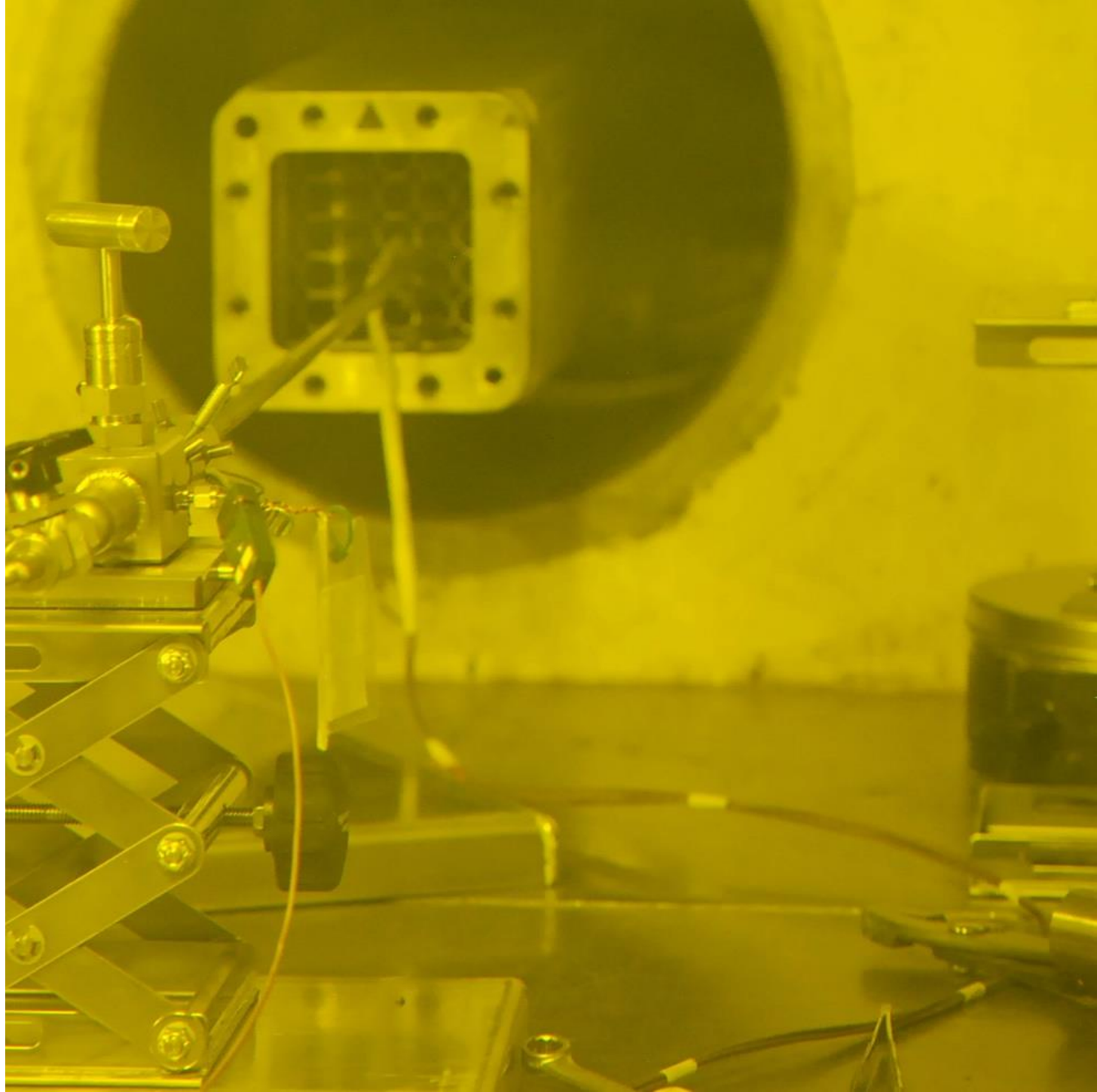
Pacific Northwest
NATIONAL LABORATORY

Nuclear Energy Research at the Pacific Northwest National Laboratory

Presented to
Embedded Sensors for Advanced
Reactor Systems Workshop
August 27, 2024

Mark Nutt
Nuclear Energy Program Development Manager



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PNNL-SA-197763

Pacific Northwest NATIONAL LABORATORY

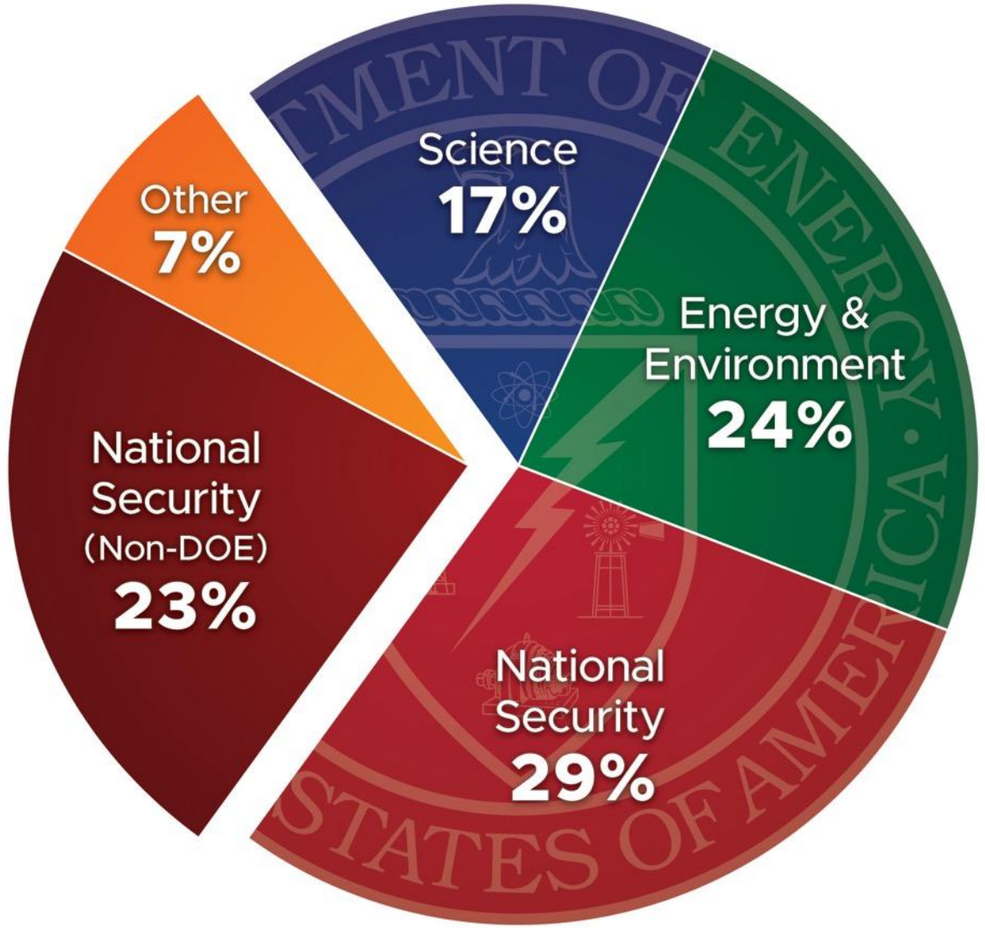
PNNL is **one of DOE's most diversified** national laboratories

