Fuel Reliability

Program Overview

Program Description

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 reliability, including fuel/water chemistry interactions, operational margins at end of life, and fuel failure root-cause resolution. Emphasis is placed on issues with the greatest operational impact, including fuel failures that can cost nuclear power plants $40-$80 million per event. The new knowledge is then applied to update fuel reliability guidance in continued support of the industry goal of zero fuel failures by 2010.

Industry Needs and Issues Addressed

- Fuel Performance & Reliability—Technical dialogue and focused projects with fuel vendors to resolve failure root causes and quantify operating margins under bounding conditions
- Pressurized Water Reactor Corrosion & Crud Control—Technologies and strategies to address water -chemistry-related concerns relative to fuel reliability in pressurized water reactors, including axial offset anomaly, zinc, elevated pH, and elevated coolant hydrogen
- Boiling Water Reactor Corrosion & Crud Control— Technologies and strategies to address water -chemistry-related concerns relative to fuel reliability in boiling water reactors, including noble metal chemical application, zinc, and water chemistry impurities
- Fuel Regulatory Issues—Technical interactions with nuclear regulators around the world to assess the bases for rulings that might impact nuclear fuel and plant operation

Impact

- Reduced likelihood of nuclear fuel failures, which can cost individual nuclear plants $40-$80 million per event in some cases
- Technical guidance to enable nuclear power plants to achieve industry goal of zero fuel failures by 2010
- Technical guidance to ensure regulatory changes are technically based and not overly conservative
- Independent technical evaluations in fuel performance and reliability

Key Accomplishments

- Failure root-cause identification in several cases with industrywide implications, including fuel pellet quality issues in AREVA and Westinghouse fuel
- Fuel reliability guidelines aimed at enabling industry to achieve zero fuel failures by 2010
- Zinc addition in high-duty pressurized water reactors and a framework for demonstrating the impact of elevated coolant hydrogen
- Optimized loading evaluation for noble metal chemical application and zinc in boiling water reactors.
- Development of water chemistry guideline sections related to reducing risks to fuel reliability
- Startup ramp rates for pressurized water reactors with known fuel pellet defects to reduce failure risk
- Technical content for industry position papers to U.S. Nuclear Regulatory Commission on loss of coolant accident and reactivity initiated accident

Current Year Objectives

- Improved input for revisions to fuel reliability guidelines for fuel surveillance, pressurized water reactor and boiling water reactor fuel corrosion and crud, grid-to-rod fretting, and pellet-cladding interaction
- Improved core design tools to avoid axial offset anomaly
- Improved input for revisions to pressurized water reactor water chemistry guidelines, including a better understanding of zinc
- Improved input for revisions to boiling water reactor water chemistry guidelines, weighing interactions between water chemistry, cladding material, and fuel duty.
- Hot cell examination of an ultra-high fluence pressurized water reactor control rod to support accurate lifetime predictions
- Poolside and hot cell measurements on boiling water reactor channels to mitigate channel bow.

Industry Involvement

- Estimated 2009 funding: $13.0

Program Technical Lead

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Summary of Projects

Project Number	Project Title	Value
	PWR Corrosion & Crud Control	This project, known as Working Group 1, is responsible for understanding the links between water chemistry, crud, and fuel reliability in pressurized water reactors (PWRs). A major focus of this group is to mitigate axial offset anomaly (AOA). The overall approach uses a combination of fuel surveillance programs and mechanistic studies that feed development of various guidelines and improvements to our predictive capabilities.
	Fuel Performance & Reliability	This project, known as Working Group 3, is responsible for quantifying fuel operational margins and identifying fuel failure mechanisms through poolside and hot cell examinations. The activities focus on fuel reliability issues with industrywide implications. This group generally works closely with the appropriate fuel vendor to ensure the results are factored into subsequent fuel designs.
	BWR Corrosion & Crud Control	This project, known as Working Group 4, is responsible for understanding the links between water chemistry, crud, and fuel reliability in boiling water reactors (BWRs). A major focus of this group is to understand the impact of the primary constituents (for example, zinc and iron) and low-concentration impurities in conjunction with fuel duty and cladding characteristics. The overall approach uses a combination of fuel surveillance programs and mechanistic studies that feed development of various guidelines and improvements to our predictive capabilities.

Project Number	Project Title	Value
	NFIR	Nuclear Fuel Industry Research (NFIR) is an EPRI-managed, 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.
	Fuel Code Enhancement and Maintenance	FALCON is the Electric Power Research Institute's (EPRI's) state-of-the-art fuel performance code to analyze operating margins of various fuel designs under both steady-state and transient operations. By maintaining and continually enhancing validated analytical capabilities, EPRI can assist members in achieving their goal of optimal fuel utilization with sufficient operating margin. This is especially important for high-duty fuel and newer, less-proven fuel designs. The current version of FALCON is FALCON MOD01.
	Fuel Regulatory Issues	Working Group 2 serves as the industry focal point on fuel regulatory issues and interacts directly with the Nuclear Regulatory Commission (NRC) on technical matters. This working group participates in experimental programs sponsored by regulators in the United States and overseas by sponsoring focused separate-effects experiments as needed. The Group also performs independent analyses and evaluations to 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.

Project Descriptions

PWR Corrosion & Crud Control (052390)

Issue
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.

Description
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 operating strategies do not adversely affect fuel performance.

Value
- 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 crud deposition process in-core 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 background 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.

2009 Products

Product Title & Description	Planned Completion Date	Product Type
Evaluation of Fuel Cladding Corrosion and Corrosion Product Deposits from Vandellos II Cycle 16 (final report): Corrosion product evaluations provide further insight into the effects of pressurized water reactor coolant chemistry on fuel performance. Results also are incorporated into a risk assessment tool to mitigate axial offset anomaly.	12/31/2009	Technical Report
Boron-induced Offset Anomaly Risk Assessment Tool (BOA), Rev. 3	4/1/2009	Software

Fuel Performance & Reliability (052392)

Issue
To remain competitive, nuclear power plants need to operate their fuel reliably under high-duty conditions, out to the highest-licensed burnup levels. Reliability must not be compromised when new fuel products are introduced or new water chemistry conditions are implemented. By acquiring and evaluating fuel performance data, this program minimizes the potential for plant operation impacts because of unexpected fuel performance issues, fuel failures, or secondary degradation when fuel is operated beyond the existing experience base in fuel duty, burnup, or coolant chemistry conditions. Needed data will be obtained primarily by conducting (nondestructive) poolside and (destructive) hot cell examinations on fