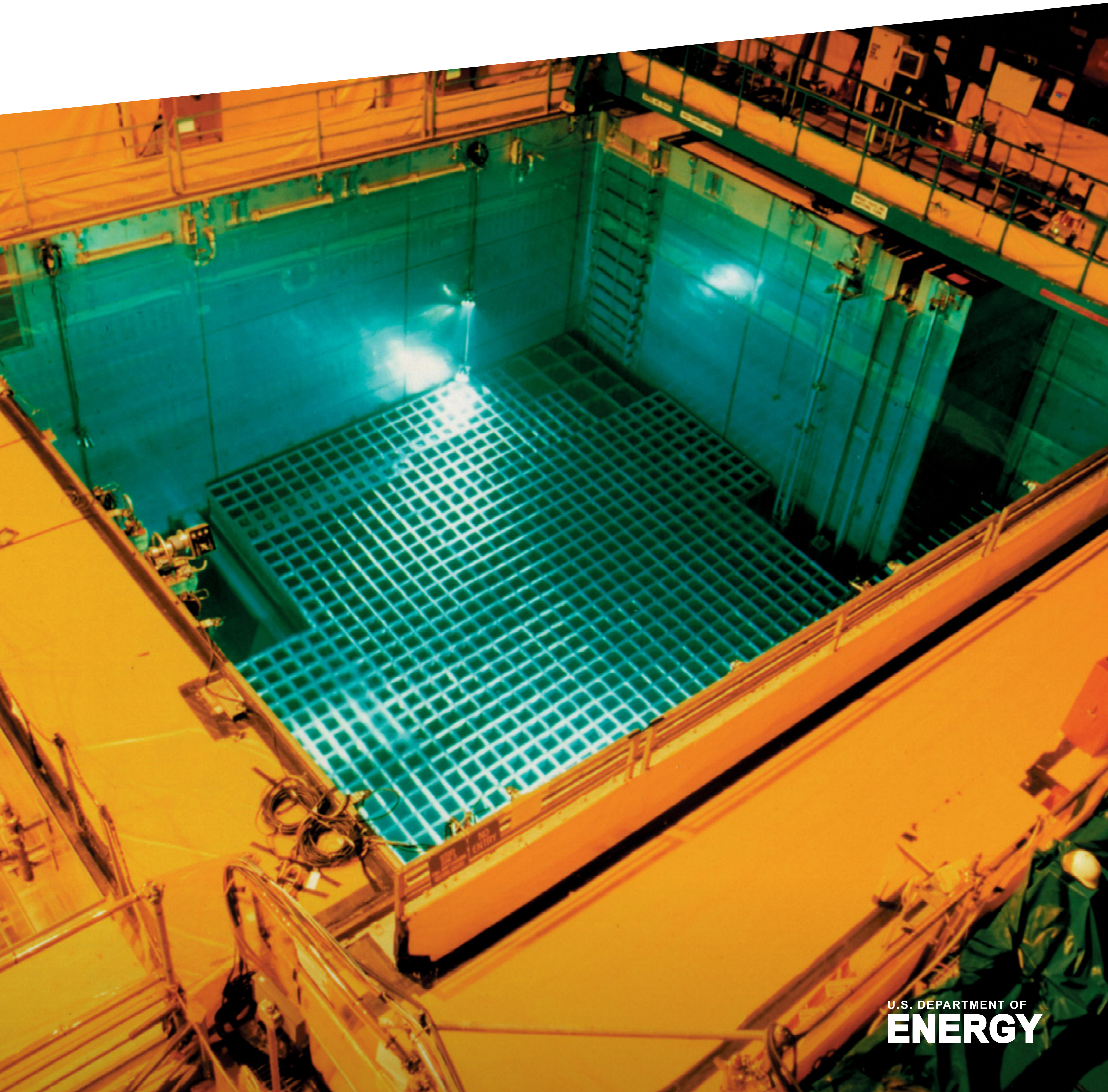
SPENT NUCLEAR FUEL AND HIGH-LEVEL RADIOACTIVE MATERIAL MANAGEMENT

Pacific Northwest NATIONAL LABORATORY

Recognized expertise in the science and technology of safe and secure management of spent nuclear fuel and high-level radioactive materials—from conditioning, to storage and transportation, to disposal.

