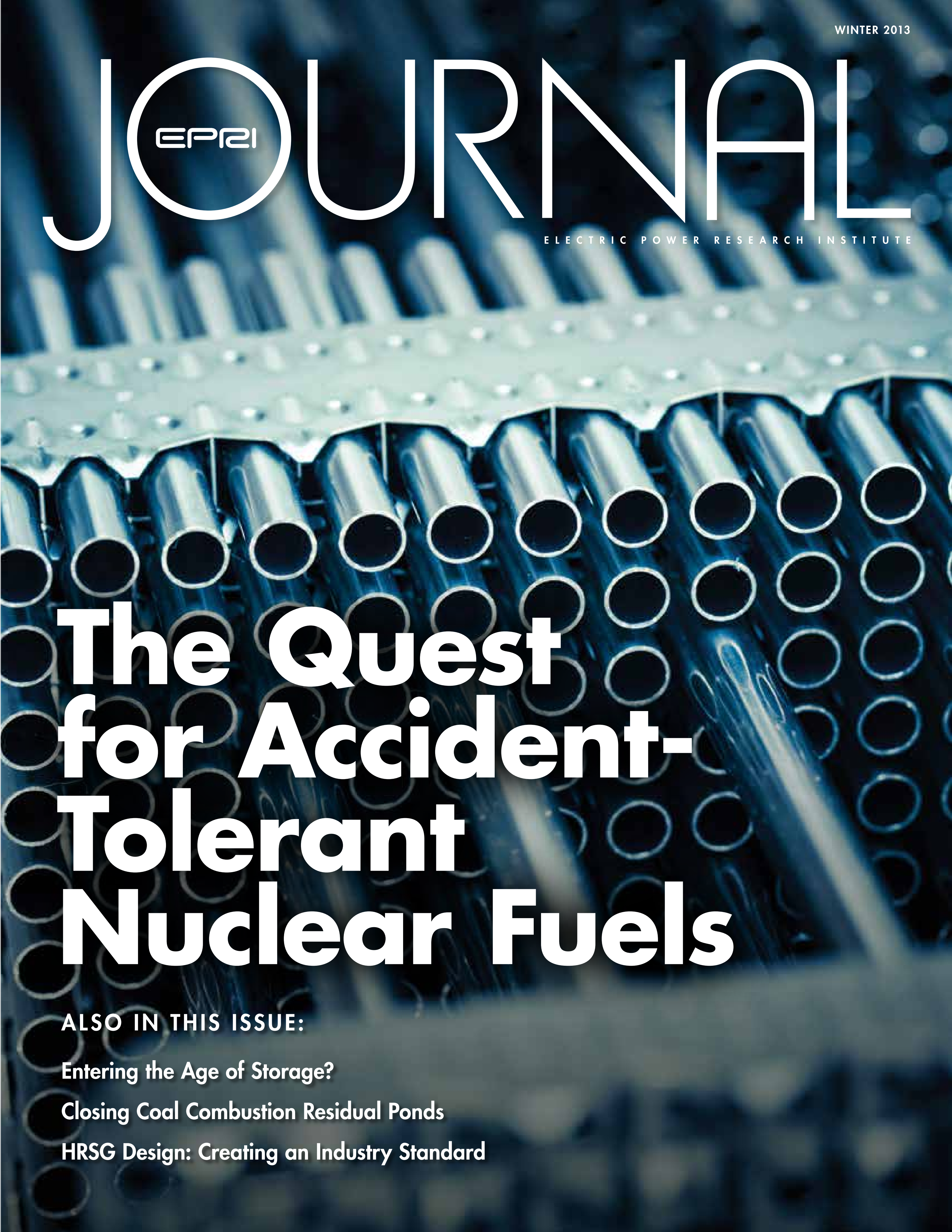

WINTER 2013

# EPRI JOURNAL

ELECTRIC POWER RESEARCH INSTITUTE

# The Quest for Accident-Tolerant Nuclear Fuels

ALSO IN THIS ISSUE:

Entering the Age of Storage?

Closing Coal Combustion Residual Ponds

HRSG Design: Creating an Industry Standard

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# WIRED IN

*Perspectives on electricity*

Barbara D. Lockwood, P.E.
*General Manager, Energy Innovation, Arizona Public Service*

## Simplifying the Quest for a Flexible Grid

It's no secret that we are in a shifting energy landscape, with the shift being led by dramatic changes in the way power is generated and consumed. The percentage of energy from intermittent resources, such as wind and solar, continues to increase. At the same time, we are seeing new uses for electricity—specifically, plug-in vehicles.

Utilities must change as well. The necessary change goes by many names: smart grid, grid modernization, flexible grid. Whatever you call it, it's about making the existing electrical infrastructure adaptable and flexible enough to meet these changes.

In 2008, Arizona Public Service (APS) embarked on a quest to understand what it will take to create the grid of the future. The Flagstaff Smart Grid Pilot deployed, managed, and studied numerous technologies that were placed at various locations on the grid. Five years later, we have learned many things from this ongoing project. The most important: a grid doesn't need to be chock full of cutting-edge technology in order to be flexible. Instead, it needs to have the following six components:

**Communications infrastructure.** A solid and ubiquitous communications infrastructure is probably the most overlooked and undervalued component of the smart grid. Fiber, WiMAX, microwave, cellular, and leased lines—we use them all and they are all needed. Without the ability to communicate bi-directionally, there is nothing "smart" about the grid.

**Communication devices.** With communications infrastructure in place, fault indicators can be readily deployed. These relatively low-cost devices immediately increase situational awareness and reduce restoration times.

**Advanced meters.** The unassuming smart meter not only provides operational benefits but also enables greater customer information and choice. The meters help customers garner a better understanding of their energy use so they can make better decisions about energy consumption. APS has almost completed installation of these meters across its service territory. Where they are already deployed, APS is able to provide better customer service. Customers no longer have to wait for a technician to come out to the house; service can now be turned on or off remotely.

**Automated switching.** In a cost-benefit comparison of advanced "self-healing" technology and automated switching, automated switching wins hands down. With the simple addition of a switch that can be remotely operated in a safe manner, grid flexibility grows by leaps and bounds. Given that most of the system is still using manual switches, changing over to automated switches will fundamentally change the current grid.

**Voltage management.** Voltage control and management devices, including smart inverters, become more and more critical as the amount of energy coming from solar-electric systems proliferates. Increasing amounts of intermittent energy require utilities to invest in maintaining proper voltage in order to ensure that power quality meets customer requirements. APS is getting a firsthand experience with this challenge. By the end of 2013, we expect to have 750 MW of solar energy on the system, enough to power about 185,000 homes.

**Operating platforms.** Moving to a digital platform that uses large computer screens allows system operators to maximize smart grid technologies. Not that long ago, APS used push pins on hand-drawn wall maps. Now that we have transitioned to a dynamic platform, our operators are able to do more than just monitor the grid. We are on a path that will allow them to predict future anomalies and, when an outage occurs, restore power remotely. A state-of-the-art operating platform with advanced analytics will bring together all the capabilities of the field devices with sophisticated computing capabilities to make the whole much greater than the sum of the parts.

Technology progresses every day. But we don't have to wait until tomorrow to prepare for the future. We can make great progress with proven technologies that will greatly improve our ability to accommodate the rapidly changing energy landscape.


*Barbara Lockwood, General Manager of Energy Innovation for APS, shows screens that allow employees to monitor the operation of solar plants around Arizona. (Photo by Amy Gleich)*

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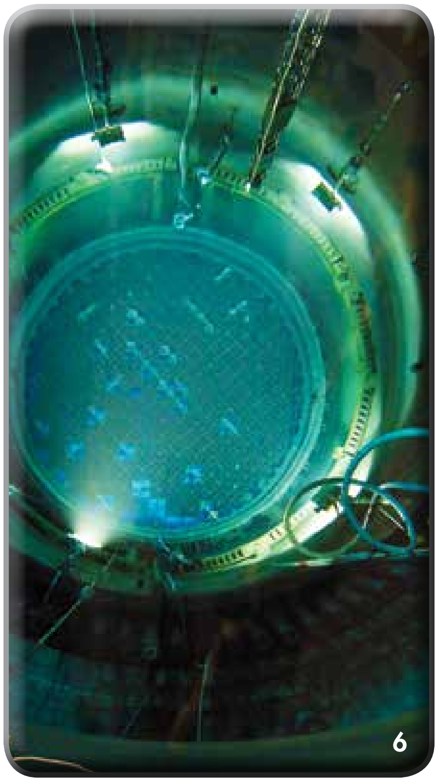



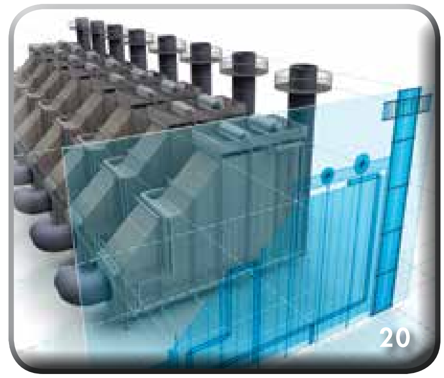


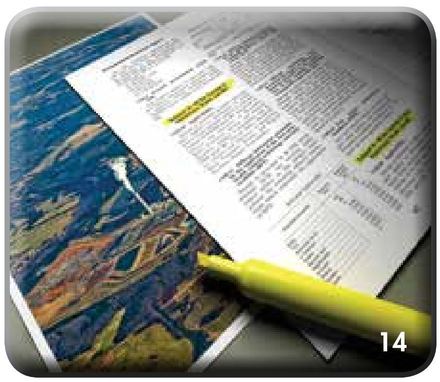



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EPRI is helping launch a strategic global initiative to develop alternatives to conventional zirconium materials that will make nuclear fuels more resilient under accident conditions.

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Spurred by advances in high-efficiency batteries for consumer electronics devices, energy storage is poised to make a big difference on the power grid as well.

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EPRI has brought together utilities, manufacturers, and other experts to develop industry-wide design specifications that will improve the durability of heat recovery steam generators under cycling operation.

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Bernard Salha, president of EDF Research and Development, cites international collaboration, innovative technology, and a progressive business model as the keys to a strong future.

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by Mike Howard, President and CEO, EPRI

## How R&D Works

As you read the Winter 2013 issue of the *EPRI Journal*, consider how research and development really works. *R&D* is a familiar term, but as with many familiar terms, we get comfortable with it and forget sometimes to consider what it really adds up to or how it works. Looking at the mix of articles and features in this publication gives us some insights:

**R&D works with the business.** EDF executive Bernard Salha in his interview describes how R&D is integral to the business of this global energy leader. Although we sometimes encounter the perception that R&D is something of an academic undertaking, Salha makes it clear that EDF invests in R&D with an expected return. EPRI works with EDF and its peers around the world. We see that the R&D investments can yield measurable results, such as improved reliability and efficiency, lower costs, and environmental sustainability.

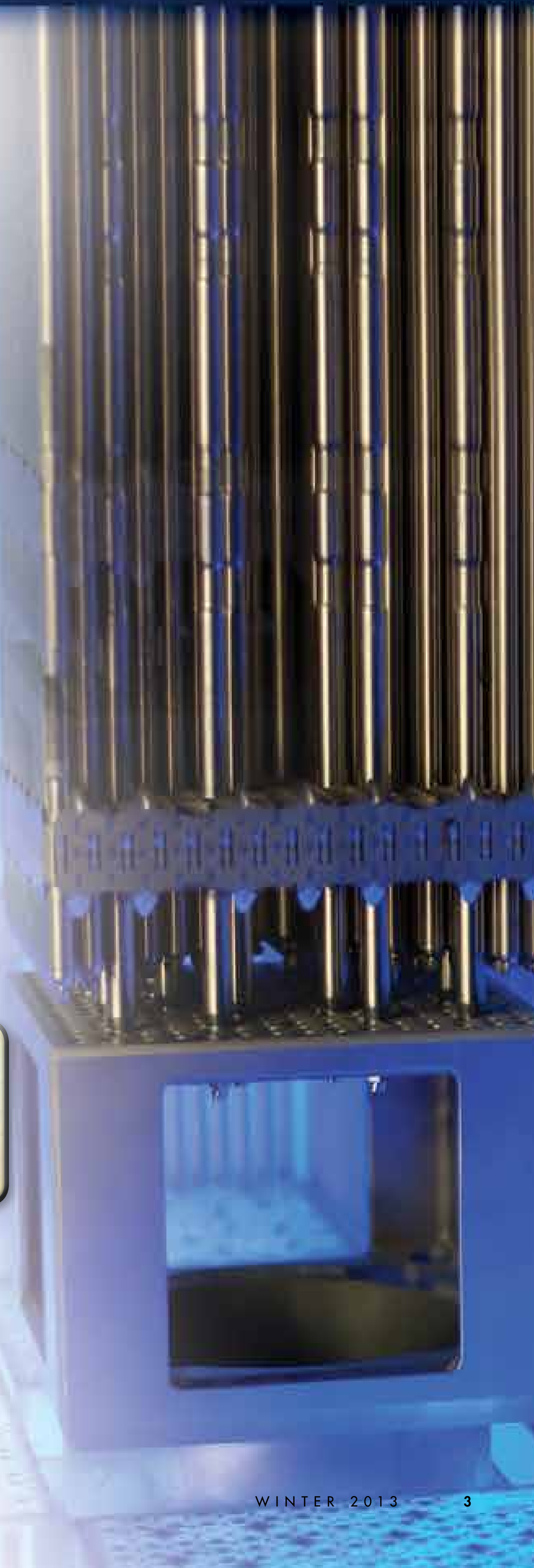
**R&D works with policy.** The words *policy* and *politics* both derive from the Greek word for citizen. So when we say that R&D works with policy, we mean that policy is an extension of the many links between R&D and the public. In this issue of the *Journal*, we report on EPRI's work associated with coal combustion residuals, and we see how research informs the development and implementation of policy as it evolves through legislation and regulation. In considering the best ways to dispose of coal combustion residuals, we can trace the changes and progress as utilities, researchers, and the body politic move along parallel paths to a common goal.

**R&D works with physics and the physical.** This past summer, utility leaders gathered at EPRI's Lenox, Massachusetts, laboratory as part of a field demonstration addressing how to make the grid more resilient. The memorable image from that day is of a utility pole (doing stand-in duty as a tree) being deliberately felled onto a power line. But the memorable information from that exercise is pure physics, which will be put to work in engineering as we develop hardware and components that can better withstand strong winds, ice, and other forces of nature. One of the more interesting aspects of R&D is how it joins pure science with practical application.

**R&D works to build bridges.** EPRI's collaborative model of proposing, conducting, and implementing R&D is well understood in the electricity sector. When we find success in



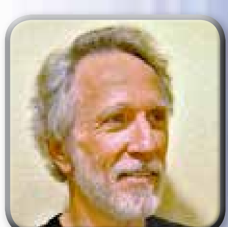




new ways of collaborating, it is doubly satisfying. Most people outside the power generation industry are not aware of heat recovery steam generators, but the story about these crucial hardware components in this *EPRI Journal* is also a story about connecting people who normally compete and arriving at some common ground to improve the performance of combined-cycle gas turbine plants.

