Light Water Reactor Sustainability

ACCOMPLISHMENTS REPORT

LWRS
Light Water Reactor Sustainability

U.S. DEPARTMENT OF ENERGY

The Susquehanna Steam Electric Station, a nuclear power station, is in Luzerne County, Pennsylvania, just south of Shickshinny, in Salem Township, Pennsylvania, United States.

The mission of the Light Water Reactor Sustainability Program is development of the scientific basis, and science-based methodologies and tools, for the safe and economical long-term operation of the nation's high-performing fleet of commercial nuclear energy facilities.

Contents

On the Cover

The Palo Verde Nuclear Generating Station is a nuclear power plant located in Tonopah, Arizona, about 45 miles west of central Phoenix.

Introduction

The Light Water Reactor Sustainability Program is a U.S. Department of Energy (DOE) program focused on research and development to support the long-term operation of our nation's commercial nuclear power plants. Extending the operating lifetimes of current plants is essential to realizing the Administration's goals of reducing greenhouse gas emissions to 80 percent below 1990 levels by the year 2050. Decisions on subsequent license renewal and the investments required to support long-term operation will be made by plant owners. The technical results from the LWRS Program provide data for owners to make informed decisions on long-term operation and subsequent license renewal, reducing the uncertainty, and therefore the risk, associated with those decisions.

Kathryn A. McCarthy, Director, LWRS Program Technical Integration Office

It is in the best strategic interests of the nation that we pursue the long-term operation of existing nuclear energy facilities; doing so enables progress toward national and global carbon management goals, heightens domestic energy security and moderates cost impacts to businesses and consumers by delaying the need to build replacement generating capacity - whether nuclear, fossil or renewable.

The DOE research, development, and demonstration role focuses on aging phenomena and issues that require long-term research and/or unique DOE laboratory expertise and facilities and are applicable to most operating reactors. DOE and its national labs uniquely possess large theoretical, computational and experimental capabilities that simply do not and economically cannot exist at the individual company level. The LWRS Program relies on a strong relationship with industry, primarily with the Electric Power Research Institute (EPRI), but also directly with several utilities and suppliers.

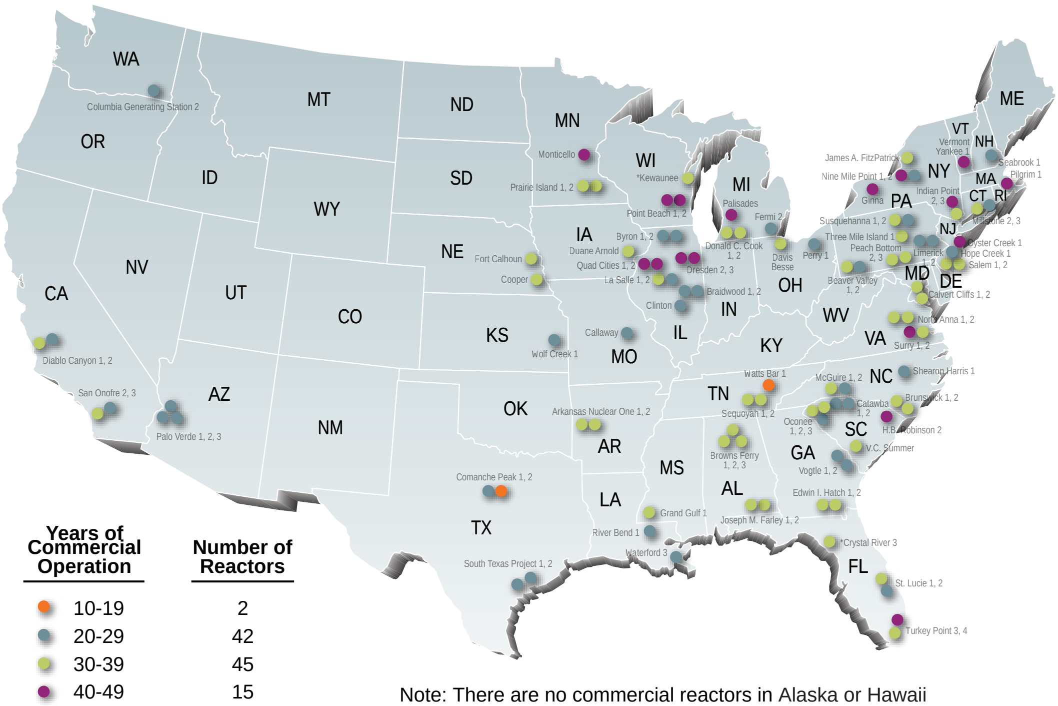
If, after reading this report, you have questions or need additional Information, I encourage you to contact me, Richard Reister (the Federal Program Manager), or the respective research pathway leaders (noted on page 19), or visit the Light Water Reactor Sustainability Program website (www.inl.gov/lwrs). The annually updated Integrated Program Plan and Technical Pathway Program Plans are also available for those seeking more detailed technical Information.

The Calvert Cliffs Nuclear Power Plant, Units 1 and 2, near Lusby, Maryland.