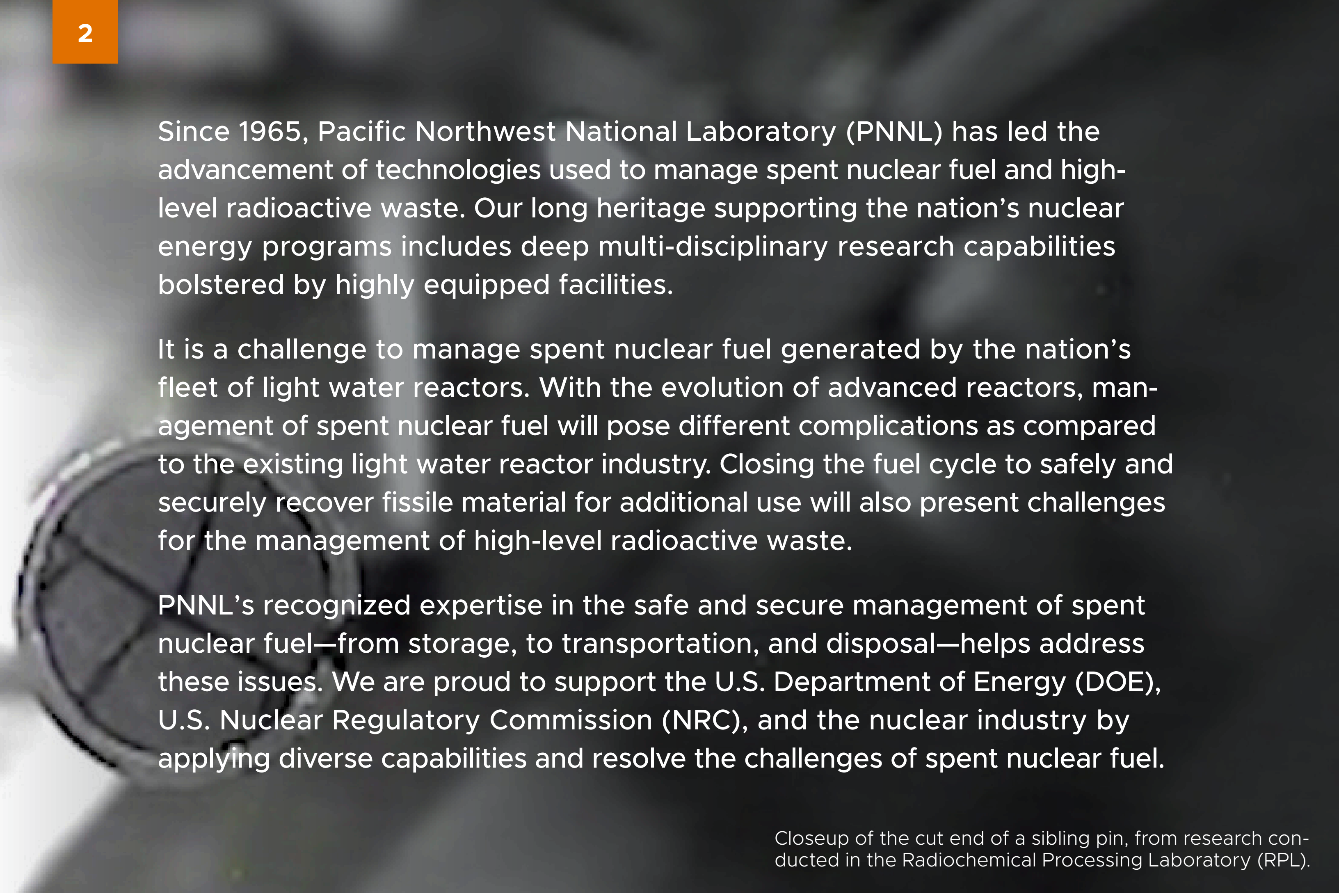


U.S. DEPARTMENT OF ENERGY

Since 1965, Pacific Northwest National Laboratory (PNNL) has led the advancement of technologies used to manage spent nuclear fuel and high-level radioactive waste. Our long heritage supporting the nation's nuclear energy programs includes deep multi-disciplinary research capabilities bolstered by highly equipped facilities.

