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FROM DOOMSDAY TO REALITY

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From Doomsday to Reality

EPRI Research to Inform Smart Decisions on High-Altitude Electromagnetic Pulses

By Chris Warren

Perspectives on what might happen to society in the aftermath of a high-altitude electromagnetic pulse (HEMP) range from "doomsday" scenarios to minimal impacts.

In one prediction, hundreds of large power transformers at substations around the country overheat and fail, resulting in blackouts lasting months or even years. In Congressional testimony in 2015, Peter Pry—executive director of a Congressional advisory board called the Electromagnetic Pulse Task Force on National Homeland Security—ominously warned that the prolonged damage to the grid could result in the death of 90% of Americans "through starvation, disease, and societal collapse."

At the other end of the spectrum: In a 2015 article, Sharon Burke and Emily Schneider of the Washington, D.C.–based think tank New America Foundation contend that severe weather and other natural hazards pose much greater risks to the grid. "Odds are you have far more to fear from nut-obsessed squirrels than nutty extremists when it comes to the reliability of your electricity," they wrote.

This divergence in views regarding potential HEMP attacks points to a lack of publicly available, scientifically credible information about the true dangers. Given the sensitive national security issues involved, rigorous research on HEMP threats is classified or otherwise unavailable for public scrutiny.

"The only thing settled is that nothing is settled," said Randy Horton, an EPRI senior program manager.

Filling the HEMP Knowledge Void

In 2016, EPRI launched a three-year project to investigate HEMPs, including threat assessment, mitigation, and recovery. The research parallels similar but distinct work at the U.S. Department of Energy and is meant to provide utilities, federal and state regulators, and policymakers with information to guide policy and investment decisions.

"EPRI's mission is to conduct research for the benefit of the public, and this drives our long-standing commitment to address anything that threatens grid reliability and safety, including HEMPs," said Rob Manning, EPRI vice president for transmission and distribution.

"EPRI wants to provide the public, utilities, and regulatory and legislative decision-makers with unbiased technical results," said Andrew Phillips, EPRI director for transmission and substations. "They can consider our findings as they evaluate the risks posed by HEMPs, including the possibility of widespread power failures."

Credible information is particularly important when it comes to protecting the electric grid. Though well intentioned, policies mandating that tens of thousands of substations and transformers nationwide be equipped with the same level of protection as missile launch sites—at a cost of tens of billions of dollars—may be an overreaction to the risks.

"Even utilities that have already taken steps to harden their facilities recognize that they don't have all the answers and need a more scientific basis for investment decisions," said Horton.

EPRI's first HEMP report, published in September of 2016, covers the state of knowledge and research gaps, drawing from 70 publicly available papers and interviews with utilities on their hardening and mitigation practices. It describes the three components of a HEMP:

- E1: A high-magnitude, short-duration pulse
- E2: A short-duration pulse similar to lightning
- E3: A pulse similar to naturally occurring geomagnetic disturbances

Each HEMP component may impact the electric grid in different ways. Prior research has pointed to the potential vulnerabilities of electronic components as a result of elevated voltages and currents associated with E1 and E2.

"They have the potential to cause electronics to fail or malfunction," said Phillips. "The ones we worry about in substations are the relays controlling the circuit breakers that protect and control the grid. Without those relays, the grid can no longer operate." An additional concern is the potential effects to control centers and energy management systems that operate the electric grid.

The E3 pulse has the potential to overheat and damage transformers, which play a critical role in bulk power system operations. Some transformers increase voltage so that electricity can be transmitted across long distances while others reduce voltage so that it can be sent to consumers. Because designing and building large power transformers can take up to 18 months, the loss of many of them could result in long-term blackouts.

"During an E3 event, transformers consume a lot of reactive power," said Phillips. "That reactive power can cause voltage collapse, and some are concerned that the voltage collapse could result in large-scale blackouts across the United States."

The report points to a lack of specific guidance to help electric utilities protect their assets from a HEMP attack and notes that an early detection system could potentially help the grid withstand its impacts.

Utility plans and actions underway include installation of high-frequency filters, grounding and surge protection devices to guard against E1 pulses, and storage of spare equipment in HEMP-protected warehouses. "Some utilities are building HEMP-proof control rooms," said Phillips. "Control rooms contain the computers and electronics for managing grid operations. They cost tens of millions of dollars, and making them HEMP-proof increases that price significantly."

Can a HEMP Destroy Hundreds of Bulk Power Transformers?

A second EPRI report published in February evaluates the threat posed by an E3 pulse to the bulk electric system in the continental United States. Many worst-case HEMP scenarios, such as long-term blackouts, stem from the potential effects of E3 on transformers.

"The fears about the E3 pulse are based on the belief that it would cause many transformers to fail," said Horton. "We thought it was important to start our research with E3 and figure out how likely that was. This can inform utilities and regulators in making fact-based decisions about hardening and mitigation investments."

Past research on E3 impacts did not accurately account for both the magnitude and duration of the geomagnetically induced currents resulting from E3. For example, one study concluded that an E3 pulse wouldn't damage transformers because the duration of the resulting currents was so short. But the study did not use thermal models to assess how increased temperatures would impact the transformers, calling the conclusions into question. Another study only evaluated the magnitude of the geomagnetically induced currents, concluding that widespread transformer damage as a result of E3 was likely.

"Think about duration like this: You can run your hand through a candle and nothing happens," said Horton. "But if you hold your hand over the flame for any significant time, you will burn it. Same principle applies here."

To quantify E3 impacts on larger power transformers, EPRI developed thermal models based on transformer data from laboratory and field tests along with 3D simulations. For instance, EPRI and a transformer manufacturer injected DC current into a transformer, observed the resulting temperature changes, and incorporated the results into the thermal models. EPRI's models are more accurate than those used in prior research because they factor both the magnitude and duration of the geomagnetically induced currents.

"The limiting factor is that we do not have a model for each transformer, but our generic models are conservative," said Horton. "That means that they should yield hotspot temperatures that are as high or higher than those that would be experienced in the field."

EPRI concluded that while an E3 pulse could generate significant currents in hundreds or thousands of transformers, only 3 to 14 units (depending on the location of the nuclear blast) were at risk of thermal damage, indicating a low likelihood of widespread, long-lasting blackouts. This finding alone isn't meant to dictate policy or investment decisions, but it should dampen a temptation to act hastily. "It says that we don't need to panic and buy hundreds of spare transformers," said Phillips.

EPRI's methodologies are presented in detail in the report. "We came up with a defensible technical basis that can be scrutinized by others," said Phillips. "The report provides all the information needed to evaluate our approach."

Future research will build on the findings of the first two reports. Later in 2017, EPRI plans to publish a report examining the potential for an E3 pulse to cause a voltage collapse or blackout. This work is distinct from the recent findings, which focused on thermal effects of E3. Then researchers will examine impacts of E1 and E2 pulses on substations. This will include modeling the electrical interactions with control cables, overhead conductors, and other infrastructure, along with testing of components to determine the pulse levels that they can withstand.

"We are beginning to test grid components, such as relays and microprocessor-based devices, to see what pulse levels they can handle," said Horton. "By combining the results of those tests with the modeling results, we can determine the probability of failure and the impacts to the grid."

The goal of this research is to develop a thorough understanding of all the possible impacts of a HEMP attack to inform smart decisions on how to defend the grid. "At the end of this research, we will put all the pieces together and know the full range of potential impacts for E1, E2, and E3," said Horton.

Key EPRI Technical Experts

Randy Horton, Andrew Phillips

A "Moonshot" for Reactor Vessel Production

Advanced Manufacturing and Fabrication Could Substantially Reduce Time, Costs of Reactor Pressure Vessel Production

By Brent Barker

Imagine being able to build a nuclear plant's reactor pressure vessel in one year instead of four, using metal powders as a starting point instead of massive forgings, and a fabrication process in which welds essentially disappear. This ambitious scenario points to savings in time, money, and materials, far more competitive nuclear power, and a faster path to small modular reactors (SMR). It also describes the central goal of a new four-year, collaborative program spearheaded by EPRI, United Kingdom–based Nuclear Advanced Manufacturing Research Center (Nuclear AMRC), and the U.S. Department of Energy (DOE). Its success could broaden the manufacturing base of reactor pressure vessels beyond Asia.

The team views this program as its "moonshot," with researchers seeking to demonstrate the effectiveness, synergy, and benefits of several advanced manufacturing and fabrication technologies for reactor pressure vessel production. Their immediate focus is on producing large, critical SMR component assemblies at two-thirds scale, using a 50-megawatt unit design from Oregon-based company NuScale Power. They selected this reactor for two reasons: it is small enough to demonstrate many of the technologies with current fabrication facilities, and its design appears closest to commercial deployment. Up to 12 NuScale Power SMRs could be linked at a single site and brought online incrementally as demand grows.

