LWRS Newsletter

Light Water Reactor Sustainability

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Meeting the Challenges Under Constrained Federal Funding

Kathryn McCarthy
Director, LWRS Technical Integration Office

I recently took over as Director of the Light Water Reactor Sustainability (LWRS) Program Technical Integration Office, so I will begin with a short introduction of myself. I spent the first half of my career primarily focused on fusion energy, which may seem about as far from life extension of light water reactors as is possible. However, my work was on fusion reactor safety, including building a licensing case for a fusion reactor; therefore, much of my work on fusion safety helped prepare me for my current role. The second half of my career primarily focused on developing an advanced fuel cycle for fission reactors, including light water reactors and advanced fission reactors. During this time, I led systems analysis activities; this gave me an appreciation for the importance of considering the entire system rather than focusing on just one part of it. The mixture of fusion and fission in my background has provided me with the ability to focus on what is important, combined with the ability to think out of the box. Donald (Don) L. Williams, Jr. continues to play an essential role as the Deputy Director for the LWRS Program Technical Integration Office and I will rely on him heavily.

We are making changes to the LWRS Program to meet the challenges presented under increasingly constrained federal funding scenarios. These changes include modifications to some of the research and development pathways and bringing Theodore (Ted) Marston into the program to help us strengthen the LWRS Program's relationship with industry. Ted has served in leadership roles at the Electric Power Research Institute in Palo Alto, California from 1976 to 2006, including Chief Technology Officer, Senior Vice President, Vice President,

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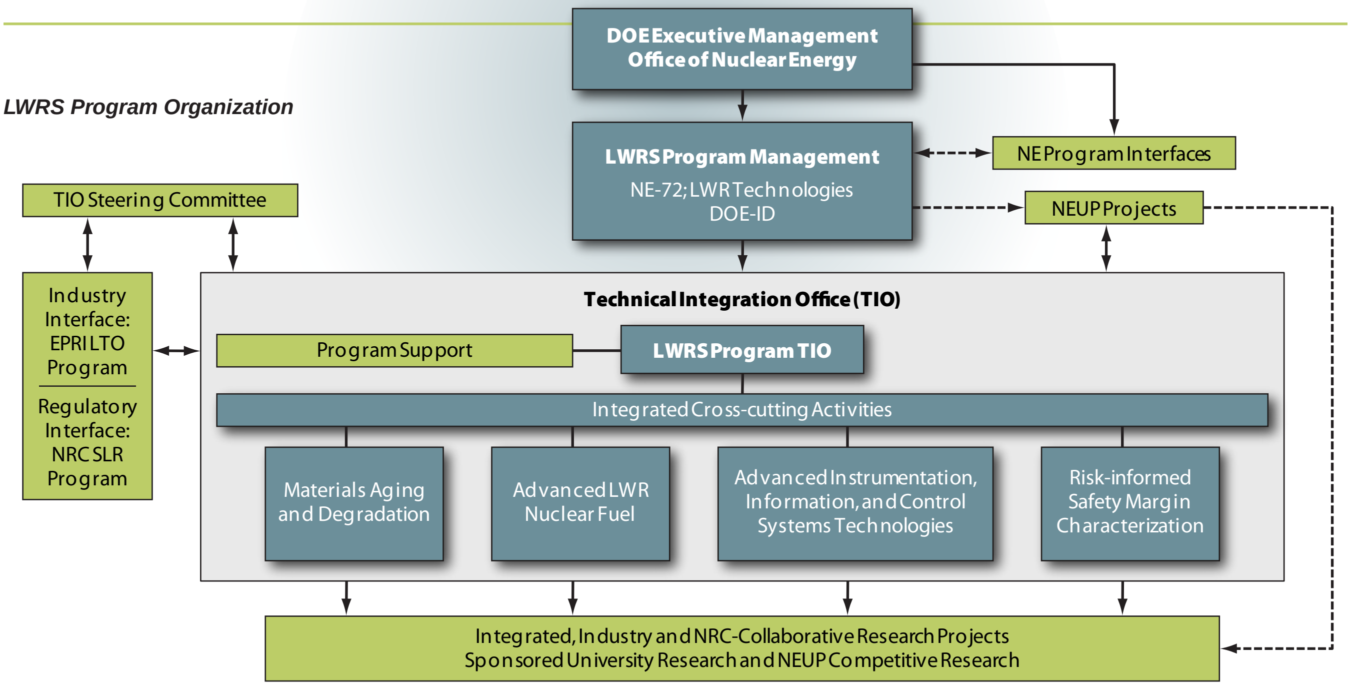
LWRS Program Organization



U.S. DEPARTMENT OF
ENERGY

Crossing the Digital Divide

Ken Thomas
Advanced Instrumentation,
Information, and Controls Systems
Technologies Pathway

One of the great successes of the power generation industry over the past two decades has been the significant increase in nuclear plant reliability and other performance standards. However, there is reason to be concerned that the design, operation, and maintenance practices used by the current fleet of plants do not leverage all possible advantages from a digital controls upgrade. Perhaps past success is the biggest barrier to future success.

Nuclear utilities continue to upgrade aging instrumentation and control systems with modern digital-based systems to address reliability and obsolescence concerns. In addition, industry has demonstrated that these systems can be successfully developed and deployed, even for highly safety-significant applications such as reactor protection.

However, the following three factors have retarded wide-scale implementation of digital technology for plant modernization and business innovation:

1. Large-scale digital upgrades entail considerable risk.
2. The upgrades are very costly and have not led to bottom-line business improvement, financial or otherwise.
3. Cybersecurity concerns discourage wide-scale digital integration.