$1.5B Spending

6,088 Staff

1,980 Peer-reviewed Publications

301 Invention Disclosures



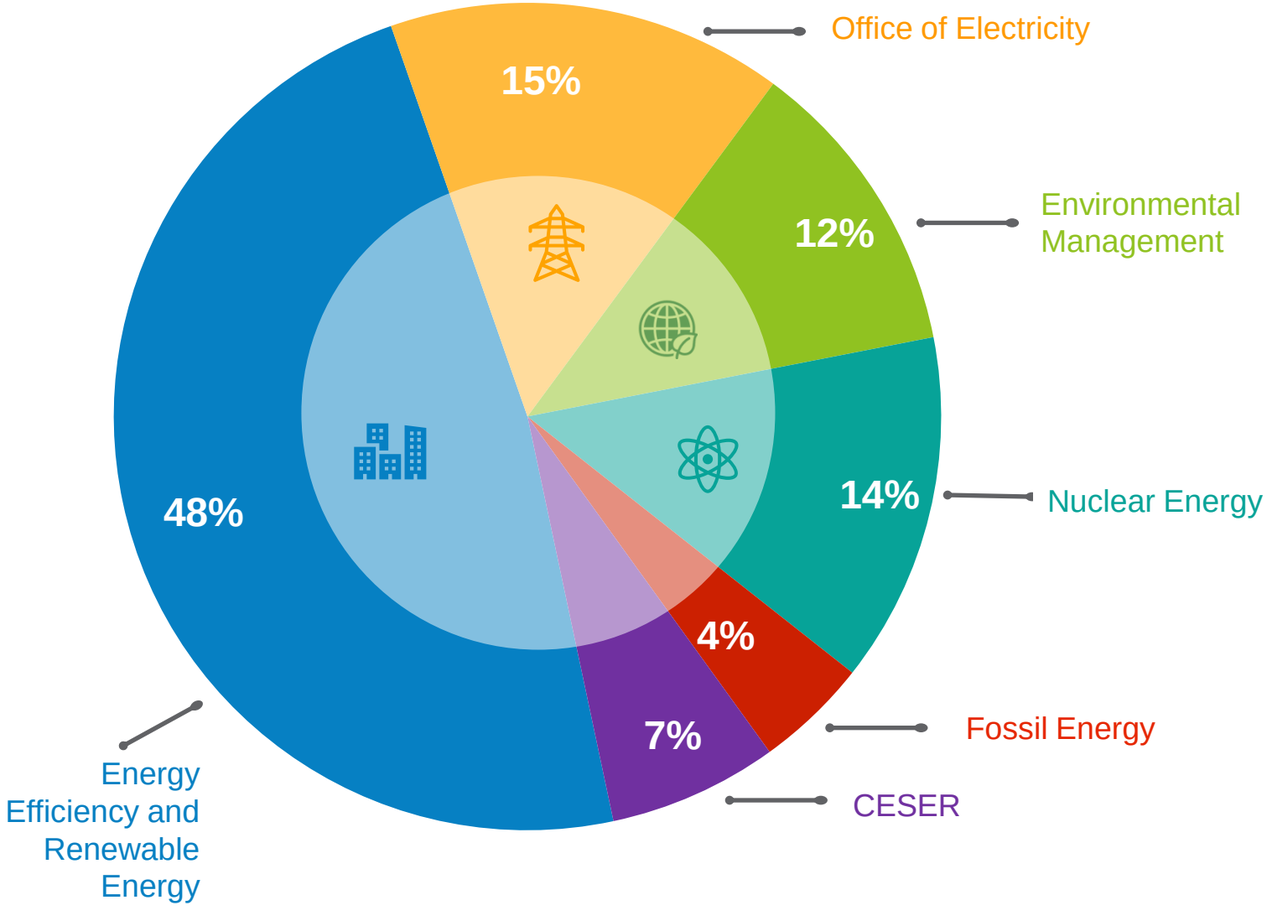
FY 2023 Spending

PNNL's diverse **Energy and Environment** portfolio

1,300 Staff

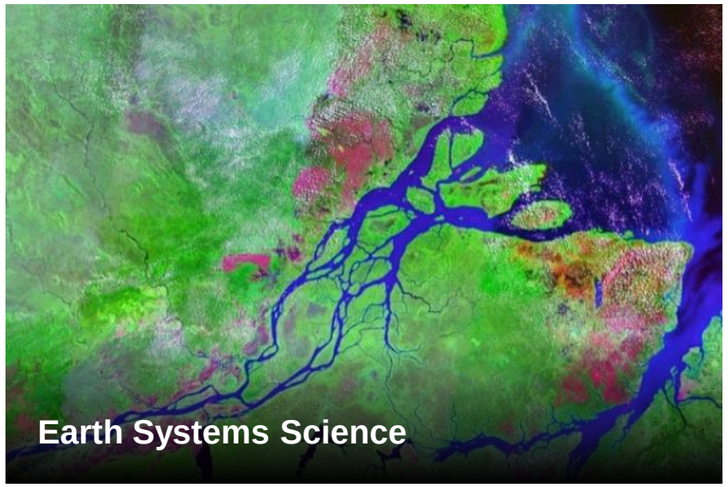
Mission Sponsors

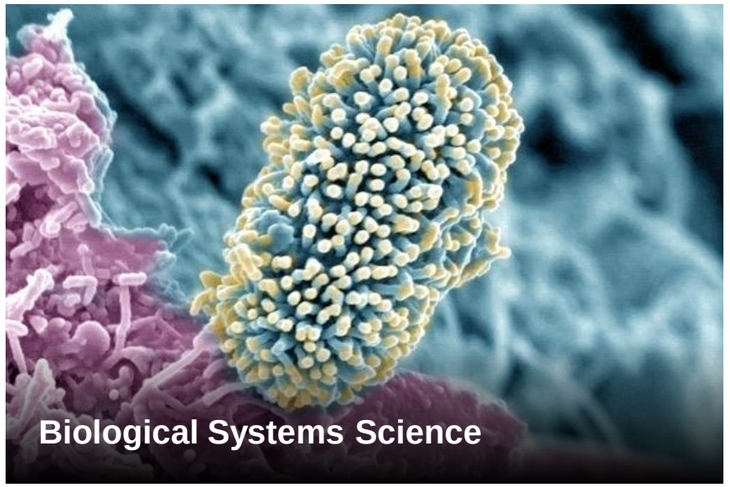
- Energy Efficiency & Renewable Energy (EERE)
- Office of Electricity (OE)
- Nuclear Energy (NE)
- Nuclear Regulatory Commission (NRC)
- Environmental Management (EM)
- Fossil Energy & Carbon Management (FECM)
- ARPA-E
- Cybersecurity, Energy Security, and Emergency Response (CESER)
- Grid Deployment Office (GDO)
- Office of Clean Energy Demonstrations (OCED)
- State & Community Energy Programs
- Manufacturing & Energy Supply Chains

