LWRS Newsletter
Light Water Reactor Sustainability
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Meet the New LWRS Program Pathway Lead

Kathryn A. McCarthy
Director, LWRS Program
Technical Integration Office

Soon after the March 11, 2011, earthquake and subsequent tsunami in Japan caused the multi-unit accident at the Fukushima Daiichi nuclear power plant, the U. S. Department of Energy's Office of Nuclear Energy established an activity to understand ongoing events at the plant and to respond to various requests from within the U.S. government and from industry and Japanese organizations. This activity has evolved into a research and development (R&D) program that supports implementation of Fukushima Daiichi lessons learned, with a focus on delivering beyond design basis accidents R&D results that are of benefit to the nuclear industry.

This activity has clear ties to the Light Water Reactor Sustainability (LWRS) Program. To ensure overall coordination with the R&D pathways currently underway in the LWRS Program, this activity is being integrated into the LWRS Program as a new pathway: "Reactor Safety Technologies. " We are fortunate that Dr. Michael Corradini of the University of Wisconsin has agreed to lead this new R&D pathway.

Dr. Michael Corradini is a Professor in the Nuclear Engineering and Engineering Physics Program at the University of Wisconsin. He has more than 30 years of research experience in the areas of multi-phase fluid mechanics and heat transfer, nuclear reactor safety, severe accidents, reactor operation, energy policy, and nuclear waste disposal. Dr. Corradini has extensive research experience in the phenomenology of beyond design basis accidents in light water reactors, including molten fuel coolant interactions, molten core-concrete interactions, hydrogen generation, and containment response. He currently is a member of the U. S. Nuclear Regulatory Commission's Advisory Committee on Reactor Safeguards.

Future newsletters will introduce you to the activities in this new pathway, which currently fall into three major categories:

1. Fukushima Inspection, Preparation, and Planning: Coordination with international partners to develop a priority list of forensic activities for Fukushima Daiichi reactor inspections
2. Accident Tolerant Components: R&D on systems, structures, and components with the potential to prevent or mitigate beyond design basis accidents
3. Severe Accident Analysis Support: Analysis using existing computer codes to provide information, knowledge, and insights on severe accident phenomenology.

Please feel free to provide input relevant to the Reactor Safety Technologies Pathway to Dr. Corradini.

Michael Corradini
University of
Wisconsin-Madison

Informing Materials Discussions and Decisions for Extended Operations

Jeremy T. Busby
Pathway Lead for Materials Aging and Degradation Pathway

Components in a nuclear power plant must withstand a very challenging environment, including extended time at temperature, neutron irradiation, stress, and/or corrosive media. The many modes of degradation are complex and vary depending on location and material. However, understanding and managing materials degradation is key for the continued safe and reliable operation of nuclear power plants.

The LWRS Program supports the long-term operations of existing domestic nuclear power plants with targeted collaborative research programs. Understanding the complex and varied aspects of materials aging and degradation in different reactor systems and components will be an essential part of informing extended service decisions. The Materials Aging and Degradation Pathway is delivering that understanding of materials aging and degradation, providing the means to detect degradation, and overcoming degradation for key components and systems through new techniques. All research activities and outcomes are designed to help inform relicensing decisions by industry and regulators.

Coordination and collaboration has been a key focus of the Materials Aging and Degradation Pathway since the LWRS Program began in 2009. Indeed, effective and efficient coordination requires contributions from many institutions, including input from the Electric Power Research Institute's (EPRI's) parallel activities in their Long-Term Operations Program and the U.S. Nuclear Regulatory Commission's (NRC's) subsequent license renewal activities. In addition to contributions from EPRI and NRC, participation from utilities and reactor vendors will be required and international coordination also has been pursued. In many of the key activities, research is well coordinated. For example, there are frequent coordination meetings with LWRS Program and EPRI researchers (including NRC technical staff as observers) to coordinate concrete and cable aging studies, culminating in development of joint research roadmaps.

Recently, there have been key opportunities to inform life-extension processes and to further collaboration with key stakeholders. Several examples are described in more detail in the following paragraphs. The examples highlight cable and concrete research, although it is important to note that there are considerable interactions in metals research as well.

