THE CHALLENGE OF
NUCLEAR FUEL RELIABILITY

by Taylor Moore
The current fleet of U.S. nuclear power plants produces some of the country’s most economical electric power, largely because of the relatively low cost of nuclear fuel. But new operating strategies aimed at enhancing plant and fuel performance have also led to increased fuel failures in recent years—a problem that threatens nuclear’s cost competitiveness. In response, EPRI has restructured its nuclear fuel reliability activities to more-effectively pursue mitigation techniques and identify root causes for the industry’s toughest fuel problems. The collaborative, international effort—involving nuclear plant operators, fuel manufacturers, and fuel service providers—seeks to better quantify operating margins, provide insights leading to advanced fuel designs, and eliminate fuel failures. The ultimate goal is zero fuel defects.
The relatively low and stable cost of uranium is one of the key factors that make the nation’s current fleet of 103 operating nuclear power plants economically competitive with other sources of electricity. The cost of fuel as a percentage of total production cost is about 25% for nuclear, while ranging from 70% to 90% for coal- and gas-fired generation.

Throughout the history of commercial nuclear power, fuel-cycle economics have continually improved as fuel manufacturers have introduced advanced, more highly enriched and higher-burnup fuel and as nuclear plant operators have come to use increasingly longer fuel cycles. Since the 1990s, both burnup and cycle length have increased by more than 50%. These increases have allowed nuclear plants to operate more efficiently and produce more electricity. The gains have saved nuclear plant operators—and consumers of the electricity—more than $1 billion a year through increased power production and reduced costs for spent fuel storage and eventual disposal. The operating changes have also resulted in more-efficient use of uranium resources.

But the long-term performance and reliability of precision-engineered and precision-manufactured commercial fuel—operating several years inside a light water reactor core under high temperature and pressure as well as intense radiation—can directly affect a nuclear plant’s cost of producing electricity. Fuel failures can jeopardize the competitive advantage of nuclear power’s low production cost through lost generation, increased inspection and repair costs, and the premature discharge of fuel assemblies, which alone can be substantial (the replacement cost of the fuel in a single plant is on the order of $150 million to $200 million). Fuel failures can also contribute to increased plant background radiation, which impacts plant outage operations, where minimizing worker exposure is a primary concern. (After all, nuclear fuel cladding is the first of three engineered barriers designed to prevent the environmental release of radioactive fission products.)

That is not to say fuel failures pose a plant safety issue; their number and extent remain well within accepted safety and licensing limits. The primary impact remains economic: fuel failures affect both the operating cycle and such downstream issues as spent fuel storage, transportation, and disposal. Fuel failures can also influence public acceptance of nuclear power.

Considering that a typical reactor contains more than half a million fuel rods, defect-free operation is a real challenge, and the fuel’s operating environment adds to the challenge. With peak temperatures higher than 1000°C, the fuel is by far the highest-temperature component in the steam supply system. The fuel is also subjected to the highest radiation fields, where neutrons passing through the cladding literally knock atoms out of their way. At the end of a fuel rod’s life, most atoms in the cladding have been displaced once or twice, and the cladding microstructure can be substantially changed. Despite the challenging environment, the industry continues to expect, and strive for, zero defects.

Problems Arise

A steady increase in fuel enrichment, burnup, and operating cycles over the last 15 years has enhanced the economics of BWRs. But these operating changes, along with modifications to the water chemistry environment, have also led to an increase in fuel failures. PWRs have experienced similar problems.
fuel cycles, higher burnup, low neutron leakage, new core reload strategies, and plant upratings.

But other factors contribute to fuel reliability problems as well. For example, as the plants themselves have aged, they have experienced a number of materials-related problems, such as stress corrosion cracking, in piping and components in the reactor vessel, primary cooling system, and other areas of the plants. Operators have generally modified a plant’s water chemistry to control or limit such corrosion and cracking: the addition of lithium to the PWR primary coolant will raise its pH, the addition of zinc can reduce the plant’s corrosion source term, and additions of noble metals can alter the coolant’s electrochemical potential to inhibit stress corrosion cracking. Many of these changes, initiated to improve balance-of-plant performance, may further increase demands on the fuel.