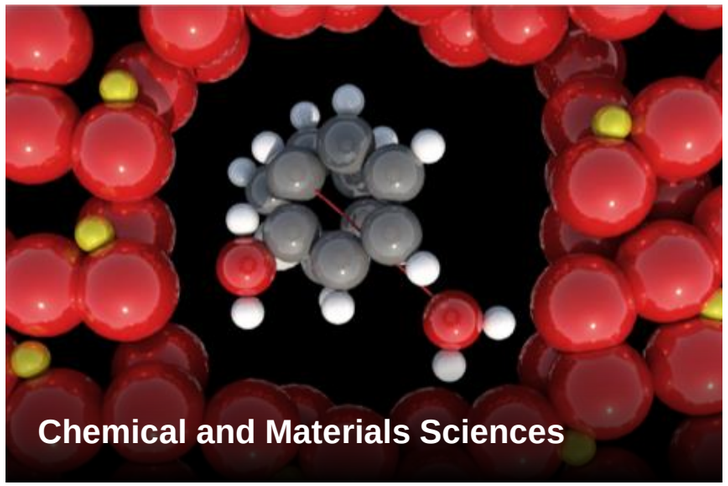


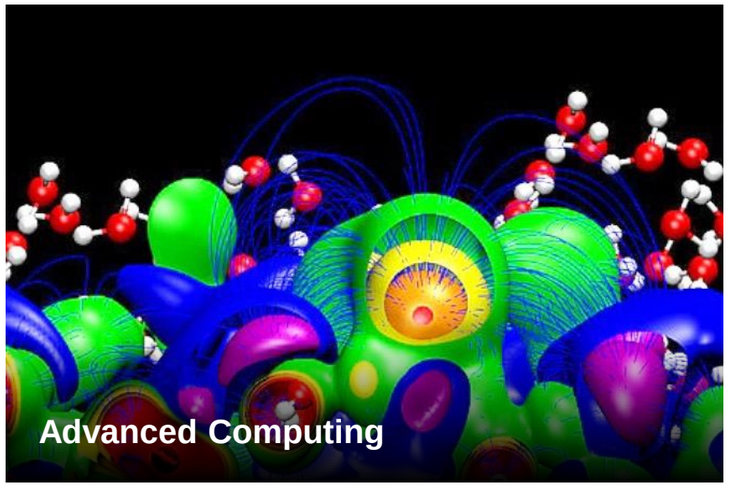
FY23 Funding

PNNL's **Science** mission advances understanding of the world around us

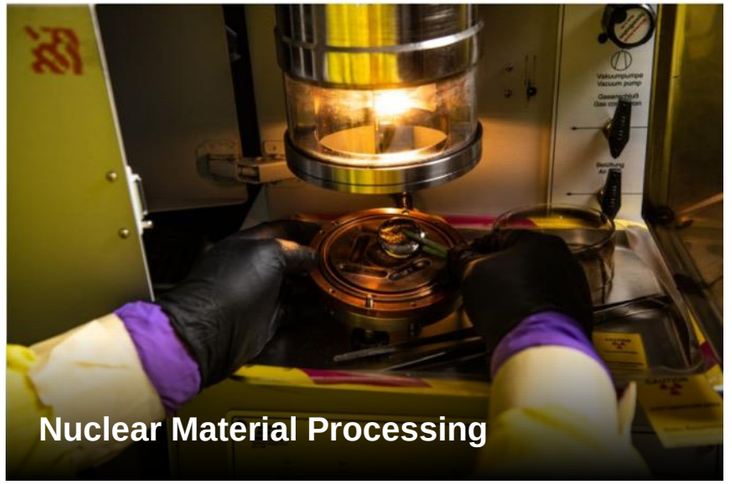


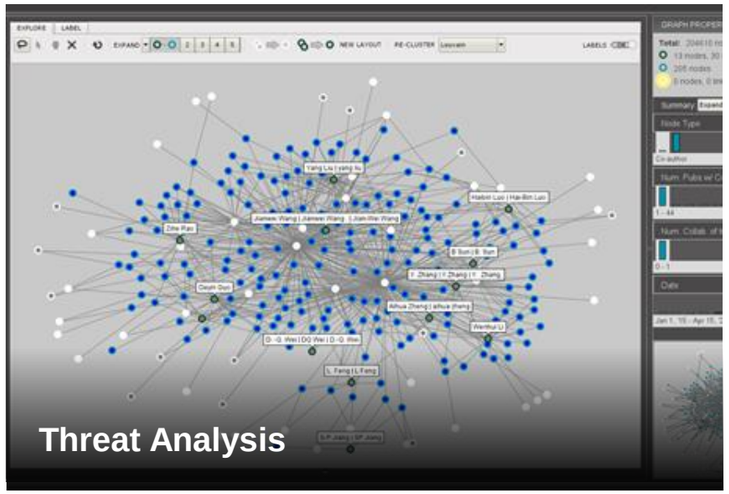




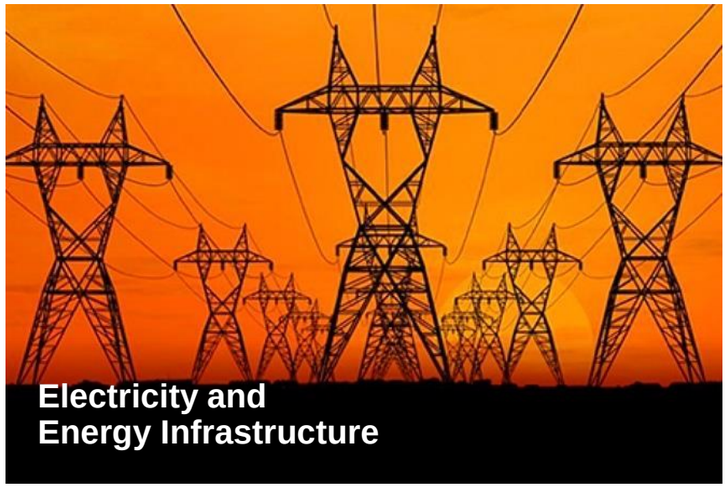


PNNL's **National Security** mission is reducing the threat from weapons of mass effect





PNNL's **Energy and Environment** mission delivers innovations for our energy future

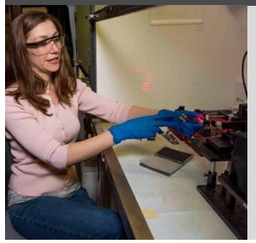


PNNL's nuclear energy expertise and capabilities are broad and diverse

Radiological Materials

- Wasteform Development
- Thermal Processing
- Process Engineering

Nuclear Chemistry & Engineering



- Separations
- Radiochemistry
- Irradiated Materials Char.
- Actinide Sciences

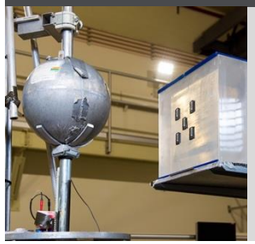
Experimental & Computational Engineering

- Multi-Phase Fluids
- Simulant Development
- Structural Analysis
- Safety Analysis

Reactor Materials & Mechanical Design

- Stress Corrosion Cracking
- Radiation Effects
- Materials Modeling
- Nano Materials Science

Irradiation Sciences



- Neutron Metrology
- Radiation Effects on Materials
- Radiation Dosimetry & Measurement

Environmental Assessment & Engineering

- NEPA Assessments
- Human & Ecological Health
- Field & Systems Engineering
- Microbiology

Risk & Decision Sciences

- Nuclear Safety & Engineering
- Risk Informed Decision Analysis
- Software Based Decision Support Tools

Subsurface Science & Technology

- Geochemical Assessment
- Remediation Science & Engineering
- Geophysics/ Geomechanics

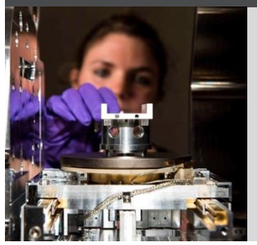
Applied Materials & Manufacturing

- Materials Development, Processing & Performance Testing
- Synthetic Chemistry
- Polymers

Non-Destructive Evaluation

- NRC Lead Organization for Development and Evaluation of Techniques
- Finite Element and Semi-Analytical Simulations
- Prognostics & Health Management