- The LWRS Program made several presentations during a briefing on December 5, 2013, between NRC staff and industry to discuss subsequent license renewal. The primary focus of the meeting was on concrete degradation research. Ed Carley (Seabrook) and Jason Remer (Nuclear Energy Institute) gave their perspectives on concrete performance. Jeremy Busby of Oak Ridge National Laboratory gave a presentation detailing potential knowledge gaps for concrete under extended service and joint R&D roadmaps, while Yann Le Pape (Oak Ridge National Laboratory) provided a detailed overview of LWRS Program activities covering concrete performance. These presentations were coordinated with research activities presented by John Lindbergh and Joe Wall of EPRI. The resulting dialogue between the LWRS Program, NRC staff, and industry representatives was heavily focused on the potential impact of irradiation on concrete structures. Nondestructive evaluation techniques and related research were another major topic of discussion during the meeting. The LWRS Program's presentations also were shared with the Nuclear Energy Institute Task Force on Extended Service. This meeting provided valuable insight into needs and priorities from key stakeholders.
- As discussed in the July 2014 edition of the LWRS newsletter, the LWRS Program led an effort to form an international group on the effects of irradiation on concrete. Thomas Rosseel (Oak Ridge National Laboratory) organized and chaired the International Committee on Irradiated Concrete Information Exchange Framework Meeting in Barcelona, Spain from March 12 through 14, 2014. Nineteen researchers from five countries attended the meeting and gave presentations on the latest results of neutron and gamma irradiation experiments, including unexpected experimental difficulties, proposed irradiation experiments, and re-evaluation of past irradiation data and models to address first-order irradiation effects. The purpose of this meeting was to develop a framework for exchanging information on the effects of irradiation on concrete used in nuclear power plants by those who wish to contribute to advancing the current state of knowledge. The key outcome of this meeting was a broad-based consensus that international cooperation is essential to providing the best opportunities to share resources, acquire valuable specimens from decommissioned nuclear power plants, and build a systematic database to provide a framework for decisions concerning extended operation of nuclear power plants in a timely and efficient manner.
- The LWRS Program participated in the NRC Advisory Committee on Reactor Safeguards' Plant License

Renewal Subcommittee Meeting on Subsequent License Renewal on April 8, 2014, in Rockville, Maryland. Richard A. Reister, LWRS Program Federal Program Manager, and Thomas Rosseel gave presentations that focused on LWRS Program materials R&D activities. Some members of the subcommittee also expressed specific interests in the LWRS Program's instrumentation, information, and control activities. Other organizations making presentations to the Advisory Committee on Reactor Safeguards subcommittee included NRC's Offices of Nuclear Reactor Regulation (Division of License Renewal) and Nuclear Regulatory Research, EPRI, and the Nuclear Energy Institute.

- The LWRS Program participated in another a briefing on April 30, 2014, between NRC staff and industry to discuss subsequent license renewal, with a focus on cable insulation performance and related research. Jeremy Busby listed expert panel findings of potential knowledge gaps for cable insulation and a detailed overview of LWRS Program's activities in this area. Kevin Simmons of Pacific Northwest National Laboratory was on hand to support discussion on cable aging, nondestructive sensor development, and rejuvenation activities. John Lindbergh and Drew Mantey of EPRI provided an overview of the joint research roadmap and EPRI activities. Sheila Ray (NRC) covered ongoing activities being led from the regulatory perspective. Key areas of discussion included research needs for submerged cables; this will be an area of increased consideration for the LWRS Program in future years. Development and use of nondestructive evaluation techniques was also broadly discussed and clearly will be an area of interest to regulators and industry in the coming years. All parties also agreed upon the necessity of continued coordination meetings and collaboration.

These meetings have been incredibly valuable forums for the LWRS Program to share ongoing research with key stakeholders and to receive feedback and input on future priorities and needs. The Materials Aging and Degradation Pathway's researchers are excited for future opportunities to inform subsequent license renewal decisions in the coming year.

Best Paper Award – European Conference of the Prognostics and Health Management Society

J. Wesley Hines
Advanced Instrumentation, Information, and Control Systems Technologies Pathway

A University of Tennessee nuclear engineering research team was honored with the Best Paper Award at the Second European Conference of the Prognostics and Health Management Society. This conference brings together the European community of prognostics and health management experts from industry, academia, and government in diverse application areas such as energy, aerospace, transportation, automotive, and industrial automation. The conference was held in Nantes, France from July 8 through 10, 2014. Dr. Wes Hines, Nuclear Engineering Department Head at the University of Tennessee and a collaborative research member of the U.S. Department of Energy's LWRS Program's Advanced Instrumentation, Information, and Control Systems Technologies Pathway, presented the award winning paper, "Prognostics for Light Water Reactor Sustainability: Empirical Methods for Heat Exchanger Prognostic Lifetime Predictions." The lead author was Zach Welz, a new graduate student in nuclear engineering, and contributing authors were Alan Nam, Dr. Michael Sharp, and Dr. Belle Upadhyaya. The U.S. Department of Energy's Nuclear Energy University Program, the Lloyds Register Foundation, and the International Joint Research Center for the Safety of Nuclear Energy provided research funding. More information is available at Nuclear Engineering Paper Earns Top Honor in Europe.

