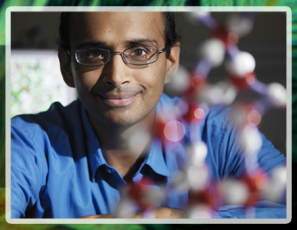
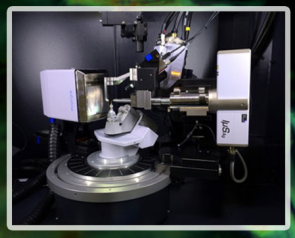
Radiation Effects in Materials Research
*at Pacific Northwest National Laboratory*





# 2016 Capability Briefing

Pacific Northwest
NATIONAL LABORATORY

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At PNNL, we are striving to detect structural degradation in materials in extreme environments before structural defects occur

**Cover background image: Researchers at Pacific Northwest National Laboratory are working with scientists at Sandia and Argonne National Laboratories to understand the formation of a uranyl hydrate phase that crystallized on a surface leading to this unusual structure. The transitory structure lasted only a few minutes before altering to another phase. The impact of this work is fundamental understanding of long-term stability of spent nuclear fuel and development of a scientific basis for the disposal of spent nuclear fuel, a critical national need.**

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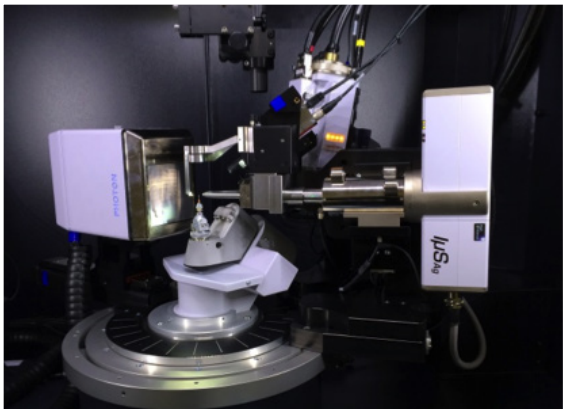


# INTRODUCTION

Revolutionary new materials are needed that can function reliably, for long periods of time, in environments marked by radiation, pressure, and elevated temperature. Few such materials exist. New materials are unlikely to be discovered rapidly using an Edisonian approach involving fabrication and characterization of literally thousands of material microstructures of systematically varied compositions and phases. Such an approach is too slow and costly to meet the demands of the energy, national security, and environmental remediation sectors.

A more rational approach engages scientists with appropriate expertise, awareness of the critical issues, and available resources to delve into the fundamental mechanisms at the atomic and molecular level to discover why materials fail. By understanding how material interfaces interact with the environment and external driving forces at these levels, researchers can develop innovative strategies to predict and control these interactions, leading to development of advanced materials with unprecedented stability in extreme environments.

For decades, progress on understanding the interactions of materials in hostile environments has been hampered by a lack of scientific instruments and computational frameworks with capabilities necessary to perform the needed analyses, simulations, and calculations. However, recent advances in instrumentation and computational platforms have provided opportunities to advance the fundamental science underlying these interactions, allowing prediction and eventual control of performance.

Advanced fission reactors and future fusion-based concepts will require materials that can function reliably in harsh environments for long periods of time. These extremes include high radiation fluxes in a highly corrosive, high-pressure or high-temperature environment. Beyond energy applications, materials that can function in extreme environments would significantly impact national security, environmental management, the telecommunications industry, space exploration and discovery, and other technologies.

**This booklet contains short biographies, including selected publications by our key staff. It also provides details on the capabilities in the Environmental Molecular Sciences Laboratory, the Radiochemical Processing Laboratory, the new Physical Sciences Facility, and the Radiological Calibrations Facility.**

Translating new material discoveries into impactful new technologies requires fundamental knowledge and approaches to scalable synthesis of materials with designed interfaces. Pacific Northwest National Laboratory (PNNL) is embracing this endeavor and is making new materials transformative to our energy challenges.

At PNNL, our teams have made significant contributions to materials science for the Department of Energy (DOE), the Nuclear Regulatory Commission (NRC), and their predecessors for nearly 50 years. We lead studies to

- *Understand and predict the atomic-level changes, microstructural evolution, and macroscale properties of materials in extreme environments*. This work includes experimental, theoretical, and computational studies that produce insights, models, and simulations of interactions across multiple time and length scales. It spans from fundamental studies in self-healing properties of ceramics to applied research into fracture toughness of highly irradiated core materials.
- *Design the materials, taking them from concept to reality.* Because of our nearly 50 years of experience in materials design, we can quickly gather the resources needed to develop tough materials. For example, our team is developing alloys and composites that function under extreme conditions.
- *Control or mitigate the effects of hostile environments.* Material fabrication and testing requires engineering capabilities, a deep understanding of industrial needs and standards, and facilities with high-end experimental instrumentation and computational resources.

At PNNL, applied materials scientists and nuclear engineers with real-world reactor experience conduct evaluations by integrating equipment and data from the Environmental Molecular Sciences Laboratory (EMSL), the Radiochemical Processing Laboratory (RPL), the Physical Sciences Facility (PSF), and the Radiological Calibrations Facility (RCF).

Each of these activities requires multidisciplinary teams and the ability to see problems from multiple viewpoints. Our teams are very effective in integrating experiment, theory, and computer simulations. Our research brings together physicists, chemists, materials scientists, engineers, applied mathematicians, and computer scientists to effectively tackle fundamental science challenges that cannot be dealt with by scientists of one discipline alone. These people come from organizations across PNNL as well as from our collaborators in the U.S. and throughout the world.

We conduct these studies by bringing together the instruments and results needed from synthesis, characterization, and computational resources at PNNL and other institutions.

We have primarily conducted research for:

- DOE's Office of Basic Energy Sciences
- DOE's Office of Fusion Energy Sciences
- DOE's Office of Nuclear Energy
- DOE's Office of High Energy Physics
- DOE's National Nuclear Security Administration
- NRC
- International Atomic Energy Agency.

Our experience and capabilities are grouped into the following focus areas:

- Fundamental Research on Radiation Effects
- Basic Energy Sciences
- Fusion Energy Materials Sciences
- High-Energy Physics
- Nuclear Process Science Initiative
- Applied Nuclear Energy Materials Sciences
- Applied Materials Research for Defense
- Applied Materials Research for Nuclear Nonproliferation.

Each focus area is described in this booklet.

**At PNNL, we create interdisciplinary teams to tackle challenges that confound single disciplines.**

# FOCUS AREAS

## Fundamental Research on Radiation Effects

The aim of PNNL's fundamental materials research on radiation effects is to understand, control, and predict the response of interfaces in materials systems that are driven far from equilibrium. Interfaces play a critical role in controlling many properties of interest, such as thermal and electrical conductivity, corrosion resistance, toughness, and radiation response, in materials used in energy technologies. One of the challenges in understanding interfaces is their chemical and structural inhomogeneity at the nanometer scale. Defects produced by radiation damage and species transport are dramatically altered by the presence of interfaces. At the same time, external driving forces can modify interfaces and change designed microstructural features, thereby altering the performance of materials.

We seek to achieve revolutionary advances in understanding interfacial oxidation and materials degradation processes in materials for current and advanced nuclear reactor systems, nuclear fuels, and nuclear waste forms. Our focus is on fundamental atomic-level origins of materials failure, nanoscale interactions under extreme conditions, defect production and microstructural evolution in extreme environments, design of tailored microstructures to mitigate radiation damage, evolution of mechanical properties in harsh environments, and harnessing the power or external driving forces to improve the properties of materials.

Our research on radiation effects addresses the following scientific questions:

- How can we master metastability to design interfaces that persist under extreme driving forces?
- How do defects and impurities interact with interfaces in driven systems to produce signatures of material degradation over a range of time scales?
- How do we design self-healing materials that retain desired thermo-mechanical properties under extreme operating conditions?

By integrating theory, predictive models, and simulations with synthesis, ion implantation, and chemical imaging, we advance the fundamental science needed to develop radiation-tolerant and corrosion-resistant materials, waste forms for long-term storage of actinides, advanced fuels, and accident-tolerant cladding materials.

## Basic Energy Sciences

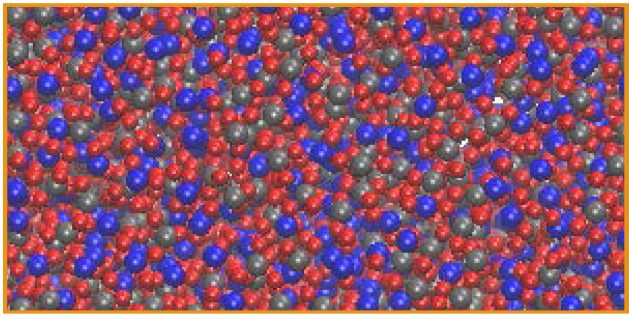
For DOE's Office of Basic Energy Sciences (BES), we answer fundamental questions that address these challenges. Our research seeks to understand the atomistic basis of materials properties and behavior and how to design materials rapidly by integrating predictive theory and modeling, innovative synthesis, ion beam modification of materials, chemical imaging, and digital data.

Recent PNNL contributions are highlighted here.

**Relating Materials Chemistry to Radiation Tolerance**. We used atomic-level computer simulations to understand how the chemistry of ceramics and diffusion of ions relate to radiation response. We found when Zr is substituted for Ti in pyrochlores, the oxygen ion diffusion speeds up, which results in more efficient damage annealing. In contrast, damage accumulates in irradiated titanate-based ceramics. Our simulations revealed details of volume expansion and atomic coordination in tracks produced by energetic particles in ceramics.

**Revealing Details of Swift Heavy Ion-Induced "Extreme" Damage in $BaTiO_3$**. We irradiated tetragonal $BaTiO_3$ single crystals using 1.5 GeV $^{238}U+$ ions at room temperature at the GANIL facility in France and characterized the microstructural changes using techniques including transmission electron microscopy (TEM) in collaboration with colleagues in Japan. We observed an amorphous core at the ion-entry spot with a diameter of about 10 nm. The spot is surrounded by polycrystalline domains with distorted structures.

Cross-sectional examination provided quantitative information about the diameter of the amorphous region and the surrounding defective material. We developed interatomic potentials for $BaTiO_3$, and performed atomic-level simulations of this irradiation. This gave



Heavily disordered structure of irradiated titanate pyrochlore. Blue, grey, and red spheres represent Gd, Ti, and O atoms, respectively.

us valuable insights about nanoscale damage structures and the microstructural evolution stages of swift heavy ion irradiated ceramics.

**Collaborators**. In conducting research for BES, we have forged strong relationships with leading scientists at universities and national laboratories in the U.S. and internationally.

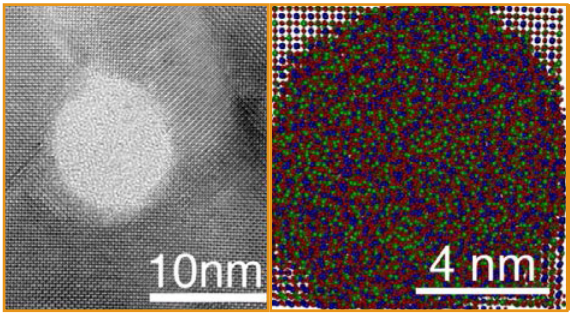
These collaborations enable us to mentor students and early career scientists, which helps ensure the availability of well-trained future scientists in this area. Results from an international collaboration were featured on the cover of a *Journal of Materials Research* Focus Issue in 2015.

## Fusion Energy Materials Sciences

Fusion reactor materials will be required to function in an extraordinarily demanding environment that includes combinations of high temperatures, chemical interactions, time-dependent thermal and mechanical loads, and intense neutron fluxes.

Exposure to fusion neutrons violently displaces atoms from their crystal lattice positions, up to hundreds of times over an operating lifetime, and changes alloy chemical compositions by transmutation, including introduction of damaging concentrations of reactive and insoluble gases. A long-standing feasibility issue is the development of structural materials that can withstand the harsh fusion environment.

The U.S. Fusion Materials Science Program is engaged in a science-based effort to understand the damage mechanisms controlling performance-limiting phenomena of materials for future fusion power systems. The program




Massively parallel molecular dynamics simulations and swift heavy ion (635 MeV $^{238}U^{+}$) irradiations present consistent and complementary evidence of atomic-level disorder and volume expansion in barium titanate ($BaTiO_3$) in extreme environments.

uses a suite of experimental and computational tools to explore life-limiting materials degradation phenomena in the fusion environment. The overarching goal is to develop experimentally validated, physics-based, predictive models of material behavior that can be used to improve existing materials or design better ones.

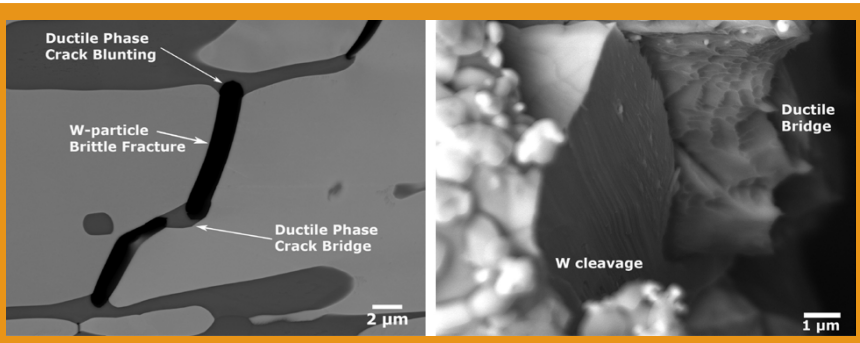
PNNL contributes strongly to all elements of the national effort, which is aimed at developing and testing irradiation-insensitive, low-activation materials. Our long-term goal is to develop a fundamental understanding of radiation effects to provide a sound basis for materials development. We focus on structural materials for first-wall and blanket applications, because the characteristics and properties of structural materials determine economic, safety, and environmental attractiveness. These properties in turn determine the feasibility of fusion energy.

Our program scope includes alloy and composite development, performance of irradiation experiments, post-irradiation examination (PIE) of mechanical properties and microstructure and their correlation, computer simulation and modeling, and coordination with the other U.S. Fusion Materials Science Programs. Recent PNNL contributions are highlighted here.

**Reduced Activation Ferritic/Martensitic (RAF/M) Steels and Ferritic Alloys**. PNNL has made important contributions to understanding helium transport and fate in RAF/M steels and oxide dispersion-strengthened (ODS) ferritic alloys through detailed TEM studies of a unique set of neutron-irradiated specimens. We use computer modeling and simulations to understand fundamental aspects of materials degradation caused by high-energy fusion neutrons and the large amounts of helium produced in irradiated materials by nuclear transmutations.

Research involves atomic-scale simulation of helium's fate and effect on microstructural evolution in RAF/M steels and ODS ferritic alloys. The work addresses long-standing uncertainties about helium's role in existing irradiation experiments and at lifetime doses in fusion energy devices.

**To develop radiation-resistant materials for fusion, we need to extrapolate beyond the empirical information from irradiations in fission reactors. This can only be done through detailed knowledge of the mechanisms of damage at the atomic scale.**




Tungsten dual-phase composites (W-Ni-Fe) are being studied at PNNL. The brittle W-particles are sintered in a ductile matrix phase and then hot-rolled to produce a dual-phase laminated composite. The goal is to create a ductile-phase toughened W-composite for fusion energy applications. These images show the merit of this approach. (Left) An SEM backscatter image showing the matrix phase (dark phase) bridging a crack in W-particles (lighter phase). (Right) An SEM image inside a crack in a tested composite showing transgranular cleavage fracture of a W-particle and ductile tearing fracture of the bridging phase.

**Silicon Carbide Composites**. Our work addresses effects of fiber-reinforced silicon carbide composite architecture on strength, crack propagation resistance, and lifetime. Silicon carbide composites could be required to isolate structural materials from a high-temperature lead-lithium coolant, so radiation effects on thermal and electrical conductivity are significant concerns, as are techniques for joining the materials. We are developing the use of solid-state displacement reactions between silicon and titanium carbide, which has the potential to produce excellent high-strength, low-activation joints with optimal density and microstructure.

**Vanadium Alloys**. Our teams are investigating the effects of stress state on the mechanical properties of vanadium alloys. These alloys are potential structural materials in fusion systems because of their thermal conductivity, elevated temperature strength, and resistance to becoming radioactive. An important issue to resolve is loss of ductility and fracture resistance following low-temperature neutron irradiation.

Our research is providing insights into deformation mechanisms controlling behavior of these materials at low irradiation temperatures.

**Collaborations**. Our program is strongly linked to fusion materials research activities in the U.S. and other countries through formal and informal collaborative agreements. The U.S. program is conducted at Lawrence Livermore National Laboratory, Oak Ridge National Laboratory (ORNL), PNNL, University of California-

Berkeley, University of California-Los Angeles, and University of California-Santa Barbara. Much of our research is carried out in collaboration with one or more of these participating institutions.

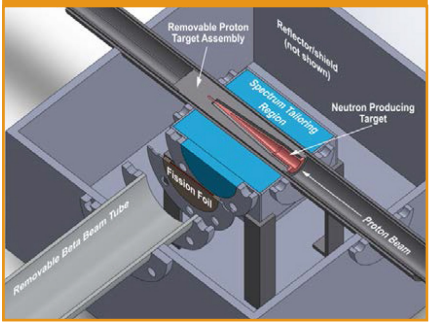
Scientific information is exchanged through formal International Energy Agency (IEA) Implementing Agreements. The PNNL program manager, Richard J. Kurtz, is Secretary for both the Annex II and Executive Committee of the IEA Implementing Agreement on Fusion Materials.

## High-Energy Physics

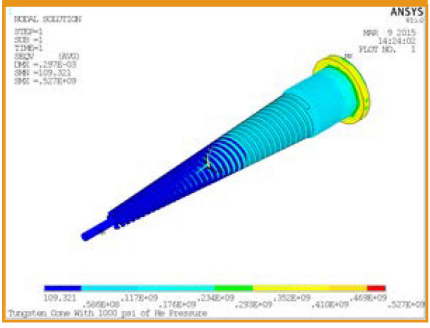
Advances in targetry[1] are central to future physics facilities using intense, high-power particle beams. High-power (multimegawatt) targets must accommodate the high energy density of the proton beam, large thermal stresses in the target material, repetitive thermal shocks from pulsed beams, intense radiation damage from the particle beam, and demanding heat removal in high heat fluxes. The challenge of target design is to accommodate these constraints while optimizing the physics performance within very limiting spatial and magnetic field constraints.

Thorough understanding of the thermomechanical properties of candidate target materials at the extremes of their operating range is vital for creating an optimal design. A good understanding of the structural integrity of bulk targets at material interfaces is key to meeting the expected lifetime of a target and

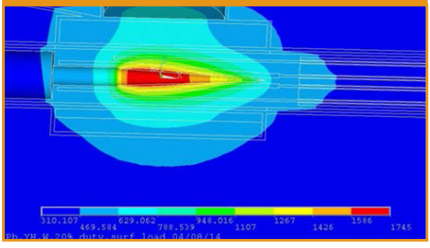
Isometric cross section of accelerator proton target configuration for neutrino anomaly experiment




VonMises stress results for proton target cone at 1000 psi helium pressure




Temperature distribution for proton target



(1) Includes particle production targets and other production devices, including focusing optics, monitors and instrumentation; beam vacuum windows and absorbers; collimators (up to 100 TeV); and facility remote handling, shielding and radiation transport, air handling, and cooling systems.

allowing timely intervention and remedial action when problems arise.

Accelerator target facilities require a beam window to separate the accelerator vacuum from the target, typically in an inert gas environment at atmospheric pressure. Candidate materials must optimize the design and geometry to accommodate significant static and dynamic stresses and temperatures.

Radiation effects can decrease the life of accelerator target materials and beam windows. Understanding how radiation damage alters the localized and bulk thermal and mechanical properties of candidate target and window materials is critical to tailoring composition and microstructure to optimize performance. Recent PNNL contributions are highlighted here.

**PNNL Capabilities Applied to High-Energy Physics Materials Challenges.** PNNL has a broad suite of technical capabilities in radiation science to address many of DOE's High Energy Physics (HEP) materials challenges. These capabilities are highly applicable to developing high power targets and beam windows at large accelerator facilities.

PNNL's capabilities range from fundamental physics and engineering to computational and experimental work. Our work includes high-power beam characteristics and interactions with materials, energy deposition using particle interaction codes, radiation materials science, thermodynamics, thermal shock, and transient thermal stress analyses including stress wave generation and propagation using finite element codes.

Our staff have designed, fabricated, and operated complex target test trains in challenging high-power nuclear environments and demonstrated a thorough understanding of the problems that must be addressed to enable the HEP mission. PNNL's experience in designing irradiation targets in reactors requires the same analysis, prototyping, and fabrication tools as accelerator target and window design, because consequences of target failure in a reactor are severe. We have the understanding and ability to predict radiation damage changes in material properties and the impact on component lifetimes.

Our capabilities can be applied to Monte Carlo N-Particle and ANSYS software simulations of candidate target and beam window materials and geometries, identifying these materials over the range of operating conditions. We can apply molecular dynamics methods for modeling displacement cascades at atomistic levels.

PNNL is addressing HEP materials challenges by helping develop the plan for a systematic program of irradiations and post-irradiation characterization for investigating key performance parameters. Our intent is to provide data for benchmarking modeling and simulation codes and correlating micro- and macro-properties and structures. Such benchmarking is prerequisite to successful design and

construction of target components for HEP high-power proton accelerator environments.

**RaDIATE Collaboration**. The RaDIATE (Radiation Damage in Accelerator Target Environments) Collaboration was founded in 2013 to foster better understanding of radiation damage mechanisms and the associated thermal and mechanical properties response for materials of interest to high-power proton beam target facilities. The collaboration now includes Fermilab; PNNL; Brookhaven National Laboratory; the Science and Technology Facilities Council in the UK; the University of Oxford; Los Alamos National Laboratory; Argonne National Laboratory; Michigan State University; ORNL; the European Spallation Source in Sweden; and the Center for Energy, Technology, and Environmental Research in Spain.

While RaDIATE is specifically concerned with proton irradiation damage (100 MeV to 120 GeV), the fundamental materials science in this area is closely related to neutron irradiation damage.

## Nuclear Process Science Initiative

PNNL is investing about $18M over five years in the Nuclear Process Science Initiative (NPSI), an internal Laboratory Directed Research and Development program investment in support of the nuclear science and technology research. This five-year investment will connect fundamental science expertise with applied program needs by building capabilities in nuclear materials characterization, chemistry, physics, modeling, and engineering to support legacy waste management and nuclear nonproliferation.

The vision of NPSI is to understand, harness, and exploit the interfacial phenomena controlling the behavior of materials in nuclear processing. One of NPSI's science thrusts focuses on discovering and exploiting the chemical and physical mechanisms controlling formation, distribution, and influence of trace species during nuclear materials processing. Another thrust aims to enable multiscale modeling of interfacial processes in harsh environments. The objective is to use experimental knowledge to advance new methodologies for linking models at different scales to anticipate problems and validate signatures in post-reactor nuclear fuel processing.

NPSI will provide the technical foundation that will enable new paradigms for chemical processing control and signature discovery/exploitation. By integrating theory, modeling, and experiment, NPSI will enable incredible discoveries around interfacial science of irradiated materials using the full suite of analytical and computational tools available at PNNL.