Nuclear Engineering & Analysis

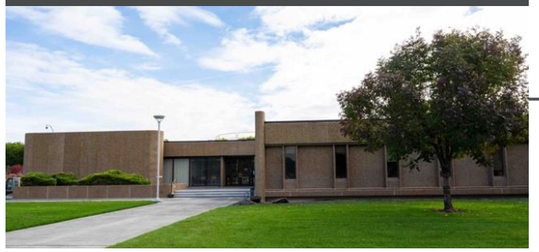


- Core Design
- Criticality Safety Assessment
- Radiation Shielding Analysis
- Fuels and Materials Performance Analysis

PNNL's Nuclear Research Corridor

Capabilities are *modern*, *comprehensive*, and *unique*

Life Sciences Laboratory 2
41,200 ft²



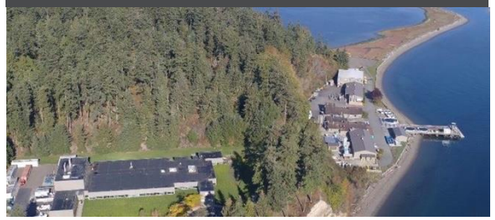
Nondestructive Evaluation Laboratory
4,500 ft²

Radiochemical Processing Laboratory 325
48,650 ft²

Advanced Engineering Laboratory
16,800 ft²

Process Development Laboratory W
5,200 ft²

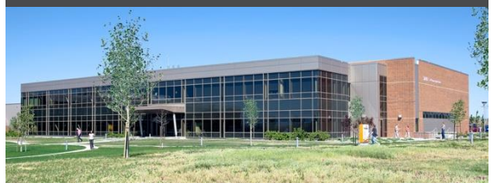
PNNL-Sequim (marine research)
17,300 ft²



Material Sciences Laboratory 3410
16,150 ft²

Radiological Exposures and Metrology Laboratory 318
13,250 ft²

Ultra-Low Background & Radiation Detection Laboratory 3420
20,500 ft²



PNNL's Nuclear Research Corridor

Capabilities are *modern*, *comprehensive*, and *unique*

Life Sciences Laboratory 2
41,200 ft^2

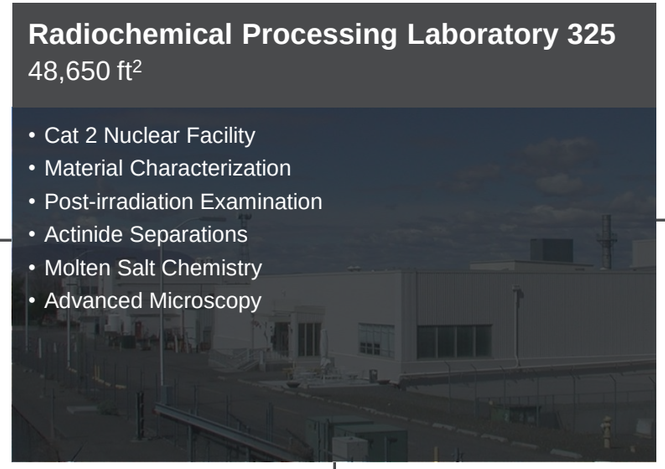
- Wasteform Development Laboratory
  - Glass
  - Grout
  - Cermet

Nondestructive Evaluation Laboratory
4,500 ft^2

- Non-linear, Phased Array, Guided Wave Ultrasound
- Eddy Current
- Online Condition Monitoring
- Simulation
- Radiographic Testing and X-ray Imaging

Radiochemical Processing Laboratory 325
48,650 ft^2

- Cat 2 Nuclear Facility
- Material Characterization
- Post-irradiation Examination
- Actinide Separations
- Molten Salt Chemistry
- Advanced Microscopy

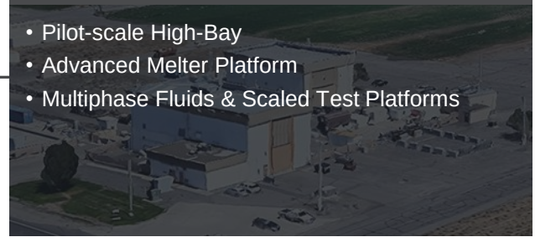


Advanced Engineering Laboratory
16,800 ft^2

- Solid Phase Processing: ShAPE, Friction Stir Welding, Cold Spray
- Nondestructive examination of Hanford Site tank bottoms and sidewalls

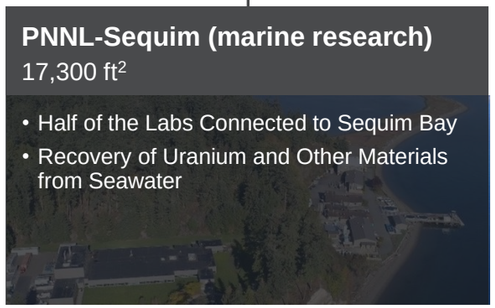
Process Development Laboratory W
5,200 ft^2

- Pilot-scale High-Bay
- Advanced Melter Platform
- Multiphase Fluids & Scaled Test Platforms



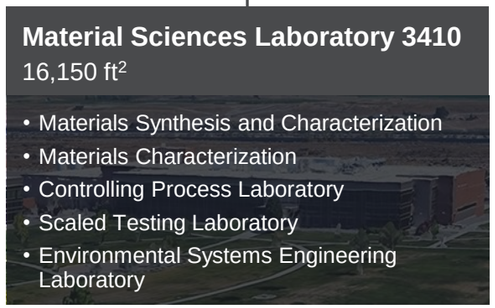
PNNL-Sequim (marine research)
17,300 ft^2

- Half of the Labs Connected to Sequim Bay
- Recovery of Uranium and Other Materials from Seawater



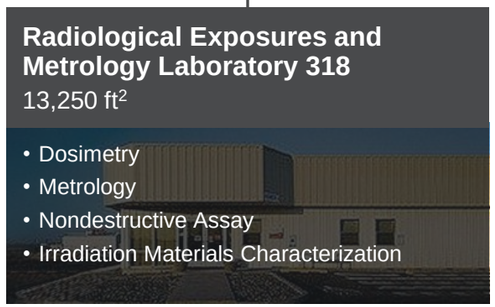
Material Sciences Laboratory 3410
16,150 ft^2

- Materials Synthesis and Characterization
- Materials Characterization
- Controlling Process Laboratory
- Scaled Testing Laboratory
- Environmental Systems Engineering Laboratory



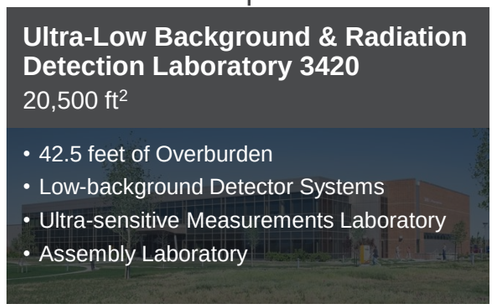
Radiological Exposures and Metrology Laboratory 318
13,250 ft^2

- Dosimetry
- Metrology
- Nondestructive Assay
- Irradiation Materials Characterization



Ultra-Low Background & Radiation Detection Laboratory 3420
20,500 ft^2

- 42.5 feet of Overburden
- Low-background Detector Systems
- Ultra-sensitive Measurements Laboratory
- Assembly Laboratory



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Our Sponsors

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UNITED STATES NUCLEAR REGULATORY COMMISSION

DEPARTMENT OF DEFENSE · UNITED STATES OF AMERICA

Kairos Power

TerraPower
A Nuclear Innovation Company

THORCON
POWERING UP OUR WORLD

CURIO

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Power for all humankind

Flibe ENERGY

orano

energy

Lightbridge

KINECTRICS

Commonwealth Fusion Systems

NVE NUVISION Engineering

University Partners for Early-Stage Applied R&D and Workforce Development

Through the DOE Nuclear Energy University Program (NEUP) and DOE Science Undergraduate Laboratory Internships (SULI)