It is a challenge to manage spent nuclear fuel generated by the nation's fleet of light water reactors. With the evolution of advanced reactors, management of spent nuclear fuel will pose different complications as compared to the existing light water reactor industry. Closing the fuel cycle to safely and securely recover fissile material for additional use will also present challenges for the management of high-level radioactive waste.

PNNL's recognized expertise in the safe and secure management of spent nuclear fuel—from storage, to transportation, and disposal—helps address these issues. We are proud to support the U.S. Department of Energy (DOE), U.S. Nuclear Regulatory Commission (NRC), and the nuclear industry by applying diverse capabilities and resolve the challenges of spent nuclear fuel.



Closeup of the cut end of a sibling pin, from research conducted in the Radiochemical Processing Laboratory (RPL).

CAPABILITIES

Storage and Transportation Packaging: PNNL is a recognized national leader in design, evaluation, development, and commissioning of packaging for nuclear material storage and transport. We evaluate and understand nuclear related systems and the handling of radioactive materials, including thermal, structural, material properties, and encompassing radioactive package performance. We perform independent technical reviews of safety basis documentation (i.e., safety analysis reports for packaging and transportation system risk assessments) for nearly all Type AF and Type B radioactive shipping packages used by the National Nuclear Security Administration (NNSA). We provide confirmatory evaluations and model development to NRC for extra-regulatory and generic safety issues related to spent nuclear fuel and radioactive material transportation and storage. PNNL is the Design Agency for NNSA Defense Programs Package 3 (DPP-3) responsible for design, development, testing, and certification of this Type B package.

Non-Destructive Evaluation: PNNL has developed and evaluated technology for a variety of industries, including conventional and advanced nuclear reactors, the petro-chemical industry, nuclear waste tanks, and national security. In particular, PNNL has served as the NRC's go-to organization in the development and evaluation of non-destructive evaluation techniques. Our capabilities help develop methods for the reliable detection of spent fuel storage canister degradation and flaws.

Thermal Analysis: PNNL utilizes its expertise in fluid dynamics and heat transfer to perform the thermal analysis of spent fuel storage and transportation casks. COBRA-SFS—developed and maintained by PNNL—is the internationally recognized, contemporary thermal analysis code for spent fuel assembly storage system thermal modeling. COBRA-SFS is used to model commercial spent fuel storage and transportation systems in support of both DOE and the NRC. COBRA-SFS incorporates forced and natural convection, as well as conductive and radiative heat transfer models, for thorough and accurate characterization of these complex thermal/fluid systems.

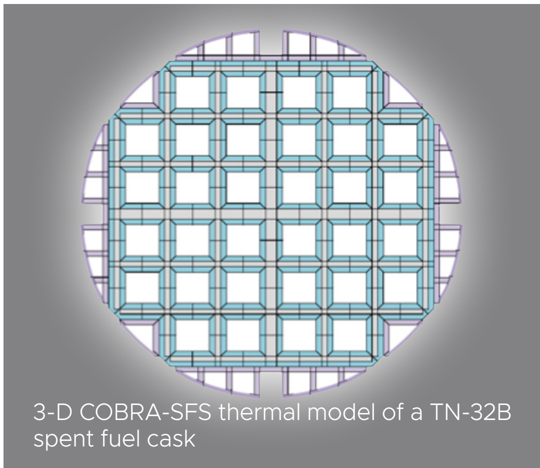
Structural Analysis: PNNL models the structural behavior and mechanical performance of radioactive material packaging under cumulative loading stemming from normal conditions of storage, transfer (from storage container to transport container if needed), and normal conditions of transport. Normal conditions of storage to normal conditions of transport understanding is necessary to establish the safety basis for both storage and transportation systems via maintaining the radioactive material containment boundary definition, maintaining criticality safety, and is one of the critical components to the preservation of aspects, such as spent fuel retrievability. We utilize a variety of tools, including the ANSYS®/LS-DYNA® finite element analysis code.

Post-Irradiation Examination: Our Hazard Category II Non-Reactor Nuclear Research Facility, the Radiochemical Processing Laboratory, supports a wide range of radiological work, including post-irradiation examination of nuclear fuel and mechanical testing of irradiated alloys. Our researchers host a wide range of capabilities and experience for post-irradiation examination of nuclear fuels and activated materials, including the examining the robustness of high burnup spent nuclear fuel. Work is done in a variety of environments, including hot cells, gloveboxes, fume hoods, and bench top settings. We have the capability to receive materials in shipping containers as large as spent fuel transportation casks.