"These advanced manufacturing/fabrication technologies are agnostic," said EPRI Technical Executive David Gandy. "They can be applied to advanced light water reactors, Generation IV nuclear reactors, ultra-supercritical fossil units, and advanced CO_2 supercritical plants. Some of the technologies are already being used at small scale in punishing environments such as aircraft engines and offshore rigs at the bottom of the North Sea."

Why Vessel Production Went Overseas

In the 1960s and 1970s, most full-scale vessels were manufactured at facilities in the United States, France, and United Kingdom, where various sections were joined using conventional welding techniques with filler materials containing tramp (trace) elements such as copper, phosphorus, and sulfur. These weld materials were found to be susceptible to embrittlement as a result of long-term radiation exposure, decreasing their strength.

To reduce the number of welds and inspections, the industry turned to forging the entire vessel in large sections and joining them with fewer, longer welds, such as the one around the vessel's girth. As a result, vessel production moved to Japan, Korea, and China, which had developed the capability for much larger-scale forging operations. Given the limited number of facilities, the global queue for large-scale forgings has lengthened considerably.

"This could eliminate the need for in-service inspection because the weld zone no longer exists metallurgically."

Current reactor pressure vessel production is laborious: Hot ingots are hammered into rough sections, which are machined, rolled, bored, and drilled into the final forms, which are welded together. The forging process can affect the metal's micro-grain structure, making nondestructive inspection more difficult.

Enabling Technologies

Three new technologies show potential for producing vessels from small sections while eliminating previous welding constraints and facilitating inspection.

1. **Powder metallurgy combined with hot isostatic pressing.** In this process, metal alloys are atomized into powder form, inserted into a metal mold (or "can"), and subjected to high temperatures and pressures. This consolidates the powder into a solid metal component.

   "Earlier work by EPRI and others demonstrated that we could use this technology with multiple alloys to produce 'near net-shape' components with a homogeneous microstructure. These require minimal machining to achieve the final geometry of complex parts, and homogeneity means a vastly easier inspection process and good properties," said Gandy.

2. **Electron beam welding** fuses two pieces of metal by focusing a high-intensity energy beam on the junction. Subsequent solution annealing, quenching, and tempering complete the process. Unlike traditional welding, no filler material is used.

   "We've demonstrated that we can remove all evidence of the weld through solution annealing," said Gandy. "Further development and demonstration will be needed to secure ASME Boiler and Pressure Vessel Code approval, but we believe that inspection may only be required immediately after fabrication. This could eliminate the need for in-service inspection because the weld zone no longer exists metallurgically."

   EPRI estimates that these two technologies, when used together on an SMR vessel, could reduce welding time by 70%, overall production time by 60%, and manufacturing costs by 40%, creating new opportunities for how, when, and where reactor pressure vessels are produced. This, in turn, could lead to more suppliers globally.

3. **Diode laser cladding** combines a metal wire or powder with a laser beam at the surface to apply extremely thin layers. This can be used to clad the inside of vessels and their nozzles with stainless steel or nickel-based alloys for corrosion resistance. This technology potentially reduces by 75% the amount of cladding material needed, providing an economic benefit. Nuclear AMRC spearheaded this technology development.

The SMR Reactor Vessel Demonstration Project

The four-year collaborative project dates back to 2009, when EPRI investigated the use of powder metallurgy and hot isostatic pressing to produce nuclear and fossil plant valves. That led to a DOE-funded project with EPRI involving the design, manufacture, and validation of large, near-net-shaped components for multiple alloy systems. The successful project produced several complex sample components, including a 3,600-pound vessel nozzle.

At the same time, DOE began looking for industrial participants to test advanced manufacturing techniques for SMRs. EPRI explored the project vision with Nuclear AMRC, drawing on its capabilities in advanced nuclear manufacturing. With DOE's support and sponsorship, a collaborative project on SMR manufacturing and fabrication emerged, building momentum in 2016.

"We have gathered an ideal combination of expertise on our team," said EPRI Technical Leader Craig Stover, who manages the collaborative with Gandy. Participants include:

- Nuclear AMRC, a co-investigator in the project with EPRI, will lead the fabrication of critical SMR assemblies.
- NuScale will provide the SMR design.
- Pennsylvania-based Carpenter Powder Products will supply the powders.
- UK-based Sheffield Forgemasters will produce several forgings for the SMR.
- Los Angeles–based Synertech-PM will lead the hot isostatic pressing efforts.

The project, which began in late 2016, has two phases. The first will focus on the reactor pressure vessel's lower assembly, which is less complex in design than the upper assembly. Phase two will build on this work to focus on the upper assembly.

The reactor pressure vessel top head assembly is considered the most complex component of the NuScale SMR design, with 16 nozzle penetrations for control rod drive mechanisms as well as 7 additional nozzle penetrations. Conventional manufacturing would require extensive boring, machining, and welding. Because a hot isostatic pressure chamber sufficiently large to produce the entire head assembly in one run is not yet available, the team will produce two halves of the assembly and weld them together with electron beam welding, followed by cladding and solution annealing. Using this approach, EPRI currently estimates that the assembly could be produced at nuclear-grade quality for less than $2 million—just 10% of current manufacturing costs.

Advanced manufacturing and fabrication technologies hold significant promise to improve nuclear power's competitiveness and support commercial operation of smaller, modular reactors. The demonstration project is expected to provide insights on these technologies at a scale sufficient to evaluate their commercialization.

Small Modular Reactors

Small modular reactors (SMRs) offer the potential to produce 300 megawatts of power on a site smaller than 10 acres. Compare that with a 1000-megawatt nuclear plant that typically requires around 800 acres. The SMR's compact architecture enables modular fabrication in the factory as well as passive safety features.

"With modern SMR designs, emergency planning zones could potentially be reduced to the site boundary," said EPRI Technical Leader Craig Stover.

With advanced manufacturing technologies, such as powder metallurgy, hot isostatic pressing, and electron beam welding, SMR capital and operations and maintenance costs "could conceivably be cut to less than one-third the costs of an advanced light water reactor," said EPRI Technical Executive David Gandy.

Additive Manufacturing: Building from the Ground Up

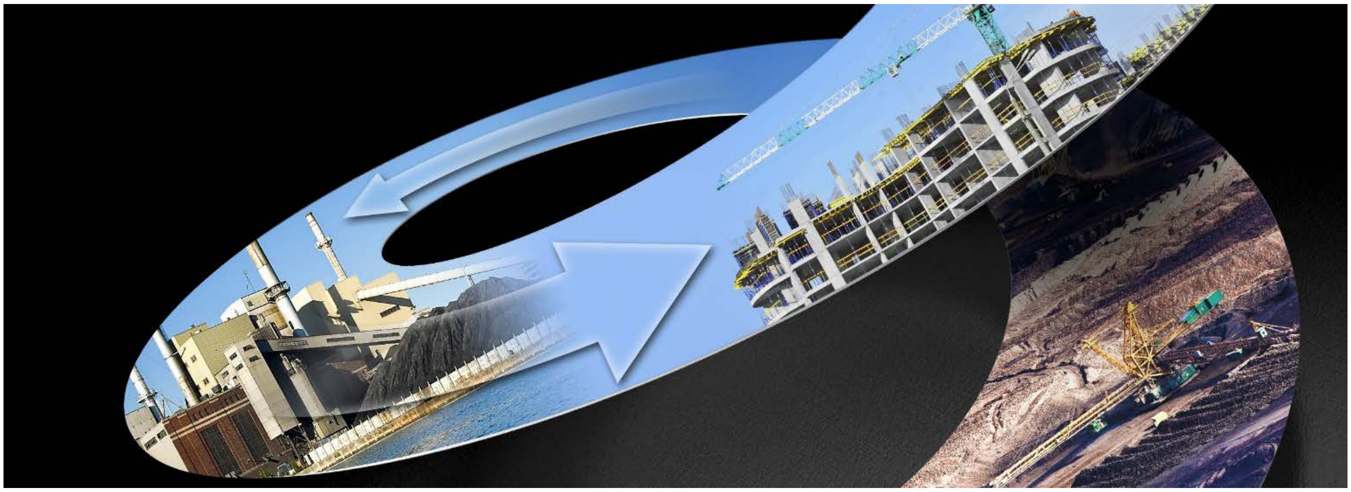
For manufacturing intricate nuclear plant parts weighing less than 100 pounds, additive manufacturing offers a compelling alternative to powder metallurgy—hot isostatic pressing, forging, and casting. Similar to 3-D printing, it involves the layer-by-layer construction of a component by mimicking the contours of an existing object.