The WSU-PNNL Nuclear Science and Technology Institute

University of Washington

Carnegie Mellon University

Clemson University

University of Alaska

FIU

University of Nevada, Reno
Inspiring Excellence Since 1874

University of Pittsburgh

The University of Oklahoma

Berkeley
University of California

University of Michigan

Oregon State University

USC University of Southern California

Colorado School of Mines
1874

UCLA

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Advancing sustainable clean nuclear energy

Irradiated Material Characterization

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

- **Our Work:** Post-irradiation examination on nuclear materials such as high-burnup fuel rods, test materials, and reactor components to quantify performance properties
- **Future Impact:** Establish the technical bases for the extended storage and subsequent transportation of high burnup spent nuclear fuel

Fuel Performance

Pressurized Water Reactor fuel assembly thimble plug

- **Our Work:** Developer of the Fuel Analysis under Steady-state and Transients (FAST), the NRC's computer code that is used to analyze nuclear fuel performance (including metallic and TRISO fuel)
- **Future Impact:** Modern code for analyzing reactor fuel performance during reactor operations and under dry storage conditions

Advanced Materials and Fuels

Advanced Tube Development Using ShAPE

- **Our Work:** Developing advanced nuclear materials and fuels for fission and fusion applications, their manufacturing processes, and components that safely operate long-term in extreme environments
- **Future Impact:** Establishing the foundation for industry implementation of high-performance materials and energy efficient/lower-cost manufacturing processes for production; developing durable, longer-life materials and more efficient repair processes

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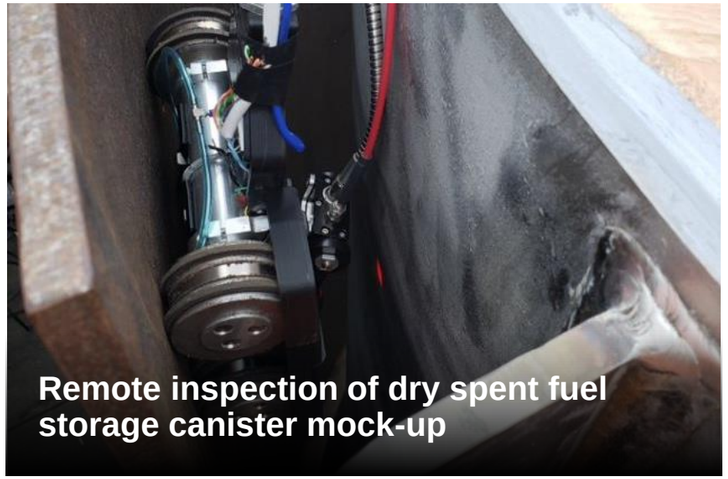
Non-Destructive Evaluation

Examination of reactor piping in the Advanced Ultrasonics Laboratory

- **Our Work:** 50+ years of advancing NDE techniques to detect flaws, cracks, or other defects
- **Future Impact:** Techniques and methods for the in-service inspection of reactor components

Remote Inspection



Remote inspection of dry spent fuel storage canister mock-up

- **Our Work:** Tools and techniques for the remote non-destructive evaluation of dry storage canisters
- **Future Impact:** In-situ inspection of independent spent fuel storage installations

Solid Phase Processing

Light water reactor component repaired by cold spray (collaboration with VRC Metal Systems and Exelon)

- **Our Work:** Developing tools and techniques – friction stir welding, cold spray, and Shear Assisted Processing & Extrusion (ShAPE)
- **Future Impact:** Improved materials and processing for improved performance in nuclear systems

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Stress Corrosion Cracking


Stress Corrosion Cracking Test Stands

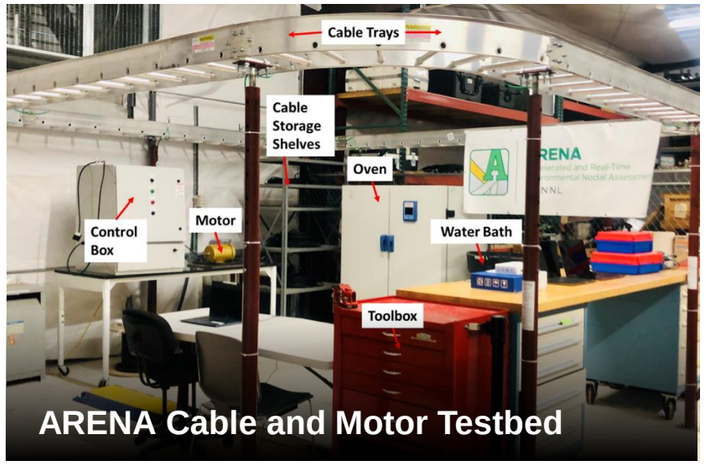
- **Our Work:** Understanding the conditions that initiate stress corrosion cracks, when cracks initiate, and how fast cracks grow in aqueous and atmospheric environments
- **Future Impact:** Experimental results and data support license renewals and aging management programs (reactors and spent fuel storage facilities)

On-Line Monitoring


Raman Spectroscopy System

- **Our Work:** Developing micro-fluidics, advanced sensors, Raman/UV-vis microscale monitoring, chemometric (AI/ML) modeling for on-line monitoring
- **Future Impact:** Real-time understanding of fluid and gas compositions for process control in advanced reactors and recycling facilities

Cable Aging and Degradation



ARENA Cable and Motor Testbed

- **Our Work:** Understanding the conditions that lead to degradation, failure modes, degradation rates, and in-service inspection techniques
- **Future Impact:** Results used for subsequent license renewals and establishing cable aging management programs for our existing fleet of reactors and for advanced reactors

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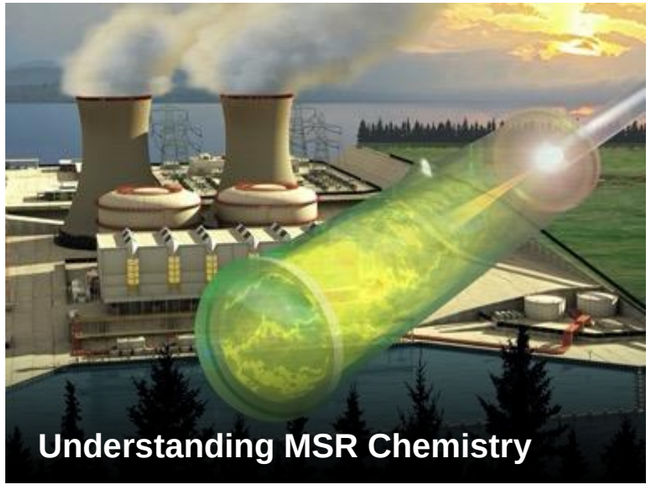
Radiation Protection

Codes in NRC's RAMP

- **Our Work:** Consolidating codes in the NRC's Radiation Protection Computer Code Analysis and Maintenance Program (RAMP); Updating RASCAL Emergency Response Tool; Updating the RADTRAN spent fuel transportation risk assessment code
- **Future Impact:** Modern codes to support new reactor deployments

Molten Salt Chemistry


Understanding MSR Chemistry

- **Our Work:** Establishing and utilizing capabilities to improve understanding of molten salt under reactor conditions, as well as actinides and radionuclides behavior
- **Future Impact:** Support the demonstration and deployment of molten salt reactors