Material Properties and Degradation: PNNL materials scientists are improving our understanding of the mechanisms by which materials degrade and our research also leads to advanced alloys and materials for use in nuclear environments. For example, we have the world's leading researchers in the science of stress corrosion crack (SCC) and chloride-induced SCC initiation and growth. Ongoing research at PNNL uses PNNL-designed and built equipment to study SCC initiation times and crack growth rates for relevant alloys, and also performs microscopic studies to characterize and understand what leads up to crack initiation. PNNL has also utilized its vast analysis repertoire to investigate the durability, aging, and degradation of cement-based systems related to a range of fields (nuclear facilities, subsurface applications, and nuclear waste forms). This repertoire can combine a range of microscopic, spectroscopic, physical, irradiated, and environmental exposure testing to assess mechanisms and projections of cement-based materials aging. We also developed a radiolysis model to predict the radiolytically induced generation of hydrogen and corrosive products, such as H_2O_2, O_2, NO_2, NO, and HNO_3 within and around a spent nuclear fuel storage canister.

Instrumented spent nuclear fuel transportation cask


Examination of reactor piping in the Advanced Ultrasonics Laboratory


3-D COBRA-SFS thermal model of a TN-32B spent fuel cask

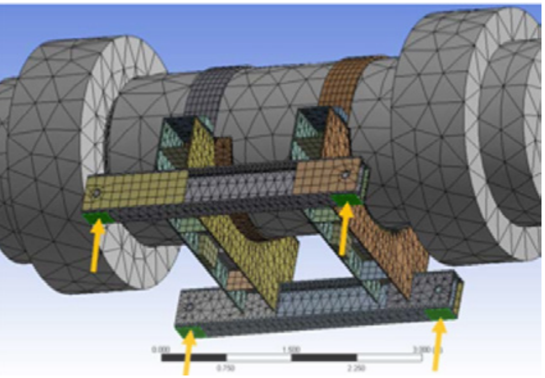
Radioactive Material Conditioning and Waste Form Development: PNNL helped pioneer nuclear waste vitrification efforts in the 1960s by developing the ceramic joule-heated, slurry-fed melting technology used at the West Valley and Savannah River sites. We have since expanded our research capabilities to include glass, glass-ceramic, grout, metal, and metal-ceramic waste forms to withstand corrosion over geologic time. We also are working to increase the throughput capability of the waste treatment plants. For example, researchers are expanding our understanding of how waste—which is dissolved in the glass—transitions through the glass feed to the final pour. Researchers in our Wasteform Development Laboratory isolate actinides and radionuclides generated during energy production (including past plutonium production at the nearby Hanford site), used nuclear fuel recycling, and legacy waste from other remediation sites.

Packaging and Transportation Related Standards Development: PNNL participates in and provides leadership to the development of national and international standards related to packaging and transportation of radioactive materials. The American National Standards Institute's N14 Accredited Standards Committee on Packaging and Transportation of Radioactive Materials provides key standards, including N14.5 Leakage Tests on Packages for Shipment, N14.1 Uranium Hexaflouride-Packaging for Transport, N14.7 Guidance for Packaging Type A Quantities of Radioactive Materials, N14.36 Measurement of Radiation Level and Surface Contamination for Packages and Conveyances, and N14.33 Characterizing Damaged Spent Nuclear Fuel for the Purpose of Storage and Transport. PNNL leadership positions include the N14 Chair and N14.33 Writing Committee Chair. PNNL also participates in and is co-convener of the International Organization for Standardization committee on transportation of radioactive materials (ISO/TC85/SC5/WG4).