Computer-Based Procedures – Progress Toward Deployment

Johanna H. Oxstrand
Advanced Instrumentation, Information, and Control Systems Technologies Pathway

Nearly all activities that involve human interaction with the systems of a nuclear power plant are guided by procedures. The paper-based procedures currently used by industry have a demonstrated history of ensuring safety; however, improving procedure use could yield significant savings in increased efficiency, as well as improved nuclear safety through human performance gains. The nuclear industry is constantly trying to find ways to decrease the human error rate, especially the human errors associated with procedure use. As a step toward the goal of improving the performance of procedure use, LWRS Program researchers, together with the nuclear industry, have been investigating the feasibility of replacing the current paper-based procedures with a computer-based procedure (CBP) system.

It is important to distinguish between an electronic procedure and a CBP. In its simplest form, an electronic procedure is an electronic copy of the paper procedure (i.e., a PDF or similar document that displays the procedure content in a manner that is very similar to the paper-version of the procedure). The more advanced electronic procedures use hyperlinks to provide additional information (e.g., photos, appendices), some user inputs (e.g., recorded values), links between procedures, and mark-up capability (e.g., writing notes and conducting traditional place-keeping in the PDF). Electronic procedures are currently offered by a variety of vendors. Also, note that a CBP and CBP system refers to slightly different things. The procedure system (i.e., CBP system) can contain many procedures (i.e., CBPs). In other words, the system is the technology or tool used to conduct the procedures.

In the context of the current research effort, a CBP is defined as a dynamic presentation of a procedure that guides the user seamlessly through the logical sequence of the procedure. In addition, the CBP system makes use of the inherent capabilities of the technology, such as incorporating computational aids, easy access to additional information, just-in-time training, and digital correct component verification. Technological advancements in the CBP system allow human performance improvement features to be even more integrated into both the procedure and the overall work process when compared to electronic procedures. For example, a CBP system offers a more dynamic means of presenting procedures to the user, displaying only the relevant steps based on operating mode, plant status, and task at hand. A dynamic presentation of the procedure guides the user down the path of relevant steps based on current conditions. This feature will reduce the user's workload, inherently reduce the risk of incorrectly marking a step as not applicable, and reduce the risk of incorrectly performing a step that should be marked as not applicable.

Context-driven job aids, such as corrective action documentation, drawings, photos, just-in-time training, etc., are accessible directly from the CBP system when needed. One obvious advantage is to reduce the time spent tracking down the applicable documentation. Furthermore, human performance tools are embedded in the CBP system in such ways that they let the worker focus on the task at hand, rather than the human performance tools. Some tools can be completely incorporated into the CBP system, such as pre-job briefs, place-keeping, correct component verification, and peer checks. Other tools can be partly integrated in a fashion that reduces the time and labor required, such as concurrent and independent verification.

Functionality of the LWRS Program's Prototype Computer-Based Procedure System

Reducing operator workload using CBPs requires a balance between automation and decision support, operator engagement, and the procedure execution process. The high-level solution to the problem is to provide information to the operator about steps completed, steps marked not applicable, future steps, decisions made that influence the path through the procedure, etc. The key functionality of the prototype CBP system (Figure 1) is described as follows:

- Automatic place-keeping. The CBP system highlights the active step (i.e., the step being conducted). Other steps are shown, but the user can only take actions related to the active step. In the rare circumstance that the operator, with the approval of his supervisor, concludes that the CBP system is incorrect due to current conditions in the plant, the CBP system can be overridden. These functions make it easy for the operator to stay on the specified path. This built-in procedural adherence has proven to reduce the amount and severity of human errors.
- Simplified step logic. A conditional step in a procedure is a step that is based on plant conditions or a combination of conditions to be satisfied prior to the performance of an action. The CBP removes complexity from step descriptions by presenting conditional statements as simple questions. For example, statements such as "IF starting pump A, THEN perform the following…" are presented as "What pump do you want to start: Pump A or Pump B?" Depending on the answer, the procedure will take the operator to either a step with the actions

needed to start Pump A or a step with the actions needed to start Pump B.

- Component verification. There are multiple ways that correct component verification can be implemented and improved by using technology. Researchers have explored correct component verification via barcodes, optical character recognition, and manual input. When using barcodes or optical character recognition, the system will match the input with a component database. If the correct component is verified, the operator will be able to continue on with the step. If the correct component is not verified, the operator will have to find the correct component before being able to proceed through the procedure. There is always the option to conduct component verification manually.

Computer-Based Procedure Research Activities

The CBP research team is exploring how best to design a CBP system that will deliver the intended benefits of increased efficiency and improved human performance. Currently, no "off-the-shelf" technology exists for the type of CBP system that is being investigated. As more technology is integrated into the procedure process, the importance of a systematic approach to the design of the procedure system increases.

