

# Fuel Reliability

## Program Overview

### Program Description

Fuel failures and other fuel-related issues can have significant operational impacts on nuclear power plants. Fuel failures, for example, have cost some nuclear power plants \$40 million or more per event to cover replacement power costs and the costs of a fuel reload. While the industry has made substantial progress in reducing the frequency of fuel failures, continued attention to technical gaps impacting fuel reliability is needed.

The Fuel Reliability Program drives improvements in nuclear fuel performance and reliability based on issues encountered at operating plants around the world. Research addresses multiple aspects of fuel performance and reliability, including fuel failure root-cause resolution, fuel/water chemistry interactions, and operational margins at end of life. The new knowledge is then applied to update fuel reliability guidance and to provide technical feedback for new fuel designs. The program also engages nuclear regulatory agencies and provides technical input regarding fuel-related rulings and regulations.

### Research Value

About \$45-\$50 billion of nuclear fuel is operating in nuclear reactors worldwide. Optimizing the use of this fuel, while ensuring its safe operation, is paramount to reliable, cost-effective nuclear plant operation. Fuel Reliability Program participants gain access to the following:

- Technical guidance to improve fuel reliability and reduce economic risks associated with fuel failures, which have cost the U.S. nuclear industry more than \$300 million over the past decade, and the global nuclear industry 2-3 times that amount.
- Global operating experience with all types of nuclear fuel assemblies and reactor types to inform decisionmaking.
- State-of-the-art software tools to analyze fuel rod performance, helping utilities manage power margins by ensuring that stresses don't exceed a threshold that could lead to fuel failures.
- Data and technical insights pertaining to the use of high-burnup nuclear fuels. Electric Power Research Institute (EPRI) studies show the industry can save about \$200 million/year by moving closer to the current burnup limit and another \$200 million/year by increasing the licensed limit.
- Technical studies to inform regulators and ensure regulations impacting nuclear fuel are technically based and not unnecessarily conservative.

### Approach

The Fuel Reliability Program develops knowledge, guidance, and tools to maximize the reliability of nuclear fuel and core components. The program also participates in international research consortiums to improve fundamental understanding of in-reactor behavior of fuel, cladding, control materials, and other core components. The overall program is organized into four Technical Advisory Committees (TACs).

- Fuel Performance and Reliability: Quantify fuel operational margins and identify fuel failure mechanisms through poolside and hot cell examinations. Results are shared with fuel vendors to ensure information is factored into subsequent fuel designs.
- PWR and BWR Corrosion and Crud Control: Improve industry understanding of the links between water chemistry, crud, and fuel reliability in pressurized and boiling water reactors. The research combines fuel surveillance programs and mechanistic studies to develop various guidelines and improve predictive capabilities.

- Fuel Regulatory Issues: Serve as the industry focal point on regulatory issues by participating in experimental programs and performing independent analyses to ensure the adequacy of proposed modifications to various accident criteria.

### Accomplishments

EPRI's Fuel Reliability Program distills global experience with nuclear fuel into actionable guidance and insights that drive measurable improvements in fuel reliability.

- Issued five first-of-a-kind fuel reliability guidelines aimed at enabling industry to achieve zero fuel failures. Coordinated reviews from more than 200 industry professionals worldwide.
- Coordinated failure root cause identification in several fuel failure cases with industrywide implications, including fuel pellet quality issues in AREVA and Westinghouse fuel.
- Evaluated zinc addition in high-duty pressurized water reactors and developed a framework for demonstrating the impact of elevated coolant hydrogen.
- Evaluated noble chemical addition and zinc in boiling water reactors to optimize operation.
- Established startup ramp rates for pressurized water reactors with known pellet defects to reduce failure risk.

### Current Year Activities

Fuel Reliability Program R&D for 2010 will focus on a number of remaining fuel reliability gaps, including the continuing threat of foreign materials, the effects of new water chemistry regimes on fuel reliability, and fuel reliability training. Specific efforts will include the following:

- Perform fuel failure investigations for events with industrywide implications.
- Improve risk assessment tool to avoid axial offset anomaly.
- Coordinate input for revisions to water chemistry guidelines for pressurized water reactors, including a better understanding of zinc.
- Develop risk assessment tool for boiling water reactors to better understand interactions between water chemistry, cladding, and fuel duty.
- Conduct hot cell examinations of an ultra-high fluence control rod to support accurate lifetime predictions.