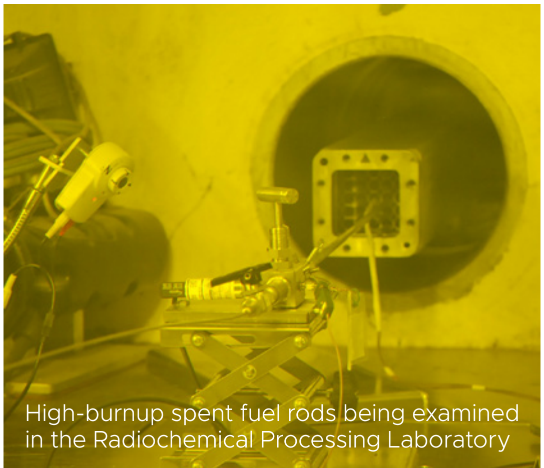
Health Physics Simulation and Analysis: PNNL conducts state-of-the-art health physics analyses and simulations using a variety of computational tools. We have the capability to perform a wide range of analyses from dose reconstruction, to detector simulation, to transport modeling using the gamut of health physics computational tools. These include radiation hazard, exposure, and dose assessments; radiation transport and shielding analysis, fate and transport modeling, and human health consequence assessment.

Integrated System Analysis, Transportation Logistics, and Transportation Infrastructure Evaluation: PNNL understands the complexities associated with transporting spent nuclear fuel from reactor sites to ultimate destinations. In support of DOE's Office of Nuclear Energy, PNNL has:

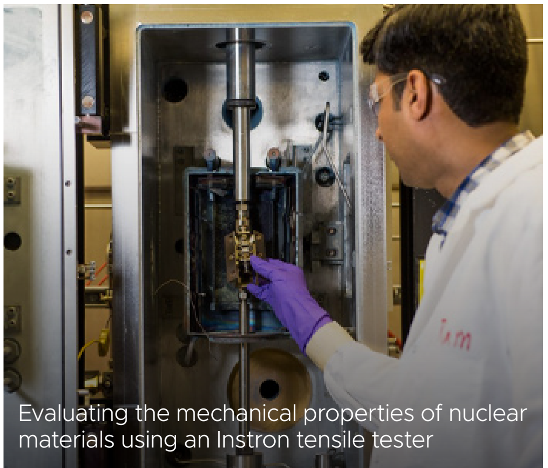
- Played a significant role in the development of the Next Generation System Analysis Model, a tool that provides a capability to model and analyze various waste management system architectures with a focus on U.S. commercial spent nuclear fuel, and in the performance of integrated waste management system analyses.



Finite element model of a spent fuel transportation cask



High-burnup spent fuel rods being examined in the Radiochemical Processing Laboratory



Evaluating the mechanical properties of nuclear materials using an Instron tensile tester

- Identified and evaluated options for establishing a large-scale national spent fuel transportation system in the U.S.
- Led evaluations of removing spent nuclear fuel from nuclear power plant sites, including characterization of the spent fuel inventory, evaluation of the on- and near-site transportation infrastructure, and assessment of site-specific transportation experience resulting in a comprehensive understanding of the actions necessary to prepare for and remove spent nuclear fuel.
- Supported DOE's engagement with states, regional groups, and Native American tribes regarding spent nuclear fuel transportation.
- Supported the DOE development, fabrication, and testing of rail assets for the transportation of spent nuclear fuel in accordance with the Association of American Railroads standard S-2043.

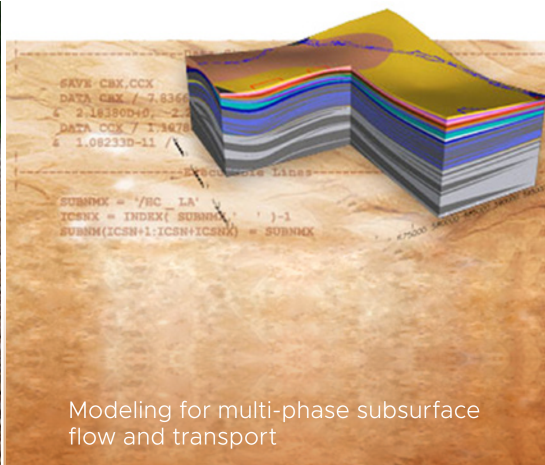
Groundwater and Vadose Zone Hydrogeology: PNNL has been developing and applying predictive models for groundwater flow and contaminant transport in hydrologic systems since the 1960s. Developments include analytic models, standard finite difference and finite element codes for fluid flow and solute transport, particle transport codes, and high-performance flow and reactive transport codes designed to run on parallelized machines. Our tools are used to optimize groundwater characterization activities; predict groundwater flow velocity and direction; predict groundwater contaminant concentrations and transport rates; and predict the long-term impacts and estimate risk to the public.