Techno-Economic Assessment of New Reactor Deployment

Techno-Economic Assessment of Deploying LWR SMRs in Washington

- **Our Work:** Assessed how new small modular reactors (SMR) could satisfy the Pacific Northwest's dynamic electricity demand and explored the viability of deployment in Washington
- **Future Impact:** Demonstrate economic viability of nuclear energy on a regional scale

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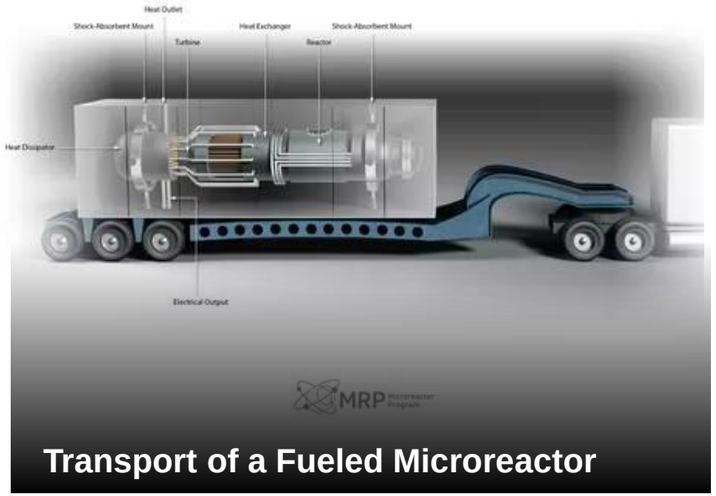
Micro-Reactor Transportation



Transport of a Fueled Microreactor

- **Accomplishment:** Framework for off-site transportation PRA; investigated the uncertainty associated with radionuclide releases for TRISO-fueled transportable microreactor transportation PRA
- **Future Impact:** Safe and secure transportation, management, and disposition of advanced microreactor technologies

Advanced Reactor Safeguards


IAEA, Vienna Austria

- **Accomplishment:** Investigated how experience gained from the IAEA safeguards domain could benefit U.S. domestic material control and accountability (MC&A) for advanced reactors
- **Future Impact:** Prepare U.S. vendors to compete internationally in markets where IAEA safeguards are required

Cyber Security


Cybersecurity – Critical for Protecting Nuclear Facilities

- **Accomplishment:** Understanding, evaluating, and developing trusted and resilient systems for critical infrastructure
- **Future Impact:** Address pressing cyber security challenges in cyber-physical systems, industrial control systems, and critical infrastructures within the energy generation sector

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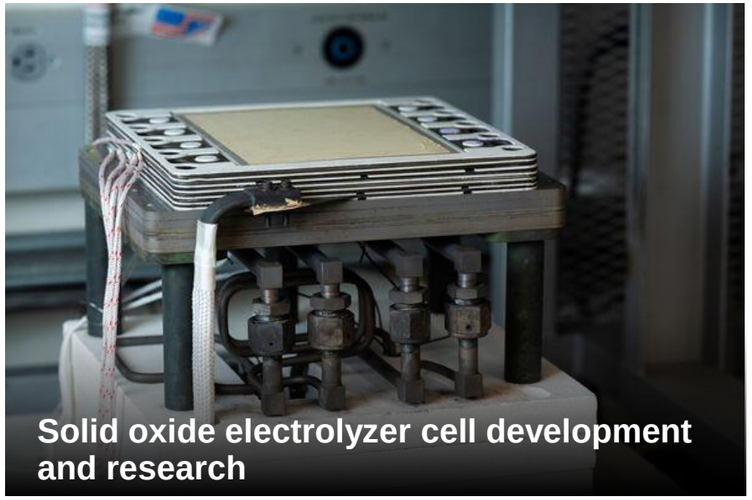
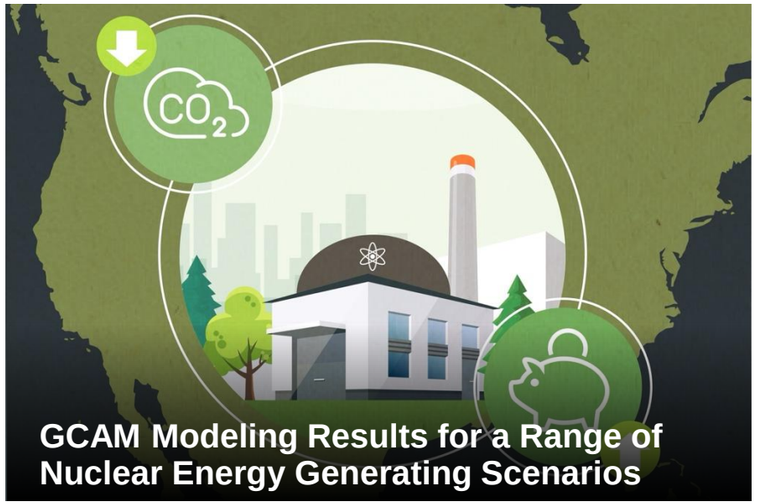
Nuclear Generated Hydrogen



Solid oxide electrolyzer cell development and research

- **Accomplishment:** Advancing solid oxide fuel cell and hydrogen carriers technologies that can be integrated with nuclear generation stations; techno-economic and risk assessment
- **Future Impact:** Support the improved integration of nuclear energy into the 21st century energy generation system

Nuclear's Role in CO_2 Reduction



GCAM Modeling Results for a Range of Nuclear Energy Generating Scenarios

- **Our Work:** Investigating nuclear energy's contribution and future role to mitigate CO_2 emission
- **Future Impact:** Inform policy and decision makers on the role of nuclear energy in the 21st century energy generation system

Probabilistic Risk Assessment

Flooding at the Fort Calhoun Nuclear Generating Station

- **Our Work:** Advancing state-of-the-art probabilistic risk assessment for both existing and next-generation advanced reactors.
- **Future Impact:** PRA resource for the NRC's Office of Nuclear Reactor Regulation and Office of Nuclear Regulatory Research

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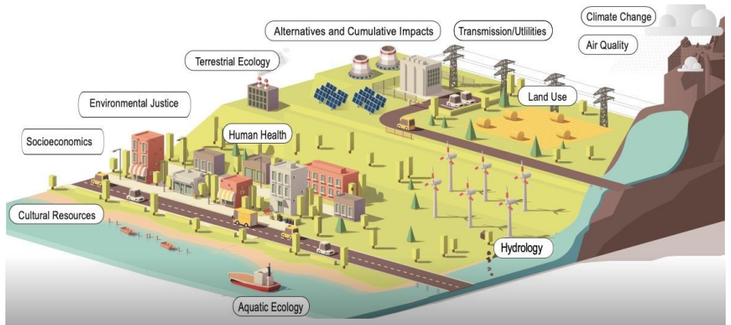
Energy Facility and Infrastructure Siting