Background

Nuclear energy is the nation's largest contributor of nongreenhouse-gas-emitting electric power generation, comprising nearly three-quarters of the nonemitting sources (http://www.eia.gov/cneaf/electricity/figures1/html). Further, a 2012 study conducted by National Renewable Energy Laboratory shows the life cycle greenhouse gas emissions from nuclear energy to have a median value nearly identical to wind and lower than all fossil sources as well as biomass, geothermal and all solar.

So whether viewed from a reliability of baseload electrical generation or environmental/carbon management standpoint, it is clearly in the best interests of consumers, industries and electric utilities to maintain nuclear energy's position in the nation's multifaceted electric generation portfolio. That's where the U.S. Department of Energy's Light Water Reactor Sustainability Program comes in. DOE's role is to partner with industry and the Nuclear Regulatory Commission to support and conduct the research needed to inform major component refurbishment and replacement strategies, performance enhancements, subsequent plant license renewal applications, and age-related regulatory oversight decisions. DOE's research, development and demonstration activities focus on aging phe-



* The Kewaunee and Crystal River Plants have been shut down.

Source: http://www.nei.org/resourcesandstats/documentlibrary/reliableandaffordableenergy/graphicsandcharts/usnuclearplantlicenseinformation/

Locations and operating ages of U.S. commercial nuclear power stations.

nomena and issues that require long-term research and/or unique DOE laboratory expertise and facilities and are applicable to most operating reactors - whether they've been in service for fewer than 20 years or more than 40.

When appropriate, demonstration activities are cost-shared with industry. Light Water Reactor Sustainability pilot projects and collaborative activities are already well under way at commercial nuclear energy facilities and with industry organizations such as the EPRI Long-Term Operations. Much of the research will be used by the Nuclear Regulatory Commission to inform the regulatory framework for subsequent license renewals.

These projects and activities are built around four research and development pathways: Materials Aging and Degradation; Advanced Instrumentation, Information and Control Systems Technologies; Risk-Informed Safety Margin Characterization; and Advanced Light Water Reactor Nuclear Fuels. The remainder of this document is broken into sections, offering high-level information on the purpose of each pathway, listings of key programmatic accomplishments and select highlights of some of the respective research efforts.

Constellation Energy Nuclear Group, LLC and its R.E. Ginna Nuclear Power Plant, located in Ontario, New York, have been important partners in working toward increased understanding of materials aging mechanisms.

Materials Aging and Degradation

Research and development efforts in this pathway seek to develop the scientific basis for understanding and predicting long-term behavior of materials in nuclear power plants. The work will provide data and methods to assess the performance of systems, structures and components essential to safe and sustained nuclear power plant operations.

The systems, structures, and components in a nuclear plant must withstand a challenging operational environment including extended time at high temperature, neutron irradiation, stress, and/or corrosive media. The many modes of degradation are complex and vary depending on location and material. Understanding and managing materials degradation is a key for the continued safe and reliable operation of our nation's nuclear power plants.

Research in this pathway relies on both experimental and analytical activities. Analysis of material samples from power plants and tests in research reactors and laboratories are coupled with research to understand the mechanisms behind the observed degradation of materials. Modeling and simulation is used to reduce the experimental burden for long-term operation studies and provide tools to interpolate and extrapolate the data trends. This pathway is also developing monitoring techniques to characterize degradation of core components, as well as processes to mitigate the effects of degradation. Together, these activities provide high-quality measurements of degradation modes, improved mechanistic understanding of key degradation modes, and predictive modeling capability with sufficient experimental data to validate these tools. The activities also provide new methods of monitoring degradation and development of advanced mitigation techniques for improved performance, reliability, and economics.

The R&D products from this pathway will be used to define operational limits and aging mitigation approaches for materials in nuclear power plant systems, structures and components subject to long-term operating conditions.