Multi-Phase Flow and Transport: PNNL develops and manages Subsurface Transport Over Multiple Phases (STOMP), a sequential numerical simulator for modeling multifluid flow and transport through geologic media. eSTOMP (exascale Subsurface Transport Over Multiple Phases) is the highly scalable (parallel) version of STOMP developed using a component-based approach. STOMP and (e)STOMP are analytical tools for investigating coupled processes involving multifluid flow, heat transport, and geochemistry in the subsurface. The simulators can be applied to geologic nuclear waste repositories; radionuclide transport; unsaturated zone hydrology; reactive barriers; nuclear waste tank thermal histories; surface barriers; soil desiccation; geologic sequestration of greenhouse gases; and coupled reactive transport. STOMP/eSTOMP have been executed on a variety of platforms at national laboratories, government agencies, private companies, and universities. PNNL staff are also part of the PFLOTRAN (petascale reactive multiphase flow and multicomponent transport) code development team and are strengthening scientists' ability to more accurately predict groundwater contaminant movement and conduct disposal facility performance assessments.

Subsurface Flow and Transport: PNNL operates 10 fully equipped, radiologically controlled wet chemistry and analytical facilities and field test sites. These facilities house advanced equipment


Molten glass pour for testing at the Wasteform Development Laboratory


Examining the railway near a nuclear power plant


Modeling for multi-phase subsurface flow and transport

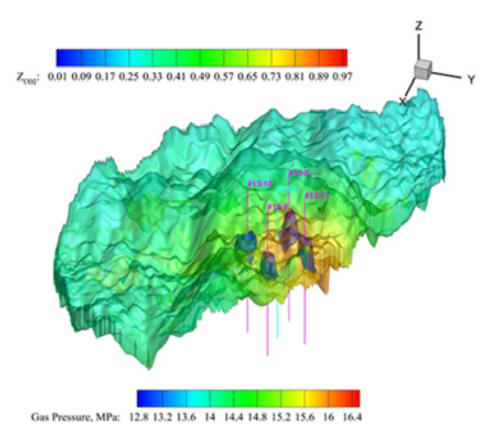
to perform flow-through column experiments under saturated or unsaturated moisture conditions, including the pressurized unsaturated flow apparatus, and from bench- through pilot- through field-scale. Our capabilities include 1D to meter-scale 3D flow cells and columns; state-of-the-art dual-energy gamma radiation system for measuring density, water, air, two immiscible non-aqueous phase liquids, and salt; integrated hydraulic apparatus; relative permeability apparatus; micromodel fabrication to specification within clean room; plus high pressure and temperature micromodels.

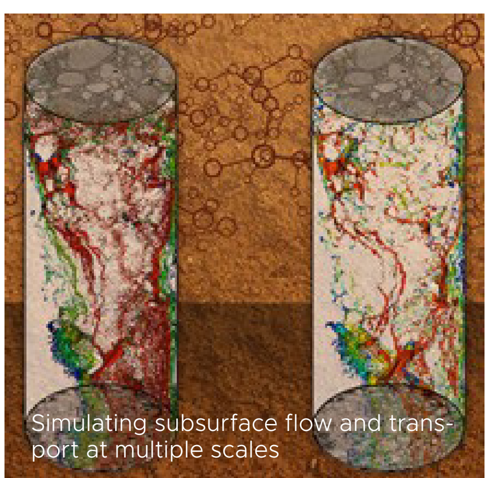
Post-Repository Closure Engineered Barrier, Spent Fuel, and Waste Form Degradation: PNNL is using modern techniques to better understand how waste forms and spent fuel degrade under long-term geologic disposal environments. We use advanced scanning electron microscopy to directly image the structure and chemical environment of irradiated uranium dioxide fuel surfaces with unprecedented spatial resolution, providing improved details for our modeling. Our findings illustrate how the complex energy landscape of materials can give rise to unexpected behavior with implications for long-term performance. We also developed the System for Analysis at the Liquid Vacuum Interface, or SALVI, that allows microscopy instruments to image liquid samples in real-time and space, providing. precise knowledge of how solids, like UO_2, and liquids, such as water, interact on a molecular level.