Environmental Assessment in Support of Siting Energy Facility and Infrastructure

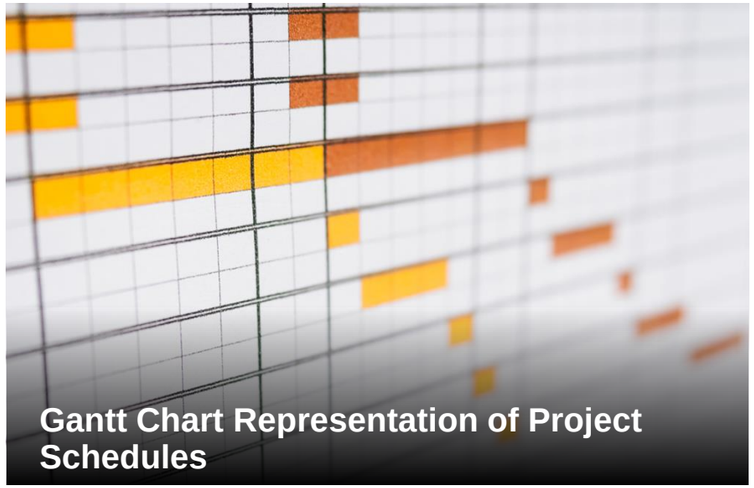
- **Our Work:** Interdisciplinary scientific analysis; technological and institutional innovation; and skillful integration of public stakeholders, science, and policy for siting energy facilities.
- **Future Impact:** Support the siting of facilities to meet deep decarbonization goals

Environmental Reviews

Clinch River Tennessee Site
(December 2019 Early Site Permit for an SMR)

- **Our Work:** Multi-disciplinary environmental assessment capabilities are applied to a range of nuclear projects (NRC Early Site Permit for the Clinch River TN site, NRC Advanced Reactor Generic EIS, License Renewal GEIS, NRIC Plant Parameter Envelope)
- **Future Impact:** Streamlined environmental reviews for license renewals and new reactor deployment (under two years)

Integrated Schedule and Cost Risk Analysis



Gantt Chart Representation of Project Schedules

- **Our Work:** Implemented cost and schedule risk analyses for dozens of projects over 15+years; helping high-visibility projects comply with DOE O 413.b, identify and prioritize risks, objectively estimate contingency requirements, and mitigate risks
- **Future Impact:** Bringing to bear advanced tools, data science, and big data approaches risk analysis

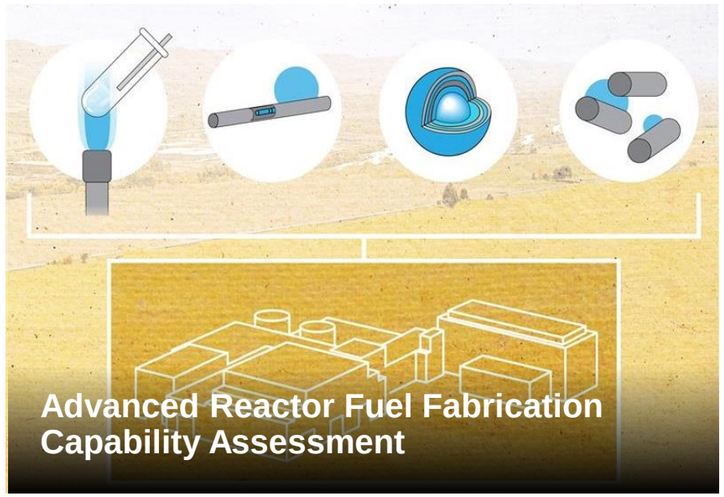
Advancing sustainable clean nuclear energy

Environmental Justice

Energy Equity and Environmental Justice Summit Hosted by PNNL

- **Our Work:** Strengthening environmental justice policies and community engagement practices for federal agencies through social science and environmental assessments
- **Future Impact:** Establishing a 21st century that combats CO2 emissions while being equitable and just for all communities

Fuel Fabrication Capability Assessment


Advanced Reactor Fuel Fabrication Capability Assessment

- **Our Work:** Leveraged industry insights of fuel fabrication capabilities needed for current nuclear power plants plus advanced reactors; evaluated the benefit of a Center for Advanced Reactor Fuel Fabrication.
- **Future Impact:** Support industry deployment of advanced fuels

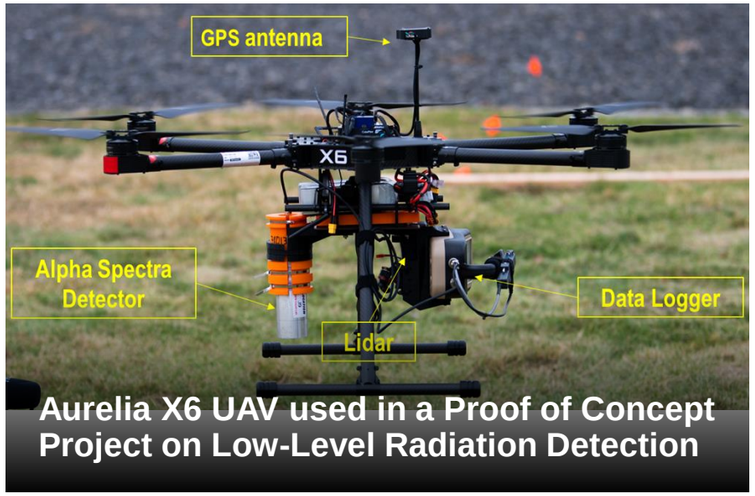
Human Factors


Advancing fundamental knowledge at the intersection of people, technology, and work environments

- **Our Work:** Human reliability analysis and probabilistic risk assessment modeling that supports the NRC in nuclear reactor research and licensing.
- **Future Impact:** Better understanding of the human-machine interface for improved safety and reliability

Advancing sustainable clean nuclear energy

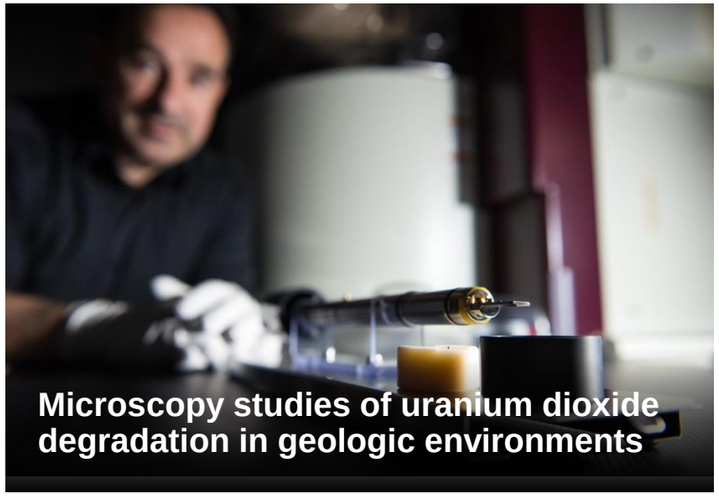
Drones for Low-Level Radiation Detection



Aurelia X6 UAV used in a Proof of Concept Project on Low-Level Radiation Detection

- **Our Work:** Demonstrated that unoccupied aerial vehicles equipped with radiological detection systems are feasible to perform the needed surveys to meet release criteria for a final status survey.
- **Future Impact:** UAVs have the potential to reduce time, cost, and safety risks to humans during decommissioning and other surveys

Spent Nuclear Fuel Degradation


Microscopy studies of uranium dioxide degradation in geologic environments

- **Our Work:** Developing advanced microscopy tools for understanding the degradation of uranium dioxide spent fuel in geologic environments (chemical and radiological)
- **Future Impact:** Improved models for the long-term safety assessment of the geologic disposal of spent nuclear fuel

Spent Nuclear Fuel Transportation Testing

Instrumented spent nuclear fuel transportation cask

- **Accomplishment:** Partnered in the multi-modal spent nuclear fuel transportation test with results showing forces acting on fuel rods are small under normal conditions of transportation
- **Future Impact:** Data for the safety case for transporting high burnup spent nuclear fuel