A new national research program is now under way in the United States to address these concerns and finally break through these barriers to achieve a true digital transformation of operating nuclear plants.

Missed Opportunity

The industry approach to digital upgrades has always been one-for-one replacements, that is, new systems replaced the earlier control system functions. Consequently, such replacements fail to completely leverage the increased capabilities of new digital replacements. The common theme of these upgrade projects has been to

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Chief Nuclear Officer, Director of Advanced Reactors Development, Director of Engineering and Operations Department, and Program Manager of Nuclear Systems and Materials. A close relationship with industry is essential to the success of the program – our products must be important to industry and usable by industry – working with industry from the beginning is the only way to ensure that outcome.

Communication is always an important part of any successful program. We are improving our communication tools, including making more information available on the LWRS Program website (http://www.inl.gov/lwrs) and developing an LWRS Integrated Program Plan. This plan will be used to communicate the LWRS Program to a broad range of stakeholders; it presents the program overview, including program objectives, technical plans, and interfaces with our industry partners. A very important part of this plan will be a description of the major deliverables to be completed by each pathway, with an emphasis on deliverables between now and 2015. This near-term focus is important because the first wave of decisions by industry on whether to pursue a second 20-year license extension will occur beginning after about 2015 and information generated in the LWRS Program (together with our industry partners) will assist industry in making an informed decision.

Below is a short description of the research and development pathways in the LWRS Program. More information on these pathways can be found in the LWRS Integrated Program Plan, which will be released at the end of January.

Materials Aging and Degradation: Research and development to develop the scientific basis for understanding and predicting the long-term environmental degradation 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 research and development products will be used by utilities, industry groups, and regulators to affirm and define operational and regulatory requirements and limits for materials in nuclear power plant systems, structures, and components subject to long-term operation conditions, providing key input to both regulators and industry.

Advanced LWR Nuclear Fuels: Research and development to improve the scientific knowledge basis for understanding and predicting fundamental nuclear fuel and cladding minimize cost and risk by avoiding large changes to the plant operating infrastructure, including plant operating procedures, training, operator familiarity, design basis, and licensing basis of the controls system. Often, digital upgrades were designed to be completely transparent to the operators, some going as far as retaining the board devices from the previous analog systems.

By forcing digital systems into the footprints of their analog predecessors, the inherent capabilities of digital designs to improve business performance are lost. Beyond plant control and protection functions, digital systems also can facilitate communications, support automated work processes, enforce human performance expectations, detect and correct errors, provide enhanced understanding through visualization techniques, and provide many other useful capabilities. By fully exploiting digital technology, it is possible to lower the cost of conducting plant operational and support activities while improving quality, efficiency, and nuclear safety.

The approach the nuclear power industry has taken with digital technology stands in contrast to that of other industries. We have seen digital technology literally redefine industry operating models by even automating and greatly improving routine tasks such as package delivery. We also have seen it successfully implemented in safety-critical applications—from flight deck avionics to advanced medical procedures—where it not only replaces the control functions but also substantially transforms how the operational activities are performed, making them much more efficient and accurate.

Consequently, the digital migration in the nuclear power industry has been somewhat disappointing. It has not led to bottom-line business improvement; instead, a good case can be made that digital control upgrades actually increase operating costs. We are simply not getting the performance dividend out of digital implementation that other industries are enjoying. To fully understand why this is such a lost opportunity, the larger context of the industry's performance needs to be considered.

Standardizing Can Be Limiting

The U.S. nuclear power industry has enjoyed impressive performance improvement over the past 15 years. It was in the mid-1990s when industry accelerated the standardizing of plant processes and conduct of operations. This emphasis on standardization was made through the concerted efforts of utilities and the Institute of Nuclear Power Operations to set challenging performance targets and to undergird these

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performance in nuclear power plants, and applying this information to development of high-performance, high burn-up fuels with improved safety, cladding integrity, and improved nuclear fuel cycle economics. The research and development products will be used by nuclear power plant fuel vendors and utilities to deploy new fuel/core designs for the existing nuclear power plant fleet with improved safety and economic operational capabilities. The products also will be used by regulators to define regulatory requirements and operational limits for the improved fuel/core designs.

Advanced Instrumentation, Information, and Control Systems Technologies: Research and development to address long-term aging and modernization of current instrumentation and control technologies through the development/testing of new instrumentation and control technologies and advanced condition monitoring technologies for more automated and reliable plant operation. The research and development products will be used by utilities and industry groups to design and deploy new instrumentation and control 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 research and development products also will be used by regulators to define regulatory requirements and operational limits for new instrumentation, information, and control technologies.

Risk-Informed Safety Margin Characterization: Research and development that brings together risk-informed, performance-based methodologies with scientific understanding of critical phenomenological conditions and deterministic predictions of nuclear power plant performance, leading to an integrated characterization of public safety margins in an optimization of nuclear safety, plant performance, and long-term nuclear power plant management. The research and development products will be used by utilities and industry groups to produce state-of-the-art nuclear power plant safety analysis information that yields new insights on actual plant safety/operational margins.

This newsletter contains articles from the Advanced Instrumentation, Information, and Control Systems Technologies Pathway and the Materials Aging and Degradation Pathway.

I welcome your feedback on this newsletter and on the program in general. You can reach me by e-mail at Kathryn.McCarthy@inl.gov.

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efforts with standards of excellence, comprehensive process templates, and human performance expectations.