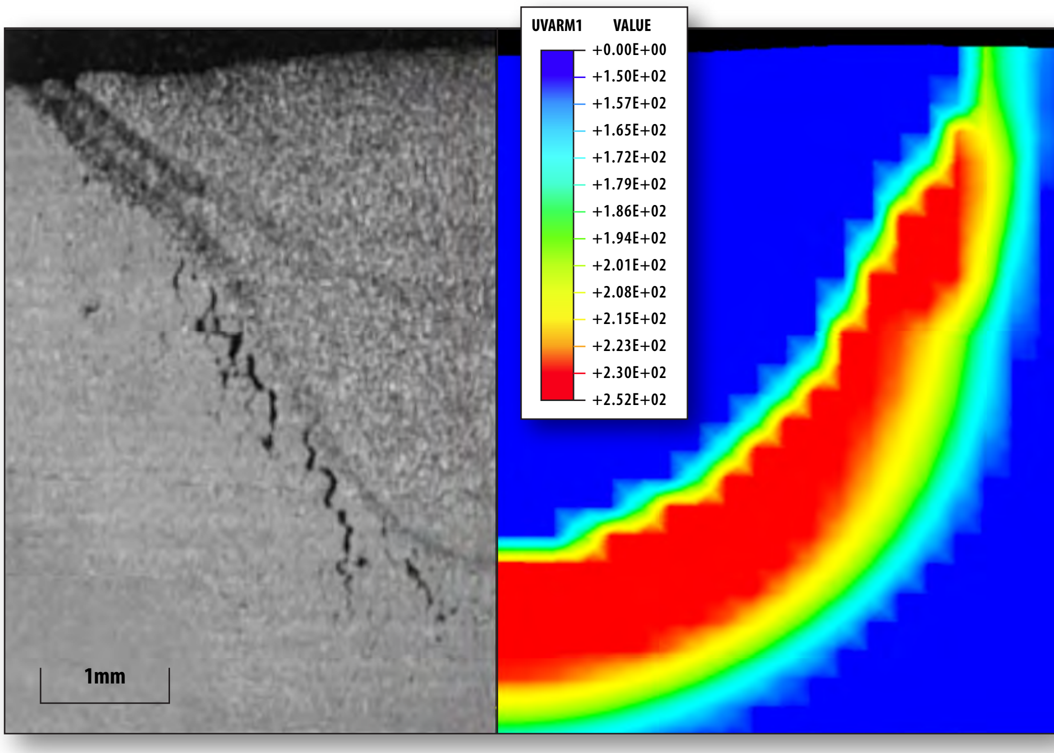
2012 Accomplishments

- Completed the first draft of the Expanded Proactive Materials Degradation Assessment Report, a gap analysis of materials degradation modes, providing a firm foundation for task prioritization and research needs for regulators, industry, and researchers; the final report will be released in 2013
- Developed guidelines for risk-Informed condition assessment and evaluation of aging safety-related concrete structure, components and systems and illustrated the process via a test case
- Analyzed surveillance specimens from R.E. Ginna and Ringhals nuclear plants; these results provide insights into material degradation modes
- Prepared plans for materials collection during plant outages at Nine Mile Point and Ginna; analysis materials from working plants provide important insights into materials degradation modes
- Completed planning document on concrete measurements to be performed at the decommissioned Barsebäck site in Sweden; decommissioned sites are an important source of materials for testing
- Completed R&D Roadmaps for nondestructive evaluation of concrete, cables, fatigue damage, and the reactor pressure vessel; these roadmaps identify needed R&D to support NDE of important plant components
- Report on high fluence effects on microstructural evolution of irradiated materials; Irradiation-induced phase transformations could lead to embrittlement and corrosion susceptibility
- Modeling plans for high fluence phase transformations and swelling effects in core internals; modeling, combined with experimental results, provides insights into degradation mechanisms and impacts
- Evaluated the influence of bulk and surface microstructures on Alloy 600 stress corrosion cracking initiation behavior; understanding and modeling the mechanisms of crack initiation is a key step in predicting and mitigating stress corrosion cracking in the primary and secondary water circuits

- Report on high fluence effects on irradiation-assisted stress corrosion cracking of stainless steels
- Research plan for surrogate materials and attenuation studies, building on reactor pressure vessel results and findings in FY-09 to FY-12
- Completed review of potential replacement alloys for light water reactors

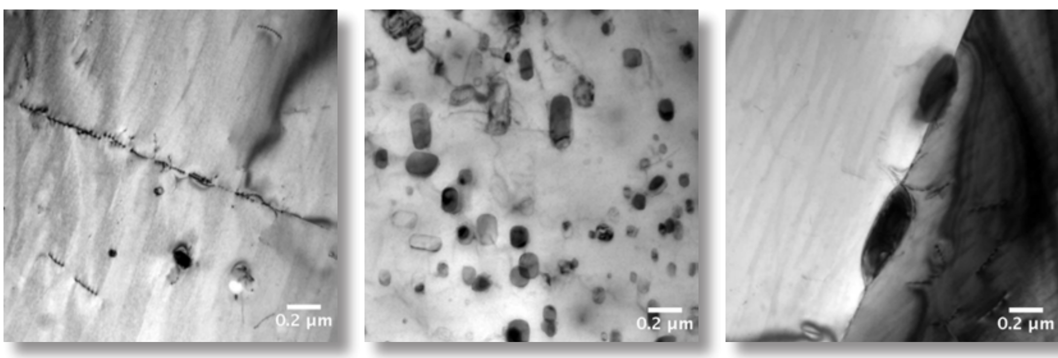
Research Highlights

Advanced Weld Repair: Welding is widely used for component repair, and weld-repair techniques must be resistant to long-term degradation mechanisms such as corrosion and irradiation. The MAaD Pathway is developing new welding and weld analysis techniques, via a combination of experimental and modeling activities that are jointly funded with EPRI. Understanding the impact that helium, present in irradiated material, has on the welding process is an important input to development of an advanced technology. The welding technology will be transferred to industry in 2018, providing an important repair technology that in some instances could enable repair rather than replacement of costly components.

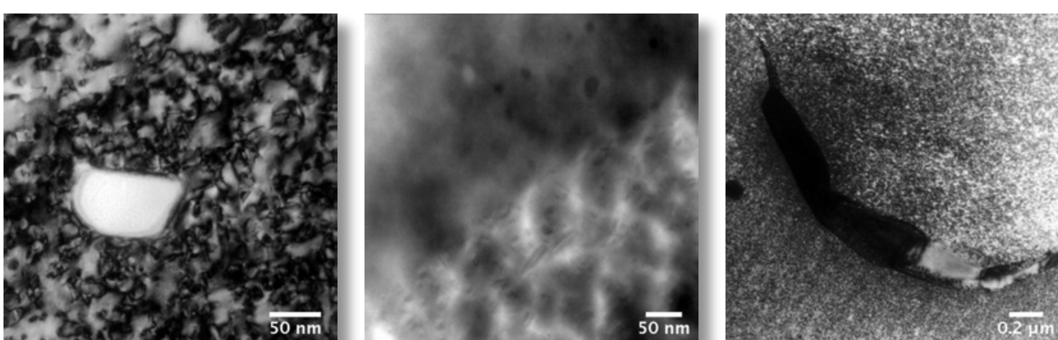


Experimental and modeling activities support the development of advanced welding techniques.