## Applied Nuclear Energy Materials Sciences

To achieve energy security and reduce greenhouse gas emissions, the U.S. must develop and deploy clean, affordable, domestic energy sources as quickly as possible. Nuclear power is a key component of a portfolio of technologies that meets our energy goals. The challenges to the increased use of nuclear energy, domestically and internationally, include:

- Extending the life of the operating nuclear power plant fleet
- Reducing construction costs for new large plants
- Achieving viable economics for use of small modular reactors
- Reducing regulatory and technological uncertainties around deployment of Generation IV reactors
- Establishing a permanent solution to nuclear waste management.

Within each challenge are specific needs for materials and materials science. Extending the life of the nation's 99 operating nuclear reactors means understanding material behavior to predict and proactively mitigate potential defects in materials.

New materials and joining techniques are needed to enable affordable construction of nuclear power plants. Advanced materials that are resilient under Generation IV reactor operating environments are needed. A permanent solution for used nuclear fuel means designing reliable waste forms for disposal and understanding the long-term characteristics of these waste forms in a geologic disposal option. Recent PNNL contributions are highlighted here.

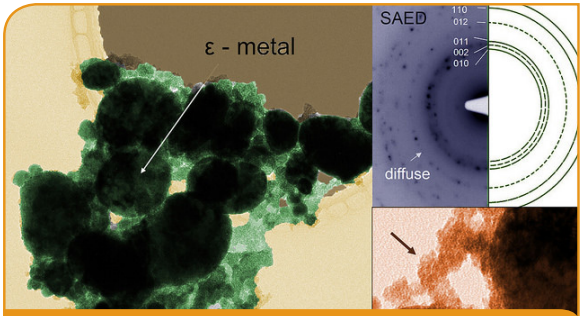
**Precursors to Structural Material Defects**. Our contributions to DOE's Light Water Reactor Sustainability Program focus on understanding the behavior and detecting forms of material degradation in metallic components and cables long before they become structural defects. Some forms of degradation have a long initiation time, followed by a rapid growth phase. One of our goals is to better understand this behavior and develop advanced monitoring and inspection techniques to detect this initiation, or defect precursor, early on.

As interim storage of spent nuclear fuel is becoming a practical necessity in the U.S., our analysis and inspection techniques for material degradation in reactors are now being applied to spent fuel storage systems.

**Materials Research for Nuclear Energy**. PNNL is experienced in detecting structural material behavior in nuclear power plants and developing advances in chemical processes and engineered materials for actinide-bearing wastes. For DOE's Office of Nuclear Energy, PNNL provides applied research in materials effects in extreme environments, such as:

- Fracture toughness of highly irradiated core structural materials for advanced, liquid-metal-cooled reactors

- Waste form development and behavior for high-level nuclear wastes from spent-fuel reprocessing
- Structural material evaluations in high thermal and radiation fields for evidence of stress corrosion cracking
- Proactive management of materials degradation
- Understanding materials behavior under the harsh environments of fast reactor or other Generation IV reactor cores, and monitoring material behavior through advanced sensoring techniques, such as under-sodium viewing.




Nuclear scientists at PNNL are studying the epsilon metal particle that forms in uranium oxide fuels during reactor operation. The phase appears to have unique catalytic properties possibly because of its small size and microstructure. These phases are of interest because of their impact on advanced nuclear fuel recycling and the long-term durability of spent fuel under geologic disposal.

**Highly Irradiated Ferritic Martensitic Steel Samples**. We are performing research on the most highly irradiated ferritic martensitic steel samples from the Materials Open Test Assembly of the Fast Flux Test Facility, a sodium-cooled fast reactor no longer in operation. Scores of specimens were exposed to irradiation damage of up to 200 dpa (displacements per atom), which is unmatched in the world today and would take years to replicate. We are using our signature hot-cell testing capabilities to measure the fracture toughness of these specimens.

**Metallic Wastes**. We are developing epsilon-phase metals for higher durability, higher waste loading, and higher confidence in metallic waste forms that emerge from the recycling of used nuclear fuels. This approach takes advantage of the plethora of noble metals that emerge from reprocessing by converting them into an engineered waste form.

**Collaborations**. We collaborate with colleagues in the nuclear industry, academia, other national laboratories, and the NRC.

## Applied Materials Research for Defense

When it comes to materials for defense, a critical need is designing, developing, demonstrating, testing, analyzing, and performing post-irradiation characterization of tritium-producing burnable absorber rods (TPBARs). TPBARs are designed at PNNL and irradiated in the Tennessee Valley Authority Watts Bar Nuclear commercial power plant to produce tritium for the nation's nuclear weapons stockpile.

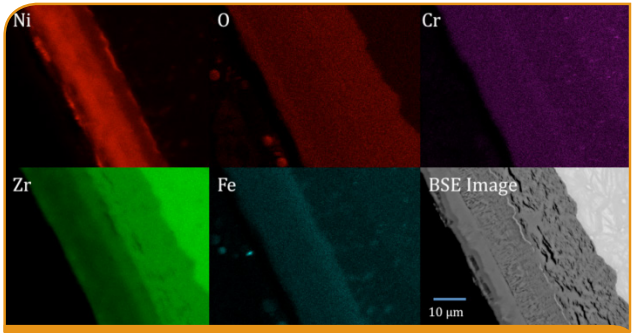
PNNL's modeling and analysis capabilities include high-power beam characteristics and interactions with materials, energy deposition using particle interaction codes, radiation materials science, thermodynamics, thermal shock, and transient thermal stress analyses.

More than 3,800 TPBARs have been irradiated to date, and the quantity irradiated in each Watts Bar operating cycle is increasing to meet stockpile requirements. During irradiation, the TPBARs release about 4 Curies (Ci) of tritium each per year. While this represents only about 0.04% of the tritium produced in each TPBAR, it is considerably higher than the 0.5 Ci/TPBAR/y predicted by performance models in 2006.

To better understand the discrepancy between predicted and observed tritium release, PNNL started a research program in 2006 supported by DOE's National Nuclear Security Administration (NNSA) to provide a scientific basis for improving the performance models. With appropriately designed tests, experimental data can be generated to improve the fundamental understanding behind the mechanisms operating in the TPBAR and thus the accuracy of key predictive models.

Data generated by the research program since 2006 have resulted in improved performance models, with a 30% reduction in the discrepancy between predicted and observed tritium permeation.

**Materials Research for Defense**. PNNL designed and executed a series of in-reactor and ex-reactor experiments in collaboration with Idaho National Laboratory (INL),




Elemental map derived from electron dispersive X-ray spectroscopy in a scanning electron microscope on an irradiated sample from the TMIST-1 experiment. The view is of a layered nickel-zircaloy intermetallic coating on a Zircaloy-4 substrate. This material is a candidate for advanced TPBAR liners or cruciforms that would improve reduction of tritium oxide released from the lithium aluminate pellets.

A post-irradiation neutron radiograph of the uppermost capsule of the TMIST-1 experiment shows the internal detail of the capsule including the gas lines, thermocouples, differential expansion bellows, heat sink, test specimens, specimen centering fixtures, and end plugs.

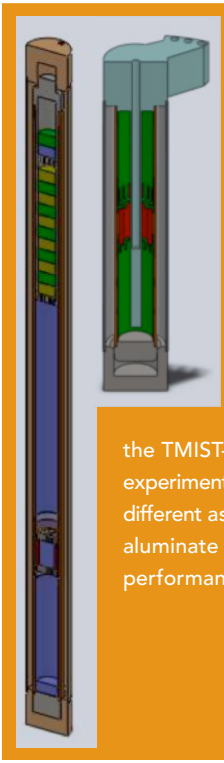
Sandia National Laboratories, and Savannah River National Laboratory. The irradiation tests comprise the TPBAR Materials Irradiation Separate-Effects Test (TMIST) series, while the related ex-reactor tests comprise the TPBAR Materials Ex-Reactor Testing and Development (TMED) series.

The experiments focus on separate-effects performance of individual TPBAR materials to elucidate in-reactor behavior of each TPBAR component. In many cases, material properties and performance are significantly different in the reactor than when evaluated under identical conditions out of reactor. A prime focus of the effort has been comparing in- and ex-reactor behavior and developing appropriate in-reactor performance models to predict TPBAR tritium releases.

Despite the progress made in these experiments and the resulting improvements in performance models, significant knowledge gaps still hinder the ability to reliably predict aspects of TPBAR operation, such as tritium distribution, component structural integrity, and performance margins. As a result, NNSA initiated a tritium science program in 2012 with PNNL as the lead. The program are providing a better understanding of fundamental mechanisms responsible for observed TPBAR component performance.

Addressing these basic science questions will provide the ability to explain and predict all aspects of TPBAR performance and anticipate changes in performance resulting from changes in reactor operating conditions.

**To better understand the discrepancy between predicted and observed tritium permeation, PNNL started an NNSA-sponsored program in 2006 to provide a scientific basis for improving performance models.**



Three-dimensional cutaway computer models showing the relative size and internal arrangement of closed (left) and flow-through (right) capsules being designed for the TMIST-3 irradiation experiment to evaluate different aspects of lithium aluminate pellet performance.

**Post-Irradiation Examination (PIE).** PNNL conducts PIE campaigns in the RPL hot-cell facilities and laboratories. The advantage of PIE of the Watts Bar TPBARs is that the materials, configuration, and irradiation conditions are fully prototypic. Whereas irradiation experiments such as the TMIST series evaluate the separate effects of experimental parameters on individual TPBAR components, PIE provides an integral evaluation of end-of-life conditions with all of the components interacting in a prototypic fashion.

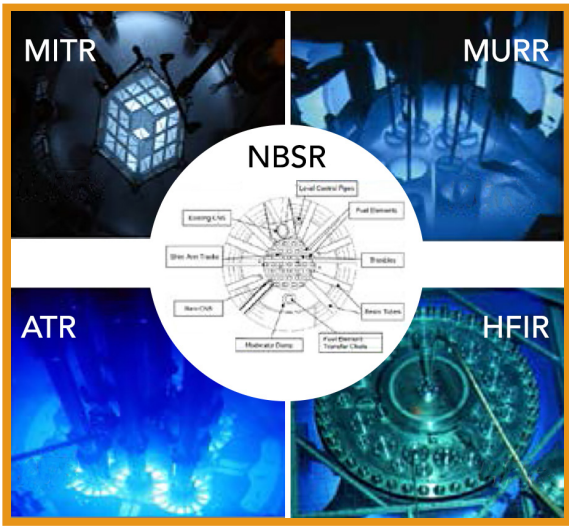
Characterization techniques included in the campaigns include

- Gamma spectroscopy
- Rod puncture and gas analysis
- Protium and tritium assays in TPBAR components as a function of axial and radial position
- Retained tritium and helium assays in the pellets
- Fourier transform infrared spectroscopy to determine oxide layer thicknesses on the zirconium-base components
- $^{3}$He and $^{4}$He assays in the stainless steel cladding
- Optical, SEM, and energy dispersive X-ray spectroscopy of irradiated TPBAR components.

## Applied Research for Nuclear Nonproliferation

Consistent with the President's highly enriched uranium (HEU) and plutonium minimization strategies, the Office of Material Management and Minimization ($M^3$) was established within DOE's NNSA. The primary objective of $M^3$ is to achieve permanent threat reduction by minimizing and, when possible, eliminating weapons-usable nuclear material around the world. This is done via three subprograms:

- Remove excess nuclear and radiological materials
- Dispose of domestic nuclear material and material returning to the U.S.
- Convert research reactors and isotope production facilities from the use of HEU to low enriched uranium (LEU).




Five U.S. civilian high-performance research reactors and a critical assembly use highly enriched uranium fuel: the MITR-II in Cambridge, MA; the University of Missouri Research Reactor (MURR) in Columbia, MO; the National Institute of Standards Reactor (NBSR) in Gaithersburg, MD; the ATR and ATR-C in Idaho Falls, ID; and the HFIR in Oak Ridge, TN. The high-density LEU-Mo fuel currently under development by $M^3$ seeks to convert these reactors to fuel that would reduce production of vulnerable nuclear and radiological material.

A major goal of the NNSA's Convert subprogram is to develop, qualify, and deploy a high-density LEU fuel that meets the performance requirements of high-performance research reactors (HPRR) operating with HEU fuel. The U.S. has five such reactors and one critical assembly. A number of other HPRRs are located throughout the world—particularly in Europe and Russia—that could use high-density LEU fuel. Recent PNNL contributions are highlighted here.

**Materials Research for Nuclear Nonproliferation**. PNNL supports the NNSA's Convert subprogram with materials research on unirradiated and irradiated LEU fuel designs. The current design consists of a monolithic LEU-molybdenum (LEU-Mo) alloy fuel foil coated with a thin zirconium diffusion barrier and clad in an aluminum alloy to produce a fuel plate.

PNNL leads the Fuel Fabrication Capability project tasked with developing and deploying a cost-effective and efficient capability that supports conversion and continued operation of U.S. HPRRs with the new LEU-Mo fuel. Our goal is to establish key process-structure-property relationships associated with the LEU-Mo fuel design. Through this effort, fuel performance requirements can be met by ensuring appropriate properties are inherent in the fuel system and processes capable of delivering required properties are developed and deployed.

**Processing**. We are investigating processing capabilities and parameters associated with LEU-Mo fuel manufacturing. These include the rolling process used to produce a monolithic foil from a cast LEU-Mo coupon and

Laboratory-scale rolling mill coupled with a furnace that allows interrupted rolling of LEU-Mo coupons as a function of multiple process parameters is key in obtaining an ideal processing window that delivers the desired microstructure and properties in the product.

technologies to apply zirconium to the foil. Finite element models of the hot rolling process have been developed by PNNL to optimize rolling schedules to improve process and material efficiency and resource use, and to ensure a high-quality product can be manufactured. Simulation results are used to establish the optimum process window for rolling experiments and actual microstructure investigations.

We also have a laboratory-scale capability that allows interrupted rolling of cast LEU-Mo coupons so that properties and microstructure can be interrogated under multiple conditions and at various stages throughout the rolling process. Improved understanding of the processing window provides parameters required to obtain a defect-free product containing the desired microstructure for ideal reactor performance as a function of the number of rolling passes, reduction ratio, temperature, etc.

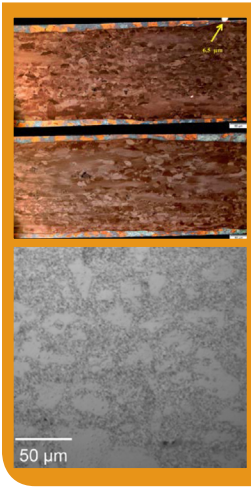
Finally, we are investigating more cost-effective process alternatives to the current co-rolling process for applying the zirconium layer to the monolithic LEU-Mo fuel foils. One promising method is electroplating a thin zirconium layer onto a bare fuel foil, building on PNNL's in-house electroplating experience and established relationships with commercial electroplating and manufacturing companies. We have developed a bench-scale capability to demonstrate the process and are advancing the technology to the lab scale.

Another promising method is co-extrusion of a zirconium layer onto a LEU-Mo billet, resulting in an intermediate shape that can be processed further by rolling into the desired foil shape. Co-extrusion offers the advantage of higher integrity bonding between the zirconium and LEU-Mo because of the higher strains that occur under hydrostatic stress, unlike rolling to bond zirconium and LEU-Mo where stress states are much more complicated because of the proximity of edges and the asymmetric aspect of reduction. PNNL has established a bench-scale capability to co-extrude zirconium and LEU-Mo shapes, adding to the previous extensive knowledge and expertise.

**Structure**. We have a wide array of microscopy capabilities to interrogate material microstructure as a function of process parameters and/or methods. Optical microscopy coupled with SEM and wavelength dispersive spectroscopy provides feedback to experiment design and finite element process model inputs and relationships.

Key considerations associated with microstructure features include segregation of molybdenum within the fuel alloy, which impacts thermodynamic stability of crystallographic phases, and size, distribution, and morphology of impurities and grains that can impact fabrication and in-reactor behavior (e.g., swelling). Hot cell optical microscopy allows us to obtain sample thickness information and investigate microstructural characteristics of irradiated fuel.

**Properties**. PNNL has capabilities to obtain the properties of unirradiated and irradiated fuels subjected to various conditions and fabricated using multiple processes. These provide information that fills important gaps in the uranium-molybdenum (U-Mo) alloy system and data for input to process and performance models.



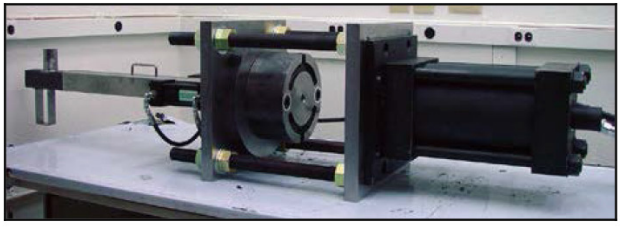

Optical microscopy images of an as-fabricated LEU-Mo fuel foil with zirconium layer on either side (top) and LEU-Mo fuel irradiated to about 60% burnup (bottom).

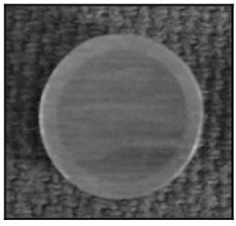
One such gap was in the flow stress property of the U-Mo alloy system, a property important in predicting the alloy's behavior during rolling or extrusion.

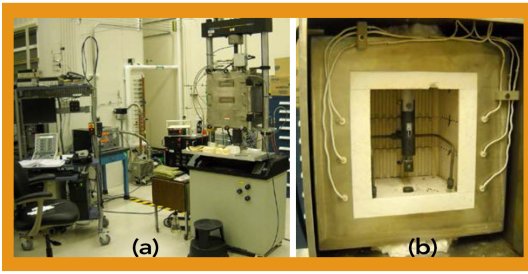
We established a U-Mo compression test capability using an atmosphere-controlled furnace mounted to an Instron hydraulic test frame. Tests can be conducted up to 900°C under argon or other inert gases that minimize sample oxidation.

The load cell used in the current system configuration allows compressive or tensile testing at up to 20,000 pounds. The capability obtains flow

PNNL's bench-top extrusion press is capable of extrusion and co-extrusion of zirconium around a U-Mo billet.







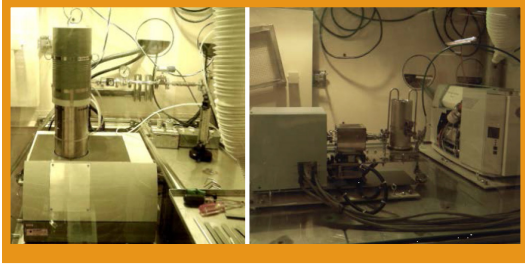

Hot compression test stand (left) with box furnace and compression testing fixture (right) allow scientists to determine the flow stress of the U-Mo alloy system, a property important in predicting how the alloy will behave during thermal-mechanical processing.

stress information on the U-Mo alloy as a function of temperature and strain rate, providing valuable input into the finite element process models.

Another gap is understanding the thermal property behavior as a function of irradiation. Filling this gap provides insight into the performance of the fuel in the very different HPRRs. PNNL has this capability in the RPL, beginning with preparation of small-scale samples from irradiated fuel segments (from 3- x 3-mm up to 9- x 9-mm). The samples are then distributed to instruments in various hot cells for the following thermal property measurements:

- Differential scanning calorimetry to obtain specific heat capacity as a function of temperature
- Gas pycnometry to obtain room-temperature density
- Laser flash apparatus to obtain thermal diffusivity as a function of temperature
- Analytical chemistry digestion and analysis, including inductively coupled plasma-optical emission spectroscopy, gamma energy analysis, alpha energy analysis, and thermal ionization mass spectroscopy
- Thermogravimetric-differential thermal analysis coupled with mass spectroscopy to obtain fission product release as a function of post-irradiation anneal time and temperature.

**Collaborations**. Our collaborators are INL, Los Alamos National Laboratory, Oak Ridge National Laboratory, Y-12 National Security Complex, Babcock & Wilcox Nuclear Operations Group-Lynchburg, and select universities.



Laser flash apparatus installed in the process development cell-2 (PDC-2) hot cell in RPL (left) and thermogravimetric-differential thermal analyzer coupled with mass spectroscopy installed in the PDC-1 hot cell in RPL (right) provide fission product release data as a function of post-irradiation anneal time and temperature.

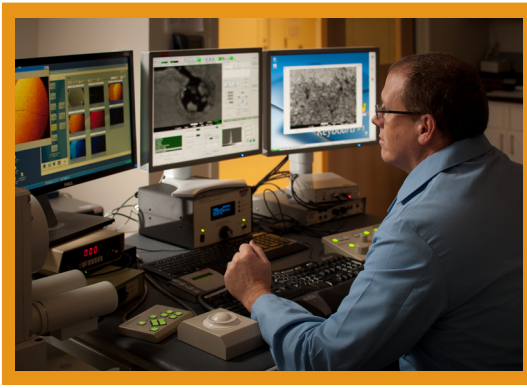
# SCIENTIFIC AND NUCLEAR FACILITIES AND CAPABILITIES AT PNNL

We conduct research on radiation effects in PNNL facilities in Richland, WA, and with our collaborators in facilities in the U.S. and abroad. Four PNNL facilities of particular note relate to our capability to better understand materials in harsh environments:

**EMSL**. A DOE scientific user facility, EMSL contains experimental and computational capabilities that benefit projects involving radiation effects on materials. EMSL's Radiochemistry Annex (RadEMSL) is designed to accelerate scientific discovery and deepen understanding of chemical fate and transport of radionuclides in terrestrial and subsurface ecosystems.

RadEMSL offers experimental and computational tools uniquely suited for actinide chemistry studies. Spectroscopic and imaging instruments are ideally designed for the study of contaminated environmental materials, examination of radionuclide speciation and detection of chemical signatures.

RadEMSL houses nuclear magnetic resonance (NMR) instruments and surface science capabilities, such as X-ray photoelectron spectroscopy, electron microscopy, electron microprobe, TEM, and SEM. Users also have access to expert computational, modeling, and simulation resources and support.



The SEM in RadEMSL is used to examine biological, geologic, and materials science samples. The information about the sample includes external morphology (texture), chemical composition, and crystalline structure and orientation of materials making up the sample.

**Radiochemical Processing Laboratory (RPL)**. As a Hazard Category 2 non-reactor nuclear facility, the RPL houses specialized laboratories for research with microgram-to-kilogram quantities of fissionable materials and megacurie activities of other radionuclides. This facility provides a platform for radiochemical process development, chemical and physical separations, radiomaterial characterization, and reactor dosimetry.

**Materials Science and Technology Laboratory**. One of the five buildings that comprise the PSF, this laboratory contains high-resolution analytical microscopes to characterize irradiated materials. For example, a cesium probe-corrected 200-kV scanning TEM is one of the first instruments of this class to be made available for characterization of highly irradiated materials.

Other instruments include a field emission gun scanning electron microscope, a 3D focused ion beam scanning electron microscope, and a microprobe. These instruments enable energy-dispersive X-ray spectroscopy, wavelength dispersive X-ray spectroscopy, and electron backscatter diffraction at the nanometer scale.

**Radiological Calibrations Facility (RCF)**. The RCF, located in the Hanford Site's 300 Area, contains 13 radiation-generating devices and irradiators. Precise neutron, gamma, and beta irradiations are performed in the facility for radiological calibrations, materials and "hardness" testing, and radiation damage studies.