Performance improvement became evident in virtually every aspect of plant operations and support, particularly improving key performance indicators such as capacity factor, scram rate, forced loss rate, dose, refueling outage length, and overall cost performance. The performance targets were met. This achievement was even more remarkable because the goals for operational excellence included both profitability and nuclear safety.

However, sustaining this rate of performance improvement has proven to be difficult. Within the past 5 years or so, the industry has experienced a reduction in the rate of performance improvement, such that today, several of the important measures have shown virtually no year-to-year improvement.

This flattening of the performance curves was not unexpected. Every operating model is subject to the classic "S" curve in the relationship between effort and performance, as illustrated in Figure 1. In the early years of the current operating model, roughly the mid-1990s to the mid-2000s, industry was below the knee of the curve and enjoyed highly leveraged performance improvement relative to effort. As the operating model matured, much of the low-hanging fruit was picked and it became increasingly difficult to maintain the rate of improvement experienced in earlier years, particularly with fleet capacity factors, scram rates, and forced loss rates. The operating point had moved out to the flat part of the performance curve, the region of diminishing returns.

A survey of staff at nuclear utilities would surely find general agreement that the industry continues to increase its performance expectations at the same time as the industry is making plant processes more complex. In addition, further reductions in consequential human error are proving difficult to achieve because improvements mainly rely on correct worker behaviors and barriers to prevent events—both are difficult to manage. Technology, as has become the norm in other safety-critical industries, is greatly underutilized in the quest to reduce human error.

Again, these factors confirm that the industry's operating model has largely exhausted its potential for substantial performance improvement in future years.

New Operating Model Needed

Ironically, the operating model that has enabled the nuclear power industry's remarkable success may become a major barrier to further performance improvement. It is my opinion that the industry requires a new operating model that provides an expanded framework for future performance improvement.

To be clear, a new operating model would not discard the valuable standards, processes, and operational principles that have been so instrumental in the notable perfor-

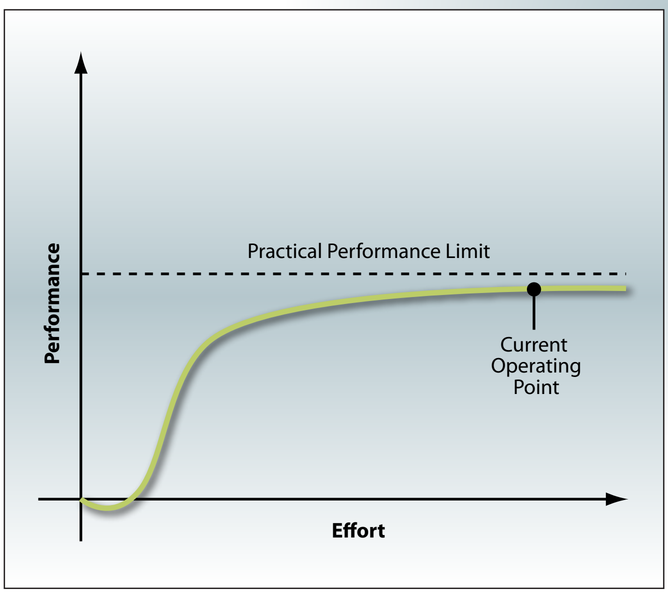

Figure 1. Old model; this performance curve is based on the current operating model.

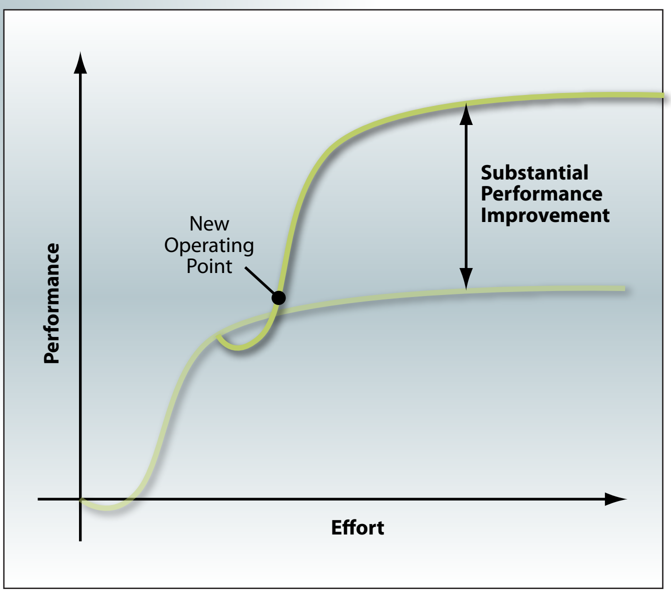

Figure 2. New model; this curve shows potential performance improvement based on a digital transformation of the operating model.

mance achievements to date. Rather, the new operating model builds on these past successes by moving from a performance system based on human skill to one based on digital automation with human oversight. This paradigm shift has the advantage of exploiting the inherent, and underutilized, capabilities of integrated digital systems to perform tedious and error-prone tasks, while allowing workers to maintain better oversight and situational awareness of the entire plant operation. This approach to plant performance, in all its forms, would draw a new performance curve, where the current operating point is located back below the knee of the curve and where highly leveraged performance improvements are possible for reasonable effort (Figure 2).

The theory of this new operating model may sound complex, but the practical aspects are reasonably simple. The main goal of the new model is to develop a digital architecture for nuclear power plants that encompasses all aspects of plant operations and support, including integrating plant systems, plant work processes, and plant workers in a seamless digital environment (Figure 3). This digital environment would serve as the platform for business innovation across the entire range of operational and support activities conducted in a nuclear plant.