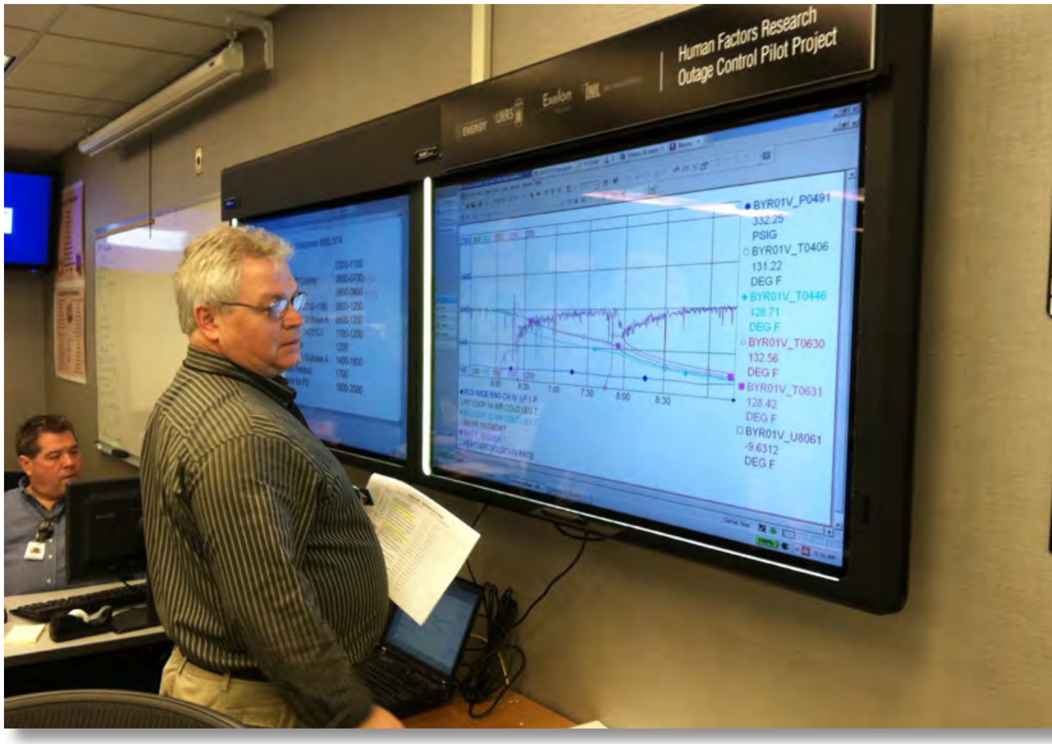
Phase Transformations at High Fluence: Under irradiation, the large concentrations of radiation-induced defects will diffuse to defect sinks such as grain boundaries and free surfaces and lead to a phenomena termed radiation-induced segregation. For example, in 316 stainless steel, chromium (important for corrosion resistance) can be depleted in some areas while elements like nickel and silicon are enriched to levels well above the starting, homogenous composition. This form of degradation can accelerate changes in the material microstructure such as phase transformations that are not favorable under thermal aging. Detailed microstructural analysis of surveillance specimens from commercial reactors, together with mechanistic studies, supports the development of a model of phase transformation under light water reactor conditions. These studies will be used to identify key operational limits (if any) to minimize phase transformation concerns, optimize inspection and maintenance schedules to the most susceptible materials/locations, and, if necessary, qualify radiation-tolerant materials for light water reactor service.



Non-irradiated stainless steel alloy



Transmission-electron microscopy images showing ultrafine carbide particles formed under irradiation in stainless steel alloy irradiated to 9.1 dpa under LWR conditions.



An outage manager at the Exelon Byron plant uses new prototype interactive display technology developed by LWRS-sponsored research to monitor the progress of outage work activities at the station.

Instrumentation, Information & Control Systems Technologies

Efforts in this pathway seek to address modernization of the current instrumentation and control (I&C) technologies used in nuclear power plants through development/testing of new I&C technologies and advanced condition monitoring technologies for more automated and reliable plant operation. The R&D products will be used to design and deploy new Instrumentation, Information & Control Systems (II&C) technologies and systems in existing nuclear power plants that provide an enhanced understanding of plant operating conditions and available margins and improved response strategies and capabilities for operational events. The goals are to enhance nuclear safety, increase productivity, and improve overall plant performance. This transformation is critical to addressing an array of issues facing plants, including the aging of legacy analog I&C systems, a potential shortage of technical workers, ever-increasing expectations for nuclear safety improvement, and pressure to reduce costs. Pathway researchers are working closely with nuclear utilities to develop instrumentation & control technologies and solutions to support the safe and reliable life extension of current reactors.