### Estimated 2010 Program Funding

\$15.4 million

### Program Manager

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## Summary of Projects

Project Number	Project Title	Description
P41.02.01.01	BWR Corrosion & Crud Control	This project conducts research and develops guidance to minimize fuel performance issues related to fuel corrosion and crud in BWRs.
P41.02.01.02	NFIR-V	Through the NFIR Program, EPRI coordinates an international consortium of utilities, fuel vendors, and research laboratories focused on a generic, long-term R&D program to ensure safe and reliable use of light water reactor (LWR) core materials and components. The NFIR program seeks to understand fundamental in-reactor behavior of fuel, cladding, control materials, and other core components and to share this valuable knowledge throughout the industry.
P41.02.01.03	Code Maintenance	This project supports maintenance of the FALCON fuel performance software code to assist nuclear power plants in achieving optimal fuel utilization with sufficient operating margin. This is especially important for high-duty fuel and newer, less-proven fuel designs.
P41.02.01.03a	FALCON Users Group	The FALCON User Group provides a forum for nuclear utilities to further develop the fuel performance and analysis capabilities of the FALCON software code.
P41.02.01.04	Fuel Regulatory Issues	The project conducts research in support of fuel regulatory issues and acts as the industry focal point with the NRC on technical issues.
P41.02.01.05	PWR Corrosion & Crud Control	The project conducts research and develops guidance to minimize fuel performance issues related to fuel corrosion and crud in pressurized water reactors (PWRs).
P41.02.01.06	Fuel Performance & Reliability	The project conducts research and develops guidance to minimize generic fuel performance and reliability issues. It places a substantial reliance on detailed poolside and hot cell exams in order to establish current margins, identify failure mechanisms, and provide technical insight for other performance issues.
P41.02.01.08	BWR Channel Deformation Action Plan (QA)	The BWR channel distortion action plan represents a coordinated industry effort to issue short-term guidance and drive research needed to improve the ability to manage and eliminate channel distortion as an issue.

### BWR Corrosion & Crud Control (061376)

#### Key Research Question

Since 2001, four boiling water reactors have suffered crud and corrosion-induced fuel failures with a significant impact on plant performance and fuel economics. While the precise conditions leading to failure are still not understood, the failures are generally attributed to a combination of water chemistry, fuel duty, and cladding materials. Tenacious crud and surface spallation also have been increasingly observed in recent years as water chemistry conditions continue to evolve. For example, to mitigate stress corrosion cracking of core internals and other components, most boiling water reactors in the United States have moved from normal water chemistry (NWC) to hydrogen water chemistry (HWC) to noble metal chemical application and, more recently, to online NobleChem (OLNC). Zinc injection has been widely adopted for shutdown dose rate reduction, but also has implications for crud on the fuel.

## Approach

The objective in this area is to mitigate the impact of fuel crud deposition and cladding corrosion on fuel reliability by studying the roles of various factors on crud deposition and cladding corrosion and associated hydrating characteristics through R&D and fuel surveillance programs. In particular, this program will 1) continue to refine guidance in the *Boiling Water Reactor Fuel Cladding Corrosion & Crud Guideline*; 2) work with the Water Chemistry Guidelines Committee to establish limits on known and potentially harmful chemical species in the feedwater and reactor water; 3) perform fuel surveillances at plants with new or bounding water chemistry conditions; 4) study the important characteristics of tenacious crud and the conditions that form types of crud carrying the most risk, including the role of specific chemistry impurities, (for example, Fe, Zn, Cu, and SiO<sub>2</sub>); and 5) develop a predictive capability for crud deposition. Research activities will be coordinated with the Boiling Water Reactor Vessels and Internals Project (BWRVIP) Mitigation Committee and Water Chemistry program to ensure maximum benefits to members.