**R&D works for the long haul.** This is somewhat intuitive but worth emphasizing. Even if you are not directly connected with issues related to nuclear fuel, take a few minutes to read about the journey we have undertaken to make nuclear fuels inherently safer in the event of accidents such as Fukushima. It's not uncommon to start a project with no firm understanding of when the work will be complete. In some cases, our researchers may be involved in launching work that may extend beyond their time at EPRI or their direct involvement with a project, but there is as much satisfaction in the early stages of work as there is when the job is done.

And speaking of the long haul, this issue of the *EPRI Journal* marks the retirement of David Dietrich, the *Journal's* managing editor. I want to take this opportunity to acknowledge his contributions and to wish him well on behalf of everyone at EPRI. Dave has been associated with the *EPRI Journal* since 1978, when he joined the organization. The breadth of his knowledge in the electricity sector and the depth of his experience at EPRI will be missed. He has earned his retirement, and in leaving he takes with him the gratitude and respect of the entire EPRI team. The *EPRI Journal* has changed in many respects over the past 35 years, and we anticipate more change in this digital age, but Dave's insight, thoroughness, and integrity have reflected well upon him and the work here at EPRI that he has so diligently and professionally reported. Good luck, Dave, and thank you.


**David Dietrich**

**Michael W. Howard**
*President and Chief Executive Officer*

## Assessing the Social Cost of Carbon

The Social Cost of Carbon (SCC) is an attempt to estimate the monetary value of the potential impacts of climate change that might be avoided with policies designed to reduce carbon dioxide emissions. Weighing the benefits of any policy against its costs requires explicit and consistent evaluation of potential risks and trade-offs, which is essential to policy design and adjustment.

The U.S. Environmental Protection Agency (EPA) has estimated the environmental and health benefits of air, land, and water regulations for years. In 2010, the U.S. government introduced its first official values for the SCC, defined as the net present value of climate change impacts from the emission of one additional net global metric ton of carbon dioxide—i.e., the marginal cost (or benefit) of one more (or less) metric ton emitted in a specific year. SCC estimates are used by the U.S. government to value changes in greenhouse gas (GHG) emissions associated with rulemaking. SCC estimates consider the climate effects of $CO_2$ emissions on, among other things, agricultural and forestry production, energy consumption for space cooling and heating, water availability, changes in sea level and coastal areas, and human health (e.g., heat stress and disease).

The SCC has lately garnered significant congressional and public attention, in large part because of a recent substantial increase in the government's estimates. In addition, the benefits of SCC-based climate mitigation represent a large fraction of policy benefits in recent proposals for reducing $CO_2$ from new and existing electric generating units. Public dialogue on the SCC is likely to continue, especially with an EPA $CO_2$ standard for existing electricity generators expected sometime in 2014-15. The development of SCC estimates is challenging and controversial. In response, EPRI has developed a new project to analyze the scientific methodologies for calculating the SCC and assess the applicability of the results to various circumstances.

### Modeling Is Key

Today's SCC estimates are derived from a few highly aggregated integrated assessment models—DICE, FUND, and PAGE—that have produced a broad range of estimates, spanning three orders of magnitude. The sets of impacts considered across models differ, as do the implications of estimated damage from similar impact categories. More important, however, is that the estimates are sensitive to assumptions that are highly uncertain. For example, SCC estimates can vary by an order of magnitude with reasonable alternative assumptions about climate responsiveness to GHGs, and by two orders of magnitude with reasonable alternative socioeconomic futures.

While the recent government revisions more than doubled SCC estimates, the full sensitivity and uncertainty of these estimates are unknown, and the new estimates are the result of only modest modeling revisions; numerous key elements have yet to be revisited. Also, new socioeconomic, climate modeling, and damage estimate input is forthcoming from the scientific community. And even larger questions are being considered: Should U.S. regulations include the costs of international damage from U.S. emissions? Should there be differential weighting for damage in other global regions because of regional differences in the marginal value of impacts? How should GHGs other than $CO_2$ be valued?

### Improving the Analytical Foundation

The methodologies used to calculate the SCC and the application of the results could directly impact costs for the public as resulting SCC estimates are incorporated into federal and state regulations. In the case of the electric industry, a thorough understanding of estimates and an appropriate approach to application are important to power generation planning and industry stakeholders in order to understand the impacts on future electric rates and prices. It is important to develop a robust analytical foundation and provide guidance on how best to estimate the social costs of GHGs. EPRI's project will provide a comprehensive assessment of SCC values, methods, assumptions, sensitivities, and issues associated with modeling to date; potential revisions; and SCC application. It is also important to understand SCC as part of the broader discussion and consideration of overall climate policy.

*For more information, contact Steven Rose, srose@epri.com, 202.293.6183.*

## Putting Photovoltaic Technologies to the Test

Historically, the high cost of crystalline silicon solar cells has encouraged the development of less expensive (though lower efficiency) thin-film photovoltaic (PV) systems. Now, with manufacturing breakthroughs in China substantially lowering the cost of silicon cells, the race for economical flat-plate arrays suitable for large-scale application is on fire, with a variety of technologies and manufacturers vying for market share. In such a rapidly moving market, efficiency and other technical claims are hard to verify and compare, and there is little information available on the reliability of individual products.

With the market for flat-plate PV systems flying high (solar PV deployment recently surpassed wind installation for the first time), EPRI is running comparative field tests of commercial-scale PV technologies—both crystalline and thin-film—to begin establishing credible, consistent data on product efficiency, reliability, and maintenance needs. Results will inform future electric utility decisions on PV product selection, system design, maintenance strategies, and performance monitoring. The tests have been under way at the Solar Technology Acceleration Center (SolarTAC) in Aurora, Colorado, since November 2012, with evaluations expected to be completed by the end of 2014.

### The Test Plan at SolarTAC

The technologies being tested include polycrystalline silicon (pC-Si) panels manufactured by Suntech and Trina Solar and a monocrystalline silicon (mC-Si) system from Helios Solarworks. The thin-film systems include cadmium telluride (CdTe) panels made by First Solar and copper indium gallium selenide (CIGS) systems from both Solar Frontier and Stion. A seventh technology—Panasonic's heterojunction cell with intrinsic thin-layer silicon (HIT-Si)—was added in June of this year. All of the systems are set up with the same racking structure and dc-to-ac power inverter.

To ensure accurate performance factor calculations (ac output relative to sunlight input) for the PV arrays, researchers are collecting detailed data on the solar resource at the test site, including insolation measurements and daily resource variability. In addition to the daytime performance factor, calculations are being made for single-day and monthly capacity factor. Performance assessment will cover a variety of weather and temperature regimes, with data sets that span all seasons throughout the year. Dc system characteristics and operational issues are being studied through current-voltage (I-V) curves, and infrared imaging is also being used to pinpoint operational problems, including thermal failures. The effect of snowfall on PV system output is being investigated as a particularly salient issue.

### Interim Insights

While the comparative tests are ongoing, results recorded for the original six technologies from January through June of this year have already produced some interesting insights (3002001927). For example, the crystalline-based technologies appear to be more affected by snow events than the thin-film technologies. During a four-day event when temperatures remained below freezing, snow tended to melt or slide off the thin-film modules while continuing to constrain power levels of the silicon arrays. These differences are thought to be related to both the bottom edges of the silicon modules and the electrical layout of the modules.

Infrared imaging of the PV systems has been able to highlight some operational issues as well, including the effect of wind circulation on temperature gradients, the ability to detect failures of connectors and other array components, and the creation of hot spots by bird droppings.

Although the results collected so far are only preliminary, it is apparent that technology performance is heavily influenced by the quality of module manufacturing—how accurately each manufacturer is able to make modules that reliably produce power at their specified nameplate rating. For example, a string failure in one of the Suntech pC-Si panels and cracks in several of First Solar's CdTe panels clearly compromised their systems' performance.

In addition to the flat-plate PV assessments, EPRI is pursuing comparative testing of concentrating photovoltaic (CPV) technologies, also at the SolarTAC site. Preliminary results for the CPV project are expected by early 2014.

*For more information, contact Travis Coleman, tcoleman@epri.com, 650.855.2009.*


Photo courtesy: PSEG

# The Quest for Accident-Tolerant Fuels

## THE STORY IN BRIEF

Zirconium, which is widely used for fuel cladding in nuclear reactors, has nearly ideal technical properties for normal plant operation. But under accident conditions, rapid degradation of the material can exacerbate accident progression through the generation of explosive hydrogen gas. EPRI is collaborating with others in launching a strategic global initiative to develop alternatives to conventional zirconium materials that will make nuclear fuels more accident tolerant.

The Fukushima Daiichi nuclear plant took the full brunt of a 50-foot tsunami that rose from the sea along the northeastern shore of Honshu Island on the afternoon of March 11, 2011. The combined onslaught of earthquake and flood left in its wake 19,000 people dead or unaccounted for and left Fukushima units 1, 2, and 3 without emergency power, desperately struggling to cool their cores. Unit 4 was out of service at the time, and the newer units, 5 and 6, retained sufficient diesel power to allow cooling of their reactors.

The depletion of battery backup power to Units 1, 2, and 3 led to three separate loss-of-coolant accidents (LOCAs), characterized by different sequences and timelines but having similar outcomes for the reactor fuel. In the extended absence of adequate heat removal, fuel temperatures rise and zirconium-clad fuel rods begin to corrode rapidly, releasing large amounts of heat as well as explosive hydrogen gas. As temperatures approach 750°C–850°C, zirconium cladding can lose structural integrity, balloon, and eventually rupture. At Fukushima, these core melts led to uncontrolled venting of hydrogen within four reactor buildings, followed by large-scale explosions that damaged or destroyed the upper portions of three reactor buildings, releasing fission products to the environment.

The Fukushima accident prompted reviews by regulators and plant operators to assess how to reduce the chance of another nuclear plant accident. Actions have been taken, and others are still under way, to address this issue worldwide. This effort has also prompted interest in replacing or modifying the zirconium cladding material used in light water reactors (LWRs) to contain the fuel. Research has been going on for years at many organizations around the world on a variety of alternative fuel materials. While not all of this research was necessarily initiated to enhance accident tolerance, some materials could improve the ability of current and new LWRs to survive under severe accident conditions, giving operators more time to reestablish cooling of the reactor.

Zirconium-based cladding is the material of choice for most LWR fuel. The technology is well accepted by regulators, vendors, and utilities alike. "It's a heavy lift to replace a proven technology," said Andrew Sowder, senior project manager at EPRI. "Zirconium performs excellently under normal operating conditions. As materials for cladding, contemporary zirconium alloys provide a near-ideal container for the uranium fuel pellets they enclose—keeping fission products from leaking out, and sustaining the energy-producing nuclear chain reaction. However, if adequate cooling is lost and core temperatures climb above 750°C, as in the case of Fukushima Units 1–3, zirconium-clad fuels quickly degrade and exacerbate severe accident outcomes."

### New Collaborative Program

Sowder is EPRI's point person in a strategic global initiative to develop and deploy accident-tolerant fuels by 2030. A variety of potential breakthough technologies are under development around the world that might do a better job under accident conditions and conceivably even enhance performance under normal conditions. "Developing accident-tolerant fuels really does call for global collaboration, because no one entity can succeed on its own," he said.

Sowder helped launch a similar global technical initiative in 2009 focused on extended storage of used nuclear fuel; that effort now involves more than 200 participating members from 20 countries. The 2009 initiative provided a starting model for the new fuels collaborative that EPRI and several other entities are working to establish. Sowder's philosophy and approach remain the same: "I'm agnostic when it comes to specific technology solutions. My role is to bring people together—to provide forums where they can meet, share knowledge, participate in discussions, form partnerships, identify gaps, and look for opportunities to leverage resources."

### The Pillars of Accident-Tolerant Fuels

Accident-tolerant fuel rods are one element of a broader endeavor to develop accident-tolerant reactors. A holistic approach is called for to ensure that all parts of the reactor core, from control rods and blades to structural supports, are brought up to the same high level of sustainable performance under severe accident conditions.

There is no single definition of an accident-tolerant fuel, but many in the industry agree that success will rest on three pillars. The first is to extend the reactor's cooling capability. Effective accident-tolerant materials must be able to withstand higher temperatures for a longer period of time, allowing the core to maintain its structural integrity and keep the cooling channels open. "Simply put, the longer you can cool the core, the better off you are," said Sowder.

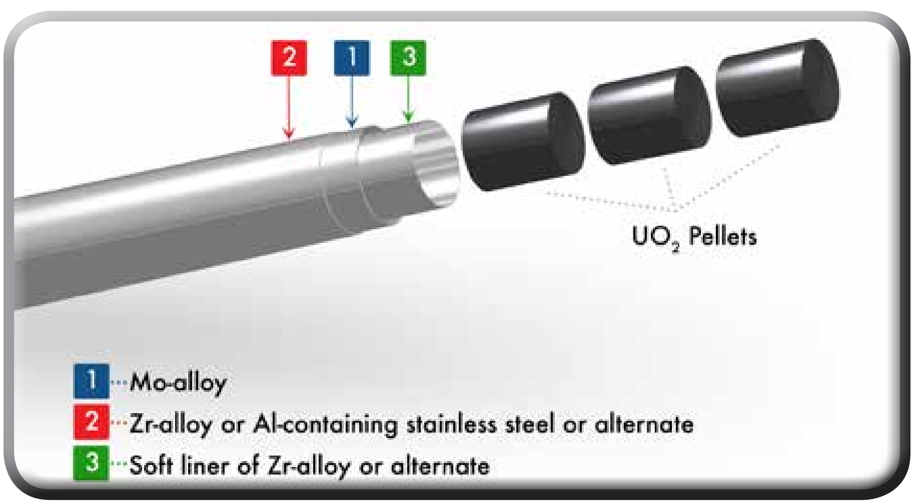
The best solution for extending the cooling capability of a reactor core may lie in refractory metals. According to Bo Cheng, an EPRI senior technical executive involved in development of accident-tolerant fuels, "niobium and molybdenum may be the only metals that have the combination of high melting temperature, acceptable neutronic properties, and sufficient mechanical properties at elevated temperatures." He pointed out that certain ceramics, notably silicon carbide, have also been extensively studied around the world for high-temperature applications.

The second pillar is to eliminate or significantly reduce hydrogen generation by using a material or a coating that minimizes oxidation in the presence of steam. Development and testing of alternatives to zirconium—or coatings that could be applied to zirconium—could reduce the likelihood of explosions like those seen at Fukushima.

The third pillar is to maintain or improve performance under normal operating conditions. According to Sowder, "a big concern arises when you talk to utilities or vendors: 'Don't give us something that's technically interesting but makes our job harder or makes the fuel uneconomic.' Vendors need something they can manufacture, and utilities need to maintain—or better yet, improve—day-to-day performance. Accident-tolerant fuels must be economic and operationally advantageous if they are to weather the long process involved in development and licensing."

## Players and Participants

Following a series of preliminary discussions and workshops in 2012 and 2013, the new initiative is beginning to take root. On the institutional side, the Nuclear Energy Agency (NEA) is helping to coalesce international collaboration. "The NEA is particularly good at bringing governments and regulators to the table," said Sowder. "Governments are often the funders of R&D, particularly in early development phases, and the regulators are the ones who have to become comfortable with these new technical developments before they can be used commercially."