Technological advancements offer great opportunities for efficiency and safety gains; however, if the system is not designed correctly, there is a risk of unintentionally introducing new opportunities for human errors.

The research team is breaking new ground in the area of CBPs with the prototype being developed. The CBP research effort aims to provide the nuclear industry with a better understanding of the benefits of transitioning to a CBP system by demonstrating proof-of-concepts and conducting activities where end-users have an opportunity to use the CBP system in their everyday work within a nuclear power plant. The prototype CBP system has been evaluated, both in utilities' training facilities and at a nuclear power plant, through an iterative process. The main functionality of the system and the research activities conducted to date are described in the following paragraphs.

Industry acceptance of advanced technology and CBP systems is vital to moving the industry closer to fleet-wide deployment of such systems. One of the most important tools for gaining traction toward industry acceptance is to put a CBP system in the hands of field workers (e.g., auxiliary operators and maintenance technicians) and other end-

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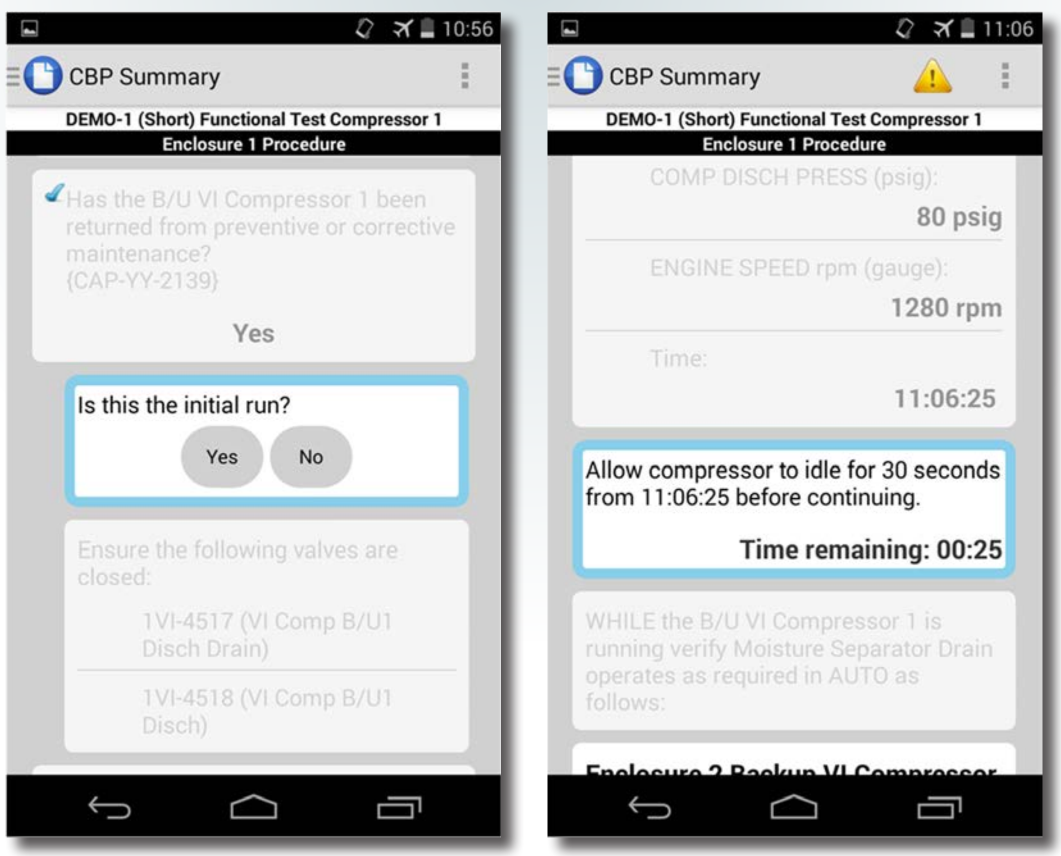
Figure 1. Screenshots from the computer-based procedure prototype, showing examples of automatic place keeping (checkmark is for a conducted step and the blue boarder is for an active step), simplified step logic (i.e., Yes/No questions), and time stamps.



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users. Hence, engaging end-users in early CBP system trials is a crucial step in enabling field workers to work in a safer and more efficient manner, with fewer mistakes.

Based on findings from a qualitative study, an initial set of design requirements was identified and used to design the first version of the CBP prototype system.

Three laboratory studies were conducted at the training facilities of the collaborating utilities (i.e., flow loop, electrical laboratory, and instrument and control laboratory) to evaluate the CBP design from a human factors' standpoint. Nuclear power plant operators and technicians participated in realistic work scenarios using both a paper-based procedure and a CBP. The evaluation studies compared deviations from the specified path, performance time, mental workload, and the general usability of device and interface. The main objective of the studies was to evaluate the effect a CBP might have on performance and efficiency of the procedural task. The researchers also collected feedback on the design of the user interface and the usability of the CBP. Suggestions from the participants, as well as insights gained from carefully observing how the participants carried out the procedures using the CBP, were incorporated into future revisions of the prototype.