"With additive manufacturing, you are essentially laying down weld metal and fusing tiny beads layer-by-layer," said EPRI Technical Executive David Gandy. "The real advantage is that you can replicate obsolete parts and make very detailed, intricate parts." The current limitation is size; most of these parts are produced inside a chamber that is less than 1.3 cubic feet. EPRI is launching a three-year research project with the U.S. Department of Energy, Westinghouse, and Rolls Royce to test the potential application of additive manufacturing for nuclear reactor components. This effort is focused primarily on reactor internals, fuels, and fuel assemblies.

Key EPRI Technical Experts

David Gandy, Craig Stover

A Second Life



EPRI Investigates Innovative Uses for Coal Ash

By Chris Warren

In 2012, Duke Energy retired the 382-megawatt, coal-fired H.F. Lee Plant in Wayne County, North Carolina, ending six decades of service. The plant began commercial operation shortly after World War II to help meet the state's growing energy demand in the 1950s and 1960s.

In December 2016, the utility launched a new chapter in the plant's history, announcing its intention to recycle most of the 6 million tons of coal ash stored on-site for use in concrete. Duke Energy also is investing in "beneficiation" technologies for processing the ash because it contains too much carbon for concrete production.

Coal ash is used in about half of the concrete produced in the United States. It increases the material's workability, long-term strength, and durability while reducing permeability. Making concrete with recycled ash also reduces mining and transportation of materials used to make Portland cement (a basic ingredient in concrete). For every ton of coal ash that replaces Portland cement in concrete, about one ton of greenhouse gas emissions is avoided. Nationwide, other beneficial uses for large volumes of ash include cement production and structural fill in embankments, roads, and other construction.

Decision Confirmed by EPRI Research

Collaborative research by EPRI, the University of Kentucky Center for Applied Research, and Golder Associates helped inform Duke Energy's efforts to ramp up ash recycling. The research, mandated by the North Carolina Coal Ash Management Act of 2014, examined three areas:

- The drivers and dynamics of established markets for coal ash in North Carolina and surrounding states, including concrete and cement manufacturing
- State of the technologies for processing ash to make it suitable for use in these markets
- Innovative coal ash uses and products still in the research stage, or with little or no market in the United States

Duke Energy had investigated these issues and wanted third-party, independent researchers to assess markets, evaluate beneficiation technologies, and identify economically viable products and uses. "I wanted to know if EPRI would find anything we hadn't found," said Tim Smart, Duke Energy's Senior Byproducts Manager.

A coal ash pond.

While focused on Duke Energy, the research is instructive for other utilities considering appropriate uses and markets for coal ash.

"It's tempting to assume that a utility can beneficially use all of its ash in local markets," said EPRI Senior Technical Executive Ken Ladwig. "But it's not that simple."

Indeed, the research revealed that the best use of ash depends on many factors, including regional supply and demand for ash, ash quality, public perception, regulatory drivers, and cost of ash processing, transportation, and incorporation into new products.

In North Carolina, supply is not a constraint for Duke Energy because it is the main fly ash producer. EPRI found that the most common beneficial use of coal ash in North Carolina, as elsewhere in the United States, is as an ingredient in ready-mixed concrete, with demand concentrated in Raleigh, Charlotte, and other areas with significant construction. For Duke Energy, the key to optimal use is to match centers of concrete-quality fly ash with current and future market centers.

EPRI, Duke Energy, and academic organizations point to the societal benefits of coal ash use, including reduced greenhouse gas emissions, water and energy use, ash storage and disposal, and land use for mining natural resources used in Portland cement.

Improving Ash Quality

For use in ready-mixed concrete, fly ash must have a certain composition and consistency to meet technical specifications. Fly ash with a high concentration of unburned carbon can reduce concrete's resistance to freezing and thawing. Beneficiation technologies can improve the quality of both recently produced fly ash (known as *production ash*) and ash stored in ponds for years.

EPRI evaluated commercially available beneficiation technologies and identified those Duke Energy facilities best positioned to deploy them cost-effectively.

For production ash, quality control can help optimize ash use. Operators can separate ash streams with low unburned carbon content (usually produced when the plant's load is constant) and high carbon content (produced when load is increasing or decreasing). Other carbon-reduction processes include thermal technologies, which employ combustion to burn the residual carbon, and electrostatic separation, which takes advantage of different electrical properties of the ash and carbon particles.

Most fly ash is stored in ponds, typically along with bottom ash and sometimes with by-products of power plant scrubbers. Such mixed ash composition can make processing more challenging and costly.

A key takeaway: Economically viable beneficiation typically combines a large ash supply (production or stored) and nearby markets that can use a consistent supply for many years. The EPRI analysis used these and other factors to assess the potential for beneficiation of Duke Energy's production and stored ash in North Carolina.

Beyond Ready-Mixed Concrete

With respect to potential new uses for coal ash, researchers investigated emerging technologies requiring significant R&D, commercially available technologies with limited markets such as foamed concrete, and mature technologies such as geopolymer concrete, alternative cements, and asphalts.

"Geopolymer concrete, for example, can potentially use large volumes of ash and develop a high-value product, particularly in pre-cast applications, but it may not be economically viable in areas already dominated by ready-mixed concrete," said Ladwig.

EPRI concluded that there are many technically viable uses for fly ash, but most face either niche applications or market constraints that limit their use. "This part of the research reaffirmed that the big marketplace out there is still ready-mixed concrete," said Duke Energy's Smart. "EPRI did not see any silver bullets on the horizon that could use significant amounts of ash."

EPRI continues to research potential products, with a focus on applications for lower-quality ash, such as that recovered from ponds and landfills and unsuitable for concrete without beneficiation. Ladwig will create a database to track emerging products and conduct market and technical research on those most promising.

Mining Ash for Metals

One potential use involves extracting rare earth elements from coal ash. These metals are used in diverse technologies, including DVDs, cell phones, and fluorescent lights. The U.S. Department of Energy (DOE) has pointed to the importance of reliable, affordable supplies of rare earth elements, particularly for use in electronics, defense equipment, and clean energy technologies such as wind turbines, photovoltaic thin films, and electric vehicles. This was highlighted in 2010 when China, the world's largest producer of the elements, scaled back production dramatically, causing prices to spike as much as tenfold.

Following the market disruption, DOE ramped up R&D on extracting rare earth elements from coal and coal ash, and EPRI is supporting these efforts by facilitating collection of samples from utilities.

"DOE wants to examine ash and coal samples from around the country to determine which ones contain the most rare earth elements," said Ladwig, who is leading this research at EPRI. "We are helping DOE with that analysis through our industry relationships."

The results will be compiled in a database that researchers and companies can use to develop technologies for extracting rare earth elements from coal ash. DOE also is funding research on extraction methods and technologies, and small demonstrations are underway.

Acid is often used in research to extract rare earth elements from coal ash, but this approach may result in large quantities of waste. "With acid leaching, we are removing less than 0.1 percent of the material," said Ladwig. "That leaves 99.9 percent for use or disposal. Research needs to address what to do with the remaining solids and liquids and how to make extraction economically viable."

EPRI is reviewing other commercially available technologies that could be used to remove rare earth elements from coal ash. "We're evaluating claims that companies make about the effectiveness and economic viability of their technologies," said Ben Colgrove, EPRI senior manager of labs and corporate safety, who is helping Ladwig manage the research.

Whether these technologies make economic sense will depend largely on global production of rare earth elements. If production is slow and prices high, extracting rare earth elements from coal and coal ash could be economically viable and help insulate countries and industries from price swings.

Extracting rare earth elements aligns the electric power industry with the nation's technology and security interests. "It could help the U.S. have a strategic domestic supply of the critical rare earth elements which are vital for the economy," said Colgrove.

Key EPRI Technical Experts

Ken Ladwig, Ben Colgrove

Viewpoint—Research in Response to Threat

The Necessity of Objective, Methodical Work

Mike Howard, President and Chief Executive Officer, EPRI

How do we as humans respond to threat? The answer depends on the nature of the threat. The instinctive "fight-or-flight" response arises to an immediate threat to our lives. In contrast, a *potential* threat can prompt study, discussion, procrastination, or denial. The middle ground is a threat that is real but is not fully understood. For these we need careful consideration of the facts if we are to respond effectively.