*EPRI and others are exploring the use of various alternatives to zirconium that could reduce the likelihood of explosions such as those at Fukushima. One cladding concept EPRI is pursuing involves molybdenum, which has a higher melting temperaure than many other alloy materials.*

On the R&D side, EPRI is collaborating with multiple entities, including the U.S. Department of Energy (DOE) and the Idaho National Laboratory—DOE's lead nuclear energy R&D lab. Many of the other national laboratories, from Oak Ridge to Los Alamos to Savannah River, are also immersed in materials research that could lead to accident-tolerant fuels. DOE has set an ambitious target to get an initial test assembly into a commercial reactor within 10 years. "Some DOE funds got redirected by the U.S. Congress following the Fukushima accident," said Sowder. "DOE quickly refocused an existing program, allocating roughly $10 million over two years for industry-led R&D. Their objective is to get some technologies through the feasibility phase and to identify the most promising candidates for evaluation as the lead test assembly."

The list of potential participants in the new collaborative program is extensive, ranging from nuclear utilities and international research organizations to major fuel vendors, government agencies, and regulatory bodies.

The evolution of a collaborative of this breadth and magnitude typically goes through three stages. The first is a voluntary, nonbinding, flexible working environment designed to explore common interests, establish trust, and define expected value. It is invitational, introductory, and collegial. The second stage is transitional in nature, where expert working groups form and begin to share information, search for joint innovation opportunities, and start to coalesce into structured arrangements. The mature stage involves more formal arrangements, agreements, and partnerships. Said Sowder, "Following positive outcomes from recent NEA- and EPRI-led meetings, there appears to be broad agreement among key international players on a near-term path forward for cooperation and information exchange."

Near-term activities include establishing common metrics and accident scenarios for evaluating improved accident tolerance; collaborating on modeling, information exchange, and gap analyses; and identifying facilities and capabilities available worldwide for testing and qualifying promising materials and technologies.

## Portfolio Phasing of New Technologies

Given the wide array of accident-tolerant fuel options and the long lead times involved in developing and commercializing nuclear technology, a portfolio approach is being proposed. "I think most participants agree that we need a balanced investment portfolio of shorter-term, mid-term, and longer-term items that keeps us from betting on just one horse," said Sowder. "And we need to phase these technologies along different timelines toward commercialization."

One nearer-term opportunity is the application of silicon carbide (SiC) in boiling water reactor (BWR) fuel channels. The material mass of current channels constitutes 35%–40% of all the zirconium metal in a typical BWR core, meaning that replacement with SiC could reduce hydrogen generation significantly during a LOCA. "We have done some testing at Oak Ridge that shows that the prototype SiC fuel channel can withstand high temperatures and then be quenched in cold water without shattering," said Ken Yueh, EPRI senior project manager. "Because it's a structural element, not a fuel, it has a much shorter timeline for possible licensing and loading into a reactor."

Various fuel cladding options are under investigation as well. Composite SiC, for example, has attractive neutronic properties and resistance to high-temperature steam but has challenges to overcome in terms of fabrication and meeting fuel rod thermal mechanical requirements. The refractory element molybdenum has high strength at elevated temperatures but reacts with steam. According to Cheng, molybdenum coated with a thin outer layer of zirconium, which is converted in the early stages of a LOCA into the equivalent of a ceramic, has the potential for resisting higher-temperature steam—in the range of 1,200°C–1,500°C.

Looking in an altogether different direction, Oak Ridge has proposed a more revolutionary fuel design involving ceramic microencapsulated fuel for LWRs. It holds the promise of greater safety margins but requires higher levels of enrichment of uranium oxide—to about 20%, versus an existing limit of 5% for commercial reactors.

Computer simulation could help accelerate technical development across the board by putting a "virtual reactor" in the hands of researchers. EPRI is a member of DOE's Consortium for the Advanced Simulation of LWRs (CASL) at Oak Ridge, which is working in this area. "The virtual reactor, once developed, will allow researchers to test and model new concepts in accident-tolerant fuels before building prototypes and executing expensive, time-consuming experimental programs," said Heather Feldman, CASL Industry Council chairman and EPRI manager of thermal hydraulics. "Experimental programs are still needed, but CASL's virtual reactor can be used to focus and guide the tests necessary for industry, vendor, and regulatory acceptance."

Added Sowder, "The exponential growth in computing power and simulation prowess within roughly the same time frame as the lifetime of zirconium cladding technology (the 1950s onward) suggests a potentially key role for modeling and simulation in accelerating the timeline for moving breakthrough technologies from research and development stages to commercialization."

Global collaboration on accident-tolerant fuels is in the formative stages, drawing together both technical and nontechnical expertise from around the world to address the substantial challenges involved in modifying or replacing zirconium, the material workhorse of LWRs. The hurdles—technical, economic, and regulatory—are formidable. Overcoming them requires not only expertise but also a multi-decade commitment to research, development, demonstration, and licensing that only a collaborative undertaking can sustain. Further, accident-tolerant fuels are but one element, perhaps the leading edge, in a longer-term quest. The larger goal is to develop nuclear reactor systems that are more resilient in the face of severe accident conditions, yet in day-to-day operations can exceed even today's high performance.

*This article was written by Brent Barker. Background information was provided by Andrew Sowder, asowder@epri.com, 704.595.2647, and Bo Cheng, bcheng@epri.com, 650.855.2442.*

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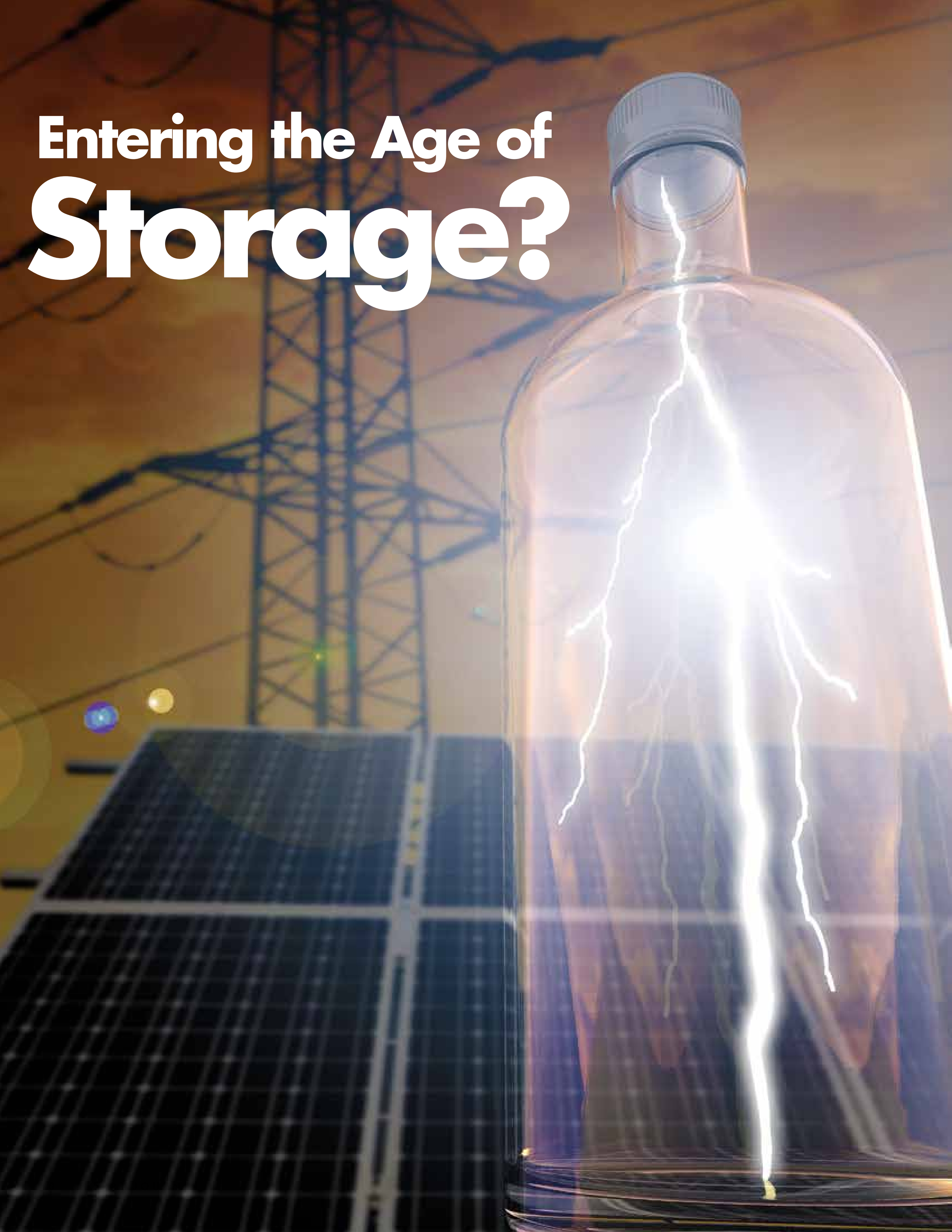
Bo Cheng is a senior technical executive in EPRI's Nuclear Sector specializing in the development of zirconium alloys and alternative fuel materials. Before joining EPRI in 1992, he held engineering and technical leadership positions at Ingersoll Rand Research Center and in General Electric Company's nuclear energy division. Cheng received a B.S. in physics from Tunghai University in Taiwan, an M.S. in nuclear physics from Florida State University, and a Ph.D. in metallurgical engineering from the University of Illinois, Urbana-Champaign.

# Entering the Age of Storage?



## THE STORY IN BRIEF

Spurred by advances in high-efficiency batteries for consumer electronics devices, energy storage is poised to make a big difference on the power grid as well. EPRI is working with a broad range of stakeholders to ensure that utility storage systems will be easy to deploy and will provide clear value for the power provider and the customer.

The energy storage landscape is changing rapidly. In October 2013, the California Public Utilities Commission established a statewide energy storage target of 1,325 MW by 2020. In March, a 36-MW battery storage project was commissioned in Texas on an Electric Reliability Council of Texas (ERCOT) grid known for its growing reliance on wind. Big developments such as these are driving the evolution of the business and technology of energy storage. Research is essential in understanding and guiding the role of storage in a more flexible and resilient power grid.

Globally, only about 2.4% of generated electricity is stored, and U.S. utilities store about 2.1%. However, EPRI research is uncovering many uses for storage in transmission and distribution and on the customer side of the meter. With proper controls, it's possible that one system can simultaneously provide a number of these services. Meanwhile, EPRI demonstrations are helping to make practical storage systems widely available, perhaps in only a few years. As with computers, cell phones, and automobiles, energy storage for on-demand usage may progress from a curiosity to a transformative technology.

With the increased use of renewables, storage systems at the transmission level offer operational flexibility for the bulk power system. Smaller systems can give utilities more control over distribution power flows, increasing reliability and allowing the option of deferring capacity expansion. Backup power sources are more essential than ever in an electrically and digitally connected world.

### Reinventing Your Cell Phone Battery

Costs for storage will continue their marked decrease of the past two decades. While this reduction can be credited in part to government- and utility-funded research, much of it results from manufacturing's investment to support consumer electronics. Today's tablets and mobile phones drive most of the worldwide annual production of lithium ion batteries. The need for power without the cord has sparked exploration of a longer-life battery that is also durable, efficient, light, and portable. "Thirty years ago, you probably didn't carry batteries with you," said Haresh Kamath, EPRI program manager for energy storage and distributed generation. "Today, most people have two or three, when you think of their cell phones, hands-free devices, tablets…. That's all been made possible because of the innovation, and investment, in battery research." That same research is being applied to creating lower-cost, longer-range electric vehicles, too.

Such investments can be of use to utilities, and recent years have seen the quiet introduction of grid-connected lithium ion batteries. Five years ago, these compact, highly efficient batteries were not being used for grid storage at all; today, 130 MW are installed on grids in various parts of the world. "That's not much compared with the size of the entire grid, but it's a start," Kamath said.

EPRI recently investigated using lithium ion batteries to increase the power transfer capability of a congested transmission corridor. When placed at the sending end of the corridor, the batteries could absorb excess power generated by renewables, reducing "spillage" of valuable energy. At the receiving end, batteries could be used to store power off-peak and then release it during peak demand, reducing the strain on the transmission system.

This arrangement can be especially valuable when load is far from generation, which is increasingly the case. Urban loads are often served by relatively few transmission lines, and upgrading lines can be a long, difficult, and expensive process. In such cases, EPRI found that an investment in lithium ion battery storage might be recouped in as little as two to three years. If off-peak charging comes from renewable sources, the decrease in emissions might offer additional economic benefit. To further illustrate the concept, EPRI conducted a case study on a generic power system model, including an economic analysis of benefits and costs.

Although the cost of storage may be falling, other technical challenges are just beginning to be addressed. For instance, there are few standard approaches to building energy storage and integrating it with the grid, so each storage system is different. "When the automobile was invented, nothing was standard," Kamath explained. "Is the driver supposed to steer with a wheel or a rudder? Do drivers use foot pedals, or should those be hand levers? It took a few years for automakers to agree. Utilities and storage suppliers will need to determine some common approaches for controls and interfaces so that everyone is not reinventing the wheel for every storage system."

Such common features won't necessarily require regulation or even agreement through a standards body. In 2011, EPRI worked with 16 utilities and more than 40 suppliers to develop a common specification for lithium ion storage systems for the grid, shaking the utility industry notion that storage solutions must be customized and redesigned for each installation. More than half the suppliers said they would be willing to provide complete turnkey systems according to such a specification, most of them with partner arrangements for the power conditioning system. Delivery lead times were estimated in the four- to eight-month range.

"The lithium ion specification we released in June 2012 showed that you could use standardized approaches—the same controls, interfaces, specifications, and expectations," Kamath said. "There are always going to be differences for each installation, because each utility's needs are different. This technology isn't 'one size fits all,' but it is possible to create a customizable, yet standardized, product." In December 2012, EPRI released a general specification applying to all battery storage systems, beyond lithium ion technologies alone.

In the project's next phase, EPRI is working with utilities to purchase battery storage systems using this standard specification. These systems will be evaluated in the field through common testing protocols to verify performance and to document installation. EPRI is also working with utilities that have already bought storage systems, in order to understand their experiences in procurement and deployment. This information will be invaluable in harmonizing the ways that the batteries are used.

Building on this work, EPRI is leading broader efforts to bring together stakeholders to explore demonstration and deployment of storage systems. The EPRI-managed Energy Storage Integration Council (ESIC) comprises technical leaders from utilities, storage vendors, and integrators, who are working on common approaches to issues such as applications, performance metrics, system specifications, and field deployment. The goal of such efforts is to make plug-and-play energy storage systems available, simplifying the use of storage for utilities and others.

EPRI is also participating in grid storage research funded by the U.S. Department of Energy's Office of Electricity and programs such as ARPA-E (Advanced Research Projects Agency–Energy, conducted through universities and national labs), which are addressing fundamental technological issues such as durability and inefficiency.