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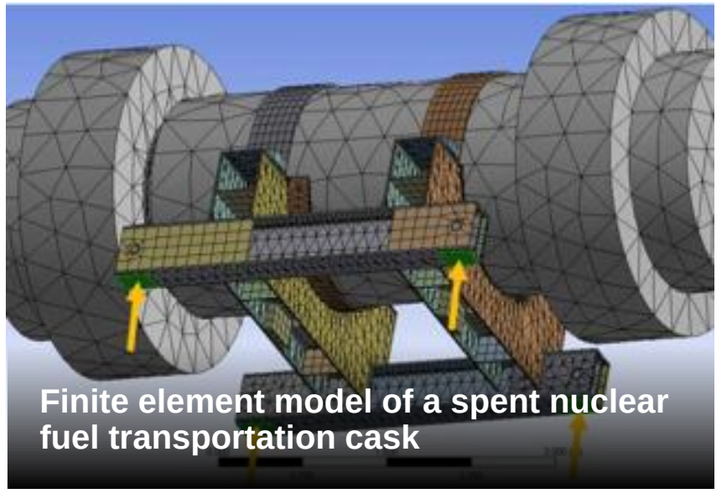
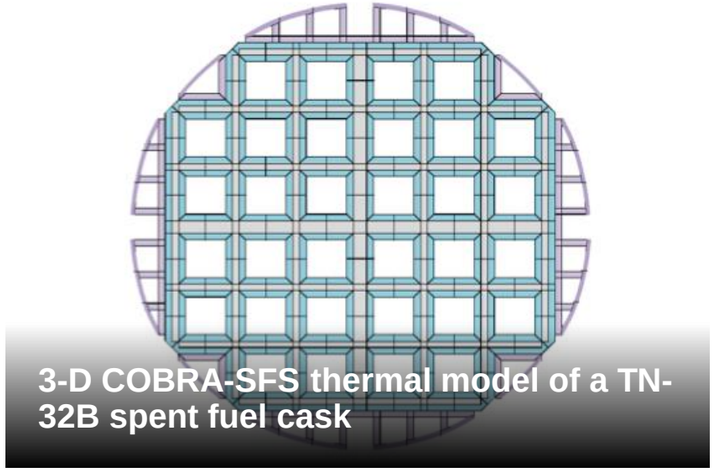
Structural Analysis of Spent Nuclear Fuel Storage and Transportation Casks



Finite element model of a spent nuclear fuel transportation cask

- **Our Work:** Structural analysis of transportation casks under normal operations and of storage casks during seismic events
- **Future Impact:** Demonstrated the safety of transporting high burnup spent nuclear fuel and of storage casks during earthquakes

Storage and Transportation Cask Thermal Analysis



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

- **Our Work:** Developing and benchmarking the COBRA-SFS code/templates and incorporated into UNF-STANDARDS; analyzed storage and transportation cask configurations using COBRA-SFS and STAR-CCM+
- **Future Impact:** Improved methods and techniques for the thermal analysis of storage and transportation canisters and casks

Reactor Site Infrastructure Evaluations

Examining the railway near a nuclear power plant

- **Accomplishment:** Conducting reactor site surveys to understand the existing infrastructure for transporting spent nuclear fuel (19 completed to date)
- **Future Impact:** Planning for transporting spent nuclear fuel from commercial nuclear reactor sites

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Spent Fuel Recycling

Contactors and on-line monitoring in the Radiochemical Processing Laboratory

- **Our Work:** Demonstrated CoDecon flowsheet testing for recycling without separating pure Pu using on-line monitoring; investigating advanced extractant for recycling HALEU; advancing approaches for TRISO recycling
- **Future Impact:** Proliferation resistant recycling with real-time process control

Waste Form Development

Molten glass pour for testing at the Waste Development Laboratory

- **Our Work:** Advancing technologies to immobilize waste streams into durable waste forms and the understanding of how they will perform in disposal environments.
- **Future Impact:** Treatment of non-disposable spent fuel forms and future recycling processes

Iodine Capture and Immobilization

Iodine loaded silver-functionalized silica aerogel

- **Our Work:** Advancing waste forms for the capture and immobilization of iodine
- **Future Impact:** Durable waste forms for the permanent disposal of iodine released during spent nuclear fuel recycling

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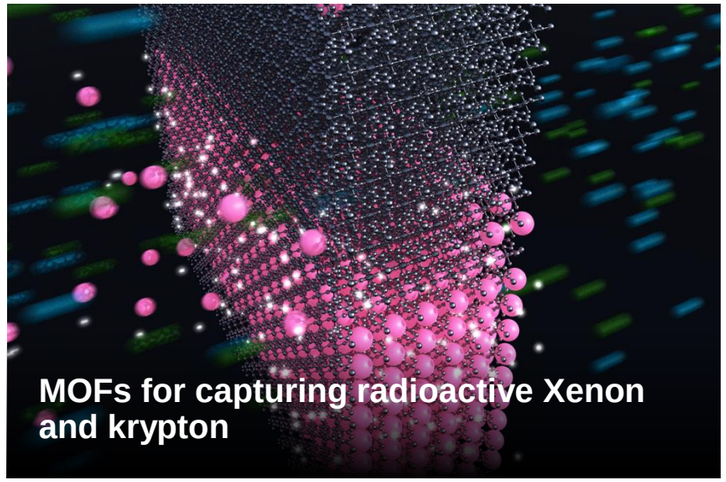
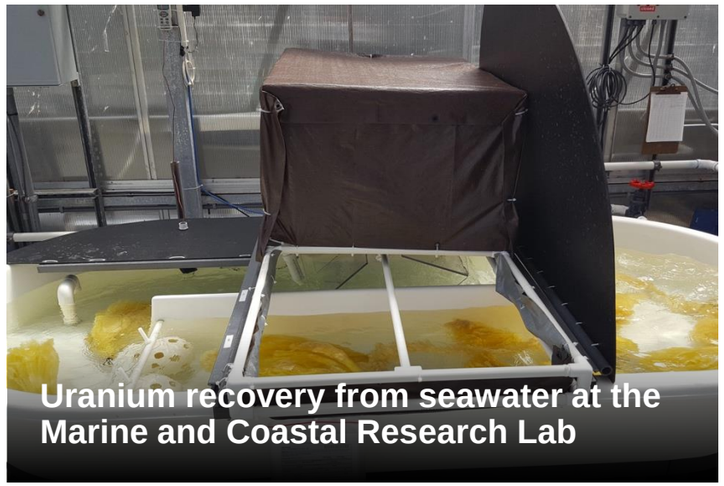
Metal Organic Frameworks



MOFs for capturing radioactive Xenon and krypton

- **Our Work:** Developing metal organic frameworks (MOFs) for capturing noble radioactive off-gases (Kr, Xe); partnering with industry to advance technology for industrial applications
- **Future Impact:** Efficient and smaller off-gas capture systems that can be used on advanced nuclear reactors or at recycling facilities

Uranium Recovery from Seawater



Uranium recovery from seawater at the Marine and Coastal Research Lab

- **Our Work:** Demonstrated the recovery of uranium from seawater using acrylic fibers
- **Future Impact:** Provide commercially attractive nuclear fuel derived from the oceans — the largest source of uranium on earth

Materials Research to Support Reactor Permit Extensions

Nuclear power plant cables being irradiated for materials aging research

- **Our Work:** Use high-dose irradiators in the Radiological Exposures & Metrology Lab to understand the behavior of aged cables in existing nuclear power plants
- **Future Impact:** Provide radiation effects testing on critical electrical and structural reactor materials to simulate end-of-life-dose, which supports permit extension of the current light water reactor fleet

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Questions & Discussion

Learn more at
www.pnnl.gov