Simply stated, we apply the scientific method to research, which provides a long-term payback but can raise questions in the early going. Are we moving too slowly? Are we pursuing the right leads, asking the right questions, and using the right data?

In recent months, growing public attention has focused on the threat to our power systems posed by nuclear weapons generating high-altitude electromagnetic pulses. The scenarios of damage and social disruption range from severe-but-manageable to catastrophic.

People are understandably concerned when confronting different opinions and assessments of this threat. Typically, they ask, "How worried should I be?" The real question is, "How should we respond and prepare to deal with the threat?"

As researchers, we respond methodically and objectively. Given scenarios of widespread destruction and suffering, we must understand that the public's sense of security can be undermined if they lose confidence in our research and preparation to face such threats.

To maintain confidence in research, it's important to stress these aspects:

- Research is deliberate and incremental. There is no short or simple path to a solution or an answer. And the *latest* word on progress is not the *last* word.
- It must draw on multiple disciplines. For EPRI, examples include electrical engineering, materials sciences, operations and maintenance, as well as data analysis.

- It must systematically and broadly incorporate diverse perspectives and experience. Various utilities excel or specialize in different operating areas and technologies. It is only by careful synthesis of these that our research can be solidly grounded.
- Risk must be understood as something with many more dimensions that just probability. For example, EPRI and nuclear power plant operators use "probabilistic risk assessment" in preparing for earthquakes, and these are based on much more than the probability of earthquakes, including also systematic consideration of the components and systems affected.
- Research speaks in precise and measured terms. Its results generally make for poor headlines, especially if you consider that a headline's first priority is to grab the public's attention. (Another way of saying this is that headlines should never be expected to convey research results accurately.) And, speaking of risk, readers who base their decisions or judgment on headlines are at great risk of being misled or misinformed.

In the United States and other countries, many of our citizens recall the Cold War's nuclear threat. Schools drilled teachers and students on preparing for attacks (duck under your desks), and public buildings such as courthouses housed fallout shelters, which at the height of the Cold War included stores of canned food, other rations, and water. Our assumptions and our preparations combined scenarios based on traditional warfare and weapons, even as they lacked a full comprehension of an attack's destruction and disruption.

Today's discussions of high-altitude electromagnetic pulses include this same combination of sweeping and specific considerations, which must be systematically considered.

As EPRI continues to work on this issue in collaboration with the electricity sector and its stakeholders, I encourage people to consider this: EPRI's very existence stems from a failure of the grid in the Northeast more than 40 years ago. From Day One, we have looked unflinchingly at anything that compromises the safety and reliability of the grid—things as small as a rusty bolt or as big as an earthquake or nuclear weapon.

We were created with a mission to work in the public interest and for the public benefit. In addition to our board of directors, EPRI's Advisory Council brings to our governance the diverse interests of consumers, environmentalists, labor, and others. We rely on them to help direct our R&D portfolio so that it effectively carries out our mission.

We are equally diligent with the small unseen work and the headline-grabbing challenges. As we face the prospect of a weapon of mass destruction targeting the grid, "fight-or-flight" is not an option. We cannot dismiss such an attack as merely a potential threat. It is real, and given the public's reliance on the electrical grid and its trust in research organizations such as EPRI, we must continue our objective, methodical work to assess the threat, to mitigate effects of an attack, and to prepare for recovery.

Mike Howard

President and Chief Executive Officer, EPRI

First Person—The "Matchmaker" for Launching Energy Technologies

The Story in Brief

"There's a buzz in the air" at Greentown Labs, says Emily Reichert, CEO of the Massachusetts-based incubator for energy technology startups. Drawing from her experience with dozens of startups, Reichert speaks about the key to successful utility partnerships, technology trends in electric power, and the importance of grid infrastructure upgrades.

EJ: Greentown Labs has a co-working space, machine shop, prototyping lab, event space, and more than 50 hardware-focused startup companies employing more than 500 people. What's a typical day like?


Emily Reichert

Reichert: Every day is completely different and filled with surprises and new things happening. On any given day, one thing you will notice immediately—and people comment on it when they walk in the front door—is that there's a buzz in the air. This buzz is generated by people developing, testing, and presenting about their technologies. They are passionate about turning their ideas into commercial reality.

More than half of our companies have an active project in our 20,000-square-foot lab and spend some portion of their days testing and learning about how a technology works. They may be getting ready for field trials to demonstrate that the technology can be a winner in the market.

In our office spaces, meetings are buzzing away all day. Startups are meeting with utilities and other large corporations, government officials, potential talent, universities, and more. In our event space, we do more than 200 energy industry networking events a year.

EJ: How are Greentown Labs and its member companies collaborating with electric utilities?

Reichert: Investment in clean energy technology is not what it was 10 years ago when traditional venture capital was available for early-stage companies. So we have taken an alternative approach by creating an environment where we connect startups with corporate partners. Our utility partners include National Grid and ENGIE, a French gas and electric company. They sponsor Greentown Labs, interact with our companies in a variety of capacities including mentorship, technology validation, and testing, and sit on our advisory board.

It's difficult for a young startup to penetrate corporate partners and particularly utilities, because their entry point is often a technology scout who is not a decision maker. That person may have to report two or three levels up to get a decision maker interested, and that can take time and sustained effort.

We have a 6-month accelerator program called *Greentown Launch*, which provides startups with mentoring, milestone planning, technical feedback, and support with prototype refinement to prepare them for successful corporate partnerships. This program has helped spark several partnerships.

One example is between Tagup, a Greentown Labs startup, and Veolia, a water and energy company. Tagup has developed a cloud-based system for continuous monitoring and analysis of industrial equipment data, with power transformers as one early application. Monitoring of transformers is typically done today by a technician who manually samples transformer oil. This happens infrequently, and there is no data the rest of the time. Tagup and Veolia have deployed the sensors at a cogeneration plant in Cambridge to validate the technology.

"It's difficult for a young startup to penetrate corporate partners and particularly utilities, because their entry point is often a technology scout who is not a decision maker. That person may have to report two or three levels up to get a decision maker interested, and that can take time and sustained effort."

Another partnership involves Sparkplug Power, a Greentown Labs member company, Massachusetts Clean Energy Center, and Holyoke Gas and Electric, a utility in western Massachusetts. They are doing a pilot project to integrate Sparkplug's energy storage system into the grid. A third example is from one of our recent graduate companies, NBD Nano, which has developed an external condenser tube coating that improves steam condensation in power plants. Tennessee Valley Authority is testing the technology at the Shawnee Plant in Kentucky.

EJ: What makes successful partnerships between startups and utilities?

Reichert: The number-one key to a successful partnership between startups and utilities is that the utility has a technology scouting group as well as decision maker in asset management—someone at a senior level that will support and authorize testing and evaluation of new equipment or technology. The utility needs to have an openness to take some risk within the confines of the regulatory world in which it operates.

It's important that the partners understand each other's world views. Utilities need to understand how quickly startups work and their tight timelines, and startups need to understand that utilities must comply with various regulations when testing or evaluating technologies.

The startup needs to be able to make the business case that its technology will offer cost savings or increased revenues or profits for the utility, without adding unnecessary risk. For example, Tagup's monitoring platform can save millions of dollars in maintenance costs if it identifies a failing transformer, and the utility can address that degradation before a catastrophic failure occurs.

Greentown Labs and other organizations like us across the United States are in a position to help guide partners and facilitate mutually beneficial introductions. We're matchmakers for startups and utilities. We make sure that the startup is ready for a partnership with a utility and that the utility is ready for a partnership with the startup.

"The number-one key to a successful partnership between startups and utilities is that the utility has a technology scouting group as well as decision maker in asset management—someone at a senior level that will support and authorize testing and evaluation of new equipment or technology."

EJ: What technology trends are you seeing with potential to transform the electric power sector?

Reichert: Based on the startups we've received applications from over the past year or so, along with current applications, we've noticed a clear trend related to energy storage. Ten years ago there was a lot of innovation in battery materials and chemistries. Today, many of those companies still exist, but energy storage companies are more focused on systems. For example, they are developing hardware and software to control, monitor, and collect data from energy storage systems; our member Sparkplug Power is developing systems to optimize grid energy storage.

We're seeing many companies developing software, algorithms, and data analytics to support grid operations. One Greentown Labs company, NewGrid, has software to help operators route power around congested areas of the grid by switching high-voltage circuit breakers.

"Utilities need to understand how quickly startups work and their tight timelines, and startups need to understand that utilities must comply with various regulations when testing or evaluating technologies."