## The Value of Energy Storage

Utilities themselves must determine whether they can afford to embrace such innovations. "From an economic standpoint, utilities have operated without storage for years, so in some ways it is difficult for them to see how they might use it," Kamath said. He cited personal computers in the 1980s. "People really didn't see a need for them. They were maybe something to play games on or to use instead of a typewriter. But some people saw an opportunity to use computers to get ahead of their competition, and they figured out ways to do that. Eventually, others had to adopt computers just to keep up. Now, 30 years later, it's difficult to imagine our world without computers."

Energy storage, too, could be an industry game changer. However, a principal challenge is grasping how it can bring value to the owner and to society—and how that will affect existing business models. "Kodak was actually a technology leader in digital photography, but they couldn't figure out how to monetize it in the context of their traditional business of selling film," said Kamath. "It wasn't a gap in understanding technology, it was a gap in understanding value. Similarly, the value of storage is a little hard to understand, especially for a grid that was designed to work without any storage."

To address this challenge, EPRI developed the Energy Storage Valuation Tool (ESVT) to help utilities, regulators, and vendors calculate the value of energy storage in light of their individual circumstances. Utilities have already used the tool to demonstrate where energy storage might improve operations, especially in avoiding potentially costly distribution upgrades. Calculations must show how the technology can best bring value through multiple applications and how that contribution will evolve over time. "We're learning from the storage systems already in place, and lessons learned will be applied to the next generation of systems," Kamath said. "They will be better. Those companies that are working on this now will have an advantage, and that's why many of them are working with EPRI."

## Another Twist: Changing Legal Classifications

Regulatory definitions have often complicated efforts to install storage. Historically, utility assets are considered to be generation, transmission, distribution, and load, and financial accounting is different for each asset type. Storage is difficult to classify because it acts as a load when it charges from the grid but as a generator when releasing power back onto the grid, and it can be viewed as transmission or distribution because its primary function is the transport of electricity (through time rather than space).

The U.S. Federal Energy Regulatory Commission (FERC) has addressed these issues in recent years, making several changes favorable to storage. In 2012, for instance, FERC Order 755 enabled developers bidding into certain markets with energy storage to obtain higher prices to account for their faster performance. This past July, passage of FERC Order 784 allowed utilities to make accounting adjustments in order to make the operation of storage less costly.

Such storage-favorable regulations are surmounting the third of the big three obstacles to mainstream storage. "The economic, technological, and regulatory doors are all opening at the same time," Kamath said. "Anyone wanting to implement grid-connected storage used to have to knock those down." In fact, he said, groundwork has been laid for dramatic changes to the grid. Both utilities and consumers likely will see more grid changes in the next decade than they saw in the last century.

"All the groundwork for this transformation is falling into place. It might seem that we're suddenly reaching a tipping point, but in actuality it took years for these things to happen. The transformation to a more flexible, resilient grid is occurring slowly—but one day soon, with some luck and hard work, we'll be there."

*This article was written by Debra Murphy. Background information was provided by Haresh Kamath, hkamath@epri.com, 650.855.2268.*

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## Focus on California: Evaluating the Costs and Values of Energy Storage

Determining value is fundamentally important in considering any investment, and energy storage is no exception. EPRI has developed a methodology for quantifying the value of grid energy storage opportunities, supported in part by the EPRI Energy Storage Valuation Tool (ESVT) software. The tool estimates the total benefit of an energy storage system's multiple services, making sure that values don't overlap and aren't counted twice, and calculating how the storage can be optimally dispatched to provide the best value in the location and market in which it operates. ESVT enables preliminary economic evaluation prior to more resource-intensive analytical efforts involving distribution planning models and production cost models. EPRI recently used ESVT to analyze the cost-effectiveness of energy storage in approximately 30 different cases for the California Public Utilities Commission (CPUC).

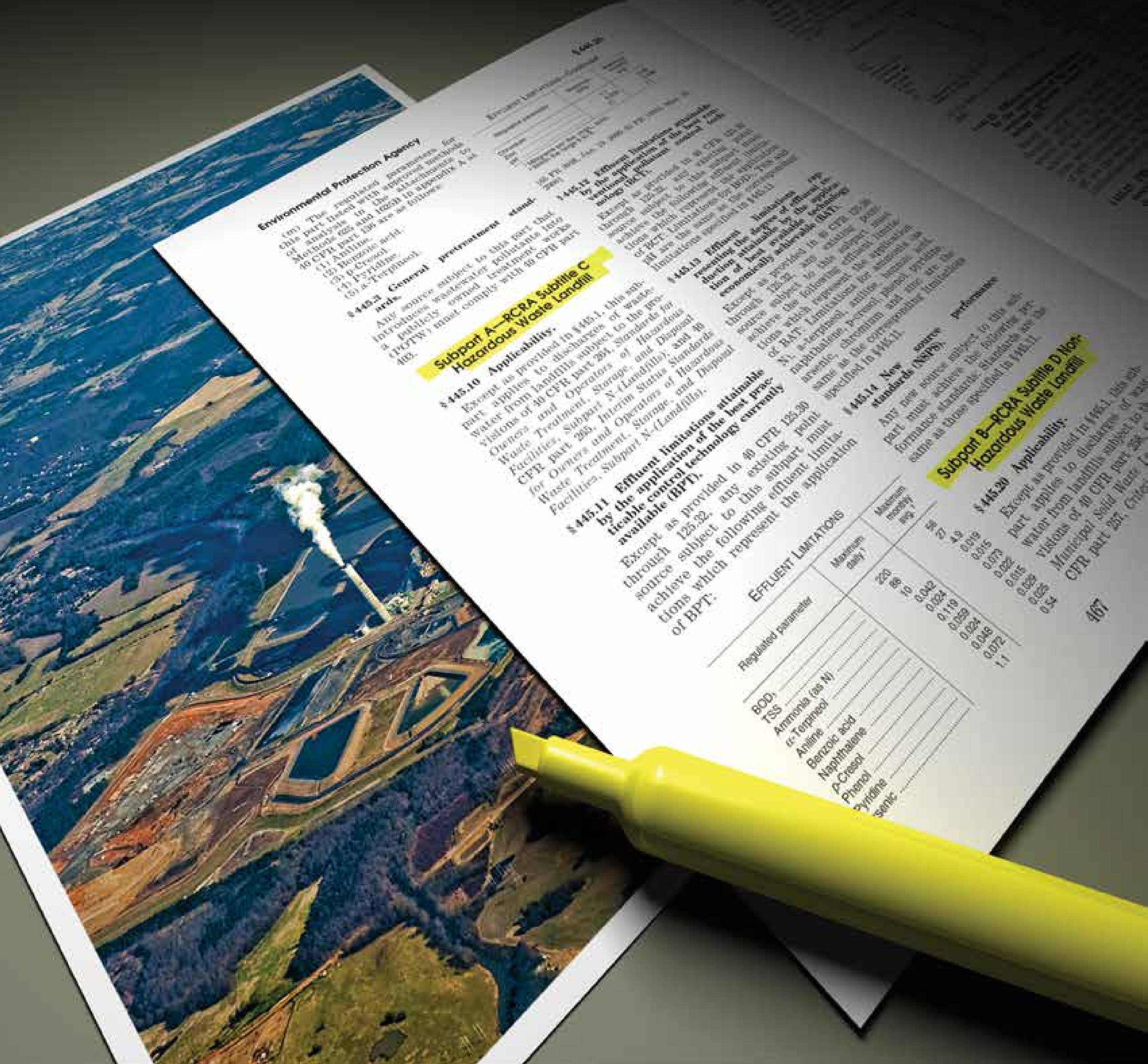
In 2010, the California Assembly passed AB 2514, requiring the CPUC and the state's investor-owned utilities to determine the right amount of storage for California. In subsequent proceedings, CPUC staff invited EPRI to use ESVT to assess the value of storage under scenarios determined by the CPUC stakeholder group.

The scenarios covered transmission-connected bulk energy storage, short-duration energy storage to provide ancillary services, and distribution-connected energy storage located at a utility substation. Under the assumptions provided by the CPUC stakeholder group (which included representatives from CPUC, electric utilities, and storage companies), most cases returned benefit-to-cost ratios of greater than one, and the break-even capital cost of energy storage ranged from $1,000 to $4,000 per kilowatt installed.

In EPRI's analysis, the cost-effectiveness of 2-hour storage systems exceeded that of 4-hour systems. Durability was key in cost-effectiveness: a battery usable for 10 years was substantially more cost-effective than a 5-year battery. Regulation service provided a significant portion of the value in most cases, while high prices for energy and ancillary services contributed to cost-effectiveness as well. Projects beginning in 2020 were more cost-effective than those beginning in 2015, primarily because of expected technology cost reductions and higher value for capacity, energy, and ancillary services.

# From Flue to Final Resting Place

## Traditional Ash Ponds Subject of Regulatory and Scientific Scrutiny



## THE STORY IN BRIEF

In light of expected EPA regulations on the disposal of fly ash and other residual matter, EPRI is performing laboratory tests and developing guidance to help utilities close disposal ponds safely and economically.

In recent years, regulatory decisions, public pressure, and technology have been shaping how coal combustion residuals (CCRs) will be handled in ponds. Armed with industry data and more than 400,000 stakeholder comments, the U.S. Environmental Protection Agency (EPA) appears poised to make a final ruling on disposal regulations that will affect CCR ponds.

The impact will be widespread. According to the American Coal Ash Association, U.S. coal plants produced more than 130 million tons of fly ash, bottom ash, and flue-gas desulfurization by-products in 2011. Although more than 43% of that material was recycled into products, the rest is stored in ponds or landfills, and the EPA's decision will affect both new CCR waste streams and materials already in storage.

### A Longstanding Storage Approach Meets New Guidelines

According to the EPA, there are more than 1,000 CCR ponds in the United States, ranging from a few acres to nearly 1,000 acres. They have been regulated by state and local governments, as the Bevill Amendment to the Resource Conservation and Recovery Act (RCRA) excluded them from federal hazardous waste regulation pending a study and regulatory determination by the EPA. In 1993 and again in 2000, the EPA made regulatory determinations that CCRs should not be subject to hazardous waste regulation.

But in 2010 the EPA proposed two new options: to regulate CCRs under RCRA's Subtitle C, as a special hazardous waste under federal regulation, or to regulate them under Subtitle D, as solid waste under state regulation and citizen oversight. Under either scenario, water discharges would be covered by the facility's National Pollutant Discharge Elimination System (NPDES) permit, and either is likely to result in closing a large number of ash ponds, at a substantial cost. EPRI estimates the industry costs to close active ash ponds under Subtitle C would exceed $5 billion.

EPRI provided the EPA with extensive comments addressing technical aspects of its proposed rule and geotechnical properties of CCRs that affect pond closure designs and schedules. As the EPA comes close to finalizing the rule, however, another proposed standard could affect the outcome.

In April 2013, the EPA proposed effluent limitations guidelines and standards to set new technology-based federal limits for wastewater discharge from steam electric power plants—the first new federal effluent guidelines and standards for that sector since 1982.

The EPA is evaluating how to integrate the two rules by coordinating their design, timing, and implementation. But the effluent limitations guidelines overlap with aspects of RCRA, potentially affecting which RCRA subtitle is chosen. Also, since the guidelines require federal oversight, the EPA may decide that RCRA Subtitle D, which provides state and citizen oversight, is sufficient. Regardless, the added costs and operational issues will likely prompt the closing of many ponds.

### EPRI's Pond Closure Research Offers Guidance

The decision to close a pond begins a process that can take more than 10 years and includes a site investigation and plan, permits, placement of fill material, and construction of an engineered cap. If plans include building dry storage, solar facilities, or other structures on top of the closed pond, it will be necessary to ensure its structural integrity under load. Considering the hefty investment and years of work necessary, it's crucial to act from a sound base of geotechnical knowledge.

Until recently, CCR pond closure guidelines have been limited. In light of proposed new RCRA rules, concerns have arisen that if ash ponds were to be required to close quickly, unsafe conditions could result, both for the workers closing them and for long-term residuals storage.

Of particular concern is the liquefaction—both static and dynamic—of materials stored in ponds. Static liquefaction

occurs when a saturated, loose matrix loses its strength, causing the material to flow; for ash ponds, this could result in overtopping or breaching containment walls. American Electric Power (AEP) began researching liquefaction when it evaluated constructing a landfill on a closed pond and raising a dam over impounded fly ash using upstream construction techniques.

"AEP had conducted tests on dynamic liquefaction in a research collaboration with Ohio State University and had performed some initial testing of the behavior of ponded ash under load," said Pedro Amaya, director of civil engineering and geotechnical services at AEP, "and we were confident about those results' applicability to the specific sites studied. But when the issue of static liquefaction was considered as the plausible cause of another company's pond failure, we wanted to know if our testing had missed something or if different types of ash just acted differently under load."

As a result, Amaya began working with EPRI senior project manager Ken Ladwig to learn more. EPRI's investigation found limited available data characterizing types of fly ash and their tendencies for static liquefaction. Collaborating with AEP, EPRI examined coal fly ash samples from 22 power plants, characterizing the properties of ponded fly ash and developing geotechnical engineering testing techniques and guidelines for predicting static liquefaction. The work consisted of tests for gradation, specific gravity of solids, and plasticity, as well as for consolidation, permeability, and strength. Samples were prepared to simulate field conditions.

Laboratory-scale model tests simulated deposition of settled ash in the pond, evaluated the maximum and minimum realizable density of fly ash, quantified its time-dependent characteristics, and evaluated the ability of cone penetration tests to assess *in situ* conditions in settled fly ash. Researchers also assessed the mechanism of chemical or physical changes in ponded fly ash, using consolidation-test results and shear-wave velocity measurements.

Test results indicated that fly ash is not prone to static liquefaction. However, results showed that the layering and chemical changes caused by wet disposal and saturated conditions can compromise stability, so those factors must be accounted for when designing engineering plans and a timetable for closing a pond. "Stability can be affected by how quickly you load the pond," said Ladwig. "Pore pressures build, then dissipate—if the pond is loaded too quickly, it can become destabilized."

The study showed that ponded fly ash has different physical and chemical characteristics than typical soils and that the geotechnical correlations used to predict static liquefaction in soils do not always apply to fly ash. The report suggests an alternative strategy to assess for static liquefaction in fly ash.

EPRI submitted the results from these tests to the September 2013 EPA CCR Rulemaking Docket. "Static liquefaction in soils has been studied for years, but there has been little work to evaluate the potential for static liquefaction in fly ash," said Ladwig. "These new data will help the EPA assess the issue more accurately."

The data also offer useful information to companies closing CCR ponds. Facilities can use the final report, *Geotechnical Properties of Fly Ash and Potential for Static Liquefaction: Volume 1—Summary and Conclusions* (1023743), to evaluate their ash ponds and help develop closure designs.

## Loading Research Expands Insights

The static liquefaction work expanded to a two-year project, with additional industry support to study the stability of closed ponds under load—an important concern if companies expect to erect new structures on these sites.