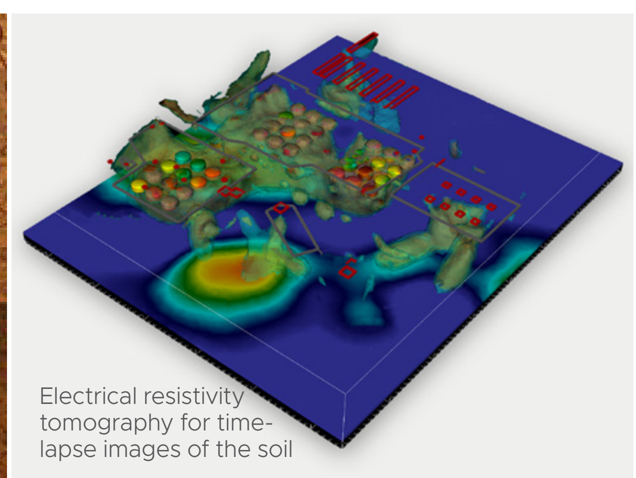
Performance and Risk Assessment: With over 50 years of experience in risk analysis and performance assessments, we are leaders in evaluating and mitigating potential nuclear safety issues. Understanding the proposed actions and options in the context of the physical, hydrologic, and biological framework of the impacted environment is key to evaluating the long-term risks of spent fuel management alternatives.

- PNNL has considerable experience and expertise integrating subsurface and surface water flow and transport predictive tools with analysis capabilities of other multi-disciplinary teams to assess local- and regional-scale water quality, human health, and ecosystem impacts.
- We have developed cost-effective and efficient technical approaches to evaluate impacts from individual facilities and to assess the cumulative and superposed impacts from multiple facilities.
- Our multi-disciplinary teams have conducted assessments over a wide range of environmental conditions and have analyzed a variety of radioactive and hazardous waste-disposal approaches and technologies.

Geophysics: World leaders in high-resolution, real-time computational and engineered geophysics, PNNL develops and implements state-of-the-art geophysical tools and methods to improve the characterization of subsurface properties and processes. Geophysical data can be collected from many different platforms (such as at the ground surface, between wellbores, and within wellbores) in order to interrogate subsurface variability over a variety of spatial scales and resolutions. The use of geophysical methods combined with conventional measurements provides spatially extensive information about the subsurface in a minimally invasive manner at a comparatively high resolution.


Subsurface analytical tools


Simulating subsurface flow and transport at multiple scales


Electrical resistivity tomography for time-lapse images of the soil

Microscopy: Institutionally, PNNL has invested over $50 million in microscopy instruments with high-resolution imaging capabilities, including complementary chemical, structural, and phase information, *in-situ* imaging in native environments, and imaging of dynamic processes with high temporal-resolution. These instruments are available in several PNNL facilities, including the Applied Process Engineering Laboratory, Radiochemical Processing Laboratory, and Environmental Molecular Sciences Laboratory (a DOE user facility based at PNNL-Richland). Capabilities include scanning electron, scanning/transmission electron, atomic force, and optical microscopes.

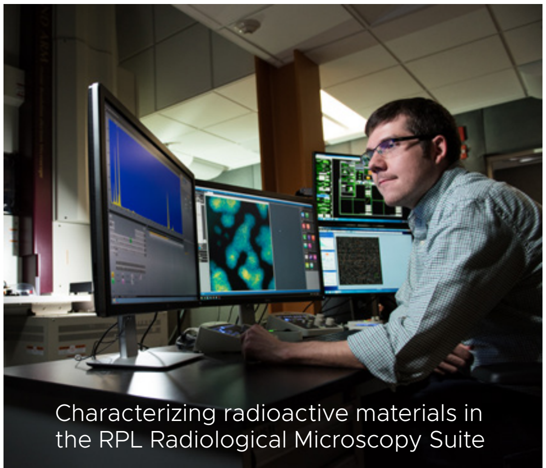
Radiochemical Analytical Capabilities: Several technical groups within PNNL provide expertise in radiochemical analysis, supporting multiple areas and sponsors. Our capabilities include analytical support operations, radiochemical process engineering, radiochemical separation, radiological dispersion and interfacial chemistry, radiological nuclear magnetic resonance laboratory, radiological surface science laboratory, reactor dosimetry, shielded facilities operations, and thermoanalytics.