There's also a lot of work happening to develop control technology for microgrids, but the challenge is that we don't have demonstration facilities where we can easily test new products. I'm hoping that the utility industry will step in to help with that.

EJ: Given your exposure to technologies in diverse aspects of power generation, delivery, and use, what might the electric power system look like in 10 years?

Reichert: Based on my experience, what the grid looks like 10 years from now will depend on how the federal government prioritizes infrastructure upgrades. Investing nationally in grid infrastructure could be a great opportunity for a much smarter grid that enables more renewable and distributed energy at a larger scale. In addition to more infrastructure such as transmission and distribution, updating grid security is an important part of this. This needs to be a federal priority because so many interconnected states are involved. A national-scale grid upgrade is the best outcome and would not only enhance security, reliability, and resiliency, but also create many jobs and stimulate economic development.

Texas is an interesting case study of what could happen nationally if we put a lot of eggs in the infrastructure basket. Over the last 15 years, the state has built a great deal of infrastructure to enable significant wind power.

A less ideal scenario would be to continue limping along with the grid we have. It may support a certain amount of renewables but was not designed to interact effectively with small-scale, distributed energy resources.

"Based on my experience, what the grid looks like 10 years from now will depend on how the federal government prioritizes infrastructure upgrades."

EJ: You have a plan to double the size of Greentown Labs. Discuss the vision for this expansion and its implications for technology innovation.

Reichert: In just five years, we've grown from four startups to nearly 60, and we see the need to accommodate even more companies, many of which are developing innovative technologies applicable to the electric power sector. We're viewing our expansion with a global perspective, understanding that not all the technology being deployed in the United States needs to be developed in the United States, and not all the technology developed in the United States needs to stay in the United States. With our new center, we want to facilitate interactions and sharing of ideas among innovators from around the world, so that technology can move as freely as possible between countries. For example, we might host startups from different countries for six months or send domestic startups to India, China, or Brazil to test and deploy technologies that can promote broader access to energy in emerging markets.

Around the world, there's a huge need for more incubator organizations to connect startups with industry expertise. By hosting startups from different countries, we want them to take the idea of a strong startup community back to where they came from and let that be a seed for new startup communities.

Shaping the Future

Generation Clean

Now Is the Time to Develop and Test Technologies for Producing Cleaner Energy

By Chris Warren

Can a crowded, energy-hungry world be clean?

Yes, but it will require sustained investment and innovation across the gamut of electric generation and other advanced energy production technologies.

With the world's population growing and urbanizing rapidly, EPRI's Integrated Energy Network outlines a pathway to meet growing demand for energy services without sacrificing the clean water and air that are essential to human health and a high quality of life. A critical part of this pathway is producing cleaner, affordable energy through more efficient, environmentally sustainable, and flexible generation.

While nuclear, fossil fuel, and renewable electricity generation have great potential to help achieve this goal, each faces significant challenges. Wind and solar capacity have soared over the past decade but still represent just 3% of global electricity supply, and their hour-to-hour, day-to-day, and seasonal variability place fundamentally new requirements on the electric system.

While deploying rapidly in some regions of the world, reliable, zero-emissions nuclear power faces an uncertain future in many countries with an aging fleet, difficult financing for new construction in the United States and Europe, and economic challenges in competitive markets with low natural gas prices and significant supply of renewables.

In recent years, abundant natural gas has been essential in creating a cleaner energy system in the United States and other regions. To achieve even tighter environmental standards, carbon capture, utilization, and storage are critical to cutting emissions from fossil generation. However, technology demonstrations have been very limited, and investment has lagged because of a lack of viable business models and policy frameworks that could help drive their introduction.

Non-electric technologies will likely play a key role in providing some energy services in a cleaner energy future. Key challenges for clean hydrogen are cost, safety, and delivery while key questions for biomass and biofuels are cost and sustainable fuel supply.

In addition to producing cleaner energy, all energy sources will have the opportunity to improve economics and enhance system flexibility by providing new products. For example, fossil and nuclear plants can produce steam and heat for certain applications, while wind and solar plants can provide grid balancing services.

To help address these challenges, EPRI identified key R&D needs for producing cleaner energy:

- Develop next-generation renewable technologies that can respond to grid and market conditions more rapidly and reliably.
- Anticipate and address environmental issues associated with renewable technologies.
- Advance forecasting tools, communications and controls, diverse energy storage options, demand response, and market mechanisms to sustain the system's efficient, reliable operation as variable renewable resources are added.

- Demonstrate low-emission fossil power cycles, carbon capture and storage, and develop the policies, business models, and regulations required to support them.
- Develop new nuclear designs, along with the policies, market reforms, and business models needed to support both new and existing plants.
- Address challenges related to bioenergy (such as production, controls, and fuel supplies) to advance its deployment with carbon capture, utilization, and storage.
- Advance the role of hydrogen as a clean carrier of energy, including clean hydrogen production, safety, and business models for developing a hydrogen infrastructure.
- Advance flexible operation of all generation technologies, including fast ramping, advanced inverters, and long-term storage.

The Three Pillars of the Integrated Energy Network

The Integrated Energy Network provides EPRI's perspective on the future of energy. Research needs are identified for each of three supporting pillars:

- **Using affordable, cleaner energy through efficiency and electrification:** focuses on the opportunities and challenges—both technical and institutional—involved with scaling the use of cleaner energy sources.
- **Producing cleaner energy:** details the potential of cleaner electric generation technologies—renewable energy, nuclear power, and fossil-fueled generation with carbon capture—along with promising non-electric technologies.
- **Integrating energy resources:** examines how new technologies and markets must be tapped to better integrate the electricity, gas, water, and transportation systems.

EPRI invites you to share your ideas and approaches for addressing each of the three pillars.

Innovation

A Sunny Forecast

EPRI Tool Helps Utilities Prepare for Influx of Solar

By Chris Warren

These days, evidence of the rapid transformation of the electric power system is anything but abstract. GTM Research and the Solar Energy Industries Association (SEIA) report the installation of more than 4,000 megawatts of solar photovoltaic (PV) capacity in the United States in the third quarter of 2016—a nearly 200% increase compared with third quarter in 2015.

To help distribution grid operators accommodate this growth safely, reliably, and efficiently, EPRI and eight member utilities developed a tool that can forecast residential PV adoption in their service territories over the next 10 years. Numerous models can forecast market penetration of products and technologies, but until now none have been PV-specific.

"If you have good forecasts for the timing, location, and speed of PV adoption on particular circuits and can estimate the circuits' hosting capacity, you can determine how quickly you'll need to upgrade them to accommodate the PV or whether you can defer investment based on the PV's ability to serve load growth," said EPRI Principal Project Manager Nadav Enbar, who helped develop the tool.

With a better understanding of PV adoption rates, utility planners can consider such options as incentives for installations on circuits that can handle the resulting increased two-way power flows.

Building a Forecasting Tool

EPRI used a research approach known as a discrete choice experiment to develop the tool. Researchers identified solar installation attributes that influence consumers' decisions, including type of financing, location on a utility customer's roof or community site, greenhouse gas emissions reduction, and cost savings.

The attributes were tested with a focus group and then used to develop questions for surveys administered to more than 2,500 customers in the service territories of the eight participating utilities. The survey's 28 questions included basic queries about income and residence size along with various solar options. The results were used to build a "choice model" for determining the combinations of attributes likely to drive customer preferences. The PV forecast adoption tool is based on this model.

"We would like to engage other utilities, survey their service areas, and use the results to make the model more robust."

"By pairing the model with ZIP Code–level demographic data from the U.S. Census Bureau as well as historical adoption data, we can also look at how demographics impact someone's willingness to purchase a solar system," said EPRI Senior Project Engineer Steven Coley.

The forecast tool also factors in falling solar prices. "We can get a sense of people's willingness to pay for solar given a set of attributes," said Coley, who worked on the tool. "You can vary the cost in the future and see how that willingness changes."

Improving and Expanding the Forecasts

The eight participating utilities will be the first to use the tool, which incorporates preferences and demographic data from their customers. Based on estimated annual solar-related costs and savings that PV provides for their residential customers, the utilities can determine the likely number, timing, and location of new solar installations, through direct purchase or lease, or as part of a community solar project.

"Based on user-defined costs, savings, and other inputs, the tool can output the number of customers in each ZIP Code that are likely to adopt solar each year," said Enbar.

After refining the tool based on feedback from these utilities, EPRI in 2017 will release a more generic version for other utilities.

"The generic version will incorporate the same data on customer preferences as the current tool, but will use statewide demographic information rather than ZIP Code–level data for more general solar growth forecasts," said Enbar. "We would like to engage other utilities, survey their service areas, and use the results to make the model more robust."