Key aspects of the loading research are as follows:

- Plate load tests. Researchers observe and measure subsurface failure mechanisms as load is incrementally applied to a plate on the surface of the CCR pond. EPRI designed the test methods; the subsurface instrumentation, such as piezometers and movement-measuring devices; the plate; and the load frame used. Final detailing of the load test was provided by a construction contractor familiar with load testing. Lab testing and fieldwork this year at LG&E–KU's Green River Generating Station will augment current understanding of the strength, drainage characteristics, and compressibility of impounded CCRs. The final report will be ready in early 2014.
- Centrifuge tests. EPRI used the most powerful U.S. Army Corps of Engineers centrifuge to evaluate different ways to apply load and to stress fly ash to failure. A scale model, using AEP fly ash, laser gauges, linear variable differential transformers, and pore pressure transducers, was placed in a centrifuge and spun. The research team did not observe a slope failure with that ash. "That's not saying that failure couldn't happen with another ash," said Alan

Rauch of Stantec, which conducted the testing. "Testing with different ashes under different conditions will help develop the geotechnical data needed to make broader correlations."

"We now have new information on the behavior of ponded fly ash under load," said AEP's Amaya. "The research collaboration with EPRI, Geosyntec, and Stantec has offered new insights into the response of ponded fly ash to undrained loading; into the propensity of some ponded ashes to exhibit early cementation; into the intrinsic layering associated with slurrying fly ash into ponds, and the associated anisotropic permeability characteristics; and more. These insights are all helpful. For example, high pH may create early cementation of fly ash, and that cemented ash can break and collapse under a load. Knowing this, we can set the loading to prevent collapse. We can use the new data to tailor our activities to address specific issues in specific ponds."

## Moving Forward

EPRI's research is providing operators with new information on safe loading rates, long-term pond stability, construction materials, monitoring strategies, and post-closure land use. Most ongoing work will be completed in 2013, and a second phase of work is planned for 2014–2015.

Given the intersection of the RCRA regulations and the effluent limitations guidelines, groundwater assessment and remediation is likely to become a more prominent issue. Whatever the concern, as the EPA makes its final decisions and the CCR pond regulatory landscape becomes more defined, EPRI will continue research to address CCR storage and disposal issues.

*This article was written by Mark Wilson. Background information was provided by Ken Ladwig, keladwig@epri.com, 262.361.8075.*

**Kenneth Ladwig** is a senior project manager in the land and groundwater area of EPRI's Environment Sector, responsible for all research in the Coal Combustion Products Environmental Effects program. Before joining EPRI in 1999, he specialized in groundwater and contaminant research at Science & Technology Management Inc., Wisconsin Electric Power Company, and the United States Bureau of Mines. Ladwig holds B.S. and M.S. degrees in geological sciences from the University of Wisconsin–Milwaukee.

## Pond Closure Guidance Documents and Geotechnical Database

EPRI has produced two reports and a geotechnical database to guide dewatering and post-closure processes:

### Dewatering and Capping Guide

Dewatering ash ponds can be a complicated process. It focuses on maintaining the stability of the CCRs and ensuring that NPDES requirements are met. EPRI's report *Coal Combustion Residuals Pond Closure: Dewatering and Capping Guidance Document* (3002001117) walks utility teams through site evaluation, dewatering the pond and the CCRs, stabilizing the CCRs, capping the pond, conducting groundwater remediation, and long-term care and monitoring.

### Post-Closure Development Guide

Building landfills or other structures over closed ash ponds can be a cost-effective way to reuse the sites. Engineers must be confident that the closed pond can withstand construction and the weight and stress of any overlying structure. EPRI's report *Coal Combustion Residuals Pond Closure: Construction over Closed or Closing CCR Ponds Guidance Document* (3002001143) reviews issues associated with building structures on top of closed ash ponds, including seismic and static liquefaction, CCR settling, foundation improvement, groundwater upwelling, wastewater infrastructure, and groundwater monitoring. For closed ash ponds, it covers feasibility evaluation, permitting and regulatory issues, geotechnical and hydrogeologic evaluations, wastewater infrastructure needs, landfill siting and design, construction and operational considerations, and long-term maintenance. It also covers considerations for structures likely to be built on such sites, including athletic fields and parks, solar facilities, wastewater treatment systems, and industrial buildings, storage facilities, and staging areas.

### Geotechnical Database

Engineering parameters used to characterize CCRs may vary considerably among facilities or even within one impoundment, so closure considerations need to address such variability. EPRI is incorporating data from field tests; laboratory tests of strength, compressibility, and hydraulic conductivity; and instrumented test fills into a geotechnical database to develop correlations specific to CCR materials. The correlations and the database used to develop the correlations will be ready by early 2014.

# R&D Quick Hits

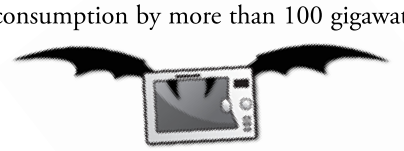
## What to Do When the Earth Moves

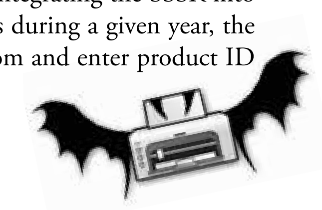
EPRI led a team with expertise in plant operations, seismic structural engineering, and the response of nuclear plants and other industrial facilities to large earthquakes in preparing updated, comprehensive guidelines for developing nuclear plant procedures for earthquake response. The guidelines define recommended immediate actions, post-shutdown actions, and longer-term actions. The guidelines provide utilities with procedures for evaluating the need for post-earthquake plant shutdown, evaluating the earthquake's effects, and developing criteria for restarting the plant. For more information, go to www.epri.com and enter product ID 3002000720 in Search.

## Helping to Drive a Stake Through the Heart of "Vampire Load?"

In 2010, EPRI supported conceptual development of the SSSR, or self-sustained synchronous rectifier, which when paralleled with a conventional diode has now been demonstrated to offer a potentially low-cost approach for minimizing power consumption by all the familiar household gadgets that rely on direct current power supply converters. Power consumption by power sources attached to idle equipment has been dubbed vampire load, and consumers, utilities, and researchers have been keen to find ways to reduce this consumption of unused power.

Validation tests demonstrated that the SSSR could reduce losses by 25%. Researchers are now looking toward the development of a single-chip, solid-state solution and are discussing this with government agencies and power supply manufacturers interested in integrating the SSSR into device designs for prototypes. If proven as tested and used in all new computer printers shipped in the United States during a given year, the SSSR could reduce annual energy consumption by more than 100 gigawatt-hours. To learn more, go to www.epri.com and enter product ID 3002002283 in Search.





## Two's Cogen, Three's a "Polygen" Factory

Could we see power plants and factories under one roof? Cogeneration is familiar as a source of heat for one use and power for another. For example, power plant waste heat can be used for district space heating, or process heat at a manufacturing plant can be paired with turbine generators to produce power for local or grid use. Looking beyond such dual-purpose cogen plants, EPRI's innovation scouts are reporting on polygeneration as a way to diversify and bring in new revenue. Simply stated, polygen would combine power generation with the production or manufacture of other products in a kind of hybrid power plant and factory.

For plant operators, it would be a new world of shared facilities, services, staff, operating strategies, and outage planning. Integrating multiple processes to function smoothly under one roof would entail a more complex facility with higher capital and operation and maintenance costs than a traditional power plant. But it could also provide savings from shared components, heat integration, and flexible operations. To read *Polygeneration: An Opportunity for Diversification and New Revenue,* go to www.epri.com and enter product ID 3002002215 in Search.

## Time to Get Pumped About Next-Gen Heat Pumps?

The next-generation electric heat pump will combine innovations in vapor compression, airflow, and frost management technologies with state-of-the-art motors, fans, pumps, and controls in a grid-interactive, consumer-friendly system. The goal is to deliver reliable operation down to 0°F and to create a flexible load management resource across the heating and cooling seasons. Such heat pumps could expand the market to a broad geographic area while offering unprecedented levels of efficiency and demand-response capability.

Through EPRI's Technology Innovation program, a novel approach for inhibiting frost formation on outdoor heat exchanger coils has been developed and demonstrated, and additional component-level innovations have been identified. EPRI is collaborating with manufacturers and utility industry partners in developing a next-generation residential heat pump; prototype testing and field demonstration are scheduled for 2014–15. To learn more, go to www.epri.com and enter product ID 3002002039 in Search.

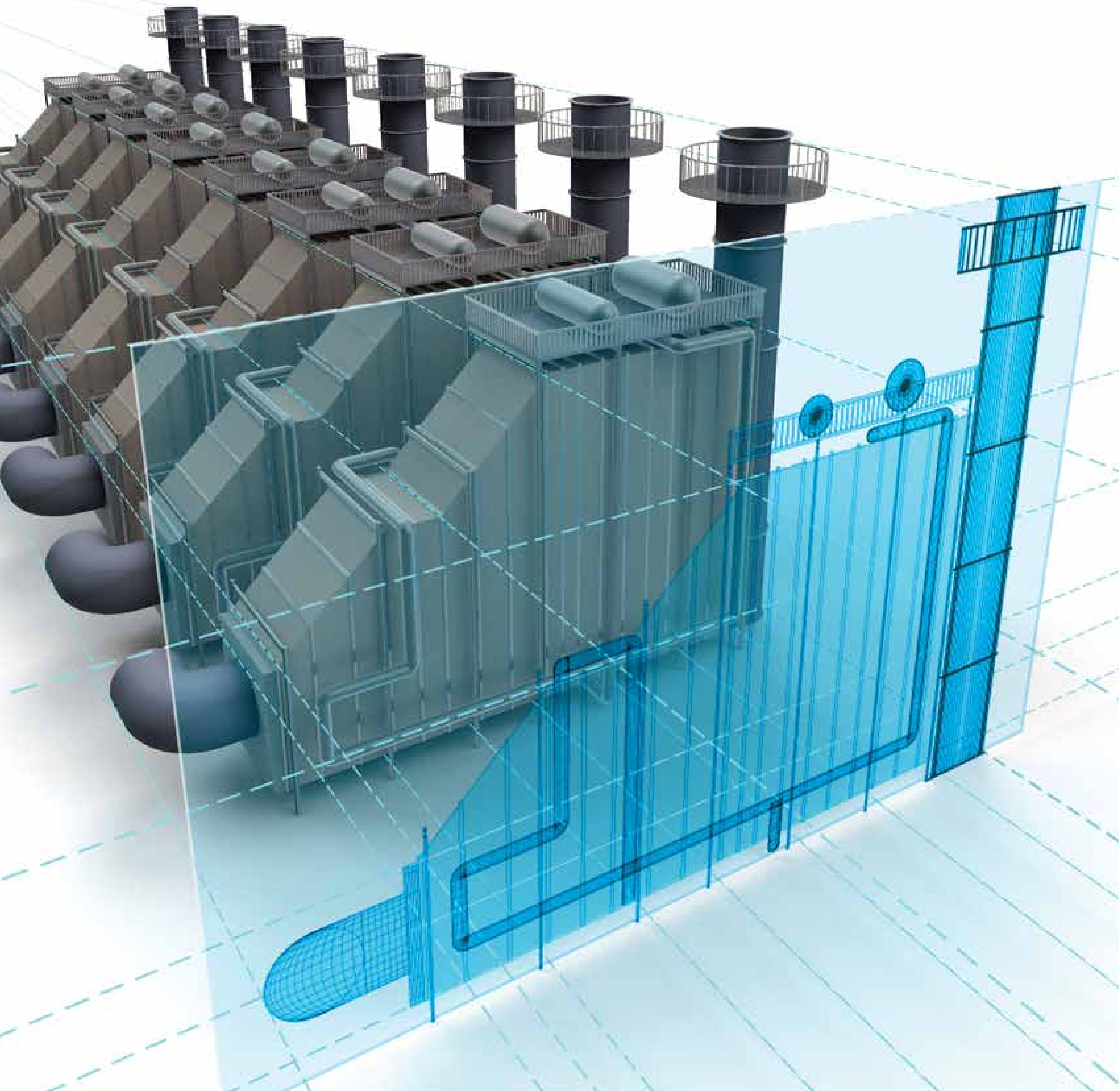
## Bees Dig Power Lines (When the Vegetation's Right)

EPRI research suggests that transmission line easements can provide quality habitat for native pollinators (think *bees*), particularly when the rights of way are managed to promote the growth of native shrubs and flowering perennials. This issue is increasing in importance because concerns have grown recently regarding the health of honeybee colonies. The overall numbers of this European immigrant have declined substantially, with potential damage to crops in the billions of dollars.

The study results indicated that in place of periodic mowing of rights of way, both integrated vegetation management (IVM) and planting of native shrubs significantly increased the number of native bee species. Also, new and rare species of native bees were collected in the easements with the longest-running IVM protocols, resulting in new county and state records for species found. No negative effects of electromagnetic fields were indicated in any of the study areas. For more than just the A, Bee, C's of the research, go to www.epri.com and enter product ID 3002001125 in Search.

# HRSG Design:

## Creating an Industry Standard



## THE STORY IN BRIEF

The flexible operation of combined-cycle power plants that were designed for continuous baseload operation creates problems for the heat recovery steam generator. Changing temperatures and the resultant stresses of flexible operation lead to a long list of reliability problems. To help avoid such problems and support the durability and reliability of the next generation of plants, EPRI brought together utilities, steam generator manufacturers, and other experts to develop industry-wide design specifications for HRSGs.

Brian Chambers, a senior engineer at Duke Energy, knew that his company's combined-cycle power plants weren't well equipped to operate in today's demanding markets. His particular concern was with thermal transients in the heat recovery steam generator (HRSG)—a critical component that captures waste heat from the combustion turbine exhaust and uses it to produce steam that drives a steam turbine. Traditionally, a plant's HRSG is designed for baseload operation, in which the unit runs constantly at full load for extended periods. Today's power markets require plants to be flexible; ramping up and down in load, and on or off daily or weekly. This results in greater physical demands and stresses on the components.

This heavy cycling is the new norm in the industry. That's why Chambers, John Smith of PEPCO, James Small of Georgia Power, Richard Hill of Consolidated Edison, and other utility representatives came to EPRI. Their request was to help the industry build a set of specifications that incorporate EPRI research with HRSG operators' lessons learned and best practices to enable the next generation of HRSGs to operate reliably for the long term under flexible conditions. With a design standard, all the manufacturers and vendors could build to the same criteria, with nothing overlooked or left out.

"Our members came to EPRI with a concern about long-term reliability," said EPRI project manager Bill Carson."They said, help us build a set of specifications to ensure all HRSGs are built to the same criteria. Owners want an HRSG that can tolerate flexible operation and provide long-term reliability. Our research has shown that issues can be overlooked or left out during a competitive negotiation process."

EPRI brought together HRSG manufacturers, industry consultants, and plant operators to brainstorm, analyze the problems, and pool operating experiences. The resulting report proposed design and construction specifications for HRSGs to address demands of today's operating environment. The new specifications are currently under review, and publication is expected by the end of 2013.

### Design Problems in Flexible Operations

When operating in a flexible mode, HRSGs may suffer latent, long-term damage. For example, when combined-cycle plants are operated from lower to higher loads, the resulting heat buildup often creates overheated steam that has to be cooled down by an attemperator, which atomizes cooler water and sprays it into the steam-filled pipes. If those systems aren't properly sized, drained, or maintained, the cold water droplets become too big to be condensed or atomized and are sprayed against the pipe walls, resulting in rapid cooling that may cause warping and thermal fatigue on internal surfaces. The EPRI report identifies other potential failure mechanisms in HRSGs that are operated in a flexible manner, including corrosion, fatigue cracking, and flow-accelerated corrosion (FAC).