Explains Chuck Welty, director of EPRI’s nuclear materials and chemistry department, “As the industry strives to address degradation and aging in other components exposed to primary coolant, it is important to consider alternative water chemistry regimes. But it is also essential that the impact of any proposed changes on fuel performance be fully understood.”

Rosa Yang, technical executive for EPRI’s Fuel Reliability Program, agrees: “While the industry has been increasingly pushing fuel to higher enrichment, higher burnup, and longer operating times, we have also been operating fuel in continually changing water chemistry environments that have turned out in some cases to have unpredicted, unintended consequences on fuel performance. To develop effective solutions to fuel reliability problems, we have to consider the interactive effects of all the variables involved—fuel design, duty cycle, coolant chemistry, crud buildup, and so on.”

The buildup of corrosion products on the fuel cladding surface has proven to be particularly significant for both BWRs and PWRs. The high temperature of the cladding surface attracts impurities and chemical additives in the reactor coolant that deposit on the fuel rod surface in a process not unlike what occurs in a tea kettle. The deposits on a fuel rod, known as crud, can be tenacious, insulative compounds capable of increasing the local clad temperature and accelerating clad corrosion—sometimes to the point of fuel failure.

The difficulties in quantifying such effects have contributed to a number of surprises. Some of these are actual fuel failures, such as corrosion failures in BWRs, power change–induced failures and crud-induced failures in both BWRs and PWRs, and severe degradation of failed fuel in a few plants. Other surprises have been operational difficulties, such as unanticipated changes in the power profile of some PWR cores—known as axial offset anomaly (AOA)—as a result of crud deposits on fuel. Both BWRs and PWRs have also experienced difficulties with control rod insertion as a result of fuel assembly or fuel channel deformation.

“These surprises have been recognized by the industry and EPRI as having the potential for adverse cost impacts, since they could result in plant deratings, operational restrictions, or unscheduled outages for repairs,” notes Yang. Several recent fuel failure events at U.S. nuclear plants have cost between $40 million and $80 million each, not including the long-term effects of plant contamination. According to Yang, the most recent data reported by utilities on fuel performance suggest that the downward trend of the previous four years is leveling off, but it is not yet clear that an actual reversal is in sight.

**New Emphasis on Reliability**

In 2003, under the leadership of Jack Skold, former chief nuclear officer at Exelon Corporation—the largest U.S. nuclear power plant operator—a group of industry chief nuclear officers made a number of recommendations for reversing the downward trend in fuel reliability. These recommendations were presented to the chairman of the nuclear industry’s Materials Executive Oversight Group and EPRI’s Fuel Reliability Program—the lead industry fuel R&D organization. The overarching efforts are part of the larger Industry Materials Initiative, which includes fuel reliability in its scope, since water chemistry and corrosion mitigation strategies can affect primary system components and fuel in different ways. “Our fundamental focus is on enabling the industry to optimally balance fuel performance and reliability,” says Yang. “Plant operators have a lot to gain by pushing the fuel,” she adds, “but if the fuel fails, they stand to lose a lot as well.”

To avoid recurring fuel failures, the EPRI program leverages extensive capabilities for fuel failure root-cause investigations, ranging from nondestructive examination of fuel in plant storage pools to transporting fuel to heavily shielded, remotely operated laboratories known as hot cells for destructive examination. A shortage of suitable hot cell capabilities in the United States has in some cases led to the shipment of failed fuel overseas, extending an already long turnaround time for results and analysis. The program is pursuing possibilities for new collaboration with the Idaho National Labora-
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In fact, such collaboration is at the heart of virtually all aspects of the research effort. EPRI’s Fuel Reliability Program is currently supported by all U.S. utility members and more than half a dozen major international nuclear utility organizations, including Electricité de France, UNESA in Spain, Sweden’s Vattenfall, Tokyo Electric Power Company, Taiwan Power Company, and Kernkraftwerk Leibstadt and Kernkraftwerk Mühleberg in Switzerland. The international collaboration brings nuclear plant operators and fuel manufacturers together in a highly leveraged, integrated effort focused on quantifying operating margins, providing insight for fuel designs with enhanced performance, and eliminating fuel failures. The ultimate goal of the industry is zero fuel defects.