Radiation Protection: We support the NRC's Radiation Protection Computer Code Analysis and Maintenance Program (RAMP).

- RAMP is comprised of a suite of NRC-sponsored radiation protection and dose assessment codes, such as GENII, that can address source term, surface water and atmospheric transport, exposure pathways, receptors, and dose/consequence assessments.
- The GENII Version 2.10 Environmental Dosimetry System, developed at PNNL, provides regulators and industry with a tool for ensuring compliance with environmental regulations. GENII Version 2.10 is a set of computer programs that can be used to estimate radionuclide concentrations in the environment and dose/risk to humans and biota from acute or chronic exposures, releases to surface water or atmosphere, and initial contamination conditions.

National Environmental Policy Act Environmental Impact Statements and Environmental Assessments: For more than 50 years, PNNL has worked with federal agencies to conduct environmental reviews and produce scientifically credible, legally defensible, and consistently useful National Environmental Policy Act (NEPA) documents for the public and government decision makers. Years of working with the DOE, NRC, Department of Defense, and other agencies has provided PNNL with a unique perspective on the needs of federal clients. This includes a familiarity with the structure of government procurements and contractual systems and knowledge of the high level of quality and accountability required by these clients.

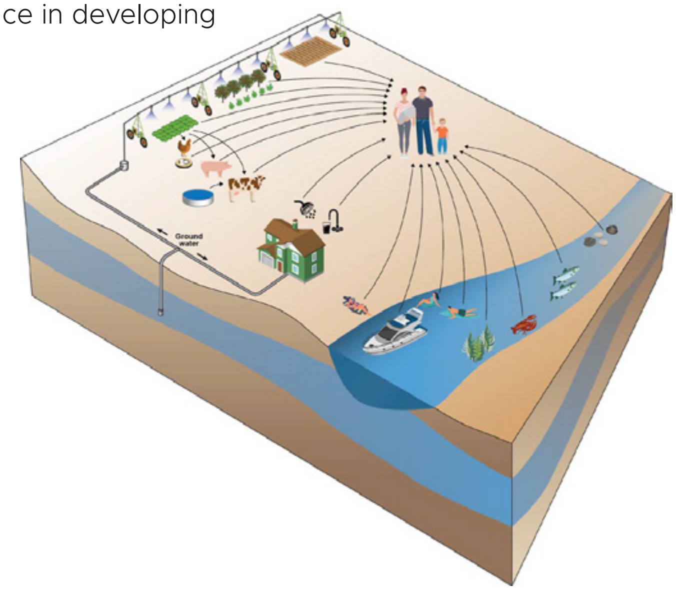
Stakeholder Engagement: PNNL staff have over 50 years of experience delivering effective public involvement and outreach. Our multi-talented professionals develop programs, techniques, and processes, refine them to the moment and the audience, and perfect their delivery. Successful stakeholder campaigns and a lineup of repeat customers serve as the greatest endorsement.



Characterizing radioactive materials in the RPL Radiological Microscopy Suite

Researchers use glove boxes, hot cells, radiological fume hoods, and specialized equipment in RPL to the team's qualifications. Public agencies trust PNNL's outreach experience for issues including waste management, energy facility siting and operations, environmental remediation, competing demands for water resources, and geological and terrestrial sequestration of carbon dioxide.

Siting: PNNL utilizes a diversified team with environmental, geotechnical, engineering, and public relations experience in developing siting methodologies and involving stakeholders. Criteria are established to identify and avoid potential technical, engineering, and environmental challenges that could adversely affect project success or schedule. PNNL understands the importance of transparency, flexibility, and responsiveness, and retains a strong focus on cooperation and consultation, ensuring the success of a consent-based siting program.



ABOUT PNNL

Pacific Northwest National Laboratory draws on signature capabilities in chemistry, Earth sciences, and data analytics to advance scientific discovery and create solutions to the nation's toughest challenges in energy resiliency and national security. Founded in 1965, PNNL is operated by Battelle for the U.S. Department of Energy's Office of Science. DOE's Office of Science is the single largest supporter of basic research in the physical sciences in the United States and is working to address some of the most pressing challenges of our time.

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On the cover: A spent fuel pool at the San Onofre Nuclear Generating Station near San Clemente, Calif. (Photo courtesy of the U.S. Nuclear Regulatory Commission.)