Consider how the new model might work one day in the future. Workers conducting plant surveillance tests would have direct access to plant data via computer-based procedures. Acceptability of test equipment and worker qualifications would be automatically verified by the computer-based procedures. In turn, the test equipment would feed data directly into the computer-based procedures. Computations and test acceptance verifications would be performed automatically. Concurrences and permissions would be obtained electronically through wireless connections to controlling or supporting organizations (including video streaming from the job sites). The completed test procedures would automatically be routed for review and approval of results and then archived. Engineering data would be posted to associated processes, such as the system health program. Job performance data (for example, duration) would be posted to the work management system.

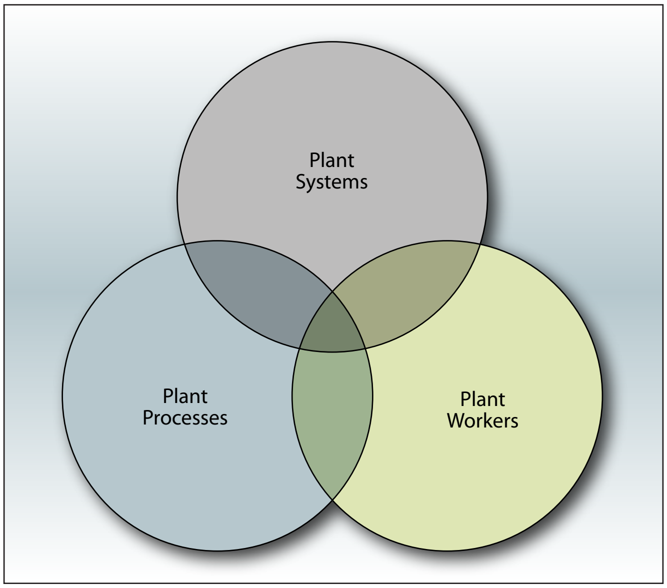

Figure 3. The vision of a seamless digital environment.

Many plant engineering and operating activities could be substantially streamlined in this manner, including tasks performed by control room operators. There is the additional advantage that plant data that normally are the domain of the instrumentation and control systems and plant computer would be seamlessly integrated into plant operational and support activities in need of this information, all the while maintaining requirements for cybersecurity and Class 1E separation. There would be substantial increases in efficiency and accuracy in obtaining, processing, and validating plant data.

A secondary goal then becomes apparent: transform the current model of nuclear plants from one that relies on a large staff performing mostly manual activities—tasks that can be automated—to a model relying on highly integrated technology with a smaller staff. This shift will be very important in addressing the loss of knowledge as a result of the pending retirement wave, future shortages of qualified workers, and the need to constantly recruit and train new staff to maintain a large, competent workforce.

Achieving this vision of transforming the nuclear power industry through the use of digital technology would require participation and support from the entire industry. It is impractical for a single utility to undertake this task. Plant staff are focused on near-term operational requirements and do not have sufficient time to devote to this longer-term development effort. In addition, the utilities will be very concerned about project risks in cost overruns, regulatory uncertainty, and schedule delays in deploying digital systems, based on recent industry experience. There also is an operational risk that must be carefully considered. Such large-scale digital integration may have undetected failure modes that will cause plant trips, transients, or even failure to perform its design functions. No utility will want to be too far in front of this digital revolution. For projects of this enormity, there is safety in numbers.

For this new digital paradigm to get traction in an industry that has been slow to embrace digital transformation, we must do three things:

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1. Mitigate the risks of pursuing wide-scale digital implementation, including operational, financial, and regulatory risk.
2. Enable the industry to move forward together such that best practices and lessons learned can be quickly and widely shared. This will allow the industry to maintain a common, albeit evolving, operating model as new technologies are integrated into the work methods. It also will reduce the risk to and burden on any one operating utility by providing a continuous peer review of the developments.
3. Build a digital environment that sufficiently addresses cybersecurity.

The Path Forward

A new national research program is under way that has been designed to address these three specific industry concerns about expanding the use of digital architectures. INL has lead responsibility for the Advanced Instrumentation, Information, and Control Systems Technologies research pathway within the LWRS Program.

The LWRS Program is a research and development program sponsored by the U.S. Department of Energy (DOE) and is performed in close collaboration with industry research and development and improvement programs.[i] The LWRS Program's purpose is to provide the technical foundations for licensing and managing the long-term, safe, and economical operation of existing nuclear power plants. DOE's program focus is on longer-term and higher-risk/reward research that contributes to the national policy objectives of energy security and environmental security. The specific concern addressed by this program is that large-scale instrumentation and control obsolescence could become a life-limiting issue for the current nuclear operating fleet.

To provide guidance for this research program, INL formed the Advanced Instrumentation, Information, and Control Technologies Utility Working Group. The Utility Working Group is currently composed of 10 nuclear utilities; new members are added as they express interest in joining. The utilities are typically represented by individuals with responsibility for a long-term instrumentation and control upgrade strategy or business innovation for site programs.

INL develops new digital technologies within the context of pilot projects. Individual pilot projects are hosted by willing nuclear utilities that have an interest in a particular technology. Together, the technologies developed in individual pilot projects compose the overall integrated digital environment that will serve as the platform for transformative business innovation. Therefore, the pilot projects allow industry to collectively integrate these new technologies into work activities one at a time and validate them over multiple operating plants to the benefit of all. The new digital environment is proven one technology at a time and is gradually built up over sufficient time to prudently manage the change.

INL provides the structured research program and expertise in plant systems and processes, digital technologies, human factors science, and cybersecurity. The utilities, through participation in the Utility Working Group, develop a collective vision of this digital operating environment and set the priority and timing of developments by their individual sponsorship of pilot projects. Those utilities hosting pilot projects provide a

Figure 4. Remote collaboration technology used in a refueling outage.