The facility also has two environmental chambers, a shaker table, and pressure chamber for environmental testing. Among the RCF's primary irradiation and environmental testing capabilities are:

- **Low Scatter Facility (LSF)**: This large (10- x 9- x 15-m) irradiation room was once part of a reactor containment structure. Its 1.37-m-thick, high-density concrete walls allow minimal background interference and scatter. The LSF houses a 14 MeV deuterium and tritium neutron generator, neutron sources ($^{252}$Cf at activities of 2.36 x $10^{-6}$ Ci to 1.12 Ci), and gamma sources ($^{137}$Cs 5 Ci, $^{60}$Co 1.31 x $10^{-1}$ Ci, and $^{241}$Am 2.5 x $10^{-2}$ Ci).
- **High Exposure Facility (HEF)**: The 15.2- x 3.7- x 3.7-m HEF houses five $^{137}$Cs sources and two $^{60}$Co sources from 0.42 mCi to 5,000 Ci with exposure rates from 30 µR/h to 60,000 R/h.
- **X-Ray Facility**: This heavily shielded 5- x 12.5- x 3-m room was once part of a reactor containment structure. It contains two X-ray machines that produce energies from 20 to 300 keV. Graded filter packs provide the necessary beam filtration to achieve each of the about 55 National Voluntary Laboratory Accreditation Program-accredited energy techniques.
- **Well Room**: This room has two gamma and two neutron radiation wells 0.3 m in diameter and

10 m deep. Sources are stored in the well bottom and mechanically raised for irradiation. Wellheads are heavily shielded with lead, concrete, and high-density polyethylene. Gamma wells hold $^{137}$Cs sources of 0.25 Ci and 12.7 Ci, and the neutron wells hold $^{252}$Cf sources of 0.77 Ci and 6.6 mCi.

- **$^{137}$Cs Irradiator**: A Shepherd Model 8 collimated beam irradiator contains a 60-Ci $^{137}$Cs source. Room dimensions are 3.7- x 6.4- x 4- m, and the walls are concrete or lead lined for shielding.
- **Large Environmental Chamber**: This 2- x 1.8- x 1.8-m chamber provides temperature ranges from -40 to 50°C and relative humidity ranges from 20% to 90%. It is primarily used for environmental testing of instruments, appliances, shipping containers, and portal monitors.

## Synthesis, Characterization, and Computational Resources

To conduct atomic- to mesoscopic- to macroscopic-level research, scientists at PNNL integrate synthesis, characterization, and computational tools to understand the behavior of materials in extreme environments.

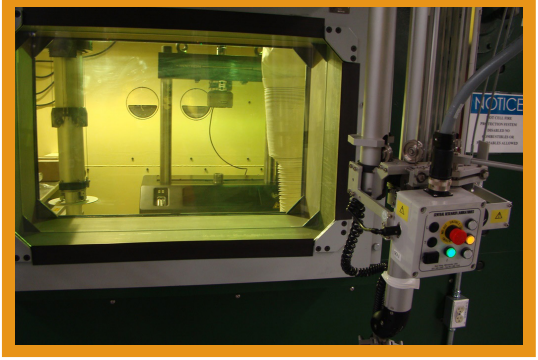
**Creating Materials**. Our synthesis work often begins with complex calculations and simulations to determine the most promising materials to solve a problem. These calculations lead to a more precise selection and design of material systems. Once the material is selected, we have access to fully equipped synthesis laboratories. Our key resources include

- Oxygen-plasma-assisted molecular-beam epitaxy systems that grow high-quality epitaxial oxide thin films and nanostructures, such as thin-film metal oxides. Location: EMSL
- Pulsed laser deposition system that grows uniform, multilayer, or compositionally spread combinatorial complex oxide thin films with abrupt interfaces. Maximum growth temperature is about 1,000°C in up to 1 atm oxygen for non-transparent substrates and 950ºC for transparent substrates. Location: EMSL
- Chemical synthesis labs for design and separation of chemicals and materials to meet specific experiment needs. Location: PSF, EMSL, RPL

**Characterizing Materials**. PNNL has a host of analytical instruments for characterizing materials and understanding defects:

**Instron® 8801 Servohydraulic Fatigue Testing System** – a compact servohydraulic system installed in the RPL in 2015, and used for fatigue testing and fracture mechanics studies of nuclear reactor materials such as cladding. Installation inside the Material Examination Cell 2, a modular hot cell, creates a unique capability for performing PIE of irradiated samples, including actual used fuel.

The Instron@ 8801 Servohydraulic Fatigue Testing System in an RPL modular hot cell.



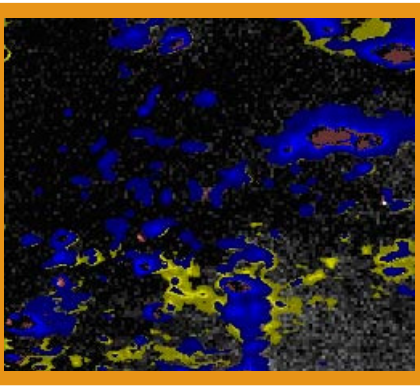

The unit's clamshell furnace allows mechanical testing at temperatures up to 1,100°C. By combining mechanical test data with multiscale modeling and structural information from scanning and transmission electron microscopy, new insights can be obtained into the evolution of structure and thermomechanical properties of highly irradiated materials. Primary clients: DOE's Office of Nuclear Energy and commercial nuclear power customers. Location: RPL

**FEI Tecnai 30S-Twin 300 keV Transmission Electron Microscope** – allows nanometer-scale imaging and phase identification of solid radioactive samples. Coupled with an energy dispersive X-ray spectrometer (EDS) for elemental analysis at similarly high x-y spatial resolution and a Gatan ORIUS digital camera. Special sample preparation techniques have been developed by scientists for handling and preparation of radioactive, dispersible samples. Location: RPL

**FEI Quanta 250 Field Emission Gun SEM** – is equipped with secondary and backscattering imaging detectors (0.5 keV to 30 keV operation) that image samples from millimeter to sub-micron scales and is used to examine coated and noncoated radioactive materials. It is coupled with an EDAX SDD EDS, EDAX TEXS wavelength dispersive spectrometer, and EDAX HIKARI electron backscattered detector for orientation image mapping and structure analysis (links to the Inorganic Crystal Structure Database). Allows crystalline/polycrystalline characteristics of a sample to be identified/mapped, and also mapping of mechanical stresses in a sample. Location: RPL

**Netzsch Laser Flash Apparatus (LFA) Model 457 Microflash** – measures and determines thermal diffusivity and conductivity of a sample by heating one side of a thin sample disk, and measuring the time-dependent temperature

Quanta 250 field emission gun SEM for sample imaging, characterization, and analysis.



An elemental map produced using Auger electron spectroscopy shows strontium (blue) deposited on a concrete sample also containing calcium (white), silicon (red), and sodium (yellow). The association of strontium and silicon suggests that strontium is bound more strongly to the silicate minerals in the concrete than to the other components.

rise on the opposite side. Located in a modular hot cell, the LFA can measure high dose samples such as nuclear reactor fuels. It includes an environmental chamber capable of vacuum, static, or dynamic controlled atmospheres over a temperature range of 25 to 1000°C. Location: RPL

**X-ray Photoelectron Spectrometer** – determines elemental composition of the top 5-10 atomic layers (2-10 nm) of a surface. Photoelectron peak shifts provide chemical (oxidation) state information. An inert gas ion sputter gun allows depth profiles; i.e., concentration profiles as a function of depth into the surface, up to about 500 nm. It uses a relatively low spatial resolution (20 µm) Auger electron spectrometer with secondary electron detector (SED) for sample imaging and low-resolution elemental mapping. A secondary ion mass spectrometry instrument on the system can determine isotopic composition as a function of depth. Location: RPL

**Auger Electron Spectrometers** – use a highly focused 50 kV electron beam to determine elemental composition of the top 5-10 atomic layers (2-10 nm) of a surface. Relatively high spatial resolution (5 µm) allows elemental mapping of surfaces. An SED allows sample imaging at this resolution. Location: RPL

**FEI Helios NanoLab 660 Scanning Electron Microscope-Focused Ion Beam (SEM-FIB)** – is used for sample examination at the sub-nanometer scale and preparing small (micron-size) samples for TEM examination. The SEM-FIB has sub-nanometer resolution. TEM samples produced will be so small that it will be possible to examine many of them with TEM instruments in locations that would otherwise be unable to access these materials, thus leveraging the full TEM capability at PNNL and at other institutions. Location: RPL

**NMR spectroscopy** – probes interactions of nuclei with local electric and magnetic fields. PNNL is home to the world's most advanced radiological NMR spectroscopy facility. Eight instruments (100 to 750 MHz field strengths) are installed in category 2 and 3 laboratories. These instruments provide a full spectrum of state-of-the-art capabilities for measuring solution- and solid-state samples. The versatility of this technique in investigating radiation effects in materials is exemplified by an array of studies on fundamental electronic structure in actinide and technetium complexes, radiation damage in model nuclear waste forms, chelation of actinide metals by organic ligands, and tank waste chemistry. Location: RPL, 331 Building, PSF, EMSL

**Aberration-corrected scanning/TEM** – images materials with sub-angstrom resolution and spectroscopic capabilities. Location: EMSL

**Cesium probe-corrected 200 kV scanning/TEM** – is fully equipped with the latest in analytical detectors, including a high-collection-angle Centurio silicon drift detector for X-ray spectroscopy, a Gatan Quantum 965 GIF, and a high-angle dark field detector. The microscope enables atomic-level analysis from a structural and chemical standpoints. Cesium probe correction produces probes less than 0.1 nm in diameter with high beam currents. Location: PSF

The field emission electron microprobe, or EMP, enables chemical analysis and imaging of radionuclides with high spatial resolution in radioactive samples. Housed in RadEMSL, the EMP allows non-destructive imaging and compositional elemental analysis of solid-phase materials at high spatial resolution with parts-per-million sensitivity.

**Electron paramagnetic resonance spectrometer** – sees radiation-induced spin defects in materials. It performs pulsed and continuous-wave magnetic resonance using electron spins to focus on certain types of molecules, while ignoring others. Location: EMSL

**Field emission gun TEM** – probes compositional fluctuations at interfaces at the nanometer level, by combining the microscope with an Oxford Link EDS. It uses electron probes 1 nm in diameter at 200 kV of accelerating

voltages and also images thin-film samples at much lower magnifications to fully characterize the structure and composition. Location: PSF

**Helium ion microscope** – obtains high-resolution images and chemical analysis with a subnanometer He+ ion probe. It offers fine structure visualization and chemical identification of native-state samples and can generate images of low Z elements, such as organic matter containing carbon, oxygen, hydrogen, and nitrogen. It can also be used in performing site-specific radiation studies of helium bubble formations. Location: EMSL

**Laser-assisted atom probe tomography** – is used to obtain data on structural properties of materials and microstructures within materials caused by defects, elemental diffusion/segregation, and defect trapping along grain boundaries and interfaces. Used with high-resolution TEM, this technique can help determine subtle atomic concentration changes in materials from radiation transmutation and segregation. Location: EMSL

**Sample receiving/preparation and analytical laboratories** – include sample characterization capabilities such as a UV-visible-near-infrared spectrophotometer, inductively coupled plasma mass spectrometry, KPA, uranium analyzer, liquid scintillation counter, micro X-ray diffractometer, carbon analyzer, and dual-station environmental chambers; NMR and electron paramagnetic resonance laboratories; a dual-focused ion beam/SEM laboratory; a high- resolution TEM laboratory; an X-ray photoelectron spectroscopy capability for surface characterization; and a DI Nanoscope atomic force microscope. Location: EMSL, RPL

**Ultrahigh-resolution thermal field emission gun scanning electron microscope** – provides images and allows analysis of nanocrystalline materials and single crystals using electron beams with final probe diameter of less than 10 nm, yet with beam currents in the range of 50 pA to 200 nA. It also allows chemical and structural information to be obtained using an Oxford 80-mm$^2$ X-Max energy-dispersive X-ray spectrometer and an HKL electron backscattered diffraction system. Location: PSF

**Computational resources**. PNNL's extensive computational capabilities perform complex calculations and simulations using a hierarchy of

The 750 MHz wide-bore nuclear magnetic resonance (NMR) in RadEMSL is a multimodal high-field system that allows users to investigate radiologically active rather than proxy model compound samples at high field, leading to an enhanced understanding of radionuclide behavior in the environment.

resources ranging from leading-edge high-performance computing (HPC) to desktop resources. Desktop workstations are used for code development, mid-level clusters for data analysis and visualization, and HPC supercomputers for massively parallel simulations.

EMSL's supercomputer Cascade is a Linux-based system with a peak performance of 3.4 petaflops available on a user proposal basis for computationally intensive research tasks. The HPC research group has extensive experience with algorithm development and modeling and simulation of model realistic systems to study both simple and complex materials and their response to radiation. A few examples are:

- Molecular Science Software Suite (MS3) provides access to high-performance, massively parallel computers for a broad range of applications, including computational chemistry techniques.
- LWR fuel performance audit codes for the NRC—Two examples are FRAPCON-3 and FRAPTRAN codes. The first calculates the steady-state response of fuel rods during long-term burnup. The second estimates how fuel rods would perform during different accident scenarios. In addition to these codes, active research efforts are focused on the development of new and more accurate approaches to phase field methodologies, multi-atom potentials, helium potentials, interatomic potentials for complex materials, and software analysis tools needed by HPC simulation.

EMSL's 3.4 petaflop supercomputer, known as Cascade, was designed to run computationally intensive climate, biological and chemistry simulations.

# STAFF BIOS

PNNL offers staff expertise in a number of topic areas related to radiation effects in materials:

**Measurement and Characterization**

- Edgar Buck
- Herman Cho
- Daniel Edwards
- Lawrence Greenwood
- Weilin Jiang
- Walter Luscher
- Matthew Olszta
- Daniel Schreiber
- Vaithiyalingam Shutthanandan
- Chongmin Wang

**Mechanism and Response**

- Stephen Bruemmer
- Douglas Burkes
- Thak Sang (TS) Byun
- Charles Henager, Jr.
- Ron Omberg
- David Senor
- Mychailo Toloczko
- John Vienna
- Dave Wootan

**Modeling and Simulation**

- Erin Barker
- Ram Devanathan
- Shenyang Hu
- Richard Kurtz
- Yulan Li
- Wahyu Setyawan

**Standards and Regulation**

- Kenneth Geelhood
- Louis Terminello
- Steve Unwin

**Other**

- David Asner
- Sue Clark
- Jim De Yoreo
- Gert Patello

# Edgar Buck, Ph.D.

ENERGY & ENVIRONMENT DIRECTORATE
MEASUREMENT AND CHARACTERIZATION

Phone: (509) 375-5166
E-mail: edgar.buck@pnnl.gov

Edgar Buck is a program manager for the Used Fuel Disposition Project at PNNL looking at radiolysis effects on spent nuclear fuel. He co-authored a special issue in the *MRS Bulletin* on actinide spectroscopy and the Chapter on Uranium for the 3rd edition of the *Chemistry of the Actinide and Transactinide Elements*. He has held other scientific leadership roles, in areas including DARPA projects, nuclear forensics, colloidal migration studies, and PNNL's metal waste form project.

Buck is knowledgeable about the interaction of electron beams with matter, electron and X-ray instrumentation, and materials science with an emphasis on radioactive materials. He has expertise in the long-term behavior of nuclear materials; including oxide spent nuclear fuels, borosilicate glass and ceramic waste forms, radio-colloids, and materials for tritium production. At PNNL, he established a center for nuclear materials microscopy that includes facilities for analysis of classified irradiated materials, as well as the capabilities for performing post-irradiation examination of oxide and metallic fuels with OM, SEM, and TEM. He is currently engaged in developing a DualBeam focused ion beam (FIB) facility for nuclear materials research.

Buck was the lead author on the *Waste Form and In-drift Colloids-Associated Radionuclide Concentrations: Abstraction and Summary*, MDL-EBS-PA-000004 for the Yucca Mountain Repository License Application. He has also conducted data interpretation for the Hanford Waste Treatment Project for more than 8 years and worked for the Tritium Readiness Program conducting Post-Irradiation Analysis of target components for more than 7 years.

He currently teaches a graduate course in electron microscopy at Washington State University Tri-Cities. Buck has served on the EMSL Rad-Facility review committee and is a PNNL contributing expert for morphology issues for the National Technical Nuclear Forensics Center (NTNFC).

**Affiliations and Professional Service**

- UK Royal Society of Chemistry
- Materials Research Society

**Selected Publications**

**Buck EC** and JA Fortner, "Detecting low levels of transuranics with electron energy loss spectroscopy," *Ultramicroscopy* 67, 69-75 (1997).

**Buck EC**, PA Finn, and JK Bates, "Electron energy-loss spectroscopy of anomalous plutonium behavior in nuclear waste materials," *Micron* 34/35, 235-243 (2004).

**Buck EC**, M Douglas, and RS Wittman, "Verifying the presence of low levels of neptunium in a uranium matrix with electron energy-loss spectroscopy," *Micron* 41, 65-70 (2010).

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**Buck EC**, NR Brown, and NL Dietz, "Contaminant uranium phases and leaching at the Fernald site in Ohio," *Environmental Science & Technology* 30, 81-88 (1996).

**Buck EC** and RS Wittman, "The formation and modeling of colloids from the corrosion of nuclear waste forms," *Materials Research Society Symposium Proceedings* 1124, 509-518 (2009).

Strachan DM, RD Scheele, **EC Buck**, JP Icenhower, AE Kozelisky, RL Sell, RJ Elovich, and WC Buchmiller, "Radiation damage effects in candidate titanates for Pu disposition: pyrochlore," *Nuclear Materials* 345, 109-135 (2005).

Strachan DM, RD Scheele, **EC Buck**, AE Kozelisky, RL Sell, RJ Elovich, and WC Buchmiller, "Radiation damage effects in candidate titanates for Pu disposition: ziconolite," *Nuclear Materials* 372, 16-31 (2008).

Douglas M, JI Friese, SB Clark, **EC Buck**, BD Hanson, S Utsunomiya, and RC Ewing, "Microscale characterization of uranium(VI) silicate solids and associated neptunium(V)," *Radiochimica Acta* 93, 265-272 (2005).

# Herman Cho, Ph.D.

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Herman Cho specializes in magnetic resonance spectroscopy, including nuclear magnetic resonance (NMR), electron paramagnetic resonance, and nuclear quadrupole resonance. Over the past 10 years, he has led the creation of a radiological NMR capability at PNNL that has pioneered first-ever achievements in the analysis of highly radioactive materials.

## Affiliations and Professional Service

- EURACT-NMR Scientific Advisory Committee
- EMSL Radiochemistry Advisory Committee
- Peer reviewer for *Journal of the American Chemical Society*, *Journal of Chemical Physics*, *Physical Review A*, *Physical Review Letters*, *Journal of Magnetic Resonance*, *Solid State NMR*, *Geochimica et Cosmochimica Acta*, *American Mineralogist*, *Journal of Physical Chemistry A and B*, *Journal of Solution Chemistry*, *Earth and Planetary Sciences Letters*, *Journal of Geophysical Research*, *Clays and Clay Minerals*, *Geophysical Research Letters*, *Canadian Journal of Chemistry*, and others
- Grant reviewer for National Institutes of Health, U.S. Department of Energy (Office of Science and National Nuclear Security Agency), National Science Foundation, National Aeronautics and Space Administration, and Austrian Science Fund
- Organizer and session chair for numerous national scientific meetings, including the American Chemical Society, Materials Research Society, and Soil Science Society of America

## Selected Publications


**Cho H**, WA de Jong, BK McNamara, BM Rapko, and IE Burgeson, "Temperature and isotope substitution effects on the structure and NMR parameters of the pertechnetate ion in water," *Journal of the American Chemical Society*, 126, 11583-11588 (2004).

Farnan I, **H Cho**, WJ Weber, RD Scheele, NR Johnson, and AE Kozelisky, "High-resolution solid-state nuclear magnetic resonance experiments on highly radioactive ceramics," *Review of Scientific Instruments* 75, 5232-5236 (2004).

**Cho H**, "2-D homonuclear correlation and separated local field experiments for solids with strong homonuclear dipolar couplings," *Solid State NMR* 29, 219-226 (2006).

**Cho H**, AR Felmy, R Craciun, JP Keenum, N Shah, and DA Dixon, "Solution state structure determination of silicate oligomers by $^{29}$Si NMR spectroscopy and molecular modeling," *Journal of the American Chemical Society* 128, 2324-2335 (2006).

Farnan I, **H Cho**, and WJ Weber, "Quantification of actinide alpha-radiation damage in minerals and ceramics," *Nature* 445, 190-193 (2007).

**Cho H**, WJ Shaw, V Parvanov, GK Schenter, A Karkamkar, NJ.Hess, C Mundy, S Kathmann, J Sears, AS Lipton, PD Ellis, and ST Autrey, "Molecular structure and dynamics in the low temperature (orthorhombic) phase of $NH_3BH_3$," *Journal of Physical Chemistry* A 112, 4277-4283 (2008).

**Cho H**, WA de Jong, and CZ Soderquist, "Probing the oxygen environment in $UO_2^{+2}$ by solid-state $^{17}$O NMR spectroscopy and relativistic density functional calculations," *Journal of Chemical Physics* 132, 084501 (2010).

**Cho H**, WA de Jong, AP Sattelberger, F Poineau, and KR Czerwinski, "Comprehensive solid state NMR characterization of electronic structure in ditechnetium heptoxide," *Journal of the American Chemical Society* 132, 13138 (2010).

**Cho H**, WA de Jong, AR Felmy, and CZ Soderquist, "Structure determination of actinide complexes by nuclear magnetic resonance spectroscopy." In: *Plutonium Futures – The Science 2010*. American Nuclear Society, LaGrange Park, Illinois (2010).

# Daniel Edwards, Ph.D.

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Dan Edwards has spent nearly 25 years working at PNNL and abroad, focusing on the characterization of materials using analytical electron microscopy and the mechanical testing of irradiated materials. His early career was spent evaluating the effects of neutron irradiation on structural materials for fusion and fission reactors, encompassing a wide range of Cu-based alloys, austenitic steels, and refractory alloys such as Mo-Re in support of the International Thermonuclear Experimental Reactor (ITER). In the 1990s he worked closely with collaborators worldwide to explore radiation effects on structural materials relevant to ITER. With scientists from Oak Ridge National Laboratory and various institutes in Russia, Edwards performed irradiation experiments in the Bor-60 fast reactor in Russia, providing key data for the ITER materials handbook. He collaborated with scientists at Risø National Laboratory in Denmark and other European scientists to explore fundamental radiation effects in copper alloys.

In the late 1990s he began studying light-water reactor (LWR) materials degradation issues, concentrating on the microstructural characterization of austenitic stainless steels and their susceptibility to IASCC. Edwards remains active with the fusion community and LWR industry, studying radiation effects in model alloys for fusion and various nuclear reactor components, including thimble tubes, core shrouds, top guides, and baffle bolts. He was recently involved in characterizing advanced ferritic-based alloys for fusion reactor applications and a study of irradiation growth and corrosion of Zr-based alloys used in LWR fuel channels and cladding.