## Impact

- Evaluate interactions among key water chemistry parameters, fuel duty, and fuel assembly materials in relation to fuel corrosion and related aspects of performance through a combination of fuel surveillance programs, fundamental research, and advanced methodologies.
- This information will be used to develop predictive capabilities for crud deposition, optimize fuel operation, and provide input for boiling water reactor fuel and water chemistry guidelines.
- This project directly supports the Institute of Nuclear Power Operators (INPO) 2010 zero fuel failure goal established by nuclear industry executives.

## How to Apply Results

Much of the technology developed will be directly applied by member nuclear power plant personnel. Since a substantial fraction of the information also will have implications for core design and fuel assembly properties, members also can use the information in working with their fuel supplier.

## 2010 Products

Product Title & Description	Planned Completion Date	Product Type
Online NMCA 2nd Cycle Fuel Surveillance at a High Duty US BWR	09/30/10	Technical Report

## NFIR-V (058707)

### Key Research Question

The nuclear fuel industry has long recognized the need for a generic, long-term R&D program to ensure safe and reliable use of light water reactor (LWR) core materials and components. Since 1982, the Electric Power Research Institute (EPRI) has been leading and managing the Nuclear Fuel Industry Research (NFIR) group, an industrywide international consortium of utilities, fuel vendors, and research laboratories. The NFIR program seeks to understand fundamental in-reactor behavior of fuel, cladding, control materials, and other core components and to share this valuable knowledge throughout the industry.

### Approach

In its current phase (NFIR-V; 2004-2010), the NFIR Group is funding projects on the following topics:

- High-burnup fuel properties measurements
- Fission gas release studies
- High-burnup structure and effect on fuel dispersal under rapid transients
- Dimensional stability of zirconium-based alloys at high exposure
- Hydride reorientation and creep

## Impact

- NFIR has the ability to cost-effectively and collaboratively work on generic issues that are important to fuel the industry, yet not necessarily tied to a specific fuel design or plant operation.
- All major vendors, international utilities, and research labs are members of the program wherein utility members can advise on fuel R&D issues affecting all vendors, not just their own fuel supplier.
- Through NFIR participation, members have the opportunity to network with industry experts from around the world and learn about current and anticipated issues.

## How to Apply Results

NFIR-V projects will provide fundamental materials properties and behavior data that lead to improved products (through vendors) and improved knowledge about behavior of core components (through fuel performance and design codes). More specifically, underlying mechanisms involved in a number of currently important industry issues will be elucidated, including the following:

- Incomplete rod insertion problems in pressurized water reactors
- Separate effects test data on cladding and fuel behaviors under rapid transients
- Clad mechanical response as affected by local hydrides in operation and storage
- High-burnup properties of  $UO_2$ , mixed oxide fuel (MOX), and advanced fuels

## 2010 Products

Product Title & Description	Planned Completion Date	Product Type
<b>Updatable DVD-ROM 2010</b> : Annual update for the Nuclear Fuel Industry Research (NFIR) program	05/31/10	Technical Update
<b>Fission Gas Release Studies: Interim Results:</b> In NFIR-V Topic 1, CEA (France) is performing hot cell fission gas release experiments on IFA-649 samples. This report will compile interim results and preliminary interpretation.	09/30/10	Technical Report
<b>High Burn-up Fuel Properties Data: Interim Results:</b> In NFIR-V Topic 2, ITU (Germany) is performing hot cell fuel properties measurements on IFA-649 samples. This report will compile interim results and preliminary interpretation on density, chemical burn-ups, and ceramographies.	09/30/10	Technical Report
<b>Post Irradiation Examinations on BOR-60 Growth Samples: Interim Results:</b> In NFIR-V Topic 3, RIAR (Russia) is performing hot cell post irradiation examinations on zirconium alloy variant growth samples, previously irradiated to high fluence levels in BOR-60. This report will compile interim results and preliminary interpretation on density, micro-hardness, metallography, and transmission electron microscopy.	12/15/10	Technical Report

## Code Maintenance (060410)

### Key Research Question

A state-of-the-art tool is required to analyze operating margins of advanced fuel design under both steady-state and transient operations. By maintaining and continually enhancing validated analytical capabilities, the Electric Power Research Institute (EPRI) can assist nuclear power plants in achieving optimal fuel utilization with sufficient operating margin. This is especially important for high-duty fuel and newer, less-proven fuel designs. While the current version of the FALCON code (FALCON MOD01) is expected to meet near-term needs, sustained code enhancements beyond the current product will be necessary.