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[i] Light Water Reactor Sustainability Research and Development Program Plan – FY 2009-2013, INL/MIS-08-14918, Revision 2, December 2009, p. 1.

project cost-share in terms of their own time and expenses, expertise in the plant systems and work process methods, and access to needed plant facilities. This arrangement has a number of distinct advantages, including the following:

- Ensuring that the end-state vision for plant modernization is shared by a significant portion of the current operating nuclear fleet.
- Ensuring that the near-term technologies are immediately beneficial even while they build up the comprehensive digital environment.
- Greatly reducing the risk of implementation for any one utility, given that the proven abilities of INL stand behind the soundness of the technologies and the oversight of the Utility Working Group provides a competent peer review.
- Allowing utilities to move forward together in transforming their operating model to fully exploit these technologies and providing a transparent process for coordination with the major industry support organizations: the Electric Power Research Institute, Institute of Nuclear Power Operations, and the Nuclear Energy Institute.
- Incorporating a perspective on regulatory issues based on INL's extensive understanding of the Nuclear Regulatory Commission's requirements in the area of digital instrumentation and control technology and human factors.

Eighteen pilot projects have been proposed over a 10-year period and are grouped into five broad areas of important performance-improvement enablers:

1. Highly integrated control rooms
2. Highly automated plant
3. Integrated operations
4. Human performance improvement for field workers
5. Outage safety and efficiency.

Two of the pilot projects are under way at nuclear plants. The first is development of an advanced outage control center at a Midwestern nuclear plant that will greatly improve communications, coordination, and collaboration activities to minimize the impact of challenges to the outage plan and schedule. It will develop technologies that facilitate real-time status and problem resolution, as well as provide direct interaction between the outage control center, the work execution center, and plant workers at the job site (Figure 4).

The second pilot project, at a Southeastern nuclear plant, will develop mobile worker technologies that enhance human performance in the area of plant status control. This involves the capability of positive component identification and assurance that correct actions have been taken (Figure 5). It also will explore possibilities of direct verification of correct component positions or use of streaming video for centralized verifications. The project involves use of heads-up displays for field workers. Included in this concept is development of computerized work packages on wireless mobile devices (such as PDAs and tablets).

Two additional pilot projects are under discussion with interested nuclear utilities. One involves integration of digital technologies within a conventional nuclear plant control room. It also includes replacement of traditional alarm systems with an advanced alarm management system. The other involves development of computer-based procedures for both operators and maintenance/support personnel. This project is intended to improve human performance, increase work efficiency, and better manage nuclear risk associated with work activities.

Figure 5. Operator using handheld technology for component identification.

Development of a Robust Predictive Embrittlement Model for Reactor Pressure Vessel Lifetime Extension

R. K. Nanstad
Materials Aging and Degradation Pathway

G. R. Odette
Materials Aging and Degradation Pathway

Neutron irradiation-induced embrittlement degrades the fracture toughness of reactor pressure vessels (RPV) and, in some cases, has potential for reducing toughness below acceptable levels. The major issues regarding extension of RPV operation to 80 years or beyond are summarized in Nanstad and Odette (2009), with a more detailed discussion of irradiation effects at high fluence, long-irradiation times, and flux effects presented in Odette and Nanstad (2009). Critical questions related to vessel integrity for extended operation that are required to be answered in a timely fashion include the following:

- How to make robust predictions of transition temperature shifts for the low-flux, high-fluence conditions to at least 10^{20} n/cm^2 (>1 MeV) for 80-full-power years of plant operation in the absence of a directly applicable database?
- How to interpret accelerated test data that can reach high fluence but may be confounded by dose rate effects?
- What are the conditions under which new threshold embrittlement mechanisms may arise, such as the formation of Mn-Ni-Si-rich hardening phases in both low and high-Cu steels?
- Can post-irradiation annealing be applied as an embrittlement remediation procedure?

Although there are a number of other important questions, Figure 1 clearly illustrates the importance of the questions listed above. Figure 1 shows a regulatory model derived from physically based data from accelerated high-flux and high-fluence test reactor irradiations (Odette and Nanstad 2009) that fit to the power reactor surveillance database (Eason et al. 2007), are nonconservative, and systematically and significantly underpredict high-fluence transition temperature shifts.

Figure 1. Predicted minus measured transition temperature shifts for the EONY model applied to test reactor data.

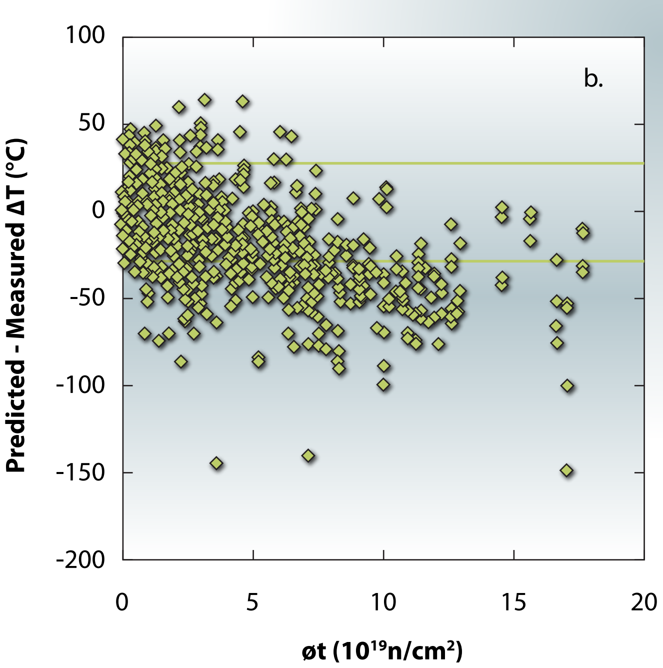
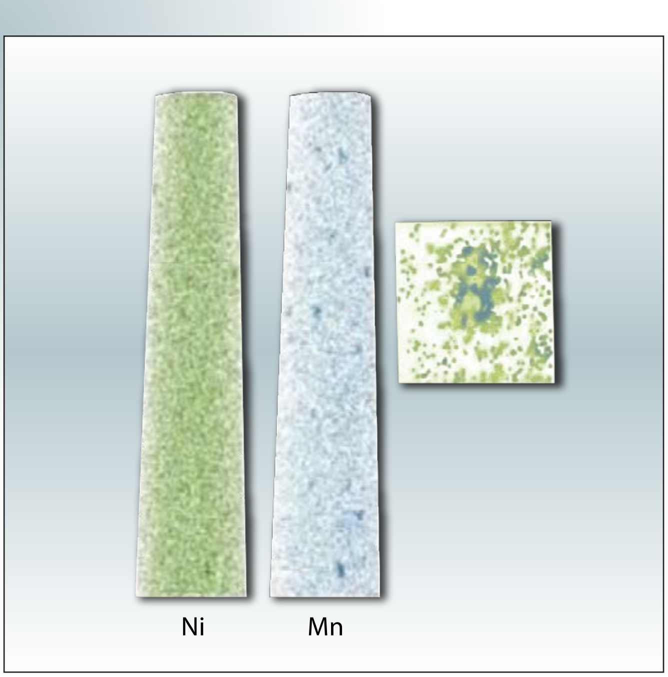


Figure 2. Atom probe tomography maps of nickel (Ni) and manganese (Mn) distributions and a blow up of an Mn-Ni LBP precipitate in a copper-free 1.6-wt.% Ni/1.6-wt.% Mn model alloy irradiated to 1.8×10^{19} n/cm^2 at high flux and 290°C.



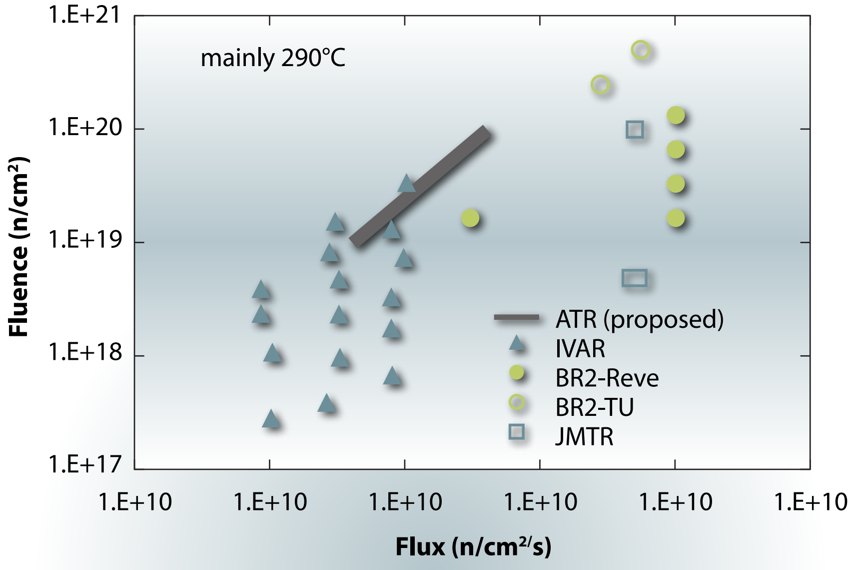


Figure 3. Schematic depiction of the flux/fluence range for the ATR-2 experiment, showing overlap of existing data from the IVAR and REVE databases.

The primary objective of the LWRS Program's RPV task is to develop robust predictions of transition temperature shifts for the low-flux, high-fluence conditions to at least 10^{20} n/cm^2 (greater than 1 MeV) pertinent to plant operation for 80-full-power years. We have shown that these non-conservative predictions may be (at least partly) an artifact of the high-flux levels in the test reactor irradiations. Unfortunately, such accelerated irradiations are the only means to reach high fluence in a timely manner. Therefore, it is critical to have a detailed physical understanding of flux, or dose rate, effects.

The new models will be built on very successful research to predict transition temperature shifts for low to intermediate flux vessel-pertinent conditions and for fluence levels to the originally licensed 40 years of vessel life. New features of the models will include (a) an improved treatment of flux effects in accelerated test reactor irradiations that are needed to reach high fluence in a timely manner, and (b) inclusion of so-called late blooming phases that could cause very severe embrittlement at high fluence, even in low copper steels (see Figure 2), and other possible damage phenomena that only emerge after a high-incubation (threshold) fluence is reached and that are not treated in current regulatory models.

In support of developing a high-fluence database, an irradiation experiment currently is underway at the INL's Advanced Test Reactor National Scientific User Facility. The experiment was awarded to the University of California, Santa Barbara and its collaborator, Oak Ridge National Laboratory (ORNL), with full funding for the facility provided by DOE through the National Scientific User Facility.

The 172 alloys comprised in the experiment were acquired by the University of California, Santa Barbara and ORNL, including contributions from Rolls Royce Marine (United Kingdom), Bettis Atomic Power Laboratory (United States), and the Central Research Institute for the Electric Power Industry (Japan). Notably, the Rolls Royce contribution included more than 50 new alloys.