In summary, the three laboratory research activities demonstrated the following benefits:

- Automatic place-keeping and the ease of moving between and within procedures when having to transfer to other procedures or conducting continuous action steps increased both efficiency and human performance.
- Context-sensitivity and simplified step logic are highly desirable features. Context-sensitive cues (e.g., labels on buttons provide cues to what action needs to be taken) in the procedure increase the operators' focus on the task at hand.
- Digital correct component verification reduces the risk of manipulating an incorrect component. The use of barcodes to verify a correct component is generally viewed as an effective implementation of the human performance tool.
- Photos of the components included in the procedure steps increased efficiency and reduced the risk of human error when locating specific components and equipment, as well as when conducting component verification.
- Computational aids, such as performing calculations based on user inputs (e.g., recorded tank levels, temperature, or engine speed), were proven to reduce the risk of human errors.

Laboratory studies provided insight on how to design dynamic presentation of a procedure and how to incorporate human performance tools into the workflow. However, a key success factor in end–users' (e.g., auxiliary operators or maintenance technicians) acceptance of such systems is to put the system in their hands and let them use it as a part of their everyday work activities. This is achieved through field tests.

To provide the highest value to the nuclear industry, a CBP system needs to encompass more than just procedures for auxiliary operators. The CBP system needs to be able to handle all types of instructions, checklists, procedures, work orders, and other documents used in the plant. The vision includes having all of the different organizations within the plant use the same system. To achieve that goal, continuing research needs to ensure that the system will be able to handle a broad variety of tasks and situations; therefore, collaborating with multiple utilities and multiple organizations within the utility (e.g., operations, maintenance, and chemistry) is essential. A series of field tests will be conducted at more than one utility to ensure that the results from this research are applicable at other plant sites.

A pilot field test was successfully conducted at Catawba Nuclear Station in the spring of 2014 (Figure 2). The lessons learned from the pilot field test were incorporated when the researchers launched a second field test at Palo Verde Nuclear Generating Station in September 2014. This test focused on a preventive maintenance work order for technicians, which is commonly conducted by multiple maintenance technicians over a couple of days. The functionality needed to handle this was added to the revised version of the CBP system. This new version also took steps toward the vision of incorporating more of the elements needed in a work package. For example, previous logs (i.e., values recorder earlier) were automatically incorporated into the system. In addition, the research team is currently in the planning stage with two other utilities that have expressed interest in hosting field test activities. For each field test planned and conducted, the CBP system will be revised to include the additional functionality needed to bring it closer to handling all aspects of a work package (i.e., the full process from initiating work request, planning, execution, and archiving).

Conclusions

Most utilities use software on handheld devices when making operator rounds in the plant, but very few utilities have similar systems for procedures. However, there is a general movement toward deploying electronic procedure systems. Most vendors offer electronic procedure systems, but not CBP systems. This research focused on the benefits, for both the vendor and utilities, of using advanced systems to the overall safety and efficiency of the nuclear power plant.

The full cost of deploying a CBP system is not yet known. Because procedures are an integral part of how

Figure 2. Two auxiliary operators use the computer-based procedure system during the April 2014 field test.

utilities conduct business, the move from paper-based procedures to CBPs has larger cost impacts than the cost of implementing a CBP system itself. Aside from the technology, there are costs associated with the training of the operators and field workers, the infrastructure, and the change of work processes (e.g., how procedures are written, validated, and maintained). Further work is needed to investigate the full range of benefits to the nuclear power industry associated with any potential transition to CBP systems and their underlying infrastructures.

The results from these research activities (i.e., the reduction of human errors and their potential consequences and time reduction when using CBPs compared to paper-based procedures) will be used to develop a business case. Further results and insights gained from field tests will be used to provide further detail to the business case, consisting of a cost-benefit analysis that is conducted based on the results from both the evaluation studies and the plant validations. The goal for the business case is to encourage utilities to invest in infrastructure to support advanced nuclear power plant worker technologies such as CBP systems, but also to provide a rationale for obtaining a portion of the benefits by transitioning to CBPs, even without having the entire infrastructure in place.

The research conducted in the LWRS Program's CBP Project specifically targets questions related to how best to design CBP systems from a human factors' perspective. The researchers are taking the concept of CBP further than the vendors' existing electronic procedure systems. The researchers are exploring ways to use the advanced technology to design a CBP system to include dynamic presentation of the procedure content, context-driven job aids, and integrated human performance tools. All of these innovations would help the operator focus on the task at hand rather than the tools. The whole system is developed from a user perspective and is proven to increase efficiency and improve human performance.