A common theme of his work is exploring unexpected, nanoscale changes that occur in an extreme environment, and that can only be probed effectively with high-resolution electron microscopy. Through his experience with such challenging microstructures, Edwards has developed a broad insight on materials characterization for nuclear materials, solid oxide fuel cells, automobile materials, and even a forensic analysis of bolts from the failed NASA Challenger shuttle launch.

Edwards currently oversees various nuclear materials-related research programs and manages the electron microscopy facilities in PNNL's Material Science and Technology Building (3410). His interests are applying aberration-corrected scanning transmission electron microscopy (STEM) to material structure change and exploring more effective ways to capture changes in materials at atomic and nanoscale levels using modern aberration-corrected TEM/STEM and 3D atom probe tomography.

**Selected Publications**

Yao B, **DJ Edwards**, and RJ Kurtz, "TEM characterization of dislocation loops in irradiated bcc Fe-based steels," *Journal of Nuclear Materials* 434, 402-410 (2013).

**Edwards DJ**, FA Garner, P Efsing, and SM Bruemmer, "Nano-cavities observed in a 316SS PWR flux thimble tube irradiated to 33 and 70 dpa," *Journal of Nuclear Materials* 384, 249 (2009).

**Edwards DJ**, LE Thomas, K Asano, S Ooki, SM Bruemmer, "Microstructure, microchemistry and stress corrosion crack characteristics in a BWR 316LSS core shroud weld." In: *Proceedings of the 13th International Symposium on Environmental Degradation of Materials in Nuclear Power Systems*, pp. 1618-1640 (2007).

**Edwards DJ**, E Simonen, and SM Bruemmer, "Radiation-induced segregation behavior in austenitic stainless steels: fast reactor versus light water reactor irradiations." In: *Proceedings of the 13th International Symposium on Environmental Degradation of Materials in Nuclear Power Systems*, pp. 1641-1657 (2007).

Thomas L, **DJ Edwards**, and K Asano, "Crack-tip characterization in BWR service components." In: *Proceedings of the 13th International Symposium on Environmental Degradation of Materials in Nuclear Power Systems*, pp. 1693-1710 (2007).

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**Edwards DJ**, EP Simonen, and SM Bruemmer, "Evolution of fine-scale defects in neutron-irradiated stainless steels," *Journal of Nuclear Materials* 317, 13 (2003).

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Lawrence Greenwood is recognized as an expert on the measurement of neutron exposure in fission reactors and accelerator-based neutron sources. He has developed the STAYSL PNNL computer code for neutron spectral analysis and the SPECTER computer code, which is widely used to calculate fundamental radiation damage in irradiated materials. He helped to develop the International Reactor Dosimetry and Fusion File (IRDFF 2014) as a consultant to the International Atomic Energy Agency and is helping to test and extend this file to higher neutron energies for fusion applications. He operates a certified laboratory for the International Monitoring System of the Comprehensive Test Ban Treaty Organization. His research interests and experience include nuclear forensics, advanced gamma spectroscopy techniques, and the production of medical isotopes. He has more than 200 publications and has made more than 100 presentations at national and international meetings.

**Affiliations and Professional Service**

- Editorial Board, *Journal of ASTM International*
- American Physical Society
- American Nuclear Society
- Sigma Xi
- American Society for Testing and Materials, where he serves on the Program Committee for International Symposium for Reactor Dosimetry

**Awards and Recognition**

- Federal Laboratory Consortium Award for the development of seeds for the treatment of prostate cancer with IsoRay (2006)
- R&D 100 Award for cesium-131 seeds with IsoRay (2006)
- Battelle Key Contributor Award 2012

**Selected Publications**

**Greenwood LR**, R Wittman, LA Metz, EC Finn, and JI Friese, "Design and Testing of a $^{10}$B4C Capsule for Spectral-Tailoring in Mixed-Spectrum Reactors," *Nuclear Instruments and Methods in Physics Research A* 743, 121-123 (2014).

Simakov S, **L Greenwood**, and RC Noy, "Validation of the International Reactor Dosimetry and Fusion File," *Progress in Nuclear Science and Technology* 4, 591-595 (2014).

**Greenwood LR** and CD Johnson, *User Guide for the STAYSL PNNL Suite of Software Tools*, PNNL-22263, Pacific Northwest National Laboratory, Richland, WA (2013).

Metz LA, JI Friese, EC Finn, **LR Greenwood**, RF Kephart, CC Hines, MD King, K Henry, and DE Wall, "Fission Yield Measurements from Highly Enriched Uranium Irradiated Inside a Boron Carbide Capsule," *Journal of Radionuclide and Nuclear Chemistry* 296(2):763-767 (2013).

Miley HS, TW Bowyer, MD Engelmann, PW Eslinger, JI Friese, **LR Greenwood**, DA Haas, JC Hayes, ME Keillor, RA Kiddy, II, RR Kirkham, JW Landen, EA Lepel, LS Lidey, KE Litke, SJ Morris, KB Olsen, RC Thompson, BR Valenzuela, VT Woods, and SR Biegalski, "Measurement of Fukushima Aerosol Debris in Sequim and Richland, WA and Ketchikan, AK," *Journal of Radioanalytical and Nuclear Chemistry* 296(2):877-882 (2013).

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Miley HS, TW Bowyer, **LR Greenwood**, and RJ Arthur, "Fission product ratios as treaty monitoring discriminants." *Journal of Radioanalytical and Nuclear Chemistry* 276(2):483-487 (2008).

Griffiths M, FJ Butcher, FA Garner, and **LR Greenwood**, "Spectral effects on stress relaxation of Inconel X-750 springs in CANDU reactors," International Conference of Physics of Radiation Phenomena and Radiation Material Science, Alushta, Crimea (2009).

**Greenwood LR** and JP Foster, "Retrospective reactor dosimetry with zirconium alloy samples." In *State of the Art 2008 Reactor Dosimetry*, pp. 58-66, World Scientific, Hackensack, NJ (2008).

# Weilin Jiang, Ph.D.

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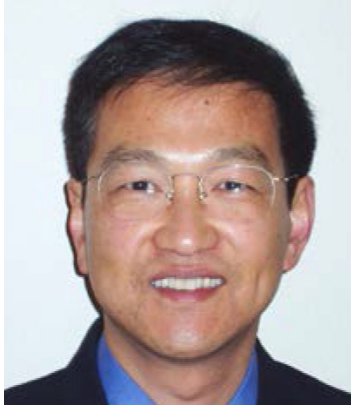

Weilin Jiang joined PNNL in 2000 after his postdoctoral research at PNNL. His research areas range from advanced structural materials for future fission and fusion reactors, model nuclear waste forms, novel nuclear sensor materials, to tritium breeder materials. Major focus areas are ion-beam irradiation-induced effects in solid materials, including single crystals, nanocrystalline materials, and nanocomposites of carbides, nitrides, oxides and metals. Jiang's research has addressed:

- Defect accumulation and amorphization processes
- Diffusion, trapping, and clustering of defects and implanted species
- Secondary-phase precipitation
- Formation of voids and gas bubbles
- Material radiolysis
- Phase segregation
- *In-situ* study of microstructural evolution induced by ion-beam irradiation
- Thermal and dynamic defect recovery
- Defects, amorphization, lattice strain, and recrystallization at interfaces.

In addition, he has investigated ion stopping powers, charge state distributions and scattering/reaction cross sections, and has developed novel ion-beam analytical methods. Jiang has more than 200 publications.

**Affiliations and Professional Service**

- American Association for Advancement of Science
- Materials Research Society
- Minerals, Metals and Materials Society
- American Ceramic Society
- American Physical Society
- Organizer and chair of technical sessions at numerous international conferences
- Editorial and advisory board member for two technical journals
- Referee of manuscripts for more than a dozen major international journals
- Peer reviewer of DOE Office of Science proposals

**Awards and Recognition**

- EED Exceptional Contribution Award (2014)
- Data selected by IAEA for a widely available EXFOR database (2011)
- Outstanding Performance Award, PNNL (2003, 2004)

**Selected Publications**

**Jiang W**, HJ Jung, L Kovarik, Z Wang, TJ Roosendaal, Z Zhu, DJ Edwards, SY Hu, CH Henager, Jr., RJ Kurtz, and Y Wang, "Magnesium Behavior and Structural Defects in $Mg^+$ Ion Implanted Silicon Carbide," *Journal of Nuclear Materials* 458, 146 (2015).

**Jiang W**, CH Henager, Jr., TVarga, H J Jung, NR Overman, C Zhang, and J Gou, "Diffusion of Ag, Au and Cs Implants in MAX Phase $Ti_3SiC_2$," *Journal of Nuclear Materials* 462, 310 (2015).

**Jiang W**, JA Sundararajan, T Varga, ME Bowden, Y Qiang, JS McCloy, CH Henager, Jr., and RO Montgomery, "In-situ Study of Nanostructure and Electrical Resistance of Nanocluster Films Irradiated with Ion Beams," *Advanced Functional Materials* 24, 6210 (2014).

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**Jiang W**, R Devanathan, CJ Sundgren, M Ishimaru, K Sato, T Varga, S Manandhar, and A Benyagoub, "Ion Tracks and Microstructures in $BaTiO_3$ Irradiated with Swift Heavy Ions: A Combined Experimental and Computational Study," *Acta Materialia* 61, 7904 (2013).

McCloy JS, **W Jiang**, T Troubay, T Varga, L Kovarik, J Sundararajan, M Kaur, Y Qiang, E Burks, and K Liu, "Ion Irradiation of Fe-Fe Oxide Core-Shell Nanocluster Films: Effects of Interface on Stability of Magnetic Properties," *Journal of Applied Physics* 114, 083903 (2013).

**Jiang W**, RM Van Ginhoven, L Kovarik, JE Jaffe, and BW Arey, "Superlattice Structure and Precipitates in $O^+$ and $Zr^+$ Ion Co-implanted $SrTiO_3$: a Model Waste Form for $^{90}Sr$," *Journal of Physical Chemistry C* 116, 16709 (2012).

**Jiang W**, JS McCloy, AS Lea, J A Sundararajan, Q Yao, and Y Qiang, "Magnetization and Susceptibility of Ion Irradiated Granular Magnetite Films," *Physical Reviews B* 83, 134435 (2011).

**Jiang W**, L Jiao, and H Wang, "Transition from irradiation-induced amorphization to crystallization in nanocrystalline silicon carbide," *Journal of the American Ceramic Society* 94, 4127 (2011).

**Jiang W**, H Wang, I Kim, Y Zhang, and WJ Weber, "Amorphization of Nanocrystalline 3C-SiC Irradiated with $Si^+$ Ions," *Journal of Materials Research* 25, 2341 (2010).

# Walter Luscher, Ph.D.

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Walter Luscher is a materials scientist with expertise in physical metallurgy and ceramic science, and has used a variety of materials characterization techniques to evaluate the physical, mechanical, and thermal properties of materials. He routinely applies statistical methods for designing experiments that efficiently explore processing envelopes to identify and optimize key fabrication parameters. This has been integral to deriving solutions ranging from the development of high specific strength proppant media for the oil and natural gas industry to fabrication of specialty components that exhibit tailored oxidation performance for the nuclear industry.

At PNNL, Luscher is actively involved in placing significant performance requirements on materials subjected to irradiation. A working knowledge of irradiation effects on material properties facilitates modeling efforts of PNNL's fuel performance analysis group, which is charged with maintaining and updating material performance models within FRAPCON-3 and FRAPTRAN fuel performance codes for the Nuclear Regulatory Commission (NRC). Luscher manages the Code Users Group, which distributes codes and related documentation to industry and academia to further nuclear fuel modeling efforts. He is also involved with the Tritium Technology Program (TTP), which oversees design and fabrication of tritium producing burnable absorber rods (TPBARs) used in commercial pressurized-water reactors. In addition to providing TPBAR design and fabrication guidance, he also participates in the design and analyses of in- and ex-reactor tests, including post-irradiation examination (PIE), needed to assess performance of new and existing components supporting advanced design and predictive modeling efforts.

Luscher has been involved with the development, execution, and analyses of in-reactor tests conducted at the advanced test reactor (ATR). In-reactor oxidation performance of zirconium alloys (TMIST-1) and hydrogen permeation performance of stainless steels (TMIST-2) were evaluated through in-reactor test campaigns to support the TTP. A third experiment is currently under way (TMIST-3) to evaluate in-reactor speciation and release kinetics of tritium from lithium aluminate during irradiation. He also has experience with the PIE of TPBARs and the characterization of irradiated nuclear fuels, and the Fuel Thermo-Physical Characterization Project for the Global Threat Reduction Initiative (GTRI).

Luscher has attended and presented technical data at numerous domestic and international conferences, authored government reports and peer-reviewed technical journals, and is lead inventor on a patent for fabricating proppants with tailored microstructures.

### Honors and Accomplishments

- Outstanding Performance Award for supporting design and fabrication of TMIST-3 in-reactor test (2011)
- Completed PNNL Scientist and Engineering Development Program (2010)
- Attended school for fuel behavior at international test reactor in Halden, Norway (2009)
- The Rustum and Della Roy Innovation in Materials Research Award at The Pennsylvania State University (2007)

### Affiliations and Professional Service

- American Nuclear Society, ANS
- American Ceramic Society, ACerS
- Minerals, Metals, and Materials Society, TMS; Nuclear Materials Committee member

### Selected Publications

Burkes DE, AJ Casella, AM Casella, **WG Luscher**, FJ Rice, and KN Pool, "Measurement of fission gas release from irradiated U-Mo monolithic fuel samples," *Nuclear Materials* 461, 61-71 (2015).

**Luscher WG**, DJ Senor, KK Clayton, and GR Longhurst, "In-reactor oxidation of Zircaloy-4 under low water vapor pressures," *Nuclear Materials* 456, 17-22 (2015).

**Luscher WG**, DJ Senor, KK Clayton, and GR Longhurst, "*In situ* measurement of tritium permeation through stainless steel," *Nuclear Materials* 437, 373-379 (2013).

**Luscher WG**, ER Gilbert, SG Pitman, and EF Love Jr. , "Surface modification of Zircaloy-4 substrates with nickel zirconium intermetallics," *Nuclear Materials* 433, 514-522 (2013).

**Luscher WG** and KJ Geelhood, "Material property correlations: comparisons between FRAPCON-3.4, FRAPTRAN 1.4, and MATPRO," NUREG/CR-7024, PNNL-19417, Pacific Northwest National Laboratory for the U.S. Nuclear Regulatory Commission (2011).

**Luscher WG**, JR Hellmann, AE Siegel, DL Shelleman, and BE Scheetz, "A critical review of the diametral compression method for determining the tensile strength of spherical aggregates," *Testing and Evaluation* 35(6) (2007).

**Luscher WG**, JR Hellmann, and BE Scheetz, "Strength enhancement of alumino-silicate aggregate through modified thermal treatment," *International Journal of Applied Ceramic Technology* 3(2), 157-165 (2006).

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Matt Olszta jointed PNNL in 2007 as a materials scientist. His research expertise and focus include:

- Polymers to biomimetic materials to electrolytic capacitor technology
- Cultivated analytical microscopy skills necessary for the high-resolution characterization of metal, intermetallic and ceramic interfaces
- Environmental degradation of corrosion-resistant metallic alloys in nuclear power systems
- Overseeing the JEOL ARM200F aberration-corrected microscope
- Crack tip and surface analysis of failed reactor components
- Developed focused ion beam milling techniques for capturing grain boundaries
- Oxidation structures and crack tips for ATEM and atom probe tomography analysis.

## Education

- B.S. Materials Science and Engineering University of Illinois at Champaign Urbana
- M.S. Materials Science and Engineering University of Florida
- Ph.D. Materials Science and Engineering University of Florida

## Selected Publications


Luo L, L Zou, DK Schreiber, **MJ Olszta**, DR Baer, SM Bruemmer, G Zhou, and CM Wang, "*In Situ* Atomic Scale Visualization of Surface Kinetics Driven Dynamics of Oxide Growth on a Ni-Cr Surface," *Chemical Communications* 52(16), 3300-3303 (2016).

**Olszta MJ**, DK Schreiber, MB Toloczko, and SM Bruemmer. "Ally 690 surface nanostructures during exposure to PWR primary water and potential influence on stress corrosion cracking initiation," In: *16th International Conference on Environmental Degradation of Nuclear Power Systems. The Minerals, Metals and Materials Society*, in press (2013).

**Olszta MJ**, D Schreiber, L Thomas, and S Bruemmer, "High-Resolution Crack Imaging Reveals Degradation Processes in Nuclear Reactor Structural Materials," *Advanced Materials & Processes* 170, 17-21 (2012).

**Olszta MJ**, DK Schreiber, LE Thomas, and SM Bruemmer, "Penetrative Internal Oxidation from Alloy 690 Surfaces and Stress Corrosion Crack Walls during Exposure to PWR Primary Water," In: *15th International Conference on Environmental Degradation of Materials in Nuclear Power Systems-Water Reactors*, pp. 331-342 (2011).

**Olszta MJ**, DK Schreiber, LE Thomas, and SM Bruemmer, "Electron Microscopy Characterizations and Atom Probe Tomography of Intergranular Attack in Alloy 600 Exposed to PWR Primary Water," In: *15th International Conference on Environmental Degradation of Materials in Nuclear Power Systems-Water Reactors*, pp. 1503-1516 (2011).

**Olszta MJ** and EC Dickey, "Interface Stoichiometry and Structure in Anodic Niobium Pentoxide," *Microscopy and Microanalysis* 14, 451 (2008).

**Olszta MJ**, X Cheng, SS Jee, R Kumar, YY Kim, SS Jee, MJ Kaufman, L Gower, and EP Douglas, "Bone Structure and Formation: A New Perspective," *Materials Science and Engineering R-Reports* 58, 77-116 (2007).

**Olszta MJ**, J Wang, and EC Dickey, "Stoichiometry and Valence Measurements of Niobium Oxides using Electron Energy-Loss Spectroscopy," *Journal of Microscopy* 224, 233 (2006).

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Daniel Schreiber is an internationally recognized leader in nanoscale microstructural characterization of materials using a combination of electron microscopy and atom probe tomography. He has developed correlated high-resolution analytical techniques to study corrosion and stress corrosion cracking processes in nuclear materials and environments. He has also performed fundamental experiments on selective oxidation processes in model alloy systems in high-temperature water environments.

## Affiliations and Professional Service

- Microscopy Society of America
- Materials Research Society
- Session chair/co-organizer for meetings and workshops on correlated electron microscopy/atom probe tomography and sample preparation methods
- Peer reviewer for numerous microscopy, materials science, and physics journals
- Proposal reviewer for Center for Nanophase Materials Sciences (Oak Ridge National Laboratory)
- Former board member of the Electron Microscopy Center's Users Executive Committee (Argonne National Laboratory)

## Selected Publications


**Schreiber DK**, MJ Olszta, and SM Bruemmer, "Directly correlated transmission electron microscopy and atom probe tomography of grain boundary oxidation in a Ni–Al binary alloy exposed to high-temperature water," *Scripta Materialia* 69(7), 509-512 (2013).

**Schreiber DK**, MJ Olszta, DW Saxey, K Kruska, S Lozano-Perez, KL Moore, and SM Bruemmer, "Examinations of oxidation and sulfidation of grain boundaries in alloy 600 exposed to simulated PWR primary water," *Microscopy & Microanalysis* 19(3), 676-687 (2013).

Gin S, JV Ryan, **DK Schreiber**, J Neeway, and M Cabie, "Contribution of atom-probe tomography to a better understanding of glass alteration mechanisms: Application to a nuclear glass specimen altered 25 years in a granitic environment," *Chemical Geology* 349-350, 99-109 (2013).

Gamalski AD, DE Perea, J Yoo, MJ Olszta, R Colby, **DK Schreiber**, C Ducati, ST Picraux, and S Hofmann, "Catalyst Composition and Impurity-Dependent Kinetics of Nanowire Heteroepitaxy," *ACS Nano* 7(9), 7689-7697 (2013).

**Schreiber DK**, MJ Olszta, and SM Bruemmer, "Complementary Atom Probe Tomography and Electron Microscopy of Oxidation of Ni-Base Alloys in High-Temperature Water Environments," *Proceedings of Microscopy & Microanalysis*, accepted/in press (2013).

**Schreiber DK**, MJ Olszta, LE Thomas, and M Bruemmer, "Grain Boundary Characterization of Alloy 600 Prior to and After Corrosion by Atom Probe Tomography and Transmission Electron Microscopy," *Proceedings of the 16th International Conference of Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors*, NACE International, accepted/in press (2013).

**Schreiber DK**, P Adusumilli, ER Hemesath, DN Seidman, AK Petford-Long, and LJ Lauhon, "A Method for Directly Correlating Site-Specific Cross-Sectional and Plan-View Transmission Electron Microscopy of Individual Nanostructures," *Microscopy & Microanalysis* 18(6) 1410-1418 (2012).

Hemesath ER, **DK Schreiber**, CF Kisielowski, AK Petford-Long, and LJ Lauhon, "Atomic structural analysis of nanowire defects and polytypes enabled through cross-sectional lattice imaging," *Small* 8(11), 1717-1724 (2012).

Hemesath ER, **DK Schreiber**, EB Gulsoy, CF Kisielowski, AK Petford-Long, PW Voorhees, and LJ Lauhon, "Catalyst incorporation at defects during nanowire growth," *Nano Letters* 12(1) 167-171 (2012).

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**Schreiber DK**, YS Choi, YZ Liu, AN Chiaramonti, DN Seidman, and AK Petford-Long, "Enhanced magnetoresistance in naturally oxidized MgO-based magnetic tunnel junctions with ferromagnetic CoFe/CoFeB bilayers," *Applied Physics Letters* 98(23), 232506 (2011).

**Schreiber DK**, YS Choi, YZ Liu, AN Chiaramonti, DN Seidman, and AK Petford-Long, "Effects of elemental distributions on the behavior of MgO-based magnetic tunnel junctions," *Journal of Applied Physics* 109(10), 103909 (2011).

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Shuttha Shutthanandan has an international reputation for his research studies of materials synthesis, modification, and characterizations using state-of-the-art ion beam and X-ray beam techniques. At PNNL, he actively participates in several projects involving research on the kinetic, dynamic, and energetic considerations of thin-film growth of metals-on-metals and oxides-on-semiconductor systems; surface and buried interface analysis using ion beams; development of novel materials for spintronics, high-dielectric, catalysts, battery and fuel cell applications; atmospheric aerosols analysis; ion beam modification and synthesis of nano materials; hydrogen interaction with materials; radiation effects in solids; and studies of ion exchange mechanism in waste storage model systems. Most recently, he is working on integrating new technologies such as high-resolution XPS imaging and helium ion microscopes to enhance sub-nanometer depth profiling, imaging, and site-specific radiation studies.