The program is working with the Institute of Nuclear Power Operations (INPO) to implement a time-critical fuel failure database, called FRED, to capture timely fuel performance and reliability data. The web-accessed database is the industry’s first comprehensive fuel performance and reliability information resource; now in beta testing, it will be fully online by the end of this year. FRED provides nuclear utilities and fuel suppliers with an accurate, comprehensive, and up-to-date database on fuel performance and reliability.

Sharing Responsibility

Fuel vendors participate directly in the Fuel Reliability Program, which works closely with them to ensure that fuel performs as advertised—a goal that has become more elusive in the current business climate. Years of oversupply in the increasingly competitive and global fuel marketplace, combined with a reduction in the number of fuel assemblies purchased due to higher burnup capabilities of current designs, have depressed prices for nuclear fuel. This, in turn, has reduced spending for R&D and led to the introduction of some new fuel designs that have undergone less-than-adequate testing. While some believe the vendors should pay all the costs of ensuring fuel reliability, most recognize that this expectation is probably not realistic, given current fuel prices. In addition, some fuel performance factors, such as the water chemistry under which the fuel is operated, are clearly more the responsibility of plant operators than of fuel vendors.

EPRI works both sides of the vendor-customer relationship. The costs of most joint efforts are shared equally with the appropriate vendor, giving EPRI members the opportunity to focus both their own resources and those of a vendor in an area of direct benefit to utilities. For vendors, the interaction provides the opportunity to address important areas that might not be addressed otherwise. The Fuel Reliability Program currently has multimillion-dollar efforts under way with all of the vendors supplying fuel in the United States to confirm the margins of existing designs, demonstrate a new fuel design, or resolve a failure root cause.

Another focus of the EPRI model is to better characterize fuel duty/water chemistry interaction so that vendors get the data they need to improve fuel designs and utilities get the data they need to operate the fuel efficiently and fine-tune plant water chemistry. “Zero defects in nuclear fuel can be reached only through teamwork and integration,” notes Yang, “and EPRI’s role is to bring all of the necessary capabilities and resources together to ensure that vendors and plant operators can work effectively toward the common goal.” Such teamwork extends down to the individual plant level to foster understanding between the fuel and water chemistry experts, who sometimes operate in a state of naturally opposing tension with each other.

Challenges and Successes

Despite continuing, evolving technical challenges to achieving zero-defect nuclear fuel performance, EPRI’s Fuel Reliability Program has had some notable successes—R&D efforts that have helped tip the balance in favor of higher performance without sacrificing reliability.

“When fuel failures occur, it’s important to fully understand their root causes in order to avoid future failures of the same type,” points out Kurt Edsinger, senior project manager in the Fuel Reliability Program. “Unfortunately, root-cause investigations typically require destructive analysis of fuel elements in hot cells, and transporting fuel from nuclear power plants to hot cells adds to the time and expense of investigations. Still, if you can identify the root cause of a failure and take actions that minimize or eliminate future problems, it’s well worth the cost.”

In a recent example involving failed fuel from a BWR, the effort paid off in just this way. The hot cell analysis, expedited by EPRI for a fast turnaround, revealed a
A manufacturing defect on the fuel pellet surface that was creating an additional stress on the zirconium alloy cladding, leading to a failure mechanism known as pellet-cladding interaction. As a result of this finding, which could not have been made except through destructive examination in a hot cell, all fuel vendors have changed their manufacturing practices, improving the quality of fuel pellets industrywide and benefiting all fuel users by effectively eliminating a common fuel failure mode. EPRI's involvement facilitated a rapid feedback loop that helped avoid costly operating restrictions on fuel and led to a quick return to economical operation.