Another potential refinement is to incorporate market data linked to why people adopt solar. "There's an opportunity to make the tool more robust by supplementing stated customer preferences for potential purchases with data on drivers for actual purchases," said Coley.

Similar tools may also be developed to forecast the adoption of commercial PV and electric vehicles.

Key EPRI Technical Experts

Nadav Enbar, Steven Coley

In Development

A Portable Laboratory for Catalysts

EPRI Test Facilities Help Utilities Optimize Emissions Reductions at Coal Plants

By Chris Warren

Selective catalytic reduction reactors are among the most important tools for reducing nitrogen oxide (NOx) emissions from coal-fired power plants. Located between the boiler and air preheater, the reactors use a catalyst material—often a honeycomb-like ceramic substrate—that can eliminate more than 90% of the NOx from a plant's flue gas stream. For optimal performance, ammonia is mixed with the flue gas before it reaches the reactors. The reactors offer an additional benefit: They oxidize mercury so that it can be captured in a coal plant's wet scrubber.

The effectiveness of NOx and mercury removal depends on the formulation and condition of the catalysts, which can last several years before being replaced. Over time, the catalysts' pores can get clogged with contaminants in the flue gas. Utilities typically monitor catalysts by periodically removing samples from the reactors and sending them to a lab for tests. Because it is prohibitively expensive to generate a coal-fired flue gas, labs burn natural gas in testing, and the resulting flue gas does not contain the fly ash present in a coal-fired facility.

"It doesn't have the ash, and that is the question mark," said EPRI Principal Project Manager Tom Martz. "The ash may or may not do some funny things when it comes to the behavior of the catalyst."

Taking the Lab on the Road

To provide insights on a range of catalyst performance issues, EPRI developed two portable catalyst test facilities that can be set up at a coal power plant in just a few days. They pull a flue gas "slipstream" from the power plant, divert it for testing, and then return it to the plant.

"The portable facilities enable us to test catalyst samples in an operating coal flue gas environment, complete with fly ash," said Martz. "Because the facilities are portable, we can evaluate catalysts at different plants with a variety of coals and operating conditions. We can provide site-specific information for plant catalyst managers."

In their inaugural application in October 2015, EPRI used the facilities to compare the effectiveness of a standard new catalyst with a regenerated one.

"Regenerated catalysts are less expensive than new ones," said Martz. "The utility wanted to know whether the regenerated catalyst was doing its job in terms of reducing NOx and oxidizing mercury. To vet the many replacement options and make informed purchase decisions, plant catalyst managers need independent catalyst performance data collected from operating power plants."

For another utility, EPRI in 2016 conducted an on-site, side-by-side comparison of a more expensive advanced catalyst with a conventional one. "There's no independent data on field performance to decide whether it's worth paying a premium for the advanced catalyst," said Martz. "The portable test facilities are perfect for answering this question."

Because the price and comparatively low emissions of natural gas make it so competitive, many coal plants are being asked to cycle more often and operate at low loads. In late 2016, EPRI used the portable facilities to examine how this affects catalyst performance.

“Operating at a lower load may require selective catalytic reduction reactors to run at lower temperatures, but catalyst vendors set a minimum operating temperature to protect the catalyst,” said Martz. “This can limit the load drop on large coal plants by as much as 100 megawatts, which is huge for utilities in terms of revenue and flexibility.”

Vendors are concerned that ammonium bisulfate may form in the catalyst pores at lower temperatures, potentially impairing catalyst performance. But EPRI research has demonstrated that the temperature at which ammonium bisulfate forms can be lower than what vendors assert.

“Observations during EPRI’s portable facility tests, combined with previous EPRI research, provide greater clarity regarding ammonium bisulfate formation,” said Martz. “They show that the minimum operating temperatures may be safely lowered in many cases. We are now able to give practical guidance to plant managers for operating the reactors at lower loads.”

“Our goal with the test facilities is to inform the industry so that plant managers have more flexibility,” said Martz.

Key EPRI Technical Experts

Tom Martz

Innovation

Taking the Heat

EPRI Examines Sensors That Can Withstand Harsh Environments in Gas Turbines

By Scott Sowers

EPRI is evaluating more rugged sensors to monitor natural gas turbines and help optimize operations of current and next-generation facilities.

Demand for natural-gas-fired generation is growing in North America, driven by low prices and ease of deployment. Some combined-cycle units are cycling more frequently or operating for more hours than they were designed to operate, challenging reliable operations. This has spurred efforts to enhance monitoring of the performance and condition of online units using sensors that measure various parameters—temperature, fuel flow, fuel pressure, air flow, air pressure, exhaust gas flow, fuel quality, and exhaust gas constituents.

A key consideration: Sensors must be able to withstand temperatures up to 1300°C—and even higher in the turbine's combustion zone—while providing accurate readings.

"Traditional electronic sensors fail quickly if exposed to high temperatures, so they are not usually viable options for the combustion zone of a gas turbine," said Principal Project Manager Susan Maley. "We need materials and designs that can sense temperature and pressure changes and other parameters at extreme temperatures for extended periods of time."

To protect today's sensors from high temperatures in gas turbines, they are often placed in "standoff tubes" located a certain distance away from areas being monitored, reducing measurement accuracy. The tubes also can lead to false readings as a result of condensation buildup.

One particularly important indicator of gas turbine operations is dynamic pressure. But at high temperatures and pressures, direct measurement is difficult. There are no accurate, commercially available sensors that can withstand combustion temperatures.

Operators often indirectly determine combustion temperature and other difficult-to-measure parameters by making calculations based on easier-to-measure parameters.

"We can back-calculate and make estimates, but these are not as accurate as direct measurements," said Maley.

Scanning the Sensor Technology Landscape

Researchers outlined measurement needs in the various parts of a natural gas turbine, including the compressor, combustion zone, and turbine. To meet these needs, they identified commercially available and emerging sensor technologies developed for the power generation industry and other industries such as aerospace. EPRI is tracking innovations at organizations such as the Propulsion Instrumentation Working Group, Air Force Research Laboratory, NASA, and the U.S. Department of Energy.

EPRI is looking at advances in wireless micro-sensors the size of a penny, sensors made of heat-tolerant ceramics, lasers that act as sensors, and fiber-optic sensors.

According to Maley, fiber optics are especially promising. "They sense and send signals using light transmission, rather than electronics, so viability in a turbine's hot zone is a worthwhile research and development effort," she said.

Correct turbine blade operation is vital, and EPRI is evaluating sensors that measure blade dynamics, which include vibration, strain, clearances, tip deflection, and timing.

"The blades are designed to have some flex. But under certain conditions, their resonant frequencies can become excited, and the blades can break off," said EPRI Senior Technical Leader Bobby Noble. "This can cause many other blades to fail and lead to a 'corn-cobbing' effect on the turbine's compressor section, which can cost millions of dollars to fix."

The next step is field evaluations of promising technologies. EPRI also will continue evaluating new sensors in collaboration with the Georgia Institute of Technology. A report on key findings is expected in 2017.

"With better sensors, we can positively impact turbine performance, efficiency, and reliability," said Maley. "We hope to identify a few options that can benefit the industry and the public through more reliable and less expensive generation of electricity."

"Just like with personal computers, sensor technology is making the impossible possible," said Noble. "What once was thought to be too hot or too hard to get to is now possible."

Key EPRI Technical Experts

Susan Maley, Bobby Noble

In The Field

Knocking the Dust Off

Pressure Wave Cleaning Offers Potential New Option for Power Plants

By Sarah Stankorb

Two workers feed a hose-like lance capped with a plastic balloon into a power plant's heat recovery steam generator (HRSG), maneuvering around tight spaces between tall bundles of tubes caked with yellow debris. Meanwhile, an engineer sitting at a computer at the other end of the lance has mapped out the HRSG on a grid. The computer controls the delivery of an ethane-oxygen mix through the lance to inflate the balloon. When the balloon is positioned at the proper grid coordinates, the engineer ignites the gases inside. The pressure wave rattles the HRSG components with a boom and dislodges debris, which settles to the bottom of the HRSG.

This new process, called pressure wave cleaning, shows promise for reducing plant operational costs and enabling less expensive, more reliable electricity.

Cleaning Tubes: An Important Job

People who like their music turned up loud have probably noticed their windows rattle with the beat. They're enjoying the vibratory force of a pressure wave, which is similar to that caused by the ignited gases in the HRSG. In this case, the wave vibrates tubes just enough to rattle off debris.