**Affiliations and Professional Service**

- International advisory committee member – BioPIXE
- Short course committee member – American Vacuum Society (AVS)
- Past President and current board member – Pacific Northwest Chapter of the AVS
- Co-Chair – Ion Beam Analysis 2013, Surface Analysis 2012 and BIOPIXE 6 International Conferences
- Chair – 21st Annual symposium of the Pacific Northwest Chapter of AVS 2010
- Organized symposia for the AVS, CAARI, ACrS, MST, and Surface Analysis 2004 Conferences
- Chair of the local arrangement committee, Surface Analysis 2004
- Co-Editor – Proceedings of the 21st international conference on Ion Beam Analysis, *Nuclear Instruments and Methods in Physics Research*. Section B Volume 332, (2014)
- Co-Editor – Proceedings of the sixth international symposium on BioPIXE, *International Journal of PIXE*, Volume 18, No 3 & 4 (2008)

**Awards and Recognition**

- Award of Appreciation, International Committee of IBA (2013)
- DOE Office of Science Mentor of the Year Award (2011)
- PNNL Director's Fitzner/Eberhardt Award for Outstanding Contributions to Science and Engineering Education (2007)
- Outstanding Contribution Award, International Advisory Committee BioPIXE Conference (2008)
- Outstanding Contribution Award, Pacific Northwest Chapter of the AVS (2004)

**Selected Publications**

Huang HC, L Zhang, G Malladi, JI Dadap, S Manandhar, K Kisslinger, VRS Vemuri, **V Shutthanandan**, H Bakhru, and R Osgood, "Radiation damage by light- and heavy-ion bombardment in single-crystal linbo3," *Optical Materials Express* 5(5) (2015).

**Shutthanandan V**, Z Zhu, ML Stutzman, F Hannon, C Hernandez-Garcia, MI Nandasiri, SVNT Kuchibhatla, S Thevuthasan, and WP Hess, "Surface science analysis of gas photocathodes following sustained electron beam delivery," *Physical Review Special Topics - Accelerators and Beams* 15(6), 063501 (2012).

Wang CM, TC Kaspar, **V Shutthanandan**, AG Joly, L Kovarik, BW Arey, M Gu, A Devaraj, BD Wirth, and RJ Kurtz, "Structure and radiation damage behavior of epitaxial CrxMo1-x alloy thin films on MgO," *Journal of Nuclear Materials* 437(1-3), 55-61 (2013).

**Shutthanandan V**, S Thevuthasan, EM Iuliano, and WB Seales, "PIXE analysis on an ancient Scroll sample," *International Journal of PIXE* 18(3-4), 279-284 (2008).

**Shutthanandan V**, YL Xie, RS Disselkamp, NS Laulainen, EA Smith, and S Thevuthasan, "Multi-technique approach to measure size and time resolved atmospheric and radionuclide aerosols," *International Journal of PIXE* 18(3-4), 209-218 (2008).

**Shutthanandan V**, S Thevuthasan, T Droubay, TC Kaspar, A Punnoose, J Hays, and SA Chambers, "Quantification of dopant concentrations in diluted magnetic semiconductors using ion beam techniques," *Nuclear Instruments and Methods in Physics Research. Section B, Beam Interactions with Materials and Atoms* 249(1-2), 402-405 (2006).

**Shutthanandan V**, S Thevuthasan, T Droubay, SM Heald, MH Engelhard, DE McCready, SA Chambers, P Nachimuthu, and BS Mun, "Synthesis of room-temperature ferromagnetic Cr-doped $TiO_2$(110) rutile single crystals using ion implantation," *Nuclear Instruments and Methods in Physics Research. Section B, Beam Interactions with Materials and Atoms* 242(1-2), 198-200 (2006).

**Shutthanandan V**, S Thevuthasan, SM Heald, T Droubay, MH Engelhard, TC Kaspar, DE McCready, LV Saraf, SA Chambers, BS Mun, NM Hamdan, P Nachimuthu, B Taylor, R Sears, and B Sinkovic, "Room-temperature ferromagnetism in ion-implanted co-doped $TiO_2$(110) rutile," *Applied Physics Letters* 84(22), 4466-4468 (2004).

# Chongmin Wang, Ph.D.

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Chongmin Wang has expertise on atomic-level characterization and visualization of materials structure using electron microscopy and spectroscopy. He works on correlating materials' structural and functional properties with their atomic and electronic structure and their chemical compositions; in particular, focusing on nanomaterials related to energy conversion, storage, and sustainability.

He recently began work on an *in situ* atomic-level study of materials relevant to electrochemical process (energy conversion and storage, including work on the lithium-ion battery), chemical reactions (catalytic process), materials behavior under extreme environment (such as stress-strain, impurity/dopant segregation, grain-boundary or interface-mediated mass transport, defect clustering), radiation damage, and stress corrosion. These aspects of his research provide insights for correlating properties and structure at the nanometer scale under dynamic reaction conditions. Wang's research has been highlighted as covers and reviews in journals and media such as *Science*, *Science Daily*, *Nano Letters*, *Nanotechnology*, *Materials Today*, *Advanced Materials*, *Journal of Physical Chemistry B*, *Ultramicroscopy*, *C&N News*. He has authored or co-authored more than 270 peer-reviewed papers and has an H-index of 60.

**Affiliations and Professional Service**

- Materials Research Society
- Microscopy Society of America
- Lead organizer, Symposium on Materials for Nuclear Applications and Extreme Environments, 2010 Spring Meeting of the Materials Research Society, San Francisco, CA
- Lead organizer, Symposium on the Frontier of Chemical Imaging across Electrons, Photos, and Ions, 2012 Fall Meeting of the Materials Research Society, Boston, MA
- Lead Organizer, Symposium on In-situ Operando Probing of Energy Materials at Multiscale down to Single Atomic Column, 2010 Spring Meeting of the Materials Research Society, San Francisco, CA

- Lead Organizer, Symposium on Transmission Electron Microscopy and Spectroscopy at or Near Realistic Conditions, 2010 Microscopy and Microanalysis, Portland, OR

**Awards and Recognition**

- Microscopy Today Innovation Award, In-situ TEM of Li-ion Batteries, Team Lead (2012)
- R&D 100 Award, Graphene Nanostructures for Lithium Batteries (2012)
- Japanese Outstanding Invention Award, Ministry of Science and Education of Japan (2001)
- Rowland B. Snow Award, American Ceramic Society (1999)
- Alexander von Humboldt Research Fellowship Award, Germany (1994)

**Selected Publications**

**Wang CM**, "*In Situ* Transmission Electron Microscopy and Spectroscopy Studies of Rechargeable Batteries under Dynamic Operating Conditions: A Retrospective and Perspective View," Invited review on special issue of in-situ diagnosis, *Journal of Materials Research* 30, 326-339 (2015).

**Wang CM**, HG Liao, and FM Ross, "Observation of Materials Processess in Liquids by Electron Microscopy," *MRS Bulletin* 40, 46-52 (2015).

Xin H, S Alayoglu, R Tao, A Genc, **CM Wang**, L Kovarik, EA Stach, LW Wang, M Salmeron, GA Somorjai, and H Zheng, "Revealing the Atomic Restructuring of Pt–Co Nanoparticles," *Nano Letters* 14, 3203-3207 (2014).

Genc A, L Kovarik, M Gu, HK Cheng, P Plachinda, L Pullan, B Freitag, and **CM Wang**, "XEDS STEM Tomography for 3D Chemical Characterization of Nanoscale Particles," *Ultramicroscopy* 131, 24-32 (2013).

Gu M, ZG Wang, JG Connell, DE Perea, LI Lauhon, F Gao, and **CM Wang**, "Electronic Origin for the Phase Transition from Amorphous LixSi to Crystalline $Li_{15}Si_4$," *ACS Nano* 7, 6303-6309 (2013).

**Wang CM**, TC Kaspar, V Shutthanandan, AG Joly, and RJ Kurtz, "Structure of Cr Film Epitaxially Grown on MgO(0 0 1)," *Acta Materialia* 59, 4274-4282 (2011).

**Wang CM**, W Xu, J Liu, JG Zhang, LV Saraf, BW Arey, DW Choi, ZG Yang, J Xiao, S Thevuthasan, and DR Baer, "*In Situ* Transmission Electron Microscopy Observation of Microstructure and Phase Evolution in a $SnO_2$ Nanowire during Lithium Intercalation," *Nano Letters* 11, 1874 (2011).

Huang JY, L Zhong, **CM Wang**, JP Sullivan, W Xu, LQ Zhang, SX Mao, NS Hudak, XH Liu, A Subramanian, HY Fan, LA Qi, A Kushima, and J Li, "*In Situ* Observation of the Electrochemical Lithiation of a Single $SnO_2$ Nanowire Electrode," *Science* 330, 1515 (2010).

# Stephen Bruemmer, Ph.D.

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MECHANISM AND RESPONSE

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Stephen Bruemmer has led a diverse set of research programs in materials science during his 38 years at PNNL. His experience includes serving as technical group leader, program manager, and principal investigator. He has led a group of material scientists and specialists focused on the study of materials interfaces and their influence on physical and structural properties for the last 15 years. Research led to more than 340 technical publications (about 50 over the last 5 years) and 75 invited presentations in the areas of grain boundary science, environmental degradation, crack-tip phenomena, and radiation effects on materials. An area of emphasis has been the high-resolution measurement, understanding, and prediction of microstructural and microchemical effects on the structural reliability of materials in nuclear power systems.

Much of Bruemmer's research has examined atomistic interfacial processes to help determine root causes for macroscopic failure phenomenon. The study of crack tips in relation to corrosion and cracking mechanisms has been a key focus of recent activities.

**Affiliations and Professional Service**

- Co-organizer for the International Cooperative Group on Environment-Assisted Cracking Meetings and the International Conferences on Environmental Degradation of Materials in Nuclear Power Systems
- Member of numerous expert panels in the United States, Japan, and China
- Co-organized workshops for the Department of Energy (DOE) Office of Basic Energy Sciences, including High-Temperature Materials for Advanced Reactor Systems with DOE Office of Nuclear Energy, and Science and Technology and Radiation Materials Science for the Structural Integrity of Reactor Components with Electric Power Research Institute

**Awards and Recognitions**

- Fellow of National Association of Corrosion Engineers and ASM International, society awards include the Distinguished Service Award for the Minerals, Metals and Materials Society

**Selected Publications**

Schreiber DK, MJ Olszta, DW Saxey, K Kruska, K Moore, S Lozano-Perez, and **SM Bruemmer**, "Examinations of Oxidation and Sulfidation of Grain Boundaries in Alloy 600 Exposed to PWR Primary Water," *Microscopy and Microanalysis* 19(3), 1-12 (2012).

Xu Z, KM Rosso, and **SM Bruemmer**, "Metal Oxidation Kinetics and the Transition from Thin to Thick Films," *Physical Chemistry Chemical Physics* 14(42), 14534 (2012).

Olszta MJ, DK Schreiber, LE Thomas, and **SM Bruemmer**, "High Resolution Crack Imaging reveals Degradation Processes in Nuclear Reactor Structural Materials," *ASM Advanced Materials & Processes* 4, 17 (2012).

**Bruemmer SM**, MJ Olszta, MB Toloczko, and LE Thomas, "Linking Grain Boundary Microstructure to Stress Corrosion Cracking of Cold-Rolled Alloy 690 in PWR Primary Water," *Corrosion Journal* 69(10), 953-963 (2013).

Wang C, A Genc, H Cheng, L. Pullan, DR Baer, and **SM Bruemmer**, "In-Situ TEM Visualization of Vacancy Injection and Chemical Partitioning During Oxidation of Ni-Cr Nanoparticles," *Scientific Reports* 4, 3683 (2014).

Schreiber DK, MJ Olszta, and **SM Bruemmer**, "Directly Correlated Transmission Electron Microscopy and Atom Probe Tomography of Grain Boundary Oxidation in Ni-Al Binary Alloy Exposed to High-Temperature Water," *Scripta Materialia* 69(7), 509 (2013).

Xu Z, D Li, DK Schreiber, KM Rosso, and **SM Bruemmer**, "Modeling Selective Intergranular Oxidation of Binary Alloys," *Journal Chemical Physics* 142, 014704 (2015).

Schreiber DK, MJ Olszta, and **SM Bruemmer**, "Grain Boundary Chromium Depletion and Migration During Selective Oxidation in Ni-5Cr Binary Alloy Exposed to Hydrogenated Water," *Scripta Materialia* 89, 41 (2014).

Alexandrov V, ML Sushko, DK Schreiber, **SM Bruemmer,** and KM Rosso, "Ab Initio Modeling of Bulk and Intergranular Diffusion in Ni Alloys," *Journal Physical Chemistry* 6, 1618 (2015).

# Douglas Burkes, Ph.D.

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Douglas Burkes is a chief engineer in the Nuclear Engineering & Analysis Group. He has more than ten years of experience with fabrication and characterization of various nuclear fuels for research, power, and space applications. He served as a senior technical advisor from 2009 to 2011 and as the national technical lead from 2011 to 2015 for the National Nuclear Security Administration's Office of Material Management and Minimization Fuel Fabrication Capability. Burkes currently oversees a number of fuel fabrication and characterization projects and business development opportunities, including novel nuclear fuel and material fabrication applications, thermal property measurements of irradiated fuels and materials, and assembly of sealed radioactive sources and radioisotope thermal-electric generators. He is also the technical lead for the Nuclear Fuels and Materials Team within the Nuclear Engineering & Analysis Group. He has published more than 33 peer-reviewed journal articles, two book chapters, three patent applications, and numerous conference proceedings and technical reports.

**Affiliations and Professional Service**

- American Nuclear Society
- American Institute of Astronautics and Aeronautics
- American Society of Mechanical Engineers
- The Minerals, Metals and Materials Society
- Project Management Professional

**Awards and Recognition**

- PNNL National Security Directorate Project Manager of the Year (2014)
- Best Presentation, 51st International Meeting on HOTLAB (2014)
- Graduate, Pacific Northwest National Laboratory Scientist and Engineer Program (2012)
- ANS Material Science and Technology Division Literary Award (2009)

**Selected Publications**

**Burkes DE**, AM Casella, AJ Casella, EC Buck, KN Pool, PJ MacFarlan, MK Edwards, and FN Smith, "Thermal properties of U-Mo alloys irradiated to moderate burnup and power," *Journal of Nuclear Materials* 464, 331-341 (2015).

**Burkes DE**, AJ Casella, AM Casella, WG Luscher, FJ Rice, and KN Pool, "Measurement of fission gas release from irradiated U-Mo monolithic fuel samples," *Journal of Nuclear Materials* 461, 61-71 (2015).

**Burkes DE**, AM Casella, and TK Huber, "Modeling the influence of interaction layer formation on thermal conductivity of U-Mo dispersion fuel," *Journal of Alloys and Compounds* 618, 7-13 (2015).

**Burkes DE**, AM Casella, EC Buck, AJ Casella, MK Edwards, PJ MacFarlan, KN Pool, FN Smith, and FH Steen, "Development and validation of capabilities to measure thermal properties of layered monolithic U-Mo alloy plate-type nuclear fuel," *International Journal of Thermophysics* 35(8), 1476-1500 (2014).

**Burkes DE**, CA Papesch, AP Maddison, T Hartmann, and FJ Rice, "Thermophysical properties of DU-10 wt% Mo alloys," *Journal of Nuclear Materials* 403, 160-166 (2010).

**Burkes DE**, JR Kennedy, T Hartmann, CA Papesch, and DD Keiser Jr., "Phase characteristics of a number of U-Pu-Am-Np-Zr metallic alloys for use as fast reactor fuels," *Journal of Nuclear Materials* 396, 49-56 (2010).

**Burkes DE**, RS Fielding, DL Porter, MK Meyer, and BJ Makenas, "A US perspective on fast reactor fuel fabrication technology and experience, part II: ceramic fuels," *Journal of Nuclear Materials* 393, 1-11 (2009).

**Burkes DE**, T Hartmann, R Prabhakaran, and JF Jue, "Microstructural characteristics of DU-xMo alloys with x = 7 to 12 wt%," *Journal of Alloys and Compounds* 479, 140-147 (2009).

**Burkes DE**, RS Fielding, DL Porter, DC Crawford, and MK Meyer, "A U. S. perspective on fast reactor fuel fabrication technology and experience part I: metal fuels and assembly design," *Journal of Nuclear Materials* 389, 458-469 (2009).

# Thak Sang (TS) Byun, Ph.D.

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Thak Sang Byun joined PNNL in October 2014. Throughout his career, his research has focused on radiation effects in nuclear structural and fuel materials, with special expertise in the theoretical modeling of mechanical behaviors, testing and evaluation of irradiated metallic and ceramics materials, and design and data interpretation of irradiation experiments. Byun has also developed innovative materials such as tri-phase microalloyed steels for automobile applications and nanostructured ferritic alloys for high-temperature reactor applications. Current research interests include:

- Localized and transformation–induced deformation in irradiated metallic materials,
- Radiation effects in fast reactor core materials
- Aging degradation in cast stainless steels
- Fretting damage in fuel cladding
- Creation of radiation-resistant nanostructured alloys.

Byun began work as a research scientist at Oak Ridge National Laboratory in January 1999. From 1992 to 1997, he was with the Korea Atomic Energy Research Institute as a fuel performance code developer and nuclear materials scientist.

**Affiliations and Professional Service**

- Member of the Advisory Editorial Board for the *Journal of Nuclear Materials*; Managing Guest Editor (2011 to present)
- The Minerals, Metals and Materials Society (TMS)
- Lead and co-organizer for the Symposium on Microstructural Processes in Irradiated Materials (MPIM) in TMS (2011 to present)
- Materials Research Society (MRS)
- Organizer for the Symposium on Materials for Future Fission and Fusion Technologies (MRS 2010)
- American Society for Testing and Evaluation (ASTM, E10 Committee)
- American Nuclear Society (ANS)
- Co-PM for DOE-BES Program: Mechanical Behavior and Radiation Effects (2014 to present)

**Awards and Recognition**

- *Journal of Nuclear Materials* Top Reviewer 2012 Award (April 2013) for "Exceptional Contribution to the Quality of the *Journal of Nuclear Materials*" by the editors of JNM and the publisher of *Materials Science*, Elsevier
- Korea Nuclear Society Best Paper Award for "Irradiation Dose Dependence of Deformation and Fracture Characteristics for SA533B Steel" (2011)
- ANS 2007 Literary Award (2008) for "Handbook of SiC Properties for Fuel Performance Modeling"
- American Ceramics Society Best Paper Award (2007) for "Influence of Specimen Type and Irregularity on the Fracture Strength of SiC Layer in Coated Particle Fuel"
- ANS 2004 Literary Award (2006) for "Plastic Instability in Polycrystalline Metals after Low-Temperature Irradiation," *Acta Materialia* 52 (2004) 1597-1608

**Selected Publications**

Vasudevamurthy G, **TS Byun**, P Pappano, LL Snead, and TD Burchell, "Effect of specimen size and grain orientation on the mechanical and physical properties of NBG-18 nuclear graphite," *Journal of Nuclear Materials* 462, 1-7 (2015).

Cockeram BV, KJ Leonard, **TS Byun**, LL Snead, and JL Hollenbeck, "The recovery of radiation damage for Zircaloy-2 and Zircaloy-4 following low dose neutron irradiation at normally 358°C," *Journal of Nuclear Materials* 461, 244-264 (2015).

**Byun TS**, JH Yoon, SH Wee, DT Hoelzer, and SA Maloy, "Fracture behavior of 9Cr nanostructured ferritic alloy with improved fracture toughness," *Journal of Nuclear Materials* 449(1-3), 39-48 (2014).

**Byun TS**, JH Yoon, DT Hoelzer, YB Lee, SH Kang, and SA Maloy, "Process development for 9Cr nanostructured ferritic alloy (NFA) with high fracture toughness," *Journal of Nuclear Materials* 449(1-3), 290-299 (2014).

Hu X, D Xu, **TS Byun**, and BD Wirth, "Modeling of irradiation hardening of iron after low dose and low temperature neutron irradiation," *Modelling and Simulation in Materials Science and Engineering* 22(6), 065002 (2014).

**Byun TS**, JH Baek, O Anderoglu, SA Maloy, and MB Toloczko, "Thermal annealing recovery of fracture toughness in HT9 steel after irradiation to high doses," *Journal of Nuclear Materials* 449(1-3), 263-272 (2014).

Tan L, **TS Byun**, Y Katoh, and LL Snead, "Stability of MX-type strengthening nanoprecipitates in ferritic steels under thermal aging, stress and ion irradiation," *Acta Materials* 71(1), 11-19 (2014).

Kim JH, **TS Byun**, DT Hoelzer, SW Kim, and BH Lee, "Temperature dependence of strengthening mechanisms in the nanostructured ferritic alloy 14YWT: part I - mechanical and microstructural observations," *Materials Science and Engineering A* 559, 101-110 (2013).

Kim JH, **TS Byun**, DT Hoelzer, CH Park, JT Yeom, and JK Hong, "Temperature dependence of strengthening mechanisms in the nanostructured ferritic alloy 14YWT: part II – mechanistic models and predictions," *Materials Science and Engineering A* 559, 111-118 (2013).

**Byun TS**, M Li, and K Farrell, "Dose dependence of strength after low-temperature irradiation in metallic materials," *Metallurgical and Materials Transactions A* 44, 84-93 (2013).

# Charles Henager, Jr., Ph.D.

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Charles Henager has worked in a variety of materials science areas. Since joining PNNL in 1976, he has concentrated on radiation effects, mechanical properties and strength of materials, and computational materials science of metals and alloys. He has published extensively in the area of deformation using atomistic models in metals and nanolayered materials. He has also explored radiation damage effects in materials, including nanolayered composites and SiC/SiC composites.

Henager pioneered hostile environmental testing of ceramics and ceramic composites at PNNL and has published several key papers on environmental cracking in SiC-composites for nuclear applications. He leads projects in ceramic joining, high-temperature SiC materials development, and ductile phase toughening of tungsten. He edited the proceedings of the 15th International Conference on Fusion Reactor Materials in 2013 for the *Journal of Nuclear Materials*.

**Affiliations and Professional Service**

- Publication Co-Chair for the 16th International Conference on Fusion Reactor Materials (ICFRM-16), Beijing, China (2011)
- Publication Chair for the 15th International Conference on Fusion Reactor Materials (ICFRM-15), Charleston, SC, USA (2011)
- Member of Editorial Advisory Board, *Journal of Nuclear Materials* (2011)
- DOE Offsite Assignment, BES, DDMS, Metals and Ceramics Science (1997-1998)
- Roland B. Snow Award of the American Ceramic Society (1991)
- Co-organizer, Computational Materials Sciences Network, DOE (1999)
- Organizer, Ceramics Joining Symposium, American Ceramic Society (2000)
- Co-organizer of Interfaces Symposium, American Ceramic Society (2005)
- Associate Editor, *Journal of Nuclear Materials* (2011)

**Awards and Recognitions**

- Roland B. Snow Award of the American Ceramic Society (1991)
- Pacific Northwest Laboratory Director's Award for Excellence (1993)
- DOE Offsite Assignment, Metals and Ceramics Science (1997-1998)
- Awarded eight U.S. Patents

**Selected Publications**


Jiang W, **CH Henager, Jr.**, T Varga, HJ Jung, NR Overman, C Zhang, and J Gou, "Diffusion of Ag, Au and Cs implants in MAX phase $Ti_3SiC_2$," *Journal of Nuclear Materials* 462, 310 (2015).

Jiang W, HJ Jung, L Kovarik, Z Wang, TJ Roosendaal, Z Zhu, DJ Edwards, S Hu, **CH Henager, Jr.**, RJ Kurtz, Y Wang, "Magnesium behavior and structural defects in Mg+ ion implanted silicon carbide," *Journal of Nuclear Materials* 458, 146 (2015).

Jiang W, JA Sundararajan, T Varga, ME Bowden, Y Qiang, JS McCloy, **CH Henager, Jr.**, and RO Montgomery, "*In Situ* Study of Nanostructure and Electrical Resistance of Nanocluster Films Irradiated with Ion Beams," *Advanced Functional Materials* 24(39), 6210 (2014).