2012 Accomplishments

- Working with industry participants, completed vision document to guide the modernization of I&C systems; a series of pilot projects are planned to carry out the modernization strategy
- Developed prototype technologies for nuclear plant status control and field work processes, with associated study of field trials at a nuclear plant
- Developed outage work status capabilities, providing a means for communicating work progress and completion status directly from field activities to the outage control centers
- Completed a digital full-scale mockup of a conventional nuclear power plant control room, providing proof of concept for future control room pilot projects
- Developed guidelines and demonstration technologies for nuclear plant operations and maintenance work processes
- Completed report on strategy and technical plans for online monitoring technologies in support of nondestructive examination deployment; this activity is collaborative with the MAaD Pathway where NDE technologies are under development
- Completed report on the online monitoring technical basis and analysis framework for large power transformers; this report will guide the FY-13 pilot project on online monitoring
- Completed report on demonstration and data collection for prototype computer-based procedures; computer-based procedures provide an efficient and effective means to guide workers

Research Highlight

Advanced Outage Control Center: Nuclear power plant refueling outages are perhaps the most challenging times in the ongoing operations of the facilities, executing typically more than 10,000 activities in a 20- to 30-day work period. This presents challenges in controlling the timing, quality, and cost of individual work activities in the face of shifting schedules, emergent issues, and strained human and equipment resources. Despite a major industry focus on outage management, there remain significant opportunities and challenges for the industry such as further reducing the duration of refueling outages while still maintaining current shutdown safety characteristics. The II&C Pathway has conducted research into new technologies that integrate outage control centers, field-work crews, and real-time plant information to achieve collective situational awareness and enable timely decision-making. Efforts are under way to develop concepts for an advanced outage control center specifically designed to maximize the use of digital technology for information analysis and shared understanding in outage control center team decision-making. In the future, the pathway will conduct research and produce implementation guidance for technologies that improve outage risk management, especially in the area of configuration control for a changing plant.

RISMC methodology is being used to help define optimal emergency backup power choices for nuclear power plant operators.

Risk-informed Safety Margin Characterization

The purpose of the Risk-Informed Safety Margin Characterization (RISMC) Pathway is to develop and deploy approaches to support the management of uncertainty in safety margins quantification to improve management and operator decision-making in the operation of nuclear power plants. The RISMC approach provides a way to incorporate plant physical processes that govern aging and degradation into the safety analysis process to better optimize plant safety and performance. The goals of the RISMC Pathway are twofold: (1) develop and demonstrate a risk-assessment method coupled to safety margin quantification that can be used by nuclear power plant decision-makers as part of their margin management and recovery strategies; and (2) create an advanced RISMC toolkit that enables a more accurate representation of a nuclear power plant safety margin.

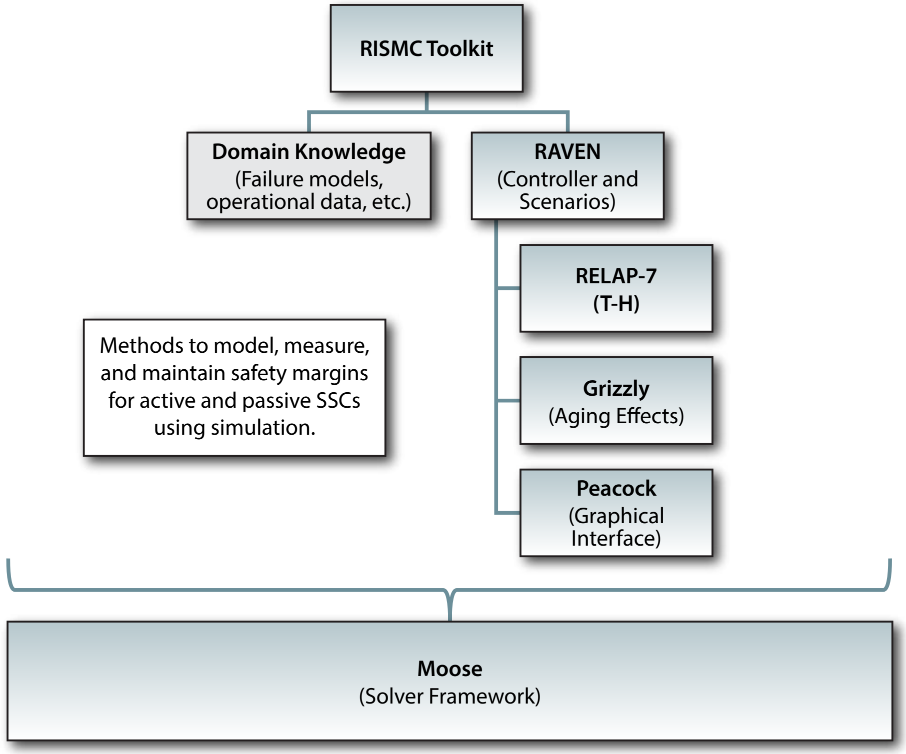
2012 Accomplishments

- Verification and validation (V&V) strategy for LWRS Modeling and Simulation activities
- Demonstrated the RISMC methodology using a test case based on the INL Advanced Test Reactor
- Demonstrated single-phase, steady-state version of RELAP-7, the primary safety analysis code used in the RISMC Pathway