## Approach

This activity includes improvements in models such as the pellet clad interaction (PCI) behavior (for example, enhanced capabilities to model fuel pellet quality issues and improved benchmarking of failure cases), creep and stress relaxation (for example, hydrogen-accelerated creep laws and properties of advanced cladding alloys), and rod internal performance (for example, fission gas release, rod internal pressure with integral fuel burnable absorber, and mixed oxide fuel models).

Future revisions could fully integrate FALCON with well-qualified neutronic and thermal hydraulic codes. The integrated code could perform a detailed three-dimensional analysis of the fuel rod to elucidate various local phenomena implicated in already-observed failures of peripheral rods, greater-than-anticipated fission gas release, and large variations in crud deposits and cladding corrosion. It also would support analytical assessments of isotopic distributions in discharged fuel for the most advanced fuel designs, a Nuclear Regulatory Commission requirement for dry storage or spent-fuel disposal.

## Impact

- Independently assess expected fuel performance relative to predictions from fuel supplier's code
- Assess the potential role of fuel rod performance in a fuel failure root-cause investigation
- Model detailed fuel rod responses not available in the fuel supplier's code

## How to Apply Results

The FALCON code can be directly applied to the member's fuel rod design and power history to calculate conditions within the fuel rod .

## FALCON Users Group (006165)

### Key Research Question

This project provides a forum for FALCON users and developers to share lessons learned and discuss code improvements necessary to enhance nuclear fuel reliability and performance .FALCON is the Electric Power Research Institute's (EPRI's) thermal-mechanical fuel performance code for steady-state and transient applications.

## Approach

The user group meets roughly once per year .The user group provides guidance in upgrading the FALCON code in response to industry needs and operating experience. Support also is available from EPRI throughout the year.

## Impact

The user group allows members to share experience, suggest improvements, and maximize the value they receive from the code.

## How to Apply Results

Through user group meetings and other communication mechanisms, participants share operating experience with the FALCON code and identify software improvements to address emerging needs.

## 2010 Products

Product Title & Description	Planned Completion Date	Product Type
<b>FalconRD Beta Release:</b> The redesigning of legacy Falcon code will be introduced to users and licensees. They will be able to use and apply this modernized code for evaluating fuel performance issues.	06/30/10	Software

## Fuel Regulatory Issues (052391)

### Key Research Question

Recent experimental evidence has raised questions about the applicability of current reactivity-initiated accident (RIA) and loss-of-coolant-accident (LOCA) criteria to high- or intermediate-burnup fuel. The Fuel Reliability Program is the industry's focal point for addressing such concerns on a coordinated, industrywide basis and for technical interactions with the Nuclear Regulatory Commission on fuel-related issues. The aim of this project is to improve fuel utilization, operational flexibility, and cycle economics without undue restrictions resulting from unnecessarily overly conservative regulatory assumptions about potential fuel behavior under postulated transients. From a regulatory perspective, this requires ensuring that proposed modifications to current licensing criteria are realistic and appropriate for such fuel when it is operated under high-duty conditions out to the currently licensed burnup limits. For additional flexibility, it also is desirable that a clear path be established for licensing even higher burnups.

### Approach

The Electric Power Research Institute (EPRI) participates in experimental programs sponsored by regulators in the United States and overseas by sponsoring focused separate-effects experiments as needed and performing independent analyses and evaluations. These efforts ensure the adequacy of any proposed modifications to current reactivity-initiated accident and loss-of-coolant-accident criteria for currently licensed or anticipated new fuel designs. The project also aims at developing a framework for licensing burnup extensions beyond the current limits.