Nguyen BN, F Gao, **CH Henager, Jr.**, and RJ Kurtz, "Prediction of Thermal Conductivity for Irradiated SiC/SiC Composites by Informing Continuum Models with Molecular Dynamics Data," *Journal of Nuclear Materials* 448, 364 (2014).

Katoh Y, LL Snead, T Cheng, C Shih, WD Lewis, T Koyanagi, T Hinoki, **CH Henager, Jr.**, and M Ferraris, "Radiation-tolerant Joining Technologies for Silicon Carbide Ceramics and Composites," *Journal of Nuclear Materials* 448, 497 (2014).

Setyawan W, M Gerboth, B Yao, **CH Henager, Jr.**, A Devaraj, VRSR Vemuri, S Thevuthasan, and V Shutthanandan, "Asymmetry of Radiation Damage Properties in Al–Ti Nanolayers," *Journal of Nuclear Materials* 445, 261 (2014).

Nguyen BN And **CH Henager, Jr.**, "Fiber/Matrix Interfacial Thermal Conductance Effect on the Thermal Conductivity of SiC/SiC Composites," *Journal of Nuclear Materials* 440(1-3), 11-20 (2013).

**Henager Jr. CH**, JS McCloy, P Ramuhalli, DJ Edwards, S Hu, and Y Li, "Investigation of Magnetic Signatures and Microstructures for Heat-Treated Ferritic/Martensitic HT-9 Alloy," *Acta Materialia* 61(9), 3285-3296 (2013).

Li Y, SY Hu, **CH Henager, Jr.**, D Huiqiu, G Fei, S Xin, and MA Khaleel, "Computer Simulations of Interstitial Loop Growth Kinetics in Irradiated bcc Fe," *Journal of Nuclear Materials* 427(1-3), 259-67 (2012).

Hu SY, **CH Henager, Jr.**, L Yulan, G Fei, S Xin, and MA Khaleel, "Evolution Kinetics of Interstitial Loops in Irradiated Materials: A Phase-Field Model," *Modelling and Simulation in Materials Science and Engineering* 20(1), 015011 (2012).

**Henager Jr. CH** and RJ Kurtz, "Low-activation Joining of SiC/SiC Composites for Fusion Applications," *Journal of Nuclear Materials* 417(1-3), 375-378 (2011).

# Ron Omberg

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Ron Omberg has 30 years of experience in reactor system design, core design, and fuel design for a variety of U.S and international clients. He currently manages a program to monitor shutdown of the last three plutonium production reactors in the former Soviet Union, ADE-4 and ADE-5 at Seversk and ADE-2 at Zheleznogorsk. He also is designated chair of the U.S.-RF Reactor Shutdown Working Group, which involves extensive interactions with Rosatom, Rosatomstroy, and the Russian regulatory agency RosTekhNadzor, and managed a project in the Russian Federation to produce Cs-131, the most effective medical isotope for curing prostate cancer.

He chaired design review of the Material Test Station being designed by Los Alamos National Laboratory (LANL) to provide materials testing for the Advanced Fuel Cycle Initiative and participated in the fuel performance and core design review of the reactor for the Jupiter Icy Moons Orbiter. Omberg was also on the Hanford Engineering Development Laboratory team that reviewed the General Electric design of the SP-100 reactor. He managed the group performing core design analyses (physics, fuel design, and thermo-hydraulics) on the Prototype Large Breeder Reactor (PLBR) for the Westinghouse Hanford Company as part of the DOE PLBR program.

Omberg taught graduate courses in nuclear reactor analysis, reactor kinetics, transport theory, and radiation detection for 17 years at the Joint Center for Graduate Study, University of Washington, where he was an Adjunct Full Professor. He has more than 100 publications.

**Affiliations and Professional Service**

- Chaired the DOE/NE/GNEP Review Panel to resolve concerns relating to a fast neutron testing source and recommend a fast neutron source to support GNEP fuels and materials testing
- Member, Nuclear Energy Advisory Committee (NEAC), which reviews the DOE the DOE Nuclear Energy Fuel Cycle Research and Development Program; Dr. Burton Richter, Nobel Laureate, Chair

- Participated in expert meetings of the Organization for Economic Cooperation and Development (OECD) in Paris; contributed to the OECD Yellow Book on Nuclear Power Growth and the OECD Red Book on Uranium Resources

**Selected Publications**

Henager CH, Jr, WD Bennett, AL Doherty, ES Fuller, JS Hardy, and **RP Omberg**, *Corrosion Report for the U-Mo Fuel Concept*, PNNL-23592, Pacific Northwest National Laboratory, Richland, WA (2014).

Doherty AL, WD Bennett, ES Fuller, KJ Geelhood, CH Henager, Jr, CA Lavender, DL Love, **RP Omberg**, and MT Smith, *FY-14 Status Report for the U-Mo Fuel Concept*, PNNL-23684, Pacific Northwest National Laboratory, Richland, WA (2014).

Wootan DW and **RP Omberg**, "Knowledge Management at the Fast Flux Test Facility." In: International Conference on Fast Reactors and Related Fuel Cycles: Safe Technologies and Sustainable Scenarios (FR13), March 4-7, 2013, Paris, France, vol. IAEA-CN-199, International Atomic Energy Agency, Vienna, Austria (2013).

Wootan DW, **RP Omberg**, BJ Makenas, DL Nielsen, JV Nelson, JR, and DL Polzin, "Knowledge Preservation at the Fast Flux Test Facility," *Transactions of the American Nuclear Society*, 105(1), 840-841 (2011).

Wootan DW, **RP Omberg**, BJ Makenas, DL Nielsen, JV Nelson, JR, and DL Polzin, "Securing Operating Data From Passive Safety Tests at the Fast Flux Test Facility," *Transactions of the American Nuclear Society*, 104(1), 894-895 (2011).

Wootan DW, RS Butner, **RP Omberg**, BJ Makenas, DL Nielsen, and DL Polzin, "Startup Testing of the Fast Flux Test Facility," *Transactions of the American Nuclear Society*, 103(1), 588-589 (2010).

Wootan DW, RS Butner, **RP Omberg**, BJ Makenas, and DL Nielsen, "Preservation of FFTF Data Related to Passive Safety Testing," *Transactions of the American Nuclear Society* 102(1), 556-557 (2010).

Wootan DW and **RP Omberg**, "Fast Reactor Technology Preservation," *Transactions of the American Nuclear Society* 98, 715-716 (2008).

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David Senor has worked in a variety of nuclear-related materials science and technology areas since joining PNNL in 1992. His work has focused on irradiation behavior evaluation; physical, mechanical and thermal property measurement; and manufacturing development of conventional and advanced nuclear materials, including SiC for fission and fusion reactor structural applications; tritium-producing burnable absorber rods for use in commercial PWRs; burnable-absorber-containing fuel channels for use in commercial BWRs; advanced spherical cermet fuel forms for use in LWRs; U-Mo fuels for use in LWRs and high-performance research reactors; and materials for high-power proton accelerator targets and windows. He has participated in various aspects of irradiation testing and post-irradiation examination of structural materials and fuels irradiation experiments in ATR, MITR, EBR-II, JOYO, FFTF, HFIR, and HFR Petten.

Senor is currently the lead experimenter for the TMIST series of materials irradiation tests in ATR investigating irradiation effects on components used in tritium-producing burnable absorber rods. He has authored or co-authored more than 130 journal articles, presentations, and technical reports in the open literature and holds two U.S. patents.

**Affiliations and Professional Service**

- American Nuclear Society (ANS): Chair, Program Chair, and Executive Committee Member of the Materials Science and Technology Division; Secretary and Executive Committee Member of the Eastern Washington Section
- The Minerals, Metals and Materials Society (TMS): Chair and Member of the Nuclear Materials Committee; Member of the Young Leaders and Education Committees
- United States Naval Institute (USNI)
- Nuclear Science User Facilities (NSUF): Chair and Executive Committee Member of the User Organization; Member of the Science Review Board; Member of the Infrastructure Database Review Panel

**Awards and Recognition**

- TMS Structural Materials Division Service Recognition Award
- ANS Materials Science and Technology Division Past Chair Award.
- TMS Young Leader Award

**Selected Publications and Presentations**

Luscher WG, **DJ Senor**, KK Clayton, and GR Longhurst, "In-reactor oxidation of zircaloy-4 under low water vapor pressures," *Journal of Nuclear Materials* 456, 17-22 (2014).

**Senor DJ**, WG Luscher, KK Clayton, and GR Longhurst, "Evaluation of In-situ tritium transport parameters for Type 316 stainless steel during irradiation," *PNNL-SA-102143*, presented at the Tritium Focus Group meeting, Aiken, SC, 22-24 April 2014.

Luscher WG, **DJ Senor**, KC Clayton, and GR Longhurst, "In-situ measurement of tritium permeation through stainless steel," *Journal of Nuclear Materials* 437, 373-379 (2013).

**Senor DJ**, DM Asner, DW Wootan, and MA Peterson, "Project X broader impacts: spallation and irradiation facility," *PNNL-22523*, invited presentation at Community Summer Study 2013 (Snowmass on the Mississippi), Minneapolis, MN, 29 July - 6 August 2013.

**Senor DJ**, WG Luscher, KJ Geelhood, SG Pitman, KK Clayton, and GR Longhurst, "In-reactor oxidation of Zircaloy-2 and Zircaloy-4 in water vapor at low partial pressures," *PNNL-SA-91393*, presented at NuMat 2012, Osaka, Japan, 21-25 October 2012.

**Senor DJ**, "Irradiation experiment planning and execution," *PNNL-SA-60807*, invited presentation at the Advanced Test Reactor National Scientific User Facility Users Week, Idaho Falls, ID, 18-22 June 2012.

Geelhood KJ, DW Matson, **DJ Senor**, and CL Painter, "Spherical fuel element concept for small reactor design," *Nuclear Technology* 164(2), 255-264 (2008).

**Senor DJ**, BD Wirth, R Hanrahan, SJ Zinkle, M Uz, EK Ohriner, and BV Cockeram (Eds), "Space reactor fuels and materials," Proceedings of the Symposium held at the TMS Annual Meeting, San Antonio, TX, 13-16 March 2006, *Journal of Nuclear Materials*, 366(3), 297-425 (2007).

**Senor DJ** and CL Painter, "Irradiation of advanced structural materials in JOYO to support the development of a space fission reactor," *PNNL-15610*, Richland, WA: Pacific Northwest National Laboratory (2006).

**Senor DJ**, GE Youngblood, LR Greenwood, DV Archer, DL Alexander, MC Chen, and GA Newsome, "Defect structure and evolution in silicon carbide irradiated to 1 dpa-SiC at 1100°C," *Journal of Nuclear Materials* 317(2-3), 145-159 (2003).

# Mychailo B. Toloczko, Ph.D.

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Mychailo Toloczko currently performs fundamental and applied research on degradation of nuclear reactor pressure boundary and core structural materials. Areas of expertise include:

- Light-water reactor stress corrosion crack initiation of nickel base alloys
- Light-water reactor stress corrosion crack growth of nickel base alloys
- Effects of neutron irradiation on microstructure and mechanical properties of fast reactor fuel clad and duct materials
- Heavy ion irradiation methods for study of high dose irradiation effects on fast reactor fuel clad and duct materials
- Expertise in the following materials: alloy 600/182, alloy 690/152/52, 9-12Cr tempered ferritic-martensitic steels, nano-featured ODS ferritic alloys, 316 stainless steel.

## Affiliations and Professional Service

- American Nuclear Society (ANS)
- The Minerals, Metals, and Materials Society (TMS)
- OECD NEA Innovative Structural Materials Expert Group
- International Coooperative Group on Environmentally Assisted Cracking
- EPRI-NRC Expert Panel on Alloy 690/152 SCC CGR Disposition Curve Development

## Awards and Recognition

- Co-inventor on patent for "Functionalized magnetic nanoparticle analyte sensor" (2014)

## Selected Publications


Bailey NA, E Stergar, **MB Toloczko**, and P Hosemann, "Atom Probe Tomography Analysis of High Dose MA957 at Selected Irradiation Temperatures," *Journal of Nuclear Materials* 459, 225-234 (2015).

**Toloczko MB**, FA Garner, VN Voyevodin, VV Bryk, OV Borodin, VV Mel'nychenko, and AS Kalchenko, "Ion-Induced Swelling of ODS Ferritic Alloy MA957 Tubing to 500 dpa," *Journal of Nuclear Materials* 453, 323-333 (2014).

**Toloczko MB**, MJ Olszta, NR Overman, and SM Bruemmer, "Observations and Implications of Intergranular Stress Corrosion Crack Growth of Alloy 152 Weld Metals in Simulated PWR Primary Water," *Proceedings of the 16th International Conference of Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors*, Asheville, NC, NACE International (2013).

**Toloczko MB**, MJ Olszta, NR Overman, and SM Bruemmer, "Stress Corrosion Crack Growth For Alloy 152/52 Dissimilar Metal Welds in PWR Primary Water," *Proceedings of the 16th International Conference of Environmental Degradation of Materials in Nuclear Power Systems*, Asheville, NC, NACE International (2013).

Stoller RE, **MB Toloczko**, GS Was, AG Certain, S Dwaraknath, and FA Garner, "On the Use of SRIM for Computing Radiation Damage Exposure," *Nuclear Instruments and Methods in Physics Research B*, 310, 75-80 (2013).

**Toloczko MB**, MJ Olszta, and SM Bruemmer, "One Dimensional Cold Rolling Effects on Stress Corrosion Crack Growth in Alloy 690 Tubing and Plate Materials," *Proceedings of the 15th International Conference of Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors*, Colorado Springs, CO, The Metals Society (2011).

**Toloczko MB**, MJ Olszta, and SM Bruemmer, "Stress Corrosion Crack Growth of Alloy 52M in Simulated PWR Primary Water," *Proceedings of the 15th International Conference of Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors*, Colorado Springs, CO, The Metals Society (2011).

Maloy SA, **MB Toloczko**, JI Cole, and TS Byun, "Core Materials Development for the Fuel Cycle R&D Program," *Journal of Nuclear Materials* 415, 302-305 (2011).

Allen TR, JT Busby, RL Klueh, SA Maloy, and **MB Toloczko**, "Cladding and Duct Materials for Advanced Nuclear Recycle Reactors," *Journal of Materials* 60, 15-23 (2008).

**Toloczko MB**, PL Andresen, and SM Bruemmer, "SCC Crack Growth of Cold-Worked Type 316 SS in Simulated BWR Oxidizing and Hydrogen Water Chemistry Conditions," *Proceedings of the 13th International Conference on the Environmental Degradation of Materials in Nuclear Power Systems*, August 19-23, Whistler, BC, Canada (2007).

**Toloczko MB**, BR Grambau, FA Garner, and K Abe, "Comparison of Thermal Creep and Irradiation Creep of HT9 Pressurized Tubes at Test Temperatures from about 490°C to 605°C," *Effects of Radiation on Materials: 20th International Symposium*, ASTM STP 1405, 557-569 (2001).

**Toloczko MB**, JP Hirth, and FA Garner, "Application of Generalized Deformation Theory to Irradiation Creep of FCC and BCC Stainless Steels," *Journal of Nuclear Materials* 283-287, 409-413(2000).

# John Vienna, Ph.D.

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John Vienna is a materials scientist with more than 20 years of experience in nuclear waste form development, processing, and testing. His experience includes serving as a national technical advisor to the Department of Energy's Offices of Environmental Management and Nuclear Energy on waste form and immobilization science program management. He is a Chief Scientist in the Materials Science Team of PNNL's Nuclear Sciences Division, where his research has led to more than 250 technical publications. Vienna is also an adjunct faculty member in the Chemistry Department at Washington State University where he has taught a graduate course in nuclear waste glass chemistry for 15 years.

### Affiliations and Professional Service

- Associate Editor of the *International Journal of Applied Glass Science*
- Member of American Ceramic Society (ACerS), ASTM International, Materials Research Society, American Nuclear Society, International Congress on Glass (ICG)
- Chair (2007), Vice Chair (2006), Secretary (2005), and Program Chair (2004) of the ACerS Nuclear and Environmental Technology Division
- ASTM International Technical Task Chairman for standards:
  - C1720, Determining Liquidus Temperature of Immobilized Waste Glasses and Simulated Waste Glasses
  - C1663, Measuring Waste Glass or Glass Ceramic Durability by Vapor Hydration Test
- Founding member of ICG Technical Committee on Nuclear and Hazardous Waste Vitrification
- Chair of numerous technical sessions at conferences
- Contributor to four IAEA guides and standards

### Awards and Recognitions

- Fellow of the American Ceramic Society

- More than 35 outstanding performance or contribution awards from PNNL, DOE, professional societies, and other organizations
- 3 U.S. patents
- 8 European patents
- Member of numerous U.S. and international expert panels

**Selected Publications**

**Vienna JD** et al. *Closed Fuel Cycle Waste Treatment Strategy*, FCRD-MRWFD-2015-000674, PNNL-24114, Pacific Northwest National Laboratory, Richland, WA (2015).

**Vienna JD**, DS Kim, IS Muller, GF Piepel, and AA Kruger, "Toward understanding the effect of low-activity waste glass composition on sulfur solubility," *Journal of the American Ceramic Society* 97(10), 3135-3142 (2014).

**Vienna JD**, "Compositional models of glass/melt properties and their use for glass formulation," *Procedia Materials Science* 7, 148-155 (2014).

**Vienna JD**, JV Ryan, S Gin, and Y Inagaki, "Current understanding and remaining challenges in modeling long-term degradation of borosilicate nuclear waste glasses," *International Journal of Applied Glass Science* 4(4), 283-294 (2013).

Mccloy JS, MJ Schweiger, CP Rodriguez, and **JD Vienna**, "Nepheline crystallization in nuclear waste glasses: progress toward acceptance of high-alumina formulations," *International Journal of Applied Glass Science* 2(3), 201-214 (2011).

**Vienna JD**, "Nuclear waste vitrification in the united states: recent developments and future options," *International Journal of Applied Glass Science* 1(3), 309-321 (2010).

**Vienna JD**, "Nuclear waste glasses," in *Properties of Glass Forming Melts*, eds. LD Pye, I Joseph and A Montenaro, pp. 391-404, CRC Press, Boca Raton, FL, (2005).

**Vienna JD**, CC Herman, and SL Marra, eds., *Environmental Issues and Waste Management Technologies in the Ceramic and Nuclear Industries X, Ceramic Transactions*, Vol. 168. American Ceramic Society, Westerville, OH (2005).

**Vienna JD** and DR Spearing, eds., *Environmental Issues and Waste Management Technologies in the Ceramic and Nuclear Industries IX*, Vol. 155. American Ceramic Society, Westerville, OH (2004).

Sundaram SK, DR Spearing, and **JD Vienna**, eds., *Environmental Issues and Waste Management Technologies in the Ceramic and Nuclear Industries VIII, Ceramic Transactions*, Vol. 143. American Ceramic Society, Westerville, OH (2003).

**Vienna JD**, P Hrma, JV Crum, and M Mika, "Liquidus temperature-composition model for multi-component glasses in the Fe, Cr, Ni, and Mn spinel primary phase field," *Journal of Non-Crystalline Solids* 292(1-3), 1-24 (2001).

# Dave Wootan

NATIONAL SECURITY DIRECTORATE
MECHANISM AND RESPONSE

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David Wootan has more than three decades of nuclear engineering experience at the Hanford site, first with Westinghouse Hanford Company, then Fluor Federal Services, and now PNNL.

Wootan joined PNNL's Core Physics group to support startup of the Fast Flux Test Facility (FFTF) in 1979, and provided direct core physics support for FFTF operation from initial startup through its years of operation and subsequent mission development efforts. Career highlights at FFTF include:

- Physics experiments to characterize the neutronic environment of the FFTF
- Design and interpretation of a variety of test assemblies such as space reactor fuel and component tests, advanced liquid metal reactor fuel, absorber concepts, and fusion material tests
- Isotope production for both U.S. and international customers
- Core designs for potential missions for the FFTF based on various fuel types (metal, uranium oxide, mixed oxide, nitride, and minor actinides)
- Applications such as medical and other beneficial isotope production, long-life cores, waste transmutation, increased test irradiation capability, and passive safety
- Innovative development of spectral tailoring and hydride moderating assemblies to provide unique neutronic environments
- Core and target design for producing $^{238}$Pu in FFTF for NASA
- Production of a variety of medical isotopes provided to medical researchers
- Preservation of FFTF-related computer codes and data
- Radionuclide inventory for long-term dry cask storage of FFTF used fuel
- Long-term radionuclide inventories in FFTF components.

Current projects at PNNL include preserving and extracting important FFTF related fast reactor technology and data in a manner consistent with DOE and U.S. industry needs; supporting ongoing post-irradiation examination for advanced metal and oxide fuel tests that were irradiated in FFTF; Advanced Small Modular Reactor prognostic health management and enhanced risk monitors; criticality safety; applications of planned high energy physics accelerators to support DOE high energy physics, nuclear physics, and nuclear energy research and development needs; and experiments using an accelerator to resolve the reactor neutrino anomaly problem.

**Selected Publications**

Asner DM, KA Burns, LW Campbell, BA Greenfield, MS Kos, JL Orrell, M Schram, BA VanDevender, LS Wood, and **DW Wootan**, "Method of Fission Product Beta Spectra Measurements for Predicting Reactor Anti-neutrino Emission," *Nuclear Instruments and Methods in Physics Research. Section A, Accelerators, Spectrometers, Detectors and Associated Equipment* 776, 75-82 (2015).

Burns KA, **DW Wootan**, RO Gates, BE Schmitt, and DM Asner, "How to produce a reactor neutron spectrum using a proton accelerator," *Physics Procedia* 66, 471-480 (2015).

Carmack WJ, HM Chichester, D Porter, and **DW Wootan**, "Metallography and Fuel Cladding Chemical Interaction in Fast Flux Test Facility Irradiated Metallic U-10Zr MFF-3 and MFF-5 Fuel Pins," *Journal of Nuclear Materials* 473, 167-177 (2016).

Polzin DL, DL Nielsen, BJ Makenas, and **DW Wootan**, *High Temperature Sodium Facility (HTSF) and the Composite Reactor Components Test Activity (CRCTA)*, PNNL-23811, Pacific Northwest National Laboratory, Richland, WA (2014).

Polzin DL, DL Nielsen, BJ Makenas, and **DW Wootan**, *OMM-032-00-003 FFTF Reactor Closure Head Temperature Control System*, PNNL-23838, Pacific Northwest National Laboratory, Richland, WA (2014).

# Erin Barker, Ph.D.

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MODELING AND SIMULATION

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Erin Iesulauro Barker is a computational scientist focusing on modeling material behavior at the microstructural scale. Currently, her work focuses on studying how microstructural features and mechanisms influence bulk mechanical properties, such as ductility and ultimate failure. To accomplish this, she develops computational tools for generating and meshing 2D and 3D polycrystal representations, development and implement of cohesive zone models for grain boundary decohesion, and software development for a parallel 3D finite element framework. The tools allow the incorporation of lower-length-scale information as well as feeding input to high-length scales, thus providing a bridge for multi-scale simulations.