- Demonstrated the capability to generate and solve accident sequences such as station blackout using the RAVEN simulation code
- Completed proof of concept demonstration of model (Grizzly) for pressurized thermal shock effects on an aged section of a reactor pressure vessel; when completed, Grizzly will enable predictive modeling of component aging effects

Research Highlight

RISMC Demonstration: Pathway researchers demonstrated application of the Risk-informed Safety Margin Characterization methodology using INL's Advanced Test Reactor. This reactor was used because it has a modern, full-scope and updated probabilistic risk assessment; it has a realistic thermal hydraulics model input deck; and it currently uses its probabilistic risk assessment to make risk-informed (versus safety margin-based) decisions. Use of the Advanced Test Reactor allowed demonstration of just how different Risk-informed Safety Margin Characterization is from Probabilistic Risk Assessment. In the latter, a safety metric (such as core damage frequency) is estimated using static fault and event-tree models; we do not know how close (or beyond) we are to physical safety limits (such as peak clad temperature) for most accident sequences described in the Probabilistic Risk Assessment. Conversely, with Risk-informed Safety Margin Characterization, we estimate how close we are (or not) to the event, not just the frequency of the event, providing information on how safety margin can be improved.



The RISMC Toolkit is being created to avoid the issues and limitations with legacy tools.

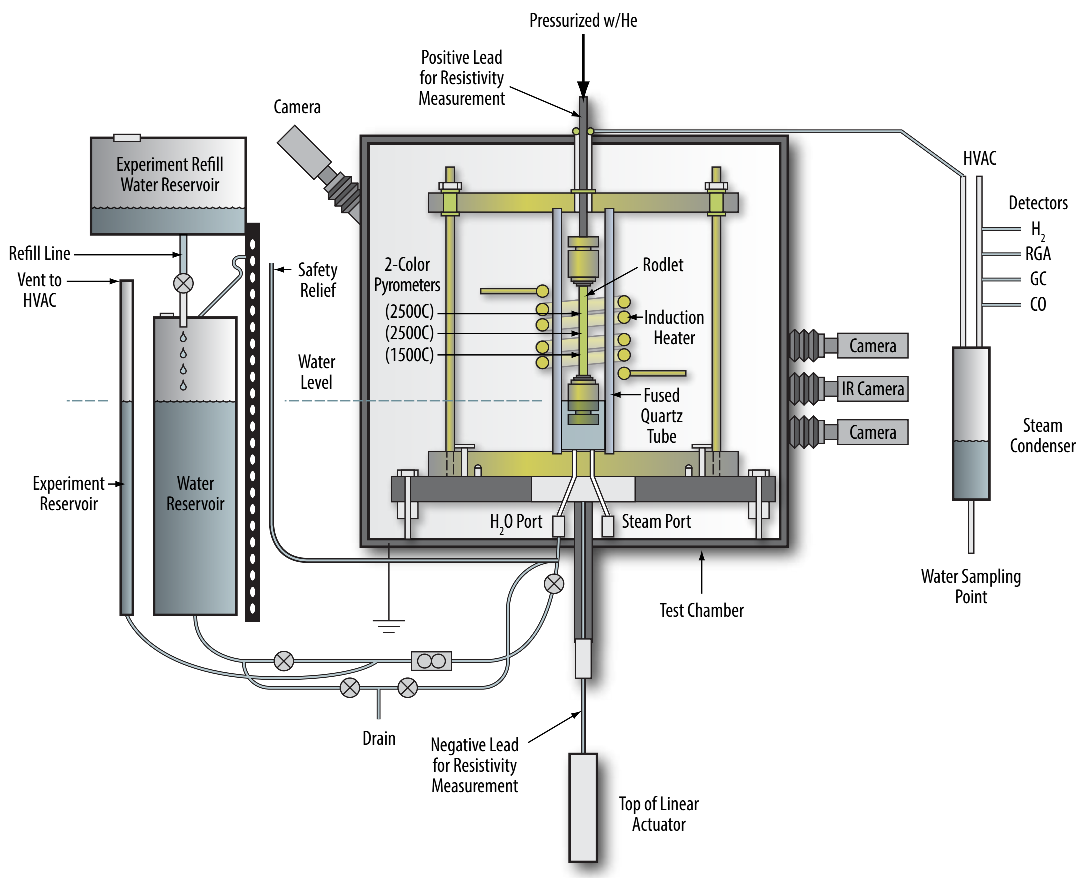
Advanced Light Water Reactor Nuclear Fuels

Research and development work in this pathway aims to improve the scientific knowledge basis for understanding and predicting fundamental nuclear fuel and cladding performance in nuclear power plants, and apply this information to development of high-performance, high burn-up fuels with improved safety, cladding integrity and improved nuclear fuel cycle economics. The R&D products will be used to deploy new fuel/core designs for the existing nuclear power plant fleet with improved safety and economic operational capabilities.