This research effort explores new territory by taking on the challenging task of designing CBPs for field workers. The majority of the previous CBP research has a strong focus on control room procedures and emergency procedures in particular. The research project has yielded valuable results supporting the hypothesis that a well-designed CBP system can improve efficiency, safety, and human performance. The research team provides research that will support the industry and vendors in moving toward CBP systems that encompass more advanced capabilities, as well as provide the basis of a sound business case for transitioning to a CBP system.

Light Water Reactor Fuels with Enhanced Accident Tolerance: Development Status

Shannon M. Bragg-Sitton
Advanced Light Water Reactor
Nuclear Fuels Pathway

United States-based development of accident tolerant cladding and fuel materials was initiated following the 2011 Great East Japan earthquake and resulting tsunami that disabled the Fukushima-Daiichi nuclear power plants. The LWRS Program's Advanced Light Water Reactor (LWR) Nuclear Fuels Pathway was initially tasked with research and development (R&D) of advanced cladding materials that would provide extended coping time under design basis and beyond design basis accident scenarios, while maintaining compatibility with standard UO_2 fuel, co-resident zirconium-alloy-clad fuel, in-core structures, and fuel-handling equipment. Under the U.S. Department of Energy's Fuel Cycle R&D Program Advanced Fuels Campaign (AFC), ongoing R&D of advanced performance LWR fuels was redirected to fuels having enhanced accident tolerance following the events at Fukushima. Work under AFC was less constrained than within the LWRS Program, allowing for investigation of advanced materials for both fuel and cladding.

Through 2012, the LWRS Program's Advanced LWR Nuclear Fuels Pathway focused on silicon carbide (SiC) based cladding concepts, selecting a "hybrid" concept that included a SiC ceramic matrix composite wrap on a zirconium alloy tube as an initial concept for development. At the same time, the AFC transitioned from development of higher performance fuel and cladding material to materials that could also provide enhanced performance under accident conditions. The AFC research encompasses a large number of fuel and cladding concepts, with research teams led by several national laboratories, universities, and industry (with U.S. Department of Energy funding support). To streamline this fuel-related R&D, the relevant LWRS Program-supported R&D work has been transitioned to the AFC over the past year and a half. A few activities remain under the LWRS Program leadership, as discussed in the following paragraphs, requiring continued coordination across the AFC and LWRS Program.

Development of LWR fuel with enhanced accident tolerance is a significant effort that is being supported by numerous research laboratories, academic institutions, and nuclear fuel vendors worldwide. A survey of International Atomic Energy Agency (IAEA) and Organization for Economic Cooperation and Development member countries reveals significant active participation in the design, analysis, and testing of fuel, cladding, and other core component materials that would have enhanced accident tolerant characteristics.

Cladding materials under investigation range from evolutionary options relative to the current metallic zirconium alloy cladding – such as modified zirconium alloys, coated zirconium alloys, and other metallic options (e.g., FeCrAl alloys and Mo-based metallic cladding) – to revolutionary options that incorporate materials having very different properties and behaviors – such as ceramic silicon carbide composites and hybrid metallic – ceramic designs. In some cases, these materials are also being considered for non-fuel components, such as boiling water reactor channel boxes (i.e., SiC in the United States and Japan) and accident tolerant control rods (i.e., SiC in Japan). Fuel materials that are being developed also include both evolutionary concepts, such as modified UO_2 to improve thermal conductivity or fission product retention, and more novel concepts that would offer improved performance, such as advanced composite fuels; increased U-235 loading (such as U_3Si_2); or improved fission product retention (such as microencapsulated fuels).

The Organization for Economic Cooperation and Development - Nuclear Energy Agency's Nuclear Science Committee recently approved the formation of an Expert Group on accident tolerant fuel (ATF) for LWRs. Chaired by Kemal Pasamehmetoglu, Idaho National Laboratory's Associate Laboratory Director for Nuclear Science and Technology, this group will conduct work under three task forces: (1) Systems Assessment, (2) Cladding and Core Materials, and (3) Fuel Concepts. The work scope for the Systems Assessment task force will include definition of evaluation metrics for ATF, technology readiness level definition, definition of illustrative scenarios for ATF evaluation, parametric studies, and selection of system codes. The Cladding and Core Materials and Fuel Concepts task forces will identify gaps and needs for modeling and experimental demonstration; define key properties of interest; identify the data necessary to perform concept evaluation under normal conditions and illustrative scenarios; identify available infrastructure (internationally) to support experimental needs; and make recommendations on priorities. Where possible, considering proprietary and other export restrictions (e.g., International Traffic in Arms Regulations), the Expert Group will facilitate the sharing of data and lessons learned across the international group membership.