She has applied these tools and her expertise to projects that include:

- Investigating the nucleation of cracks in aircraft-grade aluminum alloys
- Capturing the mechanisms leading to the wide variation in ductility of cast Mg alloys used by the auto industry
- Developing and implementing new crystal plasticity models incorporating damage caused by irradiation.

**Affiliations and Professional Service**

- The Minerals, Metals and Materials Society
- Tau Beta Pi

**Selected Publications**


**Barker EI**, KS Choi, X Sun, E Deda, J Allison, M Li, J Forsmark, J Zindel, and L Godlewski, "Microstructure Based Modeling of β Phase Influence on Mechincal Response of Cast AM Series Mg Alloys," *Computational Materials Science* 92, 353-361 (2014).

**Barker EI**, D Li, H Zbib, and X Sun, "Gradient Plasticity Model and its Implementation into MARMOT," PNNL-22702 Pacific Northwest National Laboratory, Richland WA (2013).

**Barker EI**, D Li, X Sun, and MA Khaleel, "Microstructure modeling of magnesium alloys for engineering property prediction," In: *Magnesium Technology* 2012, SN Mathaudhu, WH Sillekens, NR Neelameggham and N Hort, Editors. John Wiley & Sons, Inc., Hoboken, NJ (2012).

**Barker EI**, X Sun, and MA Khaleel, "Effects of texture on microscale deformation of Mg alloys," International Symposium on Plasticity, San Juan, Puerto Rico (2012).

Cheng G, **EI Barker**, EV Stephens, KS Choi, and X Sun, "Quantifying Grain Level Stress-Strain Behavior for AM40 via Instrumented Microindentation," *MRS Advances* 1 (12), 761-772 (2016).

Coffman VR, JP Setna, AR Ingraffea, JE Bozek, NP Bailey, and **EI Barker**, "Challenges in continuum modelling of intergranual fracture," *Strain* 47, 99-104 (2010).

Coffman VR, JP Setna, G Heber, M Liu, AR Ingraffea, NP Bailey, and **EI Barker**, "A comparison of finite element and atomistic modelling of fracture," *Modelling and Simulation in Materials Science and Engineering* 16, 065008 (2008).

# Ram Devanathan, Ph.D.

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MODELING AND SIMULATION

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Ram Devanathan performs energy and environment research using massively parallel computation integrated with materials characterization in the following focus areas:

- Modeling and simulation of nuclear fuel, cladding, and waste forms
- Prediction of the lifetime of spent nuclear fuel canisters
- Characterization of swift heavy ion damage in materials
- Fundamental studies of structure and transport in ionic liquids and polymer membranes
- Modeling of selective water transport in graphene oxide membranes.

**Affiliations and Professional Service**

- American Association for the Advancement of Science
- Fellow of the American Ceramics Society
- Materials Research Society
- American Chemical Society; Chair, Richland Section
- Past Chair, Nuclear & Environmental Technology Division, American Ceramic Society
- Chair, 2015 Fall Meeting of the Materials Research Society, Boston, MA
- Lead organizer, Symposium on Radiation Hardened Materials for Accelerators, Reactors, and Space Exploration, 247th National Meeting of the American Chemical Society, Dallas, TX, March 2014
- Lead organizer, Symposium on Mineral Response to Extreme Conditions: Implications for the Nuclear Fuel Cycle, Goldschmidt Meeting, Florence, Italy, August 2013
- Lead Organizer, Symposium on Materials Development for Nuclear Applications and Extreme Environments, Materials Science and Technology, Columbus, Ohio, October 2012
- Lead Organizer, Symposium on Design of Materials for Sustainable Nuclear Energy, Spring Meeting of the Materials Research Society, San Francisco, CA, April 2012

**Awards and Recognitions**

- Richard M. Fulrath Award, American Ceramic Society (2012)
- Outstanding Mentor Award, Department of Energy (2010)
- Invited Panelist, Department of Energy Workshop on *Computational Materials Science and Chemistry for Innovation* (2010)
- Invited by the National Academy of Engineering and Alexander von Humboldt Foundation to the German American Frontiers of Engineering Symposium, Hamburg, Germany (2007)
- U.S. Frontiers of Engineering Symposium, Albany, NY (2005)

**Selected Publications**

Yablinsky CA, **R Devanathan**, J Pakarinen, J Gan, D Severin, C Trautmann, and TR Allen, "Characterization of swift heavy ion irradiation damage in ceria," *Journal of Materials Research* 30, 1473-1484 (2015) (Cover article).

Lang M, **R Devanathan**, M Toulemonde, and C Trautmann, "Advances in understanding of swift heavy-ion tracks in complex ceramics," *Current Opinion in Solid State and Materials Science* 19, 39-48 (2015).

Zarkadoula E, **R Devanathan**, WJ Weber, M Seaton, IT Todorov, K Nordlund, MT Dove, and K Trachenko, "High energy radiation damage in zirconia: Modeling results," *Journal of Applied Physics* 115(8), 083507 (2014).

**Devanathan R**, F Gao and CJ Sundgren, "Role of cation choice in the radiation tolerance of pyrochlores," *RSC Advances* 3, 2901-2909 (2013).

Kumar A, **R Devanathan**, V Shutthanandan, SVNT Kuchibhatla, AS Karakoti, Y Yong, S Thevuthasan, and S Seal, "Radiation induced reduction of ceria in single and polycrystalline thin films," *Journal of Physical Chemistry C* 116, 361-366 (2012).

F Gao, HY Xiao, YG Zhou, **R Devanathan**, SY Hu, YL Li, X Sun, and MA Khaleel, "Ab initio study of defect properties in $YPO_4$," *Computational Materials Science* 54, 170-175 (2012).

Moore EE, LR Corrales, T Desai, and **R Devanathan**, "Molecular dynamics simulation of Xe bubble nucleation in nanocrystalline $UO_2$ nuclear fuel," *Journal of Nuclear Materials* 419, 140-144 (2011).

Lee CW, RK Behera, S Okamoto, **R Devanathan**, ED Wachsman, SR Phillpot, and SB Sinnott, "Stabilization mechanisms of $LaFeO_3$ (010) surfaces determined with first principles calculations," *Journal of the American Ceramics Society* 94(6), 1931-1939 (2011).

**Devanathan R**, L Van Brutzel, A Chartier, C Gueneau, AE Mattsson, V Tikare, T Bartel, TM Besmann, M Stan, and P Van Uffelen, "Modeling and simulation of nuclear fuel materials," *Energy and Environmental Science* 3, 1406-1426 (2010). (Cover article).

**Devanathan R**, S Thevuthasan, and JD Gale, "Defect interactions and ionic transport in scandia stabilized zirconia," *Physical Chemistry Chemical Physics* 11, 5506-5511 (2009).

# Shenyang Hu, Ph.D.

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Shenyang Hu has more than 20 years of experience in atomistic and mesoscale modeling. His research focuses on developing mesoscale phase-field models to understand the mechanisms and kinetics of microstructure and property evolution in alloys, multiphase ferroelectric and ferromagnetic materials, self-assembled nanostructures, battery materials, and nuclear materials. Focus areas include:

- Thermodynamic and kinetic property calculation using density functional theory and atomistic simulations
- Development of mesoscale phase-field models and software
- Mesoscale phase-field modeling of microstructure evolution and property degradation in nuclear reactor materials
- Mesoscale phase-field modeling of material responses for non-destructive evaluation in irradiated materials
- Mesoscale phase-field modeling of ferroelectric and ferromagnetic behavior
- Mesoscale phase-field modeling of interaction between microstructures, phase transition, crystal plasticity, and fracture
- Optimal design of material microstructure and property.

Hu currently leads and participates in research programs of predicting the effect of microstructures on material performance in irradiated materials. He has published more than 100 journal articles and technical reports in the open literature.

**Affiliations and Professional Service**

- The Minerals, Metals, & Materials (TMS) Chemistry and Physics of Materials Committee Member
- TMS Nuclear Materials Committee Member
- Guest Editor, *Journal of Nuclear Materials* (2012)

- Co-organizer of symposium and session chair: TMS 2006-2015
- Peer reviewer for *Physical Review Letters*, *Applied Physics Letters*, *Journal of Nuclear Materials*, *Journal of Physical Chemistry*, *Acta Materialia*

**Selected Publications**

**Hu SY**, AM Casella, CA Lavender, DJ Senor, and DE Burkes, "Assessment of Effective Thermal Conductivity in U-Mo Metallic Fuels with Distributed Gas Bubbles," *Journal of Nuclear Materials* 462, 64-76 (2015).

**Hu SY**, W Setyawan, W Jiang, C H Henager, Jr. and R J Kurtz, "Thermodynamic and Kinetic Properties of Intrinsic Defects and Mg Transmutants in 3C-SiC Determined by Density Functional Theory," *Journal of Nuclear Materials* 448, 121-128 (2014).

**Hu SY**, YL Li, KM Rosso, and ML Sushko, "Meso-scale Phase Field Modeling of Charge Transport in Nanocomposite Electrodes for Lithium-ion Batteries," *Journal of Physical Chemistry C* 117, 28-40 (2013).

**Hu SY**, YL Li, JS McCloy, RO Montgomery, and CH Henager, Jr., "Magnetic Hardening from the Suppression of Domain Walls by Nonmagnetic Particles," *IEEE Magnetics Letters* 4, 3500104 (2013).

**Hu SY**, YL Li, CH Henager, Jr, H Deng, F Gao, X Sun, and MA Khaleel, "Evolution Kinetics and Sink Strength of Interstitial Loops in Irradiated Materials: A Phase-field Model," *Modelling and Simulation in Materials Science and Engineering* 20, 015011 (2012).

**Hu SY**, CH Henager, Jr. and LQ Chen, "Simulations of Stress-induced Twinning and De-twinning: a Phase-field Model," *Acta Materials* 58, 6554-6564 (2010).

**Hu SY** and CH Henager, Jr., "Phase-field modeling of Void Lattice Formation in Metals under Irradiation," *Journal of Nuclear Materials* 394, 155 (2009).

**Hu SY**, CH Henager, Jr., H Heinish, M Stan, MI Baskes, and SM Valone, "Phase-field Modeling of Gas Bubbles and Thermal Conductivity Evolution in Nuclear Fuels," *Journal of Nuclear Materials* 392, 292 (2009).

**Hu SY** and LQ Chen, "A Phase-Field Model for Evolving Microstructures with Strong Elastic Inhomogeneity," *Acta Materials* 49, 1879 (2001).

**Hu SY**, S Schmauder, and LQ Chen, "Atomistic Simulation of Interactions between Cu Precipitates and an Edge Dislocation in a B.C.C. Fe single Crystal," *Physica Status Solidi B: Basic Solid State Physics* 220, 845 (2000).

# Richard J. Kurtz, Ph.D.

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MODELING AND SIMULATION

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Since joining PNNL in 1974, Richard Kurtz has specialized in the deformation and fracture of metals and alloys for nuclear power plant applications. In his early career he was involved in evaluating the reliability and effectiveness of nondestructive inspection techniques for assessing the structural integrity of nuclear power reactor pressure retaining components.

Kurtz leads a multidisciplinary effort to develop advanced, low-activation materials for first-wall/blanket structural elements of fusion power systems. He coordinates and contributes to alloy development, performance of irradiation experiments, post-irradiation evaluation of mechanical properties and microstructure, and computer simulations to model damage evolution caused by neutron irradiation.

His personal research interests include:

- Effects of radiation on the microstructure and properties of metals, ceramics, and ceramic composites
- Computational modeling of interfaces in crystalline solids and the effects of radiation
- Mechanical behavior of structural materials in hostile service environments
- Creep mechanisms of refractory metals and alloys.

**Affiliations and Professional Service**

- American Nuclear Society
- ASM International
- The Minerals, Metals and Materials Society
- Materials Research Society
- Member, International Advisory Committee, 17th International Conference on Fusion Reactor Materials
- Co-Chair, Technical Program Committee, 16th International Conference on Fusion Reactor Materials
- Chair, U.S. DOE Materials Science Coordinating Organization (2006-2012, 2015)
- Member, Science & Technology Working Group, U.S.-Russia Bilateral Presidential Commission (2011)

- Secretary, International Energy Agency Implementing Agreement on Fusion Materials Annex II & Executive Committees (2005-present)
- U.S. Representative, International Thermonuclear Experimental Reactor Test Blanket Working Group (2006-2009)

**Awards and Recognitions**

- Laboratory Fellow
- Fellow of the American Nuclear Society
- Outstanding Performance Awards, Pacific Northwest National Laboratory (1999, 2001- 2007, 2011)
- DOE Award of Appreciation, Nuclear Energy Research Initiative (2004)
- DOE Award of Appreciation, Nuclear Engineering Education Research Grant Program (2003, 2004)

**Selected Publications**

Yang L, F Gao, **RJ Kurtz**, and XT Zu, "Atomistic simulations of helium clustering and grain boundary reconstruction in alpha-iron," *Acta Materialia*, 82, 275 (2015).

Setyawan W, G. Nandipati, KJ Roche, HL Heinisch, BD Wirth, and **RJ Kurtz**, "Displacement cascades and defect annealing in tungsten, Part I: defect database from molecular dynamics simulations," *Journal of Nuclear Materials* 462, 329-337 (2015).

Nandipati G, W Setyawan, H. Heinisch, KJ Roche, **RJ Kurtz**, and BD Wirth, "Displacement cascades and defect annealing in tungsten, Part II: object kinetic Monte Carlo simulation of tungsten cascade aging," *Journal of Nuclear Materials* 462, 338-344 (2015).

Nandipati G, W Setyawan, H. Heinisch, KJ Roche, **RJ Kurtz**, and BD Wirth, "Displacement cascades and defect annealing in tungsten, Part III: The sensitivity of cascade annealing in tungsten to the values of kinetic parameters," *Journal of Nuclear Materials* 462, 345-353 (2015).

Nguyen BN, F Gao, CH Henager, Jr., and **RJ Kurtz**, "Prediction of thermal conductivity for irradiated SiC/SiC composites by informing continuum models with molecular dynamics data," *Journal of Nuclear Materials* 448, 364 (2014).

Wang CM, TC Kaspar, V Shutthanandan, AG Joly, L Kovarik, BW Arey, M Gu, A Devaraji, BD Wirth, and **RJ Kurtz**, "Structure and radiation damage behavior of epitaxial $Cr_xMo_{1-x}$ alloy thin films on MgO," *Journal of Nuclear Materials* 437, 55 (2013).

Yang, L, F Gao, ZQ Zhu, SM Peng, XG Long, XS Zhou, HL Heinisch, **RJ Kurtz**, and XT Zu, "Effects of temperature on the interactions of helium-vacancy clusters with gliding edge dislocations in α-Fe," *Journal of Nuclear Materials* 441, 6 (2013).

Yang L, HQ Deng, F Gao, HL Heinisch, **RJ Kurtz**, SY Hu, YL Li, and XT Zu, "Atomistic studies of nucleation of He clusters and bubbles in bcc iron," *Nuclear Instruments and Methods in Physics Research B* 303:68 (2013).

Deng HQ, WY Hu, F Gao, HL Heinisch, SY Hu, YL Li, and **RJ Kurtz**, "Diffusion of small He clusters in bulk and grain boundaries in α-Fe," *Journal of Nuclear Materials* 442, S667 (2013).

# Yulan Li

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Yulan Li is a materials scientist with more than 20 years of experience in modeling phase stability and transformation, nucleation and evolution kinetics of microstructures in different material processes. She has authored and co-authored more than 90 peer-reviewed journal articles including *Nature* and *Science* with more than 4,000 citations and an H-index of 29. Her contribution to the development of the phase-field method and its innovative application to predicting mesoscale microstructural evolution and properties in ferroelectric materials were recognized internationally. Li's current research effort is to develop fundamental methods and models in mesoscale for modeling and understanding microstructure nucleation and evolution in nuclear fuels and structural materials under irradiation, transparent glass ceramics strengthening, and soft magnetic material nano-crystallization.

## Affiliations and Professional Service

- Materials Research Society
- Regular reviewer for *Applied Physics Letters*, *Journal of Applied Physics*, *Journal of the American Ceramic Society*, *Solid State Science*, *Journal of Physics*, etc.

## Awards and Recognitions

- Alexander von Humboldt Research Fellow of Germany (1996)
- Japan Society for the Promotion of Science Research Fellow (1998)

## Selected Publications


**Li YL**, SY Hu,L Zhang, X Sun, "Non-classical nuclei and growth kinetics of Cr precipitates in FeCr alloys during ageing," *Modelling and Simulation in Materials Science and Engineering* 22(2), 025002 (2014).

**Li YL**, SY Hu, R Montgomery, F Gao, and X Sun, "Phase-field simulations of intragranular fission gas bubble evolution in $UO_2$ under post-irradiation thermal annealing," *Nuclear Instruments and Methods in Physics Research B* 303, 62-67 (2013).

**Li YL**, SY Hu, CH Henager, HQ Deng, F Gao, X Sun, and MA Khaleel, "Computer simulations of interstitial loop growth kinetics in irradiated bcc Fe," *Journal of Nuclear Materials* 427(1-3), 259-267 (2012).

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**Li YL**, SY Hu, S Choudhury, MI Baskes, A Saxena, T Lookman, QX Jia, DG Schlom, and LQ Chen, "Influence of interfacial dislocations on hysteresis loops of ferroelectric films," *Journal of Applied Physics* 104(10), 104110 (2008).

**Li YL**, SY Hu, D Tenne, A Soukiassian, DG Schlom, XX Xi, KJ Choi, CB Eom, A Saxena, T Lookman, QX Jia, and LQ Chen, "Prediction of ferroelectricity in $BaTiO_3/SrTiO_3$ superlattices with domains," *Applied Physics Letters* 91(11), 112914 (2007).

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**Li YL**, LE Cross, and LQ Chen, "A phenomenological thermodynamic potential for $BaTiO_3$ single crystals," *Journal of Applied Physics* 98(6), 064101 (2005).

**Li YL**, SY Hu, and LQ Chen, "Ferroelectric domain morphologies of $(001)PbZr_{1-x}TixO_3$ epitaxial thin films," *Journal of Applied Physics* 97(3), 034112 (2005).

Choi KJ, M Biegalski, **YL Li**, A Sharan, J Schubert, R Uecker, P Reiche, YB Chen, XQ Pan, V Gopalan, LQ Chen, DG Schlom, and CB Eom, "Enhancement of ferroelectricity in strained $BaTiO_3$ thin films," *Science* 306(5698), 1005-1009 (2004).

Haeni JH, P Irvin, W Chang, R Uecker, P Reiche, **YL Li**, S Choudhury, W Tian, ME Hawley, B Craigo, AK Tagantsev, XQ Pan, SK Streiffer, LQ Chen, SW Kirchoefer, J Levy, and DG Schlom, "Room-temperature ferroelectricity in strained $SrTiO_3$," *Nature* 430(7001), 758-761 (2004).

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Wahyu Setyawan specializes in simulations using density functional theory and molecular dynamics techniques in the following focus areas:

- Tungsten alloys for plasma facing materials in fusion reactors
- Self-healing nanostructured materials for radiation shields
- Radiation effects in nuclear fuels, plasma facing, and structural materials
- Fundamental studies of solutes and impurity effects on grain boundaries
- Thermal conductivity modeling of irradiated polycrystalline SiC
- Ductile-phase toughened tungsten composites for plasma facing and structural materials in fusion reactors.

**Affiliations and Professional Service**

- American Physical Society
- Materials Research Society

**Selected Publications**


**Setyawan W**, AP Selby, N Juslin, RE Stoller, BD Wirth, and RJ Kurtz, "Cascade Morphology Transition in bcc Metals," *Journal of Physics: Condensed Matter* 27, 225402 (2015).

**Setyawan W**, G Nandipati, KJ Roche, HL Heinisch, BD Wirth, and RJ Kurtz, "Displacement Cascades and Defects Annealing in Tungsten, Part I: Defect Database from Molecular Dynamics Simulations," *Journal of Nuclear Materials*, 462, 329-337 (2015).

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**Setyawan W** and RJ Kurtz, "Ab initio Study of H, He, Li and Be Impurity Effect in Tungsten Sigma 3{112} and Sigma 27{552} Grain Boundaries," *Journal of Physics-Condensed Matter* 26, 135004 (2014).

**Setyawan W**, M Gerboth, B Yao, CH Henager, A Devaraj, VRSR Vemuri, S Thevuthasan, and V Shutthanandan, "Asymmetry of Radiation Damage Properties in Al-Ti Nanolayers," *Journal of Nuclear Materials* 445, 261 (2014).

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Wurster S, N Baluc, M Battabyal, T Crosby, J Du, C García-Rosales, A Hasegawa, A Hoffmann, A Kimura, H Kurishita, RJ Kurtz, H Li, S Noh, J Reiser, J Riesch, M Rieth, **W Setyawan**, M Walter, J-H You, and R Pippan, "Recent Progress in R&D on Tungsten Alloys for Divertor Structural and Plasma Facing Materials," *Journal of Nuclear Materials* 442, S181 (2013).

**Setyawan W** and RJ Kurtz, "Effects of Transition Metals on the Grain Boundary Cohesioni Tungsten," *Scripta Materialia* 66, 558 (2012).

# Kenneth Geelhood

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Kenneth Geelhood is a senior research engineer with more than a decade of experience in nuclear fuel performance. He manages the maintenance of the Nuclear Regulatory Commission (NRC) fuel performance codes FRAPCON-3 and FRAPTRAN. This activity involves developing new analytical models to predict the behavior of ceramic nuclear fuel, such as swelling and fission gas release and of metallic nuclear fuel cladding, such as corrosion and creep under reactor conditions.

Other activities include providing independent assessment of vendor fuel codes and other NRC licensing submittals and the development of models to predict the mechanical properties of zirconium alloy cladding, both for in-reactor and used-fuel storage applications. Geelhood recently participated in a large modeling effort to examine the mechanical response and potential for fuel rod failure of used nuclear fuel during transportation to a repository.

**Affiliations and Professional Service**

- American Nuclear Society (2004-present)
- Served as Executive Committee Chair and Program Chair for Material Science and Technology Division of American Nuclear Society
- Reviewer for the journals *Nuclear Technology, Journal of Nuclear Materials, and Nuclear Science and Engineering*

**Affiliations and Professional Service**


Adkins H, **K Geelhood**, B Koeppel, J Coleman, J Bignell, G Flores, J-A Wang, S Sanborn, R Spears, and N Klymyshyn, *Used Nuclear Fuel Loading and Structural Performance under Conditions of Transport – Demonstration of Approach and Results on Used Fuel Performance Characterization*. FCRD-UFD-2013-000325, US Department of Energy, Washington, DC (2013).

**Geelhood KJ**, "Implementing Primary creep calculations during stress changes and reversals in the fuel performance code FRAPCON-3." In: *Proceedings of 2013 LWR Fuel Performance Meeting*, Charlotte, North Carolina (2013).

**Geelhood KJ**, "Recent Updates to NRC Fuel Performance Codes and Plans for Future Improvements," *Nuclear Engineering and Technology* 43(6), 509-522 (2011).

**Geelhood KJ** and CE Beyer, "Hydrogen pickup modeling for zircaloy-2, zircaloy-4, M5™ and ZIRLO™." In: *Proceedings of 2011 Water Reactor Fuel Performance Meeting*, Chengdu, China (2011).

**Geelhood KJ**, "Modeling high burnup RIA yests with FRAPTRAN." In: *Proceedings of 2010 LWR Fuel Performance Meeting*, Orlando, Florida (2010).