The issue of appropriate criteria for RIA and LOCA accidents continues to be actively debated with the Nuclear Regulatory Commission (NRC). With an interim RIA criteria issued by NRC's office of Nuclear Reactor Regulation (NRR) in 2007 focused on new plants, the working group will continue to provide input in support of the final criteria for the existing fleet. This project provides the evidence needed to demonstrate the extent of unnecessary conservatism in both areas.

### Impact

- Independent analysis of international tests being assessed by NRC and others
- Application of the most advanced tools for those assessments
- Access to key supporting information from other Fuel Reliability Program activities
- Reduced regulatory impact

### How to Apply Results

The objective of this work is to influence NRC regulations in a manner that will allow nuclear power plants to operate safely without sacrificing efficiency and with minimal impact on current operations.

### 2010 Products

Product Title & Description	Planned Completion Date	Product Type
<b>Technical Report on Proposed Revisions to LOCA Criteria</b>	09/30/10	Technical Report
<b>Technical Report on RIA Acceptance Criteria</b>	12/23/10	Technical Report
<b>Methods for use in demonstrating compliance with core coolability criteria</b>	12/23/10	Technical Report

## PWR Corrosion & Crud Control (052390)

### Key Research Question

Changes in pressurized water reactor fuel duty and reactor coolant chemistry have had adverse effects on nuclear fuel performance and reliability. The consequences have led to reduced shutdown margins (safety), fuel failures, and elevated radiation fields at many plants. The industry requires a focused and integrated research and development (R&D) approach to develop means to prevent these problems.

### Approach

This project combines plant-generated data with laboratory research and theoretical modeling to provide members with tools and skill sets to avoid the costly consequences of significant corrosion product deposition on fuel rods that can lead to deteriorating fuel performance. Plant demonstrations verify that new technologies and changes in new chemistry regimes or core operating strategies do not adversely affect fuel performance.

### Impact

- Improves fuel reliability by minimizing corrosion product (crud) formation on fuel rods. Excessive crudding can lead to fuel failures, which can cost members several hundred thousand to millions of dollars. Other issues also arise from heavy crudding, such as axial offset anomaly, which can reduce shutdown margins, presenting a safety concern, and cause elevated radiation fields during plant outages leading to higher personnel radiation exposure. Therefore, finding means to minimize excessive crudding serves industry on both financial and qualitative levels.
- Integrates plant data collection, laboratory testing, and innovative loop research with theoretical modeling to understand the in-core crud deposition process and to deliver integrated strategies for avoiding crud deposition.
- Supports the Institute of Nuclear Power Operations' 2010 Zero Fuel Failure goal established by nuclear industry executives.

### How to Apply Results

Members use the reports generated by the project to support on-site changes in programs and procedures, including the plant final safety analysis report (FSAR). Particularly valuable have been the following products, which continue to evolve and improve as a result of ongoing research: *PWR Axial Offset Anomaly Guidelines*, ultrasonic fuel cleaning technology, and the Boron-Induced Offset Anomaly Risk Assessment Tool (BOA software). Project results are appropriately integrated with other EPRI research programs, including the Materials Reliability Program (MRP) and the Chemistry and Radiation Management Programs. For example, applying zinc to pressurized water reactors to mitigate stress corrosion cracking or abate radiation field requires a carefully orchestrated effort to ensure the application of zinc does not adversely impact the performance and integrity of nuclear fuel.

### 2010 Products

Product Title & Description	Planned Completion Date	Product Type
Evaluation of Fuel Cladding Corrosion and Corrosion Product Deposits from Vandellos II Cycle 16	06/01/10	Technical Report

## Fuel Performance & Reliability (052388)

### Key Research Question

A wide range of research is needed to quantify fuel reliability margins for current and new fuel designs .This information addresses the behavior of fuel, cladding, and assembly components (for example, spacer grids, guide tubes, water rods, and boiling water reactor [BWR] channels) .There also is a need to understand and resolve fuel failure root causes for mechanisms with generic industry implications .Other industry needs include quantifying the performance of control rods and control blades.