Similarly, IAEA is initiating a Coordinated Research Project (CRP) on ATF. This CRP will be kicked off with a technical meeting on "Accident Tolerant Fuel Concepts for Light Water Reactors," which will be held at Oak Ridge National Laboratory in October 2014. This CRP will be managed under the IAEA Technical Working Group on Fuel Performance and Technology. In October 2013, IAEA held a technical meeting on "Modeling of Water-cooled Fuel including Design Basis and Severe Accidents" in Chengdu, China in collaboration with the Nuclear Power Institute of China. This meeting also kicked off a new IAEA CRP on fuel modeling in accident conditions as a follow-on to the fuel modeling at extended burn-up CRPs that focused on improvement of computer codes used for fuel behavior modeling. It is anticipated that the fuel modeling in accident conditions CRP will include consideration for ATFs that are currently under development around the world if sufficient data are available to support the models.

As of 2014, only one key R&D activity remains under the LWRS Program's leadership: the development of SiC/SiC joining technology (Figure 3) for in-core applications, with a specific focus on nuclear fuel cladding. Achieving a SiC/SiC joint that resists corrosion with hot, flowing water; is stable under irradiation; and retains hermeticity is a significant challenge. This technical work remained under the LWRS Program due to existing contracts with industry to develop joining technology (see Bragg-Sitton, S. M., Light Water Reactor Sustainability Program Status of Silicon Carbide Joining Technology Development, INL/EXT-13-30268, September 2013).

As reported in the December 2013 LWRS newsletter, subcontracted work at General Atomics to develop SiC joining technology was completed at the end of 2013, with the delivery of 15 samples to Idaho National Laboratory (10 monolithic SiC tube-end plug joints for independent testing and five assemblies of SiC/SiC composite joined to a monolithic SiC end plug that could be used in irradiation testing). Under the 1-year contract, these studies showed that General Atomics' polymer-derived joining technique and the joint geometries identified in the study are capable of supplying a suitably robust joint, although statistically relevant data sets are needed to draw more global comparisons to alternative technologies. Irradiation testing is now necessary to verify joint robustness in the intended LWR operating environment.

Joint development work at Rolls Royce High Temperature Composites has extended into 2014. As of September 2014, Rolls Royce High Temperature Composites has completed SiC/SiC joint development trials and has selected MAX phase joint composition over liquid phase sintered joints due to its survival of a 5,000-psi burst pressure test following a 1200oC exposure for 24 hours. Rolls Royce High Temperature Composites is now preparing final deliverables using the MAX phase joint. The initial set of deliverables will include ten 4-in. long tubes joined to a single end plug for out-of-pile testing and characterization. A second set of 10 samples will also be prepared. These samples will include longer, fully composite SiC/SiC tubes for possible fueled-irradiation testing. Rolls Royce High Temperature Composites will bond one end cap to each tube and will deliver this and a second end cap to seal the tube after fuel loading. The fuel loading and final joint would likely be performed at Oak Ridge National Laboratory, with subsequent irradiation testing in the Idaho National Laboratory's Advanced Test Reactor. Accomplishment of the proposed irradiation test is subject to availability of funding from the Fuel Cycle R&D Program's AFC and is currently under discussion.

The LWRS Program will continue to support evaluation of proposed ATF concepts through the Risk-Informed Safety Margin Characterization (RISMC) Pathway using advanced modeling and simulation tools. The overall goal of the work is to understand the performance of hypothetical ATF concepts under steady-state and accident conditions, such as transients and station blackout. In general, it is not

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Figure 3. Silicon carbide–silicon carbide composite assembly (General Atomics).

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appropriate to compare fuel/cladding types solely on the basis of performance in a single scenario; instead, this work will include analyses that allow risk-informed comparison of the plant-level performance across representative normal and off-normal conditions. In the absence of sufficient data on each ATF concept currently under investigation, the RISMC Pathway's work is currently proceeding with cladding parametric studies based on variation of key properties, investigating the possible range of property values for each "class" of cladding (i.e., "metallic" and "ceramic").