Also, HRSG manufacturers now must design HRSGs that meet the demands of higher pressures and temperatures from state-of-the-art gas turbines. Along with today's more frequent load changes and starts per period of operation, this makes the process more difficult and the specifications more important.

"You've got to come up with a practical approach that isn't a burden on the many parties involved in trying to design, construct, and operate a combined-cycle plant," said Steve Paterson, owner-presi-

*HRSG and stack, Soto 5 CCPP, Singapore (Copyright: Alstom)*

*HRSG at the 400-MW Tallawarra KA26 combined-cycle power plant, Australia (Copyright: Alstom)*

dent of PIKA Solutions, who consulted on the project largely on behalf of plant owners and has been lead author on many EPRI documents dealing with HRSGs. "We need a baseline standard for the utilities and the suppliers. If you've got that baseline out there, you know you've got the minimal requirements."

EPRI's role in the project is one that perhaps no other organization could fill. "EPRI is able to bring together not only utilities that are in competition with each other but also competing equipment manufacturers, and to produce a specification that everybody is confident in and shares ownership in," Carson said. "That's no small feat, since there are more than 1,600 HRSG-equipped combined-cycle plants in the United States—each with unique design-related issues."

Two units Carson visited recently are a case in point. The "sister units" used the same design but were built to different specifications by different contractors. Although identical on paper, they differ in their performance and availability

Such inconsistencies can be addressed with the new specifications, once there's agreement. "What will be offered by the HRSG supplier will be much more consistent from supplier to supplier once you get this document out," said Joe Schroeder, a vice president with Noter Ericksson, who acted as an independent consultant to the EPRI-led meetings. "Right now, everybody assumes something different in terms of life assessments and cycles and definitions."

## Designing for Reliability and Flexibility

The new specifications are designed to protect the HRSG's major components, such as main steam headers or drums, and help ensure their long-term reliability while keeping maintenance expenses reasonably low. These are expensive parts that can be difficult to replace quickly, so durability and reliability are essential. For instance, the new design needs to size the drains properly and in proportion to the attemperators. This helps keep thermal transients—and the condensation that builds up on startups and shutdowns—from overstressing these components. By standardizing components to some extent, the specifications can expedite bidding, building, and installing HRSGs. "When you send a job like this out for bids, suppliers are going to cut costs where they can," said Chambers, who served as a utility reviewer of the specifications. "What we need are some standards so that when we get a bid back from six different suppliers, we know the bids are all for the same basic unit. There'll be a level playing field. It will be more of a cookie-cutter approach, so after the specification is put together, the design should be fairly straightforward and the fabrication and installation should follow suit."

It was important that the new specifications avoid previous design limitations. And while they will define the base product and ensure high performance, the specifications do provide room for plant owners to adjust them to their particular conditions. "There has to be some variability, based on the different sizes of the plants and the fact that they use different fuels and operate at different temperatures," Carson said. "Some flexibility must be built into it.

"Take FAC for example. If you don't want to go with an FAC-resilient material in the back end, you can take that out. Our design specifications recommend this material because FAC is a major contributor to outages on these units, and just by upgrading the material to 0.5% chrome, you can eliminate the problem completely. Still, there's an incremental cost incurred with that chrome, and while it's relatively small in the overall project, it's still a capital consideration. If plant owners want to put that money into something else, it's their decision."

## Refining the Group Effort

Several issues remain to be resolved to get full agreement on the final specification. Paterson said the biggest is whether an HRSG buyer should insist that special instrumentation be installed on critical components to verify the designer's assumptions for those components. "For example, when you start up a plant, is there some cold condensate flowing around and quenching some of the components—a factor the designer didn't anticipate in his design calculations? That's a very big shift in thinking in the industry."

At present, when a plant is commissioned, tests measure performance at a certain load, efficiency under various conditions, and emissions. "But we're pushing for more of a reliability-based set of tests where you can actually show the desired temperature differences between HRSG tubes and demonstrate advantageous ramp rates during startups and shutdowns," Paterson explained. "These tests could confirm that everybody's assumptions in the design phase can actually be achieved," Paterson explained. "You can actually show the desired temperature differences between HRSG tubes and demonstrate advantageous ramp rates during startups and shutdowns."

The specifications will call for HRSG suppliers to use their skills and experience to execute a design that will respond well to load changes or more frequent starting and stopping. Then the original equipment manufacturers (OEMs) will be asked to implement the design with features that will be more damage-tolerant or will avoid damage altogether. "What we're saying to the OEMs is: Demonstrate to us that the design features you've put in—and a lot of it has to do with instrumentation, controls, and control logic—have actually worked to avoid some of the damaging transients that occur with most of the designs that are out there today," said Paterson. "Show us that you've overcome these thermal transients that we've found to be very damaging."

Schroeder has been pushing EPRI members to clarify what they need to define in a consensus specification for the product they need in the future. "The users need to better describe the startup and shutdown cycle," he said. "A lot of times, when a buyer sends a specification to an HRSG supplier, he'll say, We have *x* number of hot starts and *y* number of cold starts. But there's nothing that describes how the units are really started up and shut down, and I think that should be worked out more. What you need to do is build in enough good construction detail to make sure that when you go through that life assessment, it will be okay.

"I really have to commend EPRI for making this a public document. That's a little bit different than what's been done before," Schroeder added.

Chambers has high hopes that the new HRSG specifications can do for the industry what an earlier project—EPRI's Grade 91 steels guidelines—did in eliminating confusion and irregularities in manufacturing and installing piping. "EPRI put together Grade 91 installation standards that are accepted by the industry, the fabricators, and the utilities all over the world," he said. "Basically, when we buy that type of piping now, we're referencing the EPRI standard, and that's what everybody knows they're working with. And that's where I see this HRSG document going."

*HRSG at the Keppel Cogen Power Plant, Singapore (Copyright: Alstom)*

*This article was written by Ray Pelosi. Background information was provided by Bill Carson, bcarson@epri.com, 704.595.2204.*

**Bill Carson** is manager of EPRI's Combined-Cycle HRSG and Balance of Plant program, which focuses on the development of nondestructive examination methods, tube failure reduction strategies, and remaining-life tools for HRSG pressure parts and piping. Before joining EPRI in 2008, Carson was a boiler program manager for Dynegy Inc. He holds a B.S. degree in industrial technology from Southern Illinois University.

# Tomorrow's Technology— A Focus on Business

**Bernard Salha** is senior executive vice president, EDF, and president, EDF Research and Development. In this interview with *EPRI Journal* he reviews the scale and scope of EDF's research and development and looks at the importance of making it integral to the business.

***EJ: EDF is known globally as a leader in R&D. Give us an idea of the scope of R&D that you lead.***

**Salha:** We have around 2,000 people working on all aspects of electricity, from nuclear generation to renewables, demand management, heat pumps, electric vehicles, and batteries—all the topics. We have also developed cooperation and R&D centers all over the world.

We have partnerships with industrial companies—AREVA, Siemens, GE, IBM, and so on—but also with academic institutions all over the world. With French universities, of course, but also with MIT, University College London, Imperial College London, the University of Manchester, Tsinghua University in Beijing, Karlsruhe Institute of Technology in Germany, and the University of Bologna in Milano.

***EJ: You have a lot of ground to cover.***

**Salha:** My main purpose is to bring new ideas to the company and to make them new businesses. The work we are doing is for the growth of the company, for what the company could do in the future. To take an example, photovoltaics: If today we have a price of less than $1 U.S. per panel and it reaches €0.10 per panel within 10 years, it could change all our business in a dramatic way. We need to know that. That's why we are going to discuss with you what's happening in the United States. We are going to talk with the Karlsruhe Institute in Germany, who are really the top, top level in PV. We are going to talk with people in Korea and Japan to know what they are doing about research—to know the answer to this question.

Take the example of shale gas. This has really changed the energy industry in this country in less than 10 years. One of the challenges we faced was, how can you invest a big amount of money if suddenly you have a new way of generating energy at a lower cost that you have not seen, that you have not forecast, that you have not anticipated?

***EJ: Where are EPRI and EDF collaborating primarily?***

**Salha:** Historically, that has been on nuclear power. We are the first worldwide operator, and EPRI has a very good knowledge of the nuclear business, in safety, safety enhancement, and life extension and aging. We have EPRI research going on now in Paris, at the Materials Aging Institute. We have almost all the nuclear worldwide operators participating—the Chinese, Russians, Britons, Americans, and so on. This collaboration with EPRI for us is key.

"... our R&D priorities are strongly connected to the business, both in the short term and in the long term."

***EJ: You say that the Executive Committee of EDF is a primary customer. Thinking of EDF and its executive committee as your customers, what does your R&D organization deliver?***

**Salha:** You know, there may be a very broad scope of different results in highly technical areas. How you manage creep fatigue on stainless steel—that's a very sensitive and specialized topic. Or you could take a very global view, as EPRI's Summer Seminar does. The panel of results is very large. Those results have to be business focused; they must be used within the company and our business the next morning, or within 5 years, or perhaps 20 years, but we need something that is really driven by the business.

***EJ: So you're looking to plug R&D into everything from current operations to a strategic planning horizon of 20 years.***

**Salha:** Yes. The utility business is a long-term business—that's the main characteristic. We invest 12 billion per year, and we need to make the right investment. It's as simple as that. And to make the right investment, you need to have the right technology and the right forecast of the technology.

"If you consider the PV panel in the 10 years to come, this question may be addressed here in the U.S., and in Europe, and in Asia. In that sense, our electricity business is global. Then you have local resources on one hand and local regulation on the other."

***EJ: In what areas of technology or operations are you currently focusing a lot of resources and attention?***

**Salha:** Our portfolio is really balanced—half with the nuclear business and the other half linked with renewables, smart grids, smart meters, demand response, customer behavior, and all this sort of stuff.

***EJ: Because you are international in your operations and your scope of thinking, how do the different regulatory frameworks and business and market structures affect your portfolio and your approach to R&D?***

**Salha:** Governments everywhere look at the electricity business very carefully, to get good performance by the utilities and a good price for electricity. But the rules are different. Take the example of smart meters. The rollout of smart meters in continental Europe is mainly the role of the distribution company, which comes up with the business model to implement and authorize the investment. EDF owns EDF Energy, one of the "big six" energy suppliers in the UK, where smart meter rollout is not in the scope of the distribution company but in the scope of the sales company. So we have to find another business model to implement those meters. Our chairman asks, if we're going to buy meters for France and for the UK, is it possible to have the same contract for all? But you have different regulations. In France we use the BLC system for smart meter wireless communication, whereas in the UK they use GPRS.

***EJ: Given your experience in all these diverse markets, does EDF conduct research related to the business and the markets of electric utilities?***

**Salha:** We have for at least 10 years now. We even developed software for training and things like that. We have 19 people developing software for training management.

***EJ: How do you rank its importance?***

**Salha:** I think it's a part of the game because one of the big questions we face is whether we are going to go toward more regulation, given the complexity of the business, or toward more markets—giving more opportunity to the market. It's not so obvious. It's a question we are looking at all the time, and this question of complexity that is appearing today strengthens the need to look at market design.

"We are looking at the scope of what may happen. But the strongest focus, perhaps 90% of our nuclear effort in R&D, is on the existing fleet."

***EJ: With the attention now on technologies related to distributed resources and things that will directly affect the business model, are you directing more research into areas that have the potential to change the business model?***

**Salha:** We are deeply involved in work on renewable technology. Offshore wind in the UK is key. Marine energy is quite important—geothermic, both high temperature and low temperature. We are looking at all these technologies to see their performance in the future but also to see how to integrate them onto the grid. We are looking at demand response management, smart meters, and all the different services we may develop. And we initiated the creation of a clean tech fund called Electranova Capital—of which we own a bit less than half—through which we have a global view of startups in Europe.

***EJ: So is that in essence venture capital?***

**Salha:** It is. We do that, and we also have limited participation in some funds in America and Asia.

***EJ: Is that related or connected to R&D in the corporation?***

**Salha:** It's connected both to R&D and to finance, for obvious reasons.

***EJ: So the R&D people and the finance people have a bridge between them. How is it helpful to you as the executive responsible for R&D?***

**Salha:** It's helpful because new technologies raise the question of what is going to be the business model. All these new services.... Take, for example, the Nest thermostat, a system that you use to control the temperature in your flat, in your house, and that you can control through your iPhone. What is the business model behind that? When you ask, what is the added value of this for me today, it's difficult to answer.

***EJ: We touched on the Materials Aging Institute and the fact that a good portion of your R&D portfolio has been devoted to nuclear. What aspects of nuclear R&D do you see from EDF's perspective as the most forward looking?***

**Salha:** The existing fleet is key; aging and life extension are key because of the huge amount of investment we have there. In this respect, we face different questions: certainly integrity of the vessel; and in the UK, we operate AGR [advanced gas-cooled reactor] plants with graphite moderators, so we work with our UK colleagues on the aging of this graphite. We are looking also at the reactor for tomorrow, including small modular reactors. We are looking at the scope of what may happen. But the strongest focus, perhaps 90% of our nuclear effort in R&D, is on the existing fleet.

***EJ: Based on your nuclear background and EDF's nuclear R&D, how big will nuclear be 40 or 50 years from now?***

**Salha:** Well, I believe you will have a mix of different solutions, different technologies, including nuclear. The companies that succeed are the ones that build something with all the parts. Take the image of building a house: all those different technologies are the bricks, and if you manage to put all the bricks together, you have a house at the end. If you don't manage to integrate them in a good way, then you have a bunch of bricks that are useless.

***EJ: So thinking about the global R&D picture right now, is it a pile of bricks or is it a house? Some countries are technology innovators, while others are demonstrated leaders in getting plants built. We've got very different priorities and systems all over the world. Given your experience globally, what would you say can be done to make global R&D more collaborative and more effective?***

**Salha:** I think the technological challenges are the same. If you consider the PV panel in the 10 years to come, this question may be addressed here in the United States, and in Europe, and in Asia. In that sense, our electricity business is global. Then you have local resources on one hand and local regulation on the other. The equipment is global. Regulation is local and resources are local. The mix is of those three.

***EJ: Looking at the biggest challenges facing electricity sector R&D globally, what would you put at the top of the list for EDF?***

**Salha:** There is no R&D challenge by itself. The biggest challenge for us is to grow the company. We have big investment to do, we have our customers to satisfy, we have the different regulations, we have the new technologies appearing, so we have to be one brick in the system to make the company grow. It does not mean we are working only with a short-term view; it means our R&D priorities are strongly connected to the business, both in the short term and in the long term.

***EJ: So a primary challenge is to keep R&D integral to the business?***

**Salha:** Yes. The first lesson when you begin a management course is how to grow a company, how to make a company succeed. The two main drivers are very obvious. The first one is human resources; you need to have the right guys in the right place. And the second is the right technology. Then you can work.

> "Take the image of building a house: all those different technologies are the bricks, and if you manage to put all the bricks together, you have a house at the end. If you don't manage to integrate them in a good way, then you have a bunch of bricks that are useless."

> ". . . new technologies raise the question of what is going to be the business model."