### Approach

This area focuses on failure root-cause evaluations of mechanisms with industrywide implications and proactive assessments of fuel operating margins under limiting conditions .Ongoing root-cause investigations include corrosion-related failures at two BWRs, duty-related failures in barrier fuel, and an unknown failure mechanism in pressurized water reactor (PWR) fuel .Performance assessments have been initiated for key PWR and BWR fuel designs under bounding conditions to ensure fuel will operate safely and economically up to current design limits .These assessments include substantial poolside and hot cell programs on fuel (past examples included AREVA M5, several variations from GNF, and Westinghouse ZIRLO) .The hot cell examinations are closely coordinated with the particular fuel supplier to leverage funding and ensure the vendor can fully apply the investigation results.

This program also has responsibility for the reliability of other fuel-related components, including balance of assembly components (for example, spacers grids, guide tubes, water rods, and BWR channels) and reactivity control components (PWR control rods and BWR control blades) .A small but important area in the program also focuses on advancing nondestructive poolside techniques to quantify fuel performance margins, but also to improve our ability to locate failed rods and identify the cause of failure .The industry's fuel reliability database (FRED) is developed and maintained through this program area .FRED provides timely industrywide perspectives on trends in failure root causes, fuel reliability statistics, and good operating practices .

### Impact

- Resolution of numerous failure root causes to avoid recurrence and enable fixes to be implemented, both on the vendor side and the utility side
- Improvements in fuel cladding properties (primarily corrosion and hydrogen pickup)
- Guidelines to assist the industry in applying research results

### How to Apply Results

Many of the key results flow into fuel reliability guidelines; some of the results inform decisions on fuel designs or strategies; other results can be used in by an individual utility in working with their fuel supplier.

### 2010 Products

Product Title & Description	Planned Completion Date	Product Type
Field Examination and Hot Cell Post-Irradiation Examination of Westinghouse Fuel Channels from Hope Creek	09/30/10	Technical Report
Hot Cell Investigation of GE14 Duty Failures from Browns Ferry Unit 3	09/01/10	Technical Report
Assessment of Fuel Surveillance and Inspection Guideline (FSIG) Baseline Inspections	12/01/10	Technical Report
Swelling Model for AgInCd Absorber Material used in RCCA	12/19/10	Technical Report

Product Title & Description	Planned Completion Date	Product Type
PIE and Testing of High Fluence Control Rod AgInCd Absorber Rodlet from KWO	10/30/10	Technical Report
Hot Cell Investigation of 1st Cycle ATRIUM-10B Fuel Rod from Browns Ferry Unit 3	10/30/10	Technical Report

## BWR Channel Deformation Action Plan (QA)

### Key Research Question

Fifteen of the 35 BWRs in the United States have reported control blade interference due to channel distortion in the last 8 years .The affected fuel designs include Zry-2 channels manufactured by all three vendors, GNF, AREVA, and Westinghouse .Multiple mechanisms have been identified that can give rise to channel distortion, which manifests as bow, bulge and twist .Recent experience indicates that fuel vendor models can not sufficiently predict the channel distortion and the number of plants experiencing channel-related control blade interference has increased .While significant effort has been devoted to this issue, a more coordinated approach is needed .

### Approach

A channel distortion industry action plan has been developed to coordinate efforts amongst utilities, EPRI, fuel vendors and INPO .The plan outlines the effort needed to effectively manage channel distortion in the near term and to ultimately eliminate the issue. The plan includes a combination of field measurements, laboratory analysis, model development, and guidance.

### Impact

Despite substantial past efforts to understand the issue, recent experience indicates channel distortion is not predicted well enough. Fifteen of the 35 BWRs in the U.S. have reported control blade interference due to channel distortion in the last 8 years .Results from research in this area will lead to mode improvements that ensure core designs are less susceptible to channel distortion.

### How to Apply Results

The initial effort, to provide channel distortion guidance, will be directly applicable by the utility .The information from poolside measurements and laboratory analysis will be used to improve various models .These models will synchronize with the predictive capabilities developed by the fuel vendors that utilities use to guide core design and manage operational aspects of channel distortion.