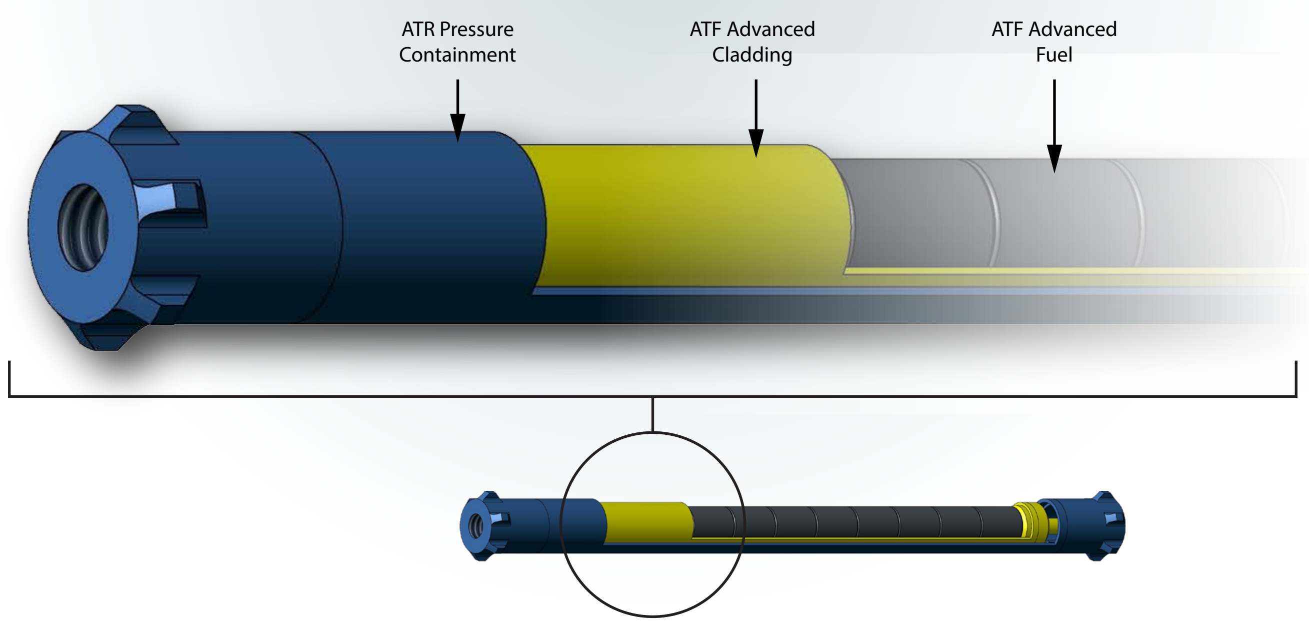
The LWRS Program's analysis work conducted under the RISMC Pathway is tightly coordinated with AFC R&D. AFC is currently supporting R&D of concepts by multiple teams, with a prioritization of those concepts planned for 2016 (see the March 2014 issue of Nuclear News, p. 83-91, for details on the concepts under development). The concept review will be conducted by an Independent Technical Review Team, which will be identified in 2015. As additional performance data are collected from out-of-pile and in-reactor testing of fuel and cladding concepts, these data will be conveyed to the RISMC Pathway's team conducting plant-level performance analysis.

The ATF Program under the Fuel Cycle R&D Program's AFC is currently in Phase 1 of development, which includes feasibility assessment and down-selection (prioritization). During this phase, fuel concepts will be developed, tested, and evaluated. Feasibility assessments are currently under way to identify promising concepts, including laboratory-scale experiments (such as fabrication, preliminary irradiation, and material property measurements); fuel performance code updates; and analytical assessments of economic, operational, safety, fuel cycle, and environmental impacts.

Under AFC's direction and funding, industry-led ATF concepts will begin irradiation in the Advanced Test Reactor (ATR) in early 2015, and additional laboratory-led concepts are expected to begin irradiation later in 2015. Figure 4 shows a cutaway drawing of the irradiation capsule for this test series. Initial rodlets include samples from the three industry teams funded under a 2012 U.S. Department of Energy Funding Opportunity Announcement: AREVA, General Electric Global Research, and Westinghouse Electric Company, LLC (Westinghouse). Initial test rodlets will be used to investigate performance of both advanced fuel and advanced cladding. Initial AREVA and Westinghouse rodlets include advanced fuel concepts in standard cladding (AREVA: modified UO_2 pellets that contain either chromia dopant or embedded SiC fibers; Westinghouse: high-density U_3Si_2 pellets), whereas initial General Electric Global Research rodlets include standard fuel with advanced cladding concepts (APMT and Alloy-33). Each team plans to provide additional concepts for irradiation later in 2015.

The overall ATF development goal is to demonstrate performance by inserting a lead fuel rod or assembly into a commercial power reactor by 2022, with deployment in the U.S. LWR fleet to follow within 20 years. The test plan progresses from feasibility experiments under normal operating conditions to integral demonstrations under accident conditions to support the lead rod irradiation program and eventual qualification of an ATF concept. Data generated by this test program will be used to establish the feasibility of certain aspects of proposed ATF concepts, as well as provide information to support screening among concepts.

Figure 4. Irradiation capsule cutaway assembly.



Recent LWRS Program Reports

Materials Aging and Degradation

- ***A Model of Radiation-Induced Microstructural Evolution***
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Editor: Teri Ehresman
Writer: LauraLee Gourley
Designer: David Combs

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