## Virtual Flaws Offer Real Benefits for NDE Training

As part of the utility industry's nondestructive evaluation (NDE) training and qualification program, trainees use ultrasonic sensors to find and describe flaws in mockups of plant components. The mockups allow personnel to realistically practice and demonstrate their proficiency under specific requirements. But many components—especially large-section equipment found in nuclear plants—are bulky and expensive to fabricate. Creating a large inventory of mockups to account for the broad range of potential applications can cost many millions of dollars and require storage and handling facilities with special handling equipment.

Through careful digital manipulation of existing ultrasonic data files, EPRI's Nondestructive Evaluation program is developing virtual mockups that can be used as improved, economical training materials for ultrasonic practitioners. This opens the possibility of a cost-effective, technically sound alternative to building inventories of physical mockups for every plant component for which ultrasonic procedures, personnel, and equipment are required to be qualified through the performance demonstration process.

### Creating New Flaws

Creating the virtual mockup begins with NDE data captured from an existing component or physical mockup. Flaw indications are then electronically manipulated—implanted, removed, or otherwise altered—to create new virtual mockups that contain unique flaws and features. For example, flaw indications can be copied from a flawed region and reinserted in a previously clean region. The copied data are then blended with existing data to ensure a smooth transition and minimize the possibility of residual visual artifacts.

Modeling and simulation also enable flaw variety to be inserted into the virtual mockups, expanding the range of NDE problems for trainees. For example, flaw indications can be stretched independently along the principal axes, their signal-to-noise ratios can be reduced through the addition of pseudo-random additive noise, and their ultrasonic data can be amplified. As a result, a small store of actual flaw data can be mixed and matched to create a limitless variety of detection problems and exercises of different degrees of difficulty.

### More Robust and Less Costly

With digital manipulation, virtual flaw data and entire virtual mockups can be produced for the NDE trainee or current practitioner with ease and at little cost.

So far, EPRI researchers have demonstrated these techniques to create both piping and reactor vessel nozzle virtual mockups. In each case, the realism of the mockups was verified by using them in an actual test, where virtual mockup data were intermingled with data from physical mockups. Qualified ultrasonic inspection experts were then given these modified data sets and asked to correctly identify each flaw in the test. For the most part, the virtual flaws in these experiments performed identically to the physical flaws in the tests. The lessons learned from these experiments will be used to further refine the virtual data insertion processes, helping to perfect the use of virtual flaws in real testing and training.

The NDE program plans to refine digital manipulation techniques to make virtual data indistinguishable from that obtained from a real mockup. The goal is to gain ASME Code and regulatory acceptance, positioning virtual mockups as a standard element of NDE qualification testing. This approach could lead to limitless ultrasonic data that personnel could use to practice and demonstrate their data analysis capabilities prior to taking qualification field examinations on actual equipment.

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## Advanced Wind Turbines

Wind power is already one of the fastest-growing forms of power generation. But sustaining the high growth rate into the next decade will require tapping offshore wind resources, which will necessitate wind turbines that are larger, require less maintenance, and deliver more power with less weight. Several cutting-edge designs are using the advantages of direct-drive generators to boost the efficiency, reliability, and longevity of next-generation wind turbines.

### Axial Flux Rare-Earth Permanent-Magnet Generators

Traditional generators need to spin at 1,500–1,800 revolutions per minute (rpm) to generate power. Low-rpm direct-drive permanent-magnet generators offer the advantage of power production at low speed, and because there is no need for a gearbox, the machine's weight is reduced. Moreover, because permanent-magnet generators do not require a battery or additional current for the excitation circuit and do not use slip rings, they are relatively maintenance-free.

In recent years, generators using rare-earth permanent magnets made from neodymium or dysprosium have gained market share, and many wind turbine manufacturers are interested in the greater overall system efficiency, higher reliability, and fault ride-through capabilities that these generators provide. There are drawbacks to these designs, however, that so far have kept them from competing economically with more conventional iron-core generators. For one thing, to retain efficiency at the low rotational speeds that are of interest for offshore applications, the generator has to have a much larger diameter, which requires tighter manufacturing tolerances during machining. The permanent magnets' rare-earth components are expensive and price-volatile, and the magnets themselves are sensitive to corrosion and overheating.

Nevertheless, several manufacturers are currently developing and testing advanced direct-drive, axial flux generators for offshore use that use neodymium permanent magnets and ironless stator cores. Sway Turbine of Norway has developed a 10-MW prototype, and Boulder Wind Power is testing a 3-MW proof-of-concept generator expected to lead to a 6-MW offshore machine. The estimated time frame for early commercial deployment is approximately three to four years for the Sway design and about four to five years for the BWP concept. Such concepts have the potential for substantially lower weight, capital cost, and cost of electricity than equivalent machines with traditional permanent magnets.

*Sway offshore wind turbine prototype*

### Superconducting Wind Turbine Generators

Even further out on the horizon are wind machines that use superconducting materials in their generator coils, offering very high efficiency and virtually eliminating resistance losses. Direct-drive superconducting generators have the potential for improved performance with reduced unit weight and size. In addition, they can be built with less than 1% of the rare-earth materials required for manufacturing the most frequently used permanent-magnet generators. Ultimately, superconduction may lead to efficient, robust, and compact wind power plants at reduced building, operating, and maintenance costs.

Even today's high-temperature superconducting (HTSC) materials must be cooled below the boiling point of liquid nitrogen (–196°C) for effective use, so advanced thermal/electrical insulation and cryogenic cooling technology will be required as part of the wind machine's structure. Still, the advantages of a superconducting generator are impressive. Wind turbines wound with superconducting wire instead of regular copper could turn today's 2- to 3-MW generators into machines with capacities above 10 MW. The increase in power density provided by superconducting turbines significantly reduces generator weight and maximizes the power per tower, meaning that fewer towers could be used for a given wind farm output. In addition, superconducting turbines have faster dynamic response than conventional generators, may provide a higher dynamic stability limit, and have better fault damping capability.

A number of domestic and international manufacturers, wind turbine operators, and government groups are interested in the development of HTSC wind turbines, but commercial units are considered to be 5–10 years away.

While not currently involved in the development of axial flux permanent-magnet or HTSC wind machines, EPRI is closely monitoring the commercial development of these advanced offshore wind options and may become engaged in prototype or first-of-a-kind assessment and testing.

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## Guidelines, Databases, and Templates to Enhance Maintenance for Workhorse Gas Plants

With falling gas prices and tougher emission regulations for coal-fired plants, utilities are increasingly turning to natural gas–fired plants to generate electricity. Gas turbine combined-cycle (GTCC) plants—formerly important for peaking duty—now often operate at capacity factors above 60%, essentially becoming baseload generation. Such changes in dispatch can have unexpected effects on maintenance planning. And while the maintenance data are robust for long-running nuclear and coal plant assets, much of the industry's GTCC fleet is too new to provide good information on such occurrences as component failures—information essential to effective preventive maintenance strategies.

EPRI has assembled an R&D collaborative to develop a comprehensive maintenance basis for critical assets in combined-cycle plants. Plant operation can use maintenance basis for determining important generation components and identifying the most effective tasks to address reliability and cycling operation challenges. A comprehensive maintenance basis ensures that overhauls are scheduled effectively and that unanticipated breakdowns do not occur.

### A Need for Better Data

Bill Morrison, vice president of generation engineering for the Tennessee Valley Authority (TVA)—one of the collaborating companies—described the challenge: "We realized that our gas plants were starting to run considerably more than our annual projections, and we recognized that the plants were not designed to run the way that they were being run. Most of our plants were built to be peaking, and we knew the maintenance and predictive maintenance programs were not in place that would allow us to support that level of sustained operational reliability."

Paulo Jorge Domingues dos Santos, subdirector servicios técnicos for the Spanish utility Endesa Generación, S.A., cited a more specific reason for participation. "My team was performing an analysis for our insurance policies, and we didn't have much pertinent reliability information. We needed to calculate if it would be worth it to invest more money in capital spares or [whether we should] keep the existing insurance policies in place and repair or replace equipment when the events happened. In order to do that, we needed to calculate reliability rates to fulfill our information requirements."

### Developing Unit-Specific Plant Maintenance Bases

EPRI, project participants, and equipment experts will identify components—especially high-cost capital components—that are important to long-term GTCC reliability; existing failure modes will be analyzed to determine the most effective avoidance strategies, with a focus on condition-based maintenance—a proven, lowest-cost approach to avoiding failure.

Users will be able to develop a plant maintenance basis reflecting the operational plan for a particular station, instead of a general maintenance strategy that could lead to unnecessary overhauls of equipment with only limited wear. The component maintenance guidelines and associated maintenance basis templates developed by this project will enable a more flexible approach to the selection of equipment monitoring and maintenance resources for critical components.

Project participants will be able choose from a variety of maintenance resources and strategies identified by the templates, using a risk evaluation associated with each task. The project will upgrade EPRI's Preventive Maintenance Basis Database failure tables—originally compiled for coal generation assets—adding specific GTCC data and creating a more complete tool for the industry. "I can tell you that implementing the proper set of maintenance processes on the coal side of the house has given us $10 million–$20 million worth of value annually," said Morrison, "and I expect our gas fleet will see the same type of benefits."

Domingues dos Santos expects the expanded failure tables to have far-reaching value internationally. "Right now, data on GTCC maintenance and breakdowns is not well compiled, and it's hard to extract conclusions. I have no doubt this information will be valuable to a lot of companies globally. They also have a lot of knowledge they could share, and we all could benefit from their involvement."

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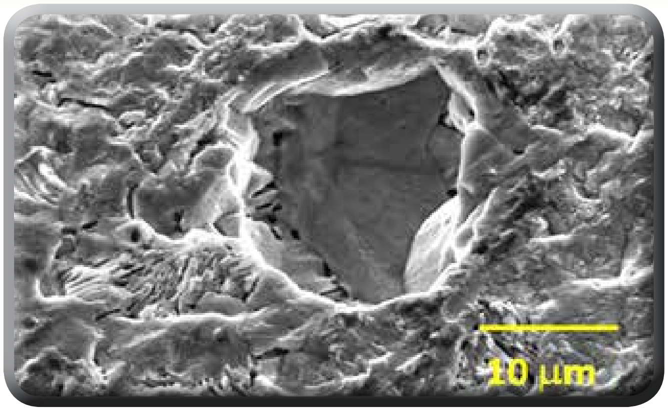
## Turbine Pitting and Corrosion Protection During Outages

When a steam turbine is taken off line for an extended period, conditions arise that can lead to damaging pitting or crevice corrosion. This risk is especially a concern in the phase transition zone (last few rows) of the low-pressure steam turbine, where moisture and corrosive salts create a potentially damaging environment. Corrosion can lead to failure of a turbine disk or blade when the unit is put back in service, which can cause additional damage and incur the expense of an unscheduled outage. In addition to direct damage to components, corrosion can form iron oxides that migrate to heat exchange surfaces, causing deposition and reduced efficiency in boilers and evaporators.



*Moisture and corrosive salts can cause severe pitting in 1018 mild steel.*

### Testing Products in the Laboratory

As part of an ongoing program to improve corrosion protection of off-line turbines and other components in the power cycle, EPRI funded a research project to investigate the properties of three commercially available corrosion-inhibiting products. The experiments were conducted at Pennsylvania State University by Digby Macdonald, an authority on electrochemistry and electrochemical corrosion.

Two of the corrosion inhibitors are proprietary hydrophobic filming amine products that can be added to the condensate/feedwater prior to unit shutdown. The chemicals are transported by steam throughout the generation unit, creating a chemical barrier in the form of protective films bonded to the metal surfaces. The third product is a vapor-phase inhibitor—a high-vapor-pressure substance that releases a protective gaseous compound; because of its temperature limitations, this product would need to be added throughout the vapor spaces after the unit has been removed from service.

Researchers measured inhibition properties by conducting accelerated tests on laboratory specimens in corrosive salt solutions. Three metals commonly used in the steam cycle and steam turbines were tested: 1018 mild steel, 304 stainless steel, and 410 stainless steel. Corrosion was measured by the specimens' weight loss. Additional tests analyzed the films and measured electrochemical effects. Detailed results of the research are reported in *Inhibition of Pitting and Crevice Corrosion in Turbine Steels* (3002000093).

### One Treatment Stands Out

Only one of the tested compounds, a filming amine trademarked Anodamine, demonstrated a marked improvement in corrosion protection under the test conditions. All of the metals exhibited lower corrosion rates with this treatment. The study determined that an apparent threshold concentration of Anodamine is required to establish effective protection of the specimens. Once that initial protection is established, it was shown, a maintenance dose of approximately 10% of the initial value provides an equal level of ongoing protection. Further investigation is needed to determine how this result might apply outside the laboratory.

Crevice corrosion, which can occur in the spaces between turbine blades and disks, is caused by electrochemical reactions similar to those in batteries. Corrosive damage occurs at the anodic (positive) part of the cell, which is typically inside the crevice. Because it is concentrated in a tiny area, a small amount of corrosion can do a lot of damage.

A particularly surprising finding was that Anodamine inverted the electrochemical potentials that can cause crevice corrosion—evidence that it acted equally to prevent activity at both the anodic and cathodic sites. By inverting the potentials, the corrosion inhibitor makes the crevice cathodic (negative), and the anode moves to other parts of the surface, away from the crevice. As a result, any corrosion that does occur is spread out over a much larger area. This action, combined with the overall protection provided by the film, greatly reduces the effects of corrosion and pitting.

"These tests told us a lot about the corrosion process and how to prevent it," said Jim Mathews, program manager of Generation Sector cycle chemistry. "EPRI is continuing to test these filming amine products, which may represent a new primary frontier in protecting equipment during shutdowns."

*For more information, contact Jim Mathews, jmathews@epri.com, 704.595.2544.*

## New Process and Initiative Address Obsolescence in Nuclear Plants

With a decades-long hiatus in new orders for nuclear power plants, manufacturers and fabricators of specialized plant components and equipment have largely abandoned many product lines for which they were receiving no new orders, and in some cases, have left the business altogether. As a result, stores of existing spares have been depleted over the years as plants have aged, and component replacements have become hard to find. About 20% of nuclear plant equipment and components have become "obsolete"—unavailable for purchase from the original manufacturers

Limited options are available for replacing an obsolete item. In some cases, new replacements can be found in the surplus marketplace. In others, operators can arrange for special manufacturing runs by the original supplier. More complicated solutions involve reverse-engineering an item and manufacturing duplicate replacements, performing equivalency evaluations for using similar items that are available, or completing engineering modifications to accommodate nonequivalent replacements. These require considerably more time and effort than a simple spares change-out. And when the situation is unanticipated, obtaining replacements often requires inefficient and costly "heroic" efforts by plant staff to avoid expensive outage extensions or plant shutdowns.

### A Plan for Looking Ahead

To help utilities avoid this reactive approach, EPRI worked with a number of nuclear plant owners to develop and refine a basic process for systematically managing equipment obsolescence. Research results are presented in a series of EPRI reports:

- *Obsolescence Management—A Proactive Approach* (1015391)
- *Obsolescence Management—Program Ownership and Development* (1016692)
- *Proactive Obsolescence Management—Program Implementation and Lessons Learned* (1019161)

All three reports present underlying concepts and discuss considerations for developing and implementing obsolescence management programs. The third report emphasizes that although identifying obsolete equipment and parts is a good starting point, the key to an effective program is to effectively identify and prioritize known obsolescence issues. In addition, processes can be implemented for tracking precursors to obsolescence.