**Geelhood KJ**, CE Beyer, and WG Luscher, "New release of fuel performance codes, FRAPCON-3.4 and FRAPTRAN 1.4." In: *Proceedings of Top Fuel 2009*, Paris, France (2009).

**Geelhood KJ**, WG Luscher, CE Beyer, DJ Senor, ME Cunningham, DD Lanning, and HE Adkins, *Predictive Bias and Sensitivity in NRC Fuel Performance Codes*. NUREG/CR-7001, PNNL-17644, Pacific Northwest National Laboratory for the U.S. Nuclear Regulatory Commission, Richland, Washington (2009).

**Geelhood KJ** and CE Beyer, "Corrosion and hydrogen pickup modeling in zirconium-based alloys." In: Proceedings from the 2008 Water Reactor Fuel Performance Meeting, Seoul, Korea (2008).

**Geelhood KJ**, CE Beyer, and WG Luscher, *PNNL Stress/Strain Correlation for Zircaloy*, PNNL-17700, Pacific Northwest National Laboratory, Richland, Washington (2008).

**Geelhood KJ**, D Matson, D Senor, and C Painter, "Spherical fuel element concept for small reactor design," *Nuclear Technology* 164(2), 255-264 (2008).

# Louis Terminello, Ph.D.

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Louis Terminello is Acting Associate Laboratory Director for the Physical & Computational Sciences Directorate (PCSD) at PNNL. He is responsible for a broad range of fundamental research sponsored by the Department of Energy's Office of Science, including work in advanced computing, atmospheric sciences, biological sciences, physical sciences, and particle physics. He was previously Chief Scientist for PCSD and Chief Science Technology Officer for the National Security Directorate. Terminello has chaired PNNL's Science and Technology Council, which helps develop and guide the Lab's integrated science and technology strategy and priorities. He is the contact for DOE's Office of Basic Energy Sciences' (BES) Materials Science and Engineering and Fusion Energy Sciences programs at PNNL and led an initiative that has greatly strengthened the Lab's leadership in chemical imaging.

Terminello came to PNNL in 2009 from Lawrence Livermore National Laboratory (LLNL), where he managed the strategic planning and development of science and technology capabilities to support core programs and external contracts for the 900-person science organization. As materials program lead for nuclear technology, he developed strategies, staff, and projects to meet significant DOE materials challenges. Technical results led to DOE L1 Pit lifetime milestone and multibillion dollar decisions for major DOE facilities. He also led integrating LLNL's strategy in nuclear forensics to ensure coordinated implementation and execution.

His research interests, which began at IBM Yorktown Heights and Massachusetts Institute of Technology, are in atomic, electronic, and bonding structure determination of novel materials using synchrotron radiation photoemission, absorption, and fluorescence.

**Affiliations and Professional Service**

- Materials Research Society (MRS): Meeting Chair for the Fall 2006 meeting, largest MRS meeting to date (more than 5,000 attendees); Strategic Program Planning Subcommittee Member, Technical Program Committee; Awards Committee Member, Turnbull Lectureship
- Symposium co-organizer for Analytical Applications and New Technical Developments in Soft X-ray Spectroscopy, PacifiChem 2010
- Chair, University of California-Berkeley Visiting Review Committee for the Department of Materials Science

- DOE BES review panel for Los Alamos National Laboratory's BES Chemistry Program
- Science Advisory Committee, LBNL Molecular Foundry
- Organized Sixth International Conference on Atomically Controlled Surfaces, Interfaces, and Nanostructures
- Organized Eighth International Conference on Electronic Spectroscopy and Structure
- Member of the American Chemical Society

**Awards and Recognition**

- American Physical Society Fellow
- LLNL Science and Technology Award for discovery of the Bucky-diamond and unraveling the structure of Si and Ge nanoclusters
- University of California-Berkeley – Chemistry and Regents Fellowships
- E.I. duPont Research Fellow
- President, Phi Lambda Upsilon Chemistry Honor Society, Massachusetts Institute of Technology
- Awarded 2 patents

**Selected Publications**

Lee JRI, TY Han, TM Willey, MH Nielsen, LM Klivansky, Y Liu, S Chung, **LJ Terminello**, T van Buuren, and JJ De Yoreo, "Cooperative Reorganization of Mineral and Template during Directed Nucleation of Calcium Carbonate," *Journal of Physical Chemistry* C 117(21), 11076-11085 (2013).

Lee JRI, HD. Whitley, RW Meulenberg, A Wolcott, JZ Zhang, D Prendergast, DD Lovingood, GF Strouse, T Ogitsu, E Schwegler, **LJ Terminello**, and T van Buuren, "Ligand-Mediated Modification of the Electronic Structure of CdSe Quantum Dots," *Nano Letters* 12(6), 2763-2767 (2012).

Meulenberg RW, TM Willey, JR Lee, **LJ Terminello**, and T Van Buren. "Erbium Doping Effects on the Conduction Band Edge in Germanium Nanocrystals," *Applied Physics Letters* 98(20), Article No. 203107 (2011).

Meulenberg RW, JRI Lee, A Wolcott, JZ Zhang, **LJ Terminello**, and T van Buuren, "Determination of the Exciton Binding Energy in CdSe Quantum Dots," *ACS Nano* 3(2), 325-330 (2009).

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Willey TM, C Bostedt, T van Buuren, JE Dahl, SG Liu, RMK Carlson, RW Meulenberg, EJ Nelson, and **LJ Terminello**, "Observation of Quantum Confinement in the Occupied States of Diamond Clusters," *Physical Review B* 74(20), Art.No.205432 (2006).

**Terminello LJ**, "Challenges in Plutonium and Actinide Materials Science," *MRS Bulletin* 26(9), 667-671 (2001).

# Steve Unwin, Ph.D.

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Stephen Unwin is manager of the nuclear market sector within PNNL's Energy and Environment Directorate that serves DOE-NE, the NRC, and other nuclear energy clients. His 33-year career has centered on the development of uncertainty and risk-analytic methodologies, their application to multi-domain problems of national and commercial importance, the founding of businesses on those capabilities, and the mentoring of earlier career staff. He has developed methods and models for uncertainty analysis, probabilistic risk assessment, and risk-informed decision-making that continue to be applied in numerous sectors, including nuclear power, oil and gas, renewable energy, national security, the chemical process industries, and the fossil energy sector.

Before joining PNNL in 2006, Unwin founded Brookhaven National Laboratory's Safety Integration Group (1987), SAIC's Risk & Reliability Management Division (1990), Battelle's Integrated Risk Management Group (1994), and Unwin Company - Integrated Risk Management (1996), which is a continuing risk management resource to commercial and government clients. He has contributed substantially to the international literature on risk/uncertainty methods and applications, and holds a first-class honors bachelor's degree in physics from Imperial College, London, and a doctorate in theoretical physics from the University of Manchester, UK.

### Affiliations and Professional Service

- Currently member of two subcommittees of the ASME Joint Committee on Nuclear Risk Management: Subcommittee on Standards Development and Subcommittee developing a PRA Standard for Advanced Non-LWR Nuclear Power Plants

### Awards and Recognition

- Certificate of Appreciation from the U.S. Nuclear Regulatory Commission "in recognition of [Unwin's] outstanding contribution to NUREG-1150 resulting in

a significant advancement in the state of technology of probabilistic risk analysis and a major contribution to the Nuclear Regulatory Commission's severe accident program."

- Awarded United States flag by the National Aeronautics and Space Administration "in recognition of contributions made to the Ulysses mission launched October 6, 1990."

**Selected Publications**


**Unwin SD** and BA Fecht, "Consumer Choice and Dempster-Shafer Models of Threat Prioritization for Emerging Dual-Use Technologies: Application to Synthetic Biology," *Defense and Security Analysis* 25, 1 (2009).

**Unwin SD**, PP Lowry, and MY Toyooka, "A New Class of Risk-Importance Measures to Support Reactor Aging Management and the Prioritization of Materials Degradation Research." In: *10th International Probabilistic Safety Assessment & Management Conference - PSAM10, June 7-11, 2010, Seattle*, WA, International Association for Probabilistic Safety Assessment & Management (IAPSAM), Mannheim, Germany (2010).

**Unwin SD** *et al.*, "An Information-Theoretic Basis for Uncertainty Analysis: Application to the QUASAR Severe Accident Study," *Reliability Engineering and System Safety* 26, 143 (1989).

**Unwin SD**, PP Lowry, RF Layton, Jr, PG Heasler, and MB Toloczko, "Multi-State Physics Models of Aging Passive Components in Probabilistic Risk Assessment," *Proceedings of the International Topical Meeting on Probabilistic Safety Assessment and Analysis: PSA2011, Wilmington, NC*, 1, 161-172, American Nuclear Society, La Grange Park, IL (2011).

Cook I and **SD Unwin**, "Controlling Principles for Prior Probability Assignments in Risk Assessment," *Nuclear Science and Engineering* 94, 107 (1986).

**Unwin SD**, RW Johnson, SW Rudy, JE Delargey and W Rogers, "Selective Catalytic Reduction (SCR) System Design and Operations: Quantitative Risk Analysis of Options," *Proceedings of the International Conference and Workshop on Risk, Reliability and Security, New York*: AIChE CCPS, 2002 (2002).

**Unwin SD**, PP Lowry, and MY Toyooka, "Reliability Models of Aging Passive Components Informed by Materials Degradation Metrics to Support Long-Term Reactor Operations," *Nuclear Science and Engineering* 171, 69-77 (2012).

Johnson RW, SW Rudy, and **SD Unwin**, *Managing Chemical Reactivity Hazards*, a book in the Essential Practices series, AIChE-CCPS, New York (2003).

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David Asner joined PNNL in June 2010 to lead the Belle/Belle II effort. The scientific goal of Belle II collaboration (600 scientists from 100 institutions across four continents) is to discover and elucidate new phenomena beyond the Standard Model of particle physics. Asner came from Carleton University where he was an Associate Professor of Physics conducting a broad research program on current and future HEP experiments at both electron and proton colliders. He brings considerable experience in flavor physics to PNNL. He was Spokesperson for the CLEO experiment (2008-10), Particle Data Group author since 2002, and has served on the steering committee of the INFN-SuperB project (2006-2010). Currently, Asner is Chief Scientist for the DOE US Belle II Project and is Research Manager for PNNL's High Energy Physics Program. He has more than 460 publications.

### Affiliations and Professional Service

- Founding member: Radiation Damage in Accelerator Target Environments (RaDIATE) Collaboration (2013)
- US Belle II Project: Chief Scientist (2011-present)
- US Belle II Operations Manager (2013-present)
- CLEO Collaboration: Spokesman (2008-10), Co-Spokesman (2007-08), Physics Coordinator (2004-05), Analysis Working Group Chair: Dalitz-plot (2003-06) & Rare Charm (2003-04)
- INFN-SuperB: International Steering Committee (2006-2010)
- Review of Particle Physics Author/Encoder, Particle Data Group (2002-present)

### Awards and Recognitions

- Fellow, American Physical Society (2014)
- Pacific Northwest National Laboratory, Laboratory Fellow (2013-present)

### Selected Publications


Adachi I, H Aihara, K Arinstein, **DM Asner** et al. (Belle Collab.), "First Observation of the P- wave Spin-singlet Bottomonium States hb(1P) and hb(2P)," *Physical Review Letters* 108, 032001 (2012).

Mizuk R, **DM Asner**, AE Bondar, TK Pedlar, et al. (Belle Collaboration), "Evidence for ηb(2S) and observation of $h_b(1P) \rightarrow \eta_b(1S)\gamma$ and $h_b(2P) \rightarrow \eta_b(1S)\gamma$," *Physical Review Letters* 109,232002 (2012).

**Asner DM** and WM Sun, "Time-independent measurements of D0 - anti-D0 mixing and relative strong phases using quantum correlations," *Physical Review D* 73 034024 (2006).

**Asner DM**, et al. [CLEO Collab.], "Determination of the D0→ K+π- Relative Strong Phase Using Quantum-Correlated Measurements in e+e-→ D0 anti-D0 at CLEO," *Physical Review D* 78, 012001 (2008).

**Asner DM** and G Tatishvili, et al. [CLEO Collab.], "Updated Measurement of the Strong Phase in D0→ K+π-," *Physical Review D* 86, 112001 (2012).

**Asner DM**, JB Gronberg, and JF Gunion, "Detecting and studying Higgs bosons at a photon-photon collider," *Physical Review D* 67 (2003) 035009.

**Asner DM**, H Burkhardt, A De Roeck, J Ellis, et al., "Higgs physics with a gamma gamma collider based on CLIC I," *The European Physical Journal C* 28 (2003) 27-44.

KA Olive et al. (Particle Data Group), "Review of Particle Physics," *Chinese Physics* C, 38, 090001 (2014). "*Resonances*", DM Asner, C Hanhart, and E Klempt, pp. 513-516 of *Review of Particle Physics*, *Chinese Physics C* 38, 090001 (2014).

**Asner DM**, "D0-anti-D0 Mixing," *Review of Particle Physics*, pp. 604-606; *Physical Review D*, 66, 010001 (2002). Revised on pp. 675-679 of *Physics Letters B* 592: 1 (2004). Revised on pp. 728-733 of *Journal of Physics G*, 33, 1 (2006). Revised on pp. 783-789 of *Physics Letters B* 667, 1 (2008). Revised on pp. 820-826 of *J. Phys. G* 37, 075021 (2010). Revised on pp. 820-826 of *Journal of Physics G* 37, 075021 (2010). Revised on pp. 903-909 of "Review of Particle Physics,"*Physical Review D* 86,010001 (2012). Revised on pp. 978-984 of *Review of Particle Physics*, *Chinese Physics* C 38, 090001 (2014).

"Review of Charm Dalitz-plot Analysis Formalism," On pp. 713-716 of the Review of Particle Physics, *Journal of Physics G* 33 1 (2006). Also on pp. 771-774 of *Physics Letters B*, 667, 1 (2008). Also on pp. 807-811 of *Journal of Physics G* 37, 075021 (2010). Also pp. 889-893 of "Review of Particle Physics," *Physical Review D* 86,010001 (2012).

"Review of Charm Dalitz-plot Analyses," On pp. 664-667 of "Review of Particle Physics," *Physics Letters B* 592: 1 (2004). Revised on pp. 716-720 of *Journal of Physics G* 33, 1 (2006). Revised on pp. 774-775 of *Physics Letters B* 667, 1 (2008). Revised on pp. 811-812 of *Journal of Physics G* 37, 075021 (2010). Revised pp. 893-895 of "Review of Particle Physics," *Physical Review D* 86,010001 (2012).

# Sue Clark, Ph.D.

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Sue B. Clark holds the position of Battelle Fellow at PNNL and Regents Distinguished Professor of Chemistry with tenure at Washington State University in Pullman, Washington. In this joint appointment, she leads a research effort focused on the chemistry and chemical engineering of processing nuclear materials.

Her current research areas include:

- Chemistry of radioactive waste systems
- Environmental chemistry
- Actinide separations
- Radioanalytical chemistry.

Prior to joining Washington State University, Clark was an Assistant Research Ecologist at the University of Georgia's Savannah River Ecology Laboratory (1992-1996), and Senior Scientist at Westinghouse Savannah River Company's Savannah River Technology Center (1989-1992).

**Affiliations and Professional Service**

- U.S. Nuclear Waste Technical Review Board, appointed by President Barack Obama (2011-2014)
- Fellow, American Association for the Advancement of Science (AAAS)
- Fellow, American Chemical Society (ACS)
- Member, Washington State Academy of Sciences
- Member, Governing Board for the U.S. Council for Chemical Research (2009-2011)
- National Academy's Nuclear and Radiation Studies Board (2004-2009); member of many study committees
- DOE Basic Energy Sciences Advisory Committee (2003-2011)
- Consultant to Battelle Memorial Institute and the Helmholtz Association of German Research Centers

**Awards and Recognition**

- ACS's Olin-Garvan Medal (2012)
- Fink Distinguished Lecturer, Georgia Institute of Technology's Department of Chemistry (2008)
- Westinghouse Distinguished Professor of Materials Science and Engineering, WSU (2002-2008)

**Selected Publications**

Snow MS, DC Snyder, **SB Clark**, M Kelley, and JE Delmore, "$^{137}$Cs Activities and $^{135}$Cs/$^{137}$Cs Isotopic Ratios from Soils at Idaho National Laboratory: A Case Study for Contaminant Source Attribution in the Vicinity of Nuclear Facilities," *Environmental Science & Technology* 49(5), 2741-2748 (2015).

Schumacher PD, NA Woods, JO Schenk, and **SB Clark**, "Preconcentratin of Trivalent Lanthanide Elements on a Mercury Film from Aqueous Solution Using Rotating Disk Electrode Voltammetry," *Analytical Chemistry* 82(13), 5663-5668 (2010).

Douglas M, **SB Clark**, JI Friese, BW Arey, EC Buck, BD Hanson, S Utsounomiya, and RC Ewing, "Microscale characterization of uranium(VI) silicate solids and associated neptunium(V)," *Radiochimica Acta* 93, 265-272 (2007).

Novikov AP, SN Kalmykov, S Utsunomiya, RC Ewing, F Horreard, A Merkulov, **SB Clark**, VV Tkachev, BF Myasoedov "Colloid Transport of Plutonium in the Far-Field of the Mayak Production Association, Russia," *Science* 314(5799), 638-641 (2006).

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Jim De Yoreo is Chief Scientist for Materials Synthesis and Simulation Across Scales at PNNL and an Affiliate Professor of Chemistry and of Materials Science and Engineering at the University of Washington. His research has spanned a wide range of materials-related disciplines, focusing most recently on understanding self-assembly and crystallization in organic, biomolecular, and biomimetic systems through the use of *in situ* imaging and spectroscopy techniques.

He received his Ph.D. in Physics from Cornell University in 1985. Following post-doctoral work at Princeton University, he joined Lawrence Livermore National Laboratory in 1989, where he held numerous positions, including Director of the Biosecurity and Nanosciences Laboratory and Deputy Director of the Laboratory Science and Technology Office. He joined Lawrence Berkeley National Laboratory in 2007 where he served as Deputy and Interim Director of the Molecular Foundry until coming to PNNL in 2012. De Yoreo has authored, co-authored, or edited more than 200 publications and patents with more than 10,000 citations and has delivered more than 150 invited talks.

**Affiliations and Professional Service**

- Fellow, American Physical Society
- Fellow, Materials Research Society (MRS)
- Member, Washington State Academy of Sciences
- Member, American Association for Crystal Growth (AACG)
- Member, American Chemical Society
- Editor, *Bioinspired Materials*, Associate Editor-in-Chief, *Frontiers of Materials Science*
- Chair, MRS Program Development Subcommittee
- Member, Executive Committee of both International Organization for Crystal Growth and the AACG
- Served as MRS President and Board Member
- Served on committees for the National Academy of Sciences, the Department of Energy, and Congress

**Awards and Recognition**

- AACG Award (American Association for Crystal Growth), 2013
- Laudise Prize (International Organization for Crystal Growth), 2010
- Fellow of the American Physical Society, 2007
- LLNL Science and Technology Award, 2001
- R&D 100 Award for Development of Rapid Growth Process for KDP, 1994

**Selected Publications**

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Gertrude (Gert) Patello is a senior project manager in the Nuclear Sciences Division of the Energy and Environment Directorate at PNNL. She has a relationship management role for the Nuclear Physics sector at PNNL that includes providing oversight for the projects funded by the DOE Office of Nuclear Physics Isotope Program and interface with DOE program staff. She also manages four projects within the PNNL Isotope Program and is responsible for their programmatic execution. Patello has participated on two programmatic review panels for the DOE Isotope Program.

Patello has had various line management positions at PNNL over the past 12 years, managing radiochemical and material research staff in PNNL's category 2 nuclear facility. She received her B.S in Ceramic Engineering and her PhD in Ceramics from Alfred University in Alfred, New York in 1988 and 1993, respectively.

**Affiliations and Professional Service**

- Fusion Energy Sciences Advisory Committee (2014-present)
- Chair, Actinide Separations Conference (2013)
- PNNL representative, Actinide Separations Conference Board (2012-2015)

**Selected Publications**


Peterson RB, B Paul, T Palmer, Q Wu, W Jost, CHT Tseng, S Tiwari, **GK Patello**, EC Buck, JD Holladay, RW Shimskey, PH Humble, PJ MacFarlan, and J Wainright, "Microscale Power Generation based on Radiolytic Processes." In: *The Sixth International Workshop on Micro and Nanotechnology for Power Generation and Energy Conversion Applications (PowerMEMS 2006), November 29-December 1, 2006, Berkeley, California*, pp. 235-238. IOPScience, Bristol, United Kingdom (2007).

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## ACRONYMS AND INITIALISMS

| | |
|---|---|
| ATR | Advanced Test Reactor |
| ATR-C | Advanced Test Reactor Critical Facility |
| $BaTiO_3$ | barium titanate |
| BES | Basic Energy Sciences |
| DOE | U.S. Department of Energy |
| EDS | energy dispersive X-ray spectrometer |
| EMSL | Environmental Molecular Sciences Laboratory |
| HEF | High Exposure Facility |
| HEP | High Energy Physics |
| HEU | highly enriched uranium |
| HFIR | High Flux Isotope Reactor |
| HPC | high-performance computing |
| HPRR | high-performance research reactors |
| IEA | International Energy Agency |
| INL | Idaho National Laboratory |
| LEU | low enriched uranium |
| LFA | laser flash apparatus |
| LSF | Low Scatter Facility |
| LWR | light-water reactor |
| $M^3$ | Office of Material Management and Minimization |
| MITR | Massachusetts Institute of Technology Research Reactor |
| MS3 | Molecular Science Software Suite |
| MURR | University of Missouri Research Reactor |
| NBSR | National Institute of Standards and Technology research reactor |
| NMR | nuclear magnetic resonance |
| NNSA | National Nuclear Security Administration |
| NPSI | Nuclear Process Science Initiative |
| NRC | Nuclear Regulatory Commission |
| ODS | oxide dispersion-strengthened |
| ORNL | Oak Ridge National Laboratory |
| PDC | process development cell |

| | |
|---|---|
| PIE | post-irradiation examination |
| PNNL | Pacific Northwest National Laboratory |
| PSF | Physical Sciences Facility |
| RadEMSL | EMSL's Radiochemistry Annex |
| RaDIATE | Radiation Damage in Accelerator Environments |
| RAF/M | reduced activation ferritic/martensitic |
| RCF | Radiological Calibrations Facility |
| RPL | Radiochemical Processing Laboratory |
| SED | secondary electron detector |
| SEM | scanning electron microscopy |
| SEM-FIB | scanning electron microscope-focused ion beam |
| STEM | scanning transmission electron microscopy |
| TEM | transmission electron microscopy |
| TMED | TPBAR Materials Ex-Reactor Testing and Development |
| TMIST | TPBAR Materials Irradiation Separate-Effects Test |
| TPBAR | tritium-producing burnable absorber rod |

## About Pacific Northwest National Laboratory

Pacific Northwest National Laboratory is a U.S. Department of Energy Office of Science national laboratory where interdisciplinary teams advance science and technology and deliver solutions to America's most intractable problems in energy, the environment, and national security. PNNL employs 4,300 staff, has an annual budget of nearly $950 million, and has been managed by Ohio-based Battelle since the Lab's inception in 1965.

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Radiation Effects in Materials Research

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