Additionally, surveillance materials from various operating nuclear reactors are included to enable a direct comparison of results from a test reactor at high flux and a power reactor at low flux. The University of California, Santa Barbara's Advanced Test Reactor-2 experiment includes approximately 1,625 small specimens in three basic geometries, including tensile specimens for a large matrix of alloys; so-called multipurpose coupons that will support microhardness, shear punch, and a wide variety of microstructural characterization studies (e.g., small-angle neutron scattering and atom probe) for all alloys; and 20-mm-diameter disc compact tension fracture specimens for three alloys (i.e., the Palisades B weld and two University of California, Santa Barbara forgings [CM17 and LP]). The test assembly includes a thermal neutron shield and active temperature control with three major regions at nominal temperatures of 270, 290, and 310°C, and one small region at 250°C. The specimens are being irradiated at a peak flux of about 3.3×10^{12} n/cm^2-s (greater than 1 MeV) to a fluence of approximately 0.9×10^{20} n/cm^2. The objective is to obtain a high-fluence, intermediate-flux database for coupling to a large body of existing data for a large set of common alloys (greater than or equal to 100) irradiated over a wide range of fluxes and fluences as indicated in Figure 3. The mechanical property measurements will be accompanied by extensive microstructural characterization

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studies, including small angle neutron scattering and x-ray diffraction-scattering, resistivity-Seebeck coefficient, atom probe tomography, positron annihilation spectroscopy, and transmission electron microscopy. A major effort will be made to use a suite of advanced characterization tools to identify the detailed nature of unstable matrix defects, which is not known at this time.

The University of California, Santa Barbara's Advanced Test Reactor-2 irradiation test assembly was completed in late spring of 2011 and was successfully installed in the Advanced Test Reactor on May 26, 2011. The irradiation began on June 7, 2011, and should achieve its target fluence of 0.9×10^{20} n/cm^2 (E>1 MeV) in the late summer of 2012. Thermocouple monitors show that the specimens are generally being irradiated at or close to their target temperatures.

The RPV task also is in the process of obtaining irradiated materials from various commercial nuclear plants. The Nuclear Plant Life-Extension Demonstration Project is a partnership between DOE, the Electric Power Research Institute, and Constellation Energy (owner of the Ginna Nuclear Plant). Materials from the Ginna pressurized water reactor RPV are of the highest interest due to their higher irradiation fluence (to 3.7×10^{19} n/cm^2) and demonstrated irradiation-induced embrittlement from the RPV surveillance program. Four capsules were removed and tested over the course of reactor operation with Charpy impact 30 ft-lb shifts from 148 to 221°F. The tested specimens were located at the Westinghouse hot cell facility and have been shipped to ORNL. The plan is to perform microstructural examination of the specimens using atom probe tomography and small-angle neutron scattering.

The RPV task, in cooperation with the Electric Power Research Institute, the Nuclear Regulatory Commission, and Westinghouse, is engaged in discussions with Zion Solutions, Inc., owner of the Zion Nuclear Plant Units 1 and 2. These two reactors have been shut down since 1998, after operating for only about 15 effective full-power years. The recommendations include shipment of large sections of the RPVs to be used for machining of specimens from a Linde 80 weld at a peak fluence close to 1×10^{19} n/cm^2. These specimens would be tested to evaluate attenuation effects and thermal annealing.

Dr. Pal Efsing of Vattenfall AB (in Sweden) has provided small samples of surveillance materials removed from tested Charpy impact specimens. All surveillance specimens are from low-copper, high-nickel weld metals in Ringhals Units 3 and 4 (both of which are pressurized water reactors). The materials have nickel contents of about 1.6 wt%, copper contents of 0.08 wt% (or less), and have been irradiated to relatively high neutron fluences (about 6×10^{19} n/cm^2). These specimens will be used to prepare samples for atom probe tomography and small-angle neutron scattering to characterize the microstructure relative to irradiation-induced precipitates and other defects. This relates to the issue of late-blooming nickel-manganese-silicon phases, especially because these materials have low copper contents.

In addition to the enormous amount of post-irradiation testing that will be done for the Advanced Test Reactor-2 experiment, selected thermal annealing experiments also will be performed. It also is possible that some amount of annealed material from the Advanced Test Reactor-2 experiment could be included in a subsequent reirradiation experiment. Thermal annealing of light water reactor RPVs is a technically viable and, at least, a partially demonstrated technology. However, thermal annealing is not likely to be deployed for plants operating to 40 or 60 years based on the current understanding of RPV degradation and the resulting reduced uncertainty in safety margins, as well as the potential liability of permanently damaging a reactor vessel. However, in some cases, thermal annealing may be required to extend plant life to 80 years. Moreover, additional efforts will be required to gain acceptance of this remediation within the nuclear power industry. A number of issues have been identified regarding the potential use of thermal annealing to recover the fracture toughness of RPVs in the United States that may experience irradiation-induced embrittlement significant enough to threaten structural integrity (Nanstad and Server 2011). Additional research is needed to overcome the technical needs described above, reduce the uncertainties, reduce the liabilities, and make this technique more acceptable for industry.

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Human Performance in Plant Status Control

Ron Farris
Advanced Instrumentation,
Information, and Control Systems
Technologies Pathway

INL's Human Factors Group is working with its industry partner, Duke Energy, to deploy new technology to improve human performance in plant status control at the Catawba Nuclear Station. Plant status control is the process of maintaining plant components in the correct position for the given plant condition. Our approach has been to find new technologies that will maximize the collective situational awareness of the nuclear station staff in order to improve accuracy in positioning the plant components. By providing plant personnel with rich data (e.g., electronic forms, text, video, photos, and voice) in real-time, the plant groups involved in a work activity can leverage the knowledge and experience of the entire team to maximize success in plant status control.