### Implementation at Constellation

Constellation Energy Nuclear Group (CENG) used the EPRI reports to implement its obsolescence program in a single year. The CENG project team used them to clarify roles, define an obsolescence management process, develop prioritization examples, and implement key performance indicators. The resulting program incorporates obsolescence into a plant's system health reporting, automates the collection of obsolescence data, and implements processes for tracking precursor signals of equipment obsolescence. The program has already raised awareness of obsolescence issues at CENG's three nuclear power stations—Ginna, Calvert Cliffs, and Nine Mile Point.

"A key EPRI recommendation we implemented was a graded approach that uses top ten lists to prioritize the most important issues for each station," said Laura Farrell, an engineer at CENG's Ginna station. "The development of these lists has improved the visibility, ownership, and management of each station's high-risk obsolescence issues." The sites are now working down their prioritized lists and training people to support the program.

Another insight was the importance of having quality make/model data for identifying the obsolete parts, according to Tim Rogers, CENG's director of supply planning and assurance. "CENG has implemented several initiatives to improve the quality of make/model data—from data gathering projects to revising design and configuration management processes to ensure the data are captured appropriately."

CENG's hands-on experience and lessons learned are being shared with other utilities. "Obsolescence issues remain a major challenge for the nuclear industry," said Gene Van Slyke, CENG's senior vice president of support services. "We are developing solutions that benefit not only CENG's performance but the performance of every nuclear energy facility in the country. We are only beginning our journey in resolving these challenging issues."

*For more information, contact Marc Tannenbaum, mtannenbaum@epri.com, 704.595.2609.*

## Field Workshops Combine Physics, Falling "Trees," and Other Tests in Research to Make the Grid More Resilient

A "tree" fell, but it was not in the forest and there were plenty of people around to hear it when it came down. It was not in fact a tree, but a 60-foot, 6,000-pound pole serving as a tree and purposely felled onto a typical distribution line. EPRI researchers conducted this and other field demonstrations in conjunction with a July 2013 workshop at EPRI's Power Delivery and Utilization Laboratory in Lenox, Massachusetts. The workshop was the first update for all the members of a large industry collaborative that is evaluating technologies and the economics of investment alternatives for improving the resilience of electric distribution systems and response to major storm events.

### Trading Destruction for Understanding

So why knock a pole onto a power line? The test was designed to better understand the physics of falling trees and power lines. Armed with better knowledge of the physics, EPRI researchers will work to determine ways to lessen the damage. By using better materials and designs and limiting damage, utilities can begin to build systems for which crews can restore power more quickly.

A second field test dealt with the way that conductors are tied to insulators atop utility poles. If this connection is very strong, all the force from a tree falling into a line is transferred to the top of the distribution pole, and more damage is likely. If EPRI can find modes of attachment that allow slip or minor breakage during severe impacts such as falling trees, it may be possible to limit damage to poles and components mounted on them. In the second field test at Lenox, researchers recorded the peak force and the failure mode when a 100-pound weight was dropped onto a power line.

The third test examined the question of whether utility poles are more likely to bend or break just above the point of attachment for telephone and cable TV lines. A 3,000-pound weight was dropped on the top utility wire to mimic the force of a tree falling across a line between poles. In the first test, the pole bent but did not break, and the telecom wire slipped out of the clamp holding it to the pole. The second test involved a pole with three telecom lines attached, and the test pole broke just above the attachment point. The third test evaluated a resiliency enhancement where the connection at the top of the pole was designed to slip; the test validated this approach in that the pole did not break and the top conductor slipped through.

### Moving Toward Pilot Projects

EPRI program manager Matthew Olearczyk said that the workshops and field tests have brought practical advice and direction to the team of researchers who will develop various aspects of the program, including more in-depth field tests.

"We'll evaluate the performance and failure modes of more complete pole-top assemblies. We have data on the strength of individual components, but we need a clearer understanding of how these components and others perform as assemblies," said Olearczyk.

Workshop participants, which included over 60 utility engineers and managers, suggested that the testing look at new and aged equipment, with both single-phase and three-phase lines; consider designs for extreme winds; and look at trees of various weights and sizes.

Olearczyk said that the research will deploy field applications quickly. "We want to get pilot projects applied at host utilities that can begin to test various resilience enhancements proven in the laboratory. The interest is strong, and everyone is focused on practical results in the field."

*For more information, contact Matthew Olearczyk, molearcz@epri.com, 704.595.2257.*

Check out video that highlights a series of tests held at EPRI's laboratory in Lenox, Massachusetts. The tests measure the stress points and tolerances of power lines, poles, and other equipment in an on-going research effort to help make the nation's grid more resilient.
http://www.youtube.com/watch?v=Oc7-trMOWQ&feature=youtu.be

# TECHNOLOGY AT WORK

*Member applications of EPRI science and technology*

## Good Design Essential for Consumer Behavior Studies

Reducing peak loads can substantially improve energy economics for both the utility and the customer, in some cases avoiding the need to build peak-generation units, and in other cases helping to prevent outages. To design and operate successful peak-reduction programs, electric power companies undertake consumer behavior studies to assess the effectiveness of various ways to alter electricity usage. Examples include charging higher rates during peak periods, offering incentives for lowering usage, and offering customers smart meters and device controls that turn off high-consumption appliances automatically during these periods. Other behavior modification approaches involve feedback to customers on their levels of consumption or educational campaigns on the benefits of conservation.

If potential benefits are to be fully realized, system planners and operators need reliable estimates of the impacts of these programs. This is especially true for programs that employ new technologies, which carry high investment costs that need to be justified to regulators and stakeholders.

### Improving Study Design and Reporting

Numerous consumer studies on behavior-change inducements have been conducted over the last 10 years, and yet many questions remain unanswered. Studies have often been narrowly focused, have differed substantially in their execution, and have not been uniform in how the methods and results were reported. The result is that few widely accepted conclusions have been drawn, despite a substantial collective investment (1025856).

A new EPRI report, *Quantifying the Impacts of Time-Based Rates, Enabling Technology, and Other Treatments in Consumer Behavior Studies: Protocols and Guidelines* (3002000282), aims to reduce duplication of effort, missed opportunities, and misleading findings that can result from the methodological shortcomings, inappropriate analyses, and inadequate reporting that have limited the value of utility pilot programs. The report serves as a single-source reference and primer on the methods and practices available to produce generally credible and actionable findings for a wide variety of utility and customer circumstances.

The guidance is focused on designing studies to comply with the rigorous requirements for ensuring validity of the results. Following these procedures helps ensure that studies produce credible findings. In addition, consistent practices, thorough reporting, and transparency can help prevent redundancy in studies by making sure that experimental results can be generalized to other utilities and other consumption patterns.


### Protocol Recommendations

The report outlines specific protocols for three critical phases of programs: experimental design, analyses for measuring the observed effects on customer electricity usage, and the reporting of results.

An important part of the process is the determination of a reference load, which is an estimate of what the usage would have been had the customer not received the inducement, or treatment. The structure and application of the experimental design determine this reference load. Under a randomized control trial design, customers are randomly assigned to treatment and control groups. If assignment is not randomized, then the analysis must employ measures to isolate treatment effects properly. Understanding the consequences of the chosen method is essential for selecting the right analysis methods and interpreting the results properly.

Study evaluation types are divided into two broad complementary groups. In one group, effect sizes are estimated using statistical analyses without imposing any specific behavioral structure. The other group is based on economic models, which can help explain why and how customers respond to rates or treatments and can lead to more universally applicable conclusions.

The report stresses that methods and results need to be reported fully. Documentation of procedures should include, at a minimum, a description of the sample frame and target population; a description of all the treatments that are applied; the randomization or other assignment methods used; the recruitment approach used; the number of customers in each step of the enrollment and retention process; the number that installed the required technology; and a description of the actual implementation.

*For more information, contact Bernard Neenan, bneenan@epri.com, 865.218.8133.*

## Groundwater Assessments at Nuclear Plants

Inadvertent leaks and spills from nuclear power plant operations can potentially enter the soil and the groundwater that flows under the site. Although the radioactivity of leaks from such operations is typically too low to constitute an immediate health or safety issue, groundwater quality must be protected to ensure public and environmental safety and to minimize contamination concerns when the plant is decommissioned and the property released for other uses. Key to effective groundwater protection is an accurate and precise understanding of a site's hydrogeology, which determines how material may migrate through groundwater pathways.

To support groundwater quality management, EPRI developed a guidance document, *Groundwater Protection Guidelines for Nuclear Power Plants* (1015118). The document provides practical guidelines for designing and implementing a technically sound groundwater protection program tailored to site-specific hydrogeology and the plant's systems, structures, and components (SSCs) and work practices. Further guidance is provided by an EPRI decision-making protocol for soil and groundwater remediation, *Groundwater and Soil Remediation Guidelines for Nuclear Power Plants* (1021104). Together, these documents support the nuclear industry's Groundwater Protection Initiative, adopted in 2006. EPRI has drawn on these efforts and other research to support Tokyo Electric Power Company as it implements groundwater protection, monitoring, and remediation plans at the Fukushima Daiichi site.

### Building on Strengths

EPRI also offers independent third-party support to power plants performing groundwater self-assessments, with EPRI's groundwater protection team providing an on-site review of a plant's groundwater protection program in a multistep process. The EPRI team does the following:

- Reviews the plant's groundwater protection program documentation and meets with plant personnel to discuss the program
- Reviews site hydrogeological information, well locations, and construction details of deep foundations, wells, buried piping, and other SSCs that may influence groundwater flows and mitigation efforts
- Develops a site-specific report that details the strengths and gaps associated with the program and highlights prioritized recommendations and potential benefits

Duke Energy recently tapped EPRI's expertise and technical support for assistance in performing groundwater self-assessments at its nuclear plants in the southeastern United States. EPRI identified a number of strengths in Duke Energy's groundwater protection program, including a robust network of monitoring wells, proactive efforts in groundwater and environmental protection, and effective collaboration among various internal and external organizations. Duke's Site Groundwater and Tritium Management Steering Committee, which includes members of its engineering, operations, radiation protection, and site services groups, focuses closely on groundwater and underground piping and tank issues. For added protection, yard drain lines and chemical treatment ponds have been lined to reduce the potential for leaks and environmental impacts.

*Groundwater monitoring wells at Duke Energy's Oconee Nuclear Station*

### Fine-Tuning the System

EPRI worked with the Duke Energy team to strengthen their monitoring-well network by identifying new well locations and opportunities to enhance well maintenance. EPRI recommended monitoring the groundwater characteristics around underground dewatering systems to better understand impacts on groundwater flow and to serve as a detection point for leaks or spills into the area. Periodic well-depth measurements were also advised to spot unnoticed well damage or faulty function. To bolster SSC and work practice issues, EPRI suggested that Duke inventory the sumps in the power block and continue work to incorporate groundwater protection provisions into radiation work packages and design change packages.

"The assessment confirmed the strengths in our program and pointed out areas where we could do better," said Cyndi Martinec, who manages radiation protection at Duke Energy. "We put a strong emphasis on the monitoring-well network; the assessment helped us take a harder look at groundwater flow impacts and enhanced our understanding of the site hydrogeology and the effects of building foundations and recovery-well operations. The assessment exit meeting was especially helpful in getting plant senior management to appreciate the depth of activities completed so far and the efforts needed to perform the recommended enhancements."

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# REPORTS & SOFTWARE

*Key deliverables now available*

*The following is a small selection of items recently published by EPRI. To view complete lists of your company-funded research reports, updates, software, training announcements, and other program deliverables, log in at www.epri.com and go to Program Cockpits.*

### Life Management of Creep Strength–Enhanced Grade 91 Steels—Atlas of Microstructures and Welds (3002000081)

Components fabricated from creep strength–enhanced ferritic Grade 91 steel are prone to weldment cracking. New research investigates and quantifies the factors affecting creep life in these welds, including the angle of the weld interface relative to the applied stress, the level of weld preheat, and the influence of weld metal composition on life and damage development.

### EPRI Alpha Monitoring and Control Guidelines for Operating Nuclear Power Stations, Revision 2 (3002000409)

This report provides guidelines, developed by a group of international radiation safety professionals, for monitoring the presence of alpha-emitting radionuclides in operating nuclear reactors and protecting workers from exposure. To support guideline implementation, the document has appendices that include information on source term assessments, the technical bases of the guidelines, radon compensation, and instrumentation, with examples given for work control and internal dose assessment.

### Cathodic Protection Application and Maintenance Guide: Volume 1 and Volume 2 (3002000596)

This guide provides information on implementing and maintaining cathodic protection systems at nuclear power plants to protect buried piping, tanks, and structures from corrosion and deterioration. In addition to guidance on equipment selection and system design and installation, the document covers periodic testing and troubleshooting and makes recommendations for monitoring and maintenance. The guide outlines common failure modes and describes predictive and preventive maintenance techniques.

### Identification of Geographic Information System Data Dependencies: An IntelliGrid Report (3002001042)

A geographic information system (GIS) can track the location of numerous devices within a smart grid distribution infrastructure. This report explores the dependencies between GIS and other core smart grid systems; examines the evolution of relevant work flow between key systems and the GIS through the creation of use cases; and discusses how the GIS interfaces with the International Electrotechnical Commission Common Information Model.

### Assessment of Furnace Coal Flow Balancing on Combustion Efficiency and Emissions (3002001115)

Researchers performed analyses to determine the effect of coal/air flow balance on boiler efficiency and emissions and specifically to determine the degree of control that adjustable coal flow distributors can induce in a three-way (trifurcate) split and to measure the effect of such adjustments on air flow. The tests confirmed that balancing pipe-to-pipe coal flow rates can produce small but measurable improvements in boiler performance.

### High-Impact, Low-Frequency (HILF) Events in the Electric Power Industry: Potential Impacts, Mitigation, and Risk Management (3002001935)

High-impact, low-frequency events such as electromagnetic pulse weapons, geomagnetic disturbances, coordinated cyber and/or physical attacks, and pandemics are arousing concern. This report consolidates EPRI work to address such events through holistic risk management and includes a preliminary integrated management and mitigation approach for dealing with associated risks.

### Water Prism, Volume 2: Prototype Applications (3002002120)

Collaborative planning promotes efficient use of water supplies by all water-using sectors—industrial, agricultural, municipal, electric power, and environmental. Water Prism can be used to evaluate management plans for these sectors at the regional, watershed, and local levels. This technical update focuses on two large watersheds—Ohio's Muskingum River Basin and Kentucky's Green River Basin—to illustrate how Water Prism can be applied for effective water conservation.

### EPRI Comments on Proposed Effluent Limitations Guidelines Rule (3002002231)

On September 20, 2013, EPRI submitted comments to the U.S. Environmental Protection Agency (EPA) on its proposed Effluent Guidelines rule, which aims to reduce the amount of toxic metals and other constituents discharged to surface waters from power plants. The comments address scientific and technical questions about the cost-effectiveness of proposed flue gas desulfurization wastewater treatment, the attainability of discharge limits using EPA-designated best-available technology, the statistical approach to discharge limits, and the cost-effectiveness of proposed conversion from wet to dry bottom ash handling.

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