2012 Accomplishments

- Completed development plan for silicon carbide (SiC) ceramic matrix composite (CMC) nuclear fuel cladding; this plan will guide future R&D on advanced cladding
- Completed failure mode and performance analysis for SiC CMC, providing important insights on the behavior of SiC CMC

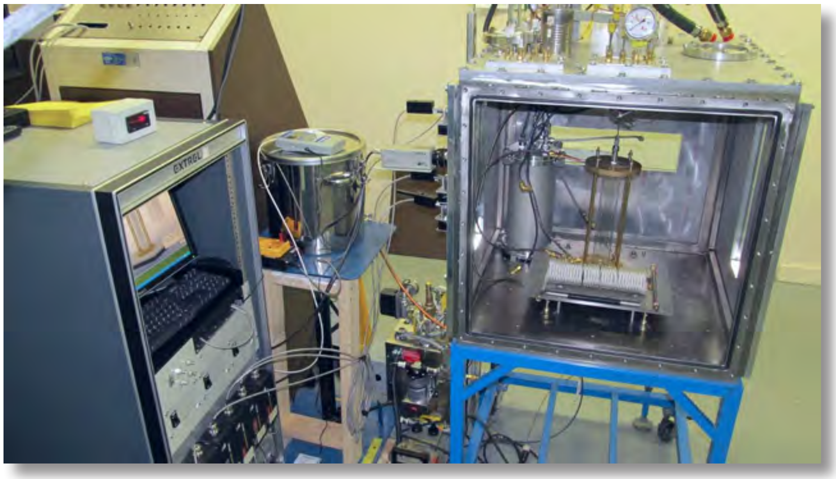
Schematic of the Oxidation Kinetics System (OKS). The OKS will evaluate the behavior of candidate cladding materials in high-temperature oxidative environments characteristic of postulated accident conditions.



- Documented required analyses to support irradiation readiness for SiC CMC rodlets in the INL Advanced Test Reactor; test articles must undergo rigorous testing prior to insertion in a test reactor
- Completed fuel clad trade-off study, documenting the pros and cons of performance of a range of advanced claddings
- Completed the design and installation of a nuclear fuel cladding test system that simulates nuclear fuel heating and provides a steam atmosphere
- Selected two industry proposals for SiC CMC joining technology development; joining technologies are a major challenge for SiC CMC

Research Highlight

Oxidation Kinetics Test System: A test system was constructed to measure and evaluate potential performance improvements that may be offered by advanced cladding concepts under postulated accident conditions relative to currently-used zirconium-based cladding. The oxidation kinetics system (OKS) was designed and constructed to evaluate the behavior of candidate cladding materials in high-temperature oxidative environments. The system instrumentation monitors the onset and evolution of oxidation, internal phase changes, thermal stress behavior, and ballooning/rupture of pressurized rodlets.



Oxidation Kinetics System experiment setup

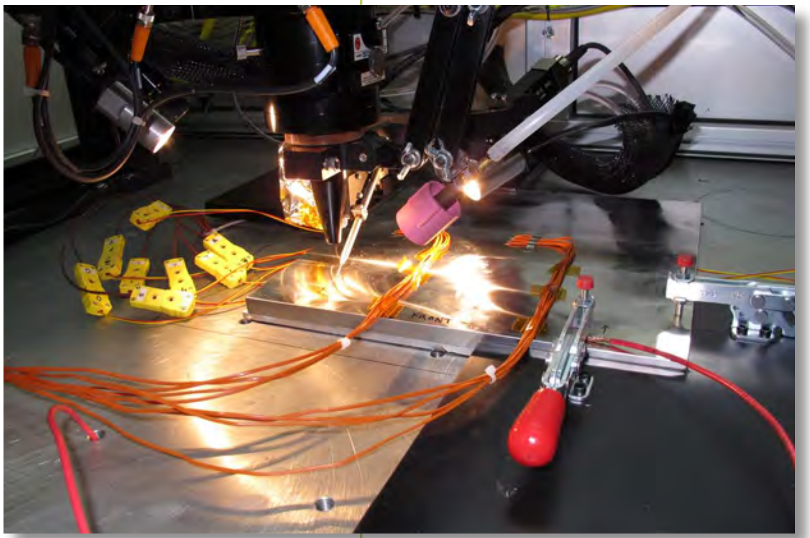
Looking ahead, it should be noted that fuel development activities associated with this Light Water Reactor Sustainability Program pathway are moving to the DOE Fuel Cycle R&D Program beginning in Fiscal 2013. The LWRS Program will maintain the lead role in performing analyses to determine the potential impact of advanced nuclear fuel rods on reactor safety margins via coordination with the RISMC Pathway.

Near-term Milestone Preview

Building on the successes achieved in Fiscal 2012, the Light Water Reactor Sustainability Program has laid out an aggressive set of milestones to focus its collaborative efforts in 2013.

Materials Aging and Degradation

- Issue the final Expanded Materials Degradation Assessment
- Develop risk-informed guidelines for evaluating performance of aging safety-related concrete structures, systems, and components
- Complete analysis of recent characterization of irradiated specimens and irradiation-induced phase transformations in high fluence core internals
- Validate data contained in the concrete performance database and place database in public domain
- Complete proactive welding stress control model development with in-situ differential interference contrast/infrared experiment validations
- Cables
  - Complete measurements of physical properties on cables subjected to range of accelerated aging conditions, and assess result for key early indicators of cable aging
  - Complete preliminary listing of aging conditions and measurement methods for physical properties to be examined for key indicators of cable aging
  - Complete measurements and comparison to historical data for already obtained field returned cables (Zion and CNEA)
- Stress Corrosion Cracking
  - Measure stress corrosion cracking initiation response in Alloy 690 including effects of cold work
  - Measure stress corrosion cracking initiation response of Alloy 600
  - Determine mechanisms of irradiation-assisted stress corrosion cracking based on measurements
  - Complete report on high fluence irradiation-assisted stress corrosion cracking



Laser welding system at ORNL, part of the LWRS/EPRI partnership.