Purpose

Success in this area will enable nuclear utilities to improve performance during maintenance and operational activities by reducing human error, reducing safety vulnerabilities, and becoming more efficient. These efforts directly support the goals of DOE's LWRS Program to develop technologies and other solutions that can improve reliability, sustain safety, and extend the life of the current reactors.

Problem

Human error significantly contributes to the causes and complications of events that occur in the commercial nuclear industry. Costs that are associated with the corresponding plant upsets, equipment damage, and subsequent event investigations are high. The use of human performance in training, mentoring, and error reduction has shown to be a powerful tool in targeting individual behaviors that contribute to human error. However, despite the beneficial gains, there are limits to the success of the tools' applications.

Costs associated with improvement of the human performance tool and employee resistance to integration of another human performance error reduction tool have created a saturating effect in terms of job complexity. One operator identified that focusing on the process of error prevention made it difficult to focus on the work task.

Another aspect of this problem is that human beings are undoubtedly fallible. Reliance on fallible humans to back up other humans is problematic and expensive. The very error reduction tools employed to eliminate error, when overly relied upon, become a secondary source of error due to the distracting effect of the added job complexity.

Nuclear equipment operator scanning equipment tag during Catawba demonstration.

Progress

In August, INL's research team demonstrated potential solutions using advanced technologies to identify plant status control issues. The demonstration took place in Catawba's flow loop training facility. The main objectives for the demonstration were to execute several research scenarios to collect data from participants in the flow loop training facility, solicit feedback from plant staff and observers, demonstrate potential technical solutions for field workers, and interface with interested industry observers.

Future Research

Future research includes integration of wearable information technologies (i.e., hands-free displays), component identification technology (i.e., bar code), streaming video to control centers, access to real-time plant data, use of computer-based procedures to create a technology platform for an information-enabled field operator, data collection and human factors evaluations for initial use of technology by nuclear power plant operators, and development of a fleetwide scale-up plan.

The INL/Duke research team will continue to gather information from industry partners for continued improvements for plant status control issues in 2012. The INL team will demonstrate two complex activities at the Catawba flow loop training facility (scheduled for January 2012). In addition, a plant status control improvement interest group from the utilities, facilitated by the INL research team, is being formed to discuss and advise the research team on needed applications to

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improve the use of wireless technologies in improving plant status control, information management, and knowledge management. The INL research team will further enhance its working relationship with the Halden Reactor Project (Norway) to gather plant status control improvement technologies and process improvements from European and Asian nuclear plants. A member of the Halden Reactor Project is currently a contributing member of the INL research team.

Recent LWRS Milestones

- ***Advanced Instrumentation, Information and Control System Technologies: Nondestructive Examination Technologies FY11 Report***, R. M. Meyer, P. Ramuhalli, J. B. Coble, L. J. Bond, Pacific Northwest National Laboratory, PNNL-20671, August 2011
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- ***Develop Baseline Computational Model for Proactive Welding Stress Management to Suppress Helium-Induced Cracking During Weld Repair,*** W. Zhang and Z. Feng, ORNL, September 2011
- ***Implementation Plan and Initial Development of Nuclear Concrete Materials Database for Light Water Reactor Sustainability Program,*** Weiju Ren and Dan Naus, ORNL, Barry Oland, XCEL Engineering, ORNL/TM-2010/177, September 2010
- ***Lifecycle Prognostics Architecture for Selected High-Cost Active Components,*** N. Lybeck, B. Pham, and M. Tawfik, INL, and J. B. Coble, R. M. Meyer, P. Ramuhalli, and L. J. Bond, Pacific Northwest National Laboratory, INL/EXT-11-22915, August 2011
- ***LWRS II&C Industry and Regulatory Engagement Activities for FY 2011,*** Kenneth D. Thomas, INL, INL/EXT-11-23451, September 2011
- ***Physics-Based Stress Corrosion Cracking Component Reliability Model Cast in an R7-Compatible Cumulative Damage Framework,*** S. D. Unwin, K. I. Johnson, R. F. Layton, P. P. Lowry, S. E. Sanborn, and M. B. Toloczko, PNNL-20596, July 2011
- ***Reactor Pressure Vessel Task of Light Water Reactor Sustainability Program: Assessment of High Value Surveillance Materials,*** R. K. Nanstad, ORNL, ORNL/LTR-2011/172, June 2011
- ***Reactor Pressure Vessel Task of Light Water Reactor Sustainability Program: Initial Assessment of Thermal Annealing Needs and Challenges,*** R. K. Nanstad, ORNL, and W. L. Server, ATI Consulting, ORNL/LTR-2011/351, September 2011
- ***Report on Assessment of Environmentally-Assisted Fatigue for LWR Extended Service Conditions,*** Saurin Majumdar and Ken Natesan, Argonne National Laboratory, ANL-LWRS-47, September 2011
- ***U.S. Department of Energy Accident-Resistant SiC Clad Nuclear Fuel Development,*** George Griffith, INL, INL/CON-11-23186, October 2011

Milestones: https://lwrs.inl.gov/SitePages/Reports.aspx

Editor: Teri Ehresman
Writer: LauraLee Gourley

To submit information or suggestions, contact Cathy J. Barnard at **Cathy.Barnard@inl.gov**.