Sometimes innovation comes through the use of existing technology in new ways. Entergy, Areva, and EPRI shared the Nuclear Energy Institute's (NEI) 2005 “Best of the Best” Top Industry Practice (TIP) Award for developing an advanced technique for fuel crud sampling and analysis at Entergy's 966-MW River Bend nuclear plant in St. Francisville, Louisiana. The team developed new remote tools and procedures to obtain small flakes of corrosion deposits on fuel and developed advanced methods to analyze the flakes. The technique, based on other EPRI and vendor work on PWR fuel, revealed detailed information about the nature of fuel corrosion products that was previously available only through the expensive and time-consuming route of destructive hot cell examinations. The ability to collect the information from the poolside results in a quicker analysis that allows plants to adjust water chemistry and correct fuel problems in time for the next operating cycle.

Several other successes have come out of research to reduce AOA, where crud buildup on fuel cladding surfaces causes uneven heating of the reactor core. The situation is exacerbated by boron, which is added to the coolant to control power levels but which also becomes concentrated and deposited within thick crud deposits. The boron depresses power locally, shifting power from high-crud regions to lower-crud regions. Utilities are faced with the choice between reducing overall reactor power, which is economically undesirable, and finding a way to better control crud.

The initial approach for PWR utilities to avoid AOA was through conservative reload management, which translated to the purchase of additional fuel. More advanced approaches, based on EPRI-led research, use higher coolant pH levels and zinc injection to reduce crud transport and make use of the AOA analytic code BOA (Boron-Induced Offset Anomaly) developed by EPRI and Westinghouse. Notes Jeff Deshon, a project manager in the Fuel Reliability Program, BOA is a valuable software tool many utilities use to assess AOA risk; BOA can predict a specific core design's likely onset of AOA, as well as the extent and location of crud deposits. A major revision to the code is expected soon. Another strategy that has been investigated includes using boric acid specifically enriched with the boron's neutron-absorbing isotope so that the overall concentration of the element can be reduced.

While such mitigation techniques represent important advances, an EPRI-patented ultrasonic fuel-cleaning (UFC) technology attacks the problem more directly. In this process, the complete fuel assemblies are placed in each of two canisters, which contain high-energy ultrasonic transducers that loosen the crud by the repeated formation and collapse of tiny bubbles. The technology, which received the prestigious R&D 100 Award in 2005, will have been applied at a dozen nuclear plants worldwide by the end of the year.
assembly is placed in a canister surrounded by high-energy ultrasonic transducers that loosen the crud by the repeated formation and collapse of tiny bubbles. The crud is then swept out of the canister and captured in specially designed filters. It takes only about 4–6 minutes to clean each assembly, so the entire batch of reloaded fuel can easily be cleaned during a routine outage. Removing the crud by UFC has been proven beneficial in two areas—increasing the margin to AOA by reducing the crud available for boron hideout, and reducing plant dose rates from the overall decrease in crud inventory.

UFC technology has now been licensed to a number of service providers for PWR applications, although the technology has also been qualified and demonstrated for use in BWRs. EPRI and four of its member companies—AmerenUE, Exelon Corp., South Texas Project Nuclear Operating Co., and Dominion Engineering, Inc.—were given R&D Magazine’s prestigious R&D 100 Award in 2005 for the UFC technology. By the end of 2005, the technology will have been applied at 12 plants worldwide.

Not all success stories are purely technical. The Fuel Reliability Program has been extremely valuable as the industry focal point for interaction with the NRC and other regulators regarding potential safety implications of fuel behavior under postulated design-basis accidents. EPRI’s industrywide perspective and support have helped to avoid regulatory “ratcheting” to the most conservative, restrictive interpretations and assumptions for experimental results or regulatory criteria. The program participates in experimental efforts sponsored by nuclear regulators in the United States and overseas, and it sponsors additional separate-effects experiments and independent analyses. Results of these efforts have prevented the NRC from backfitting the criteria for avoiding reactivity-initiated accidents (RIA) for the currently licensed burnup limit of 62 gigawatt-days per metric ton of uranium. The program has also submitted a topical report proposing a new RIA criterion for high-burnup fuel. The report is currently under review by the NRC.

Currently, the regulatory issue of greatest concern involves the criteria for loss-of-coolant accidents (LOCAs) for fuel at mid-to-high burnup levels. Under postulated LOCA conditions, the temperature...
Technical Working Groups Get the Job Done

EPRI’s Fuel Reliability Program is managed through technical working groups that proactively identify high-priority and emerging issues related to fuel performance, water chemistry, and root-cause analysis of failed or defective fuel—along with cost-effective strategies for resolving them—and fuel-related regulatory issues.