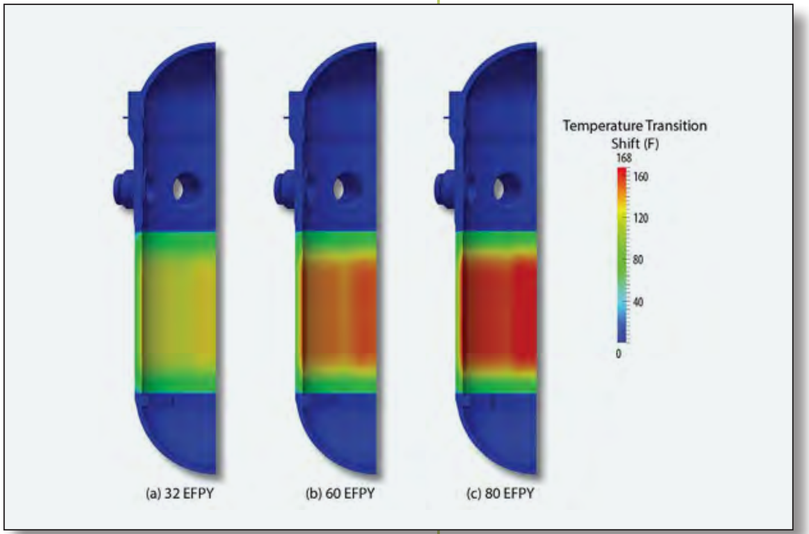
Instrumentation, Information and Control

- Complete and document four pilot projects
  - On-Line Monitoring, Active Components
  - Digital Control Room Upgrades
  - Improved Operator Performance with Computer-Based Procedures
  - Advanced Outage Control Center
- Complete the assembly of the Human Systems Simulation Laboratory (HSSL) and demonstrate its capability to model a hybrid (analog and digital) nuclear power plant control room
- Complete evaluation of final Computer-Based Procedure prototype for field workers

INL's Human Systems Simulation Laboratory (HSSL), capable of modeling a hybrid (analog and digital) nuclear power plant control room.

Risk-informed Safety Margin Characterization

- RELAP-7 Development
  - Implement two-phase flow model in RELAP-7 capabilities to enable modeling of two-phase flow
  - Demonstrate the integration of reactor pipe network and components for two-phase flow model for a simplified BWR reactor loop
  - Complete RELAP-7 simulation resolving a station blackout scenario on a simplified BWR geometry
- Using Grizzly, demonstrate the modeling of late blooming phases and precipitation kinetics in aging reactor pressure vessel steels
- Produce technical report that outlines the risk-informed margin management process and its relation to RISMC characterization



A new modeling tool (Grizzly) is under development to simulate RPV degradation.

Advanced Light Water Reactor Fuels

- Complete LWRS Program Fuel Development Inventory Database
- Industry team will deliver a final report documenting their SiC/SiC joining solution together with SiC/SiC joint samples

Light Water Reactor Sustainability Contacts

Program Management

Richard Reister
Federal Program Manager
Light Water Reactor Deployment
Office of Nuclear Energy
U.S. Department of Energy
richard.reister@nuclear.energy.gov
(301) 903-0234

Technical Integration

Kathryn A. McCarthy
Technical Integration Office Director
Idaho National Laboratory
kathryn.mccarthy@inl.gov
(208) 526-9392

Donald L. Williams
Technical Integration Office Deputy Director
Oak Ridge National Laboratory
williamsdljr@ornl.gov
(865) 574-8710

Cathy Barnard
Technical Integration Operations Officer
Idaho National Laboratory
cathy.barnard@inl.gov
(208) 526-0382

"The federal government's role is to support the sustainability of the nation's nuclear energy facilities by providing the science to enable the long-term safe, clean, and reliable operation of this important energy source through its unique facilities and expertise at DOE's national laboratories."

– **Richard Reister**
Federal Program Manager

R & D Pathway Leads

Materials Aging and Degradation
Jeremy T. Busby
Oak Ridge National Laboratory
busbyjt@ornl.gov
(865) 241-4622

Instrumentation, Information & Control Systems Technologies
Bruce P. Hallbert
Idaho National Laboratory
bruce.hallbert@inl.gov
(208) 526-9867

Risk-informed Safety Margin Characterization
Curtis L. Smith
Idaho National Laboratory
curtis.smith@inl.gov
(208) 526-9804

Advanced LWR Nuclear Fuels
Shannon M. Bragg-Sitton
Idaho National Laboratory
shannon.bragg-sitton@inl.gov
(208) 526-2367

LWRS
Light Water Reactor Sustainability

THE LIGHT WATER REACTOR SUSTAINABILITY PROGRAM

Working together to ensure energy security through the technically validated extended operation of nuclear power plants

12-GA50657