Over time, power plant performance depends on keeping tube bundles clean in both coal-fired boilers and HRSGs. Tubes in HRSGs pick up heat from the plant's combustion turbine for reuse in spinning steam turbines. When those tubes become fouled—by ammonia, sulfur, or rust—the resulting back pressure can damage the turbine and increase heat rate, leading to lost energy and higher generation costs.

According to EPRI Program Manager Bill Carson, tube bundles typically need cleaning after a few years in service, and traditional methods include chemical cleaning and groom ice cleaning. Many plants' permits prohibit disposal of wastes from chemical cleaning, and groom ice cleaning requires significant work hours and resources to build scaffolding and complete the job. Considering that each approach can have drawbacks, EPRI is examining the effectiveness of pressure wave cleaning to provide utilities with another option to consider.

Pressure wave cleaning requires no labor-intensive scaffolding construction. Swiss company Bang & Clean developed the technology and in 2015 successfully tested it on an HRSG at ESB's Dublin Bay Power plant in Ireland. GE has licensed the technology in the United States.

EPRI has played a key role in bringing the technology to the United States and facilitating industry collaboration. In 2015, ESB personnel presented on their field experiences at EPRI's Boiler Reliability Interest Group meeting attended by dozens of utilities, and the group recommended that EPRI spearhead a project to test the technology in the United States. In subsequent tests in an HRSG at TVA's Southaven Combined-Cycle Plant, inspections by TVA and EPRI indicated that no component damage occurred.

Successful Demonstrations in the Southeast

Jacob Pursley is an operations technician and HRSG system owner at a power plant in the U.S. Southeast. A few years ago, a round of groom ice cleaning helped the plant to reduce problems with back pressure. "We pulled out a few tons of debris from each unit, and we thought, 'Hey, we're good to go,'" recalled Pursley.

But after three months offline during a rainy fall and a major outage, fouling again accumulated on the HRSG tubes, and back pressure increased to unprecedented levels. "I was concerned that if we went back in there with ice cleaning, had all the people in there, put up all the scaffolding, racked up all the man hours, and banged up all the tubes again—would we get the results we needed?"

After reviewing EPRI data on pressure wave cleaning, Pursley and the plant's management team decided to test GE's PressureWave Plus™ technology. The previous round of groom ice cleaning required 20 work days (10 days, two shifts each day) to clean three modules in each HRSG. Using pressure wave cleaning, the team also cleaned a fourth module that could not be reached by scaffolding, completing the entire job in 14 work days (one shift each day)—including two days for a vacuum truck to remove debris.

"The safety side of it is that nobody is inside the HRSG when it's going on, and you have none of the hazards with constructing scaffolding inside the HRSG," said Pursley.

With chemical and ice cleaning, personnel must enter the HRSG to perform the cleaning, increasing risk of injury. (To EPRI's knowledge, there have been no reported injuries as a result of these methods.)

With respect to efficacy, tests at Pursley's plant demonstrated that pressure wave cleaning can reach deeper into tube bundles and clean sections unreachable by other methods.

"Our units are near design level now," says Pursley. "It's like we just put in two brand new HRSGs."

The Work Ahead

A preliminary finding from these and other field tests since 2015: In the near term, it appears that pressure wave cleaning does not result in cracking or other adverse metallurgical impacts in tubes, liners, and other HRSG components. With the Colorado School of Mines and other partners, EPRI will follow the development of this technology and continue field testing to confirm that there are no such short-term effects. It will also examine potential long-term effects on component integrity and plant reliability.

Pressure wave cleaning must be done when the plant is offline, but that could change.

"There is potential for online cleaning in conventional boilers," said Carson. "EPRI will be looking into that with Bang & Clean."

EPRI also will examine pressure wave cleaning for air heater baskets, electrostatic precipitators, wires, and other boiler surfaces.

"It's premature to say that pressure wave cleaning is superior to other methods," said Carson. "EPRI is still researching the technology and its possibilities. But early results show that it could offer the industry new options."

Key EPRI Technical Experts

Bill Carson

Technology At Work

Maximizing Reliability of Instrumentation and Controls

EPRI Collaborates with Chinese Nuclear Utility to Transfer Insights from Successful Reliability Program

By Scott Sowers

An EPRI report documents an innovative program at China General Nuclear Power Corporation (CGN) that has significantly reduced the frequency of unplanned reactor shutdowns related to instrumentation and control (I&C) equipment failures. The product of a two-year collaboration between EPRI and CGN, the study offers insights and lessons to nuclear operators worldwide.

I&C equipment serves as a nuclear power plant's central nervous system, measuring and controlling various parameters for safe, reliable operations. While most printed circuit cards that reside in the equipment continue to work well, the nuclear industry has observed that more circuit cards are failing, leading to unscheduled shutdowns, lost revenue, and other operational problems for power producers.

"Failure rates have increased primarily due to component aging and improper storage and handling," said EPRI Technical Leader Stephen Lopez.

A New Program to Reduce "Scrams"

Beginning in the late 1990s, CGN plant workers noticed an increased frequency of unplanned shutdowns, or "scrams," attributable to failing circuit cards and I&C equipment.

"I&C reliability was the main contributor to scrams in our nuclear power plants," said Ma Shu, a chief engineer with CGN. "We discovered that these issues created 70% to 80% of our unplanned outages, many of which occurred at peak demand."

To reduce these scrams, CGN developed and implemented an I&C aging management program, with positive results: While there was an average of nearly six unscheduled shutdowns per year in the late 1990s as a result of I&C equipment failures, no such incidents were reported from 2003 to 2013.

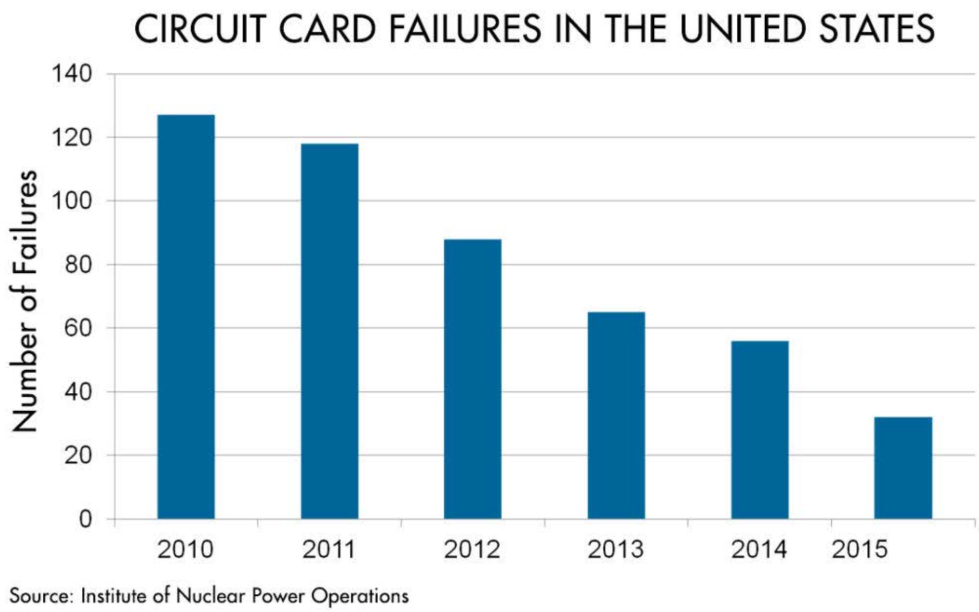
The program categorizes components based on how essential they are to reliable operations along with their aging characteristics, then tracks failure rates throughout the life of the equipment. Different strategies are assigned to each category and stage of equipment life to help prioritize testing, monitoring, and maintenance. CGN also developed technical standards and technologies to diagnose degradation and faults in circuit boards and other I&C components, including power supplies, fuses, and relays.

The program's other key aspects include:

- A database for tracking equipment status, test history, and operating experience
- Monitoring plant environmental conditions, such as temperature, humidity, and radiation
- Preventive maintenance and replacement of critical equipment with spare parts

After CGN joined the Instrumentation and Control Program in EPRI's Nuclear Sector in 2014, EPRI researchers made a series of visits to China to learn how the program reduced I&C-related reactor and turbine trips and to collaborate on technology transfer.

"The best way to reduce circuit card and circuit card–related I&C failures is to study reliability, develop a program that monitors components and mitigates failures, and then implement and track the program," said Lopez. "CGN dedicated funding to long-term planning and resource development that supported new laboratory testing facilities and highly qualified staff to operate and manage them. Another strength is CGN's use of metrics to benchmark the performance of its reliability program against other such programs."