Like all other technical programs in the nuclear industry’s broad-based Industry Materials Initiative, the Fuel Reliability Program conducted an in-depth gap analysis to identify and prioritize critical knowledge gaps and to target R&D plans to bridge them. “As a result of the gap analysis, important new areas have been added to the program’s overall scope,” notes Kurt Edsinger, an EPRI senior project manager and manager of one of four working groups addressing the key technical areas of focus.

“Newly added areas address the response of BWR fuel to water chemistry changes and the lifetime of reactivity control elements,” says Edsinger. “The gap analysis particularly recognized that issues related to BWR crud deposits and their effects on fuel performance could substantially benefit from a dedicated working group structure similar to what was already in place for PWRs, where fuel performance, chemistry, and core design experts are working as a team.” The PWR Fuel and Crud Control Working Group addresses PWR performance issues related to AOA, particularly issues related to crud, and proactively identifies issues arising from new water chemistry regimes (for example, high pH and zinc injection).

Activities to establish fuel performance design margins and investigate fuel failures, both of which rely heavily on hot cell investigations, are managed by the Fuel Performance and Reliability Working Group.

The working group on fuel regulatory issues involves EPRI, fuel vendors, and utility experts who serve as the industry focal point, through NEI, for interaction with the NRC Regulatory Office to resolve generic fuel licensing issues and maintain regulatory stability.

The Fuel Reliability Program also collaborates with the NRC’s Office of Research and other regulatory agencies worldwide to jointly conduct safety-related fuel research—for example, research involving reactivity-initiated accidents and loss-of-coolant accidents.

of the fuel increases rapidly, and even though a number of fuel rods would be expected to fail, the overall core geometry must be maintained to allow adequate cooling. The program is cosponsoring a series of LOCA-related experiments at Argonne National Laboratory jointly with the NRC, as well as other experiments to evaluate the adequacy of current LOCA criteria for currently licensed burnups and beyond.

Commitment to Progress

“The Fuel Reliability Program is a good example of where EPRI has worked closely with industry organizations and regulatory agencies both in the United States and internationally to address complex technical issues,” notes Yang. “The industrywide nature of the program has allowed for more-effective use of funds through the pooling of resources from U.S. and international utilities. Fuel vendors participate directly to ensure the availability of robust fuel designs for defect-free operation, while NEI and INPO support the program in a liaison role. As a result, we have been able to respond to an industry challenge—that is, increased fuel failure rates—quickly and comprehensively.”

Nevertheless, the challenges ahead remain formidable, and EPRI’s utility-driven Fuel Reliability Program was formed with a clear understanding among its sponsors that resolving many of the key issues and achieving the program objectives will require an extended multi-phase, multi-year effort. “This is tough, pain-taking technical work, and changing a problem situation sometimes takes longer than we initially anticipate,” says Joe Sheppard, chief executive and chief nuclear officer for the twin-unit South Texas Project and chairman of the Fuel Reliability Program’s executive committee. “We are making progress, albeit never as fast as we would want.”

Sheppard points out that it can take as long as three years from the time a fuel rod develops a defect—and is removed during the next refueling outage, cools sufficiently in a plant’s spent fuel pool for shipment to a hot cell, and can be examined and analyzed—until the time results are reported to a utility as to the root-cause mechanism of the failure. The Fuel Reliability Program’s utility managers and executives have high hopes that the developing relationship with INL will help to reduce that turnaround time and speed up the feedback loop on performance data, Sheppard notes.

“The challenges we’re tackling require innovative, groundbreaking R&D,” adds Sheppard, “for which it’s not always evident at the start how widespread the benefits will be. An example is the ultrasonic fuel cleaning technology originally developed to address AOA in PWRs but now being commercially developed for dose-reduction application in BWRs—an unanticipated, ancillary benefit. Sometimes with R&D, you have to bet on the come: you’ll run down a few blind alleys, but the flip side is that you’ll often get more benefits than you had planned.”

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