Since EPRI launched its Gold Card project, the number of circuit card failures has significantly decreased.

"It's our honor to become a member of EPRI. We are delighted to see CGN working with EPRI on technical collaboration," said Ma Shu.

EPRI has been examining I&C reliability and circuit card issues in nuclear plants for more than a decade. Published in 2010 and updated in 2011, EPRI's "Gold Card" report provides information on degradation mechanisms and failure risks for I&C circuit cards, along with best practices to prevent failures.

The nuclear industry has used the Gold Card report and other guidance to improve circuit card reliability, as demonstrated by declining circuit card failures reported to the Institute of Nuclear Power Operations (see chart). CGN has used the EPRI guidance to enhance equipment storage, refurbishment, and processes to control electrostatic discharge. As another example, FirstEnergy has applied it to reduce "infant mortality" failure (occurring shortly after components are installed) and to improve its circuit card refurbishment process (see p. 34 in the Winter 2014 issue of *EPRI Journal*).

"Through the exchange of information and technology, EPRI continues to help address challenges facing the nuclear industry by bringing together its members and diverse scientific and technical communities," said Lopez.

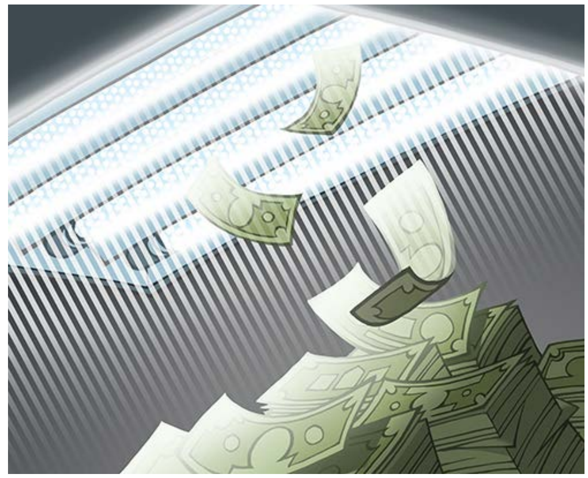
Key EPRI Technical Experts

Stephen Lopez

R&D Quick Hits

Gigawatt-Hour Savings in Store?

Study: LEDs Can Replace Fluorescent Lights with Equal Performance and High Efficiency



An EPRI study indicates that utilities should consider linear light-emitting diode (LED) lamps and troffers for rebates and incentives in their energy efficiency programs to replace linear fluorescent lights in the commercial sector. The switch offers significant energy savings with adequate light levels and payback.

Researchers scanned the LED market for potential fluorescent light replacements and examined 20 products in EPRI's lighting laboratory, measuring light output, efficacy, illuminance, energy savings, and payback. LED lamps offered energy savings of 25–61% relative to fluorescents. LEDs in dimmable troffers provided 28–36% savings at full output and 47–53% savings when dimmed to match the fluorescents' luminous flux.

Based on energy savings, LED lamp payback is 1–5 years, while payback for the more expensive troffers is 10–12 years. If LEDs last longer than fluorescents as manufacturers claim, reduced maintenance costs could shorten payback.

Because of varying LED product designs, the authors recommend that utilities vet products before providing rebates. They point to additional potential energy savings when dimmable LED troffers are combined with networked controls and demand response programs.

For decades, linear fluorescent lights have dominated U.S. commercial and industrial lighting. Replacing them with LED products offers the potential to save thousands of gigawatt-hours per year.

R&D Quick Hits

Driving Cleaner Air in the Tennessee Valley

EPRI Study: Driving EVs and Off-Road Electric Equipment Could Improve Air Quality

By 2030, deployment of electric vehicles and off-road electric equipment can lead to modest, but widespread, emissions reductions and air quality improvements in the service area of Tennessee Valley Authority (TVA), according to an EPRI study.

Using an EPRI model and TVA market data, researchers projected that in 2030, electric vehicles would account for 9% of vehicle miles in the TVA region, and various types of electric off-road equipment would capture market share ranging from 17% to 85%. Based on this, they modeled the impacts on air quality and emissions. Main findings:

- Ozone decreases across the region, including reductions of up to 1 part per billion in urban areas. This is significant given the stringency of the National Ambient Air Quality Standards.
- Nitrogen oxide (NOx) emissions decrease by 3%, with 44% of the reduction coming from off-road electrification.
- Volatile organic compound emissions decrease by 5%, with 65% of the reduction coming from off-road electrification.
- Particulate matter emissions decrease by 1%, mainly in urban areas and along interstates in eastern Tennessee, with 79% of the reduction coming from off-road electrification.

Electrification more extensive than that modeled in the study could reduce emissions more significantly. The TVA results mirror those of a 2015 EPRI-Natural Resources Defense Council study that quantified nationwide air quality benefits from increased vehicle electrification.

R&D Quick Hits

What Might the Electricity Mix Look Like in 2030?

EPRI Models 13 Scenarios to Examine Key Uncertainties

Between 2015 and 2030, coal's share of the U.S. electric generation mix could decline significantly, while natural gas's share is likely to grow, according to a recent EPRI study.

Using EPRI's U.S. Regional Economy, Greenhouse Gas, and Energy (US-REGEN) model, researchers examined 13 scenarios, including low and high natural gas prices, flat and increasing electric load, low-cost utility-scale solar photovoltaic technology, refurbishment costs for aging coal- and natural-gas-fired plants, potential paths to implement the federal Clean Power Plan, and other policies to reduce CO_2 emissions in the U.S. electric sector. Key insights:

- Between 2015 and 2030, coal's share of the U.S. generation mix could decline from 33% to less than 25% if natural gas prices remain low, new federal climate policies are enacted in addition to the Clean Power Plan, or aging coal units face significant refurbishment costs.
- New natural gas generation remains a significant part of the U.S. generation mix in most scenarios, including those with a stringent CO_2 emissions cap, and is expected to grow significantly in some scenarios. The main risks are high natural gas prices and targeted regulation to reduce dispatch or deployment of natural-gas-fired units.
- Relative to natural-gas-fired generation, renewable generation from utility-scale wind and solar power remains economically uncompetitive in most scenarios without CO_2 policies, even with a 17% reduction in capital costs for onshore wind between 2015 and 2030. This result is driven by the assumptions of low natural gas prices, expiring tax credits, and no further increases to state renewable portfolio standards.
- Existing and new nuclear generation are expected to be competitive in scenarios with significant CO_2 reduction requirements or high natural gas prices.

R&D Quick Hits

Time to Plan for the Future Workforce

Knowledge related to nondestructive evaluation (NDE) in nuclear plants needs to be preserved and transferred to a new generation of workers, or it will be lost, an EPRI study concluded.

A 2016 survey of major NDE personnel providers for the nuclear industry found that:

- About half the workers are older than 45, and about 25% are older than 55.
- Since 2014, the size of the workforce has declined by 3% each year.
- Trainees and workers with entry-level certifications account for 6% of the workforce—not enough to fill the gap left by retiring workers with higher level certifications.

Over the next 10 to 20 years, half of the NDE personnel will potentially leave the workforce. To sustain safe, reliable operations of the nuclear fleet, the authors say that it is essential for industry stakeholders to collaborate on recruitment of new personnel for NDE careers.

R&D Quick Hits

Go with the (Better) Flow?

Study: Highly Fluid Concrete Can Reduce Time and Labor of Nuclear Plant Construction

Self-consolidating concrete offers potential to significantly reduce time and construction costs associated with placing concrete for nuclear power plants, according to an EPRI study.

Photo of construction of Vogtle Unit 3 courtesy of Georgia Power.

When conventional concrete is placed, technicians must temporarily liquefy it with vibrators so that it flows around obstacles and fills forms. This is particularly labor-intensive work in building nuclear plants' complex structures with reinforcing steel. Developed in Japan in the mid-1980s, self-consolidating concrete contains chemicals that promote fluidity and stability and has been used successfully in commercial and industrial buildings and nuclear plants in the United States and China. When placed in one area of a concrete form, it flows throughout the form without the use of vibrators, potentially reducing time and labor.

Laboratory tests determined that it has slightly higher compressive strength relative to conventional concrete, given comparable water-cement proportions. Self-consolidating concrete exhibited slightly more shrinkage and slightly less splitting tensile strength. In test molds for power plant foundations and walls, self-consolidating concrete flowed freely through complex structures (see video).

As with conventional concrete, researchers found that careful selection and proportioning of ingredients can help avoid problems such as segregation. Different mixtures may be needed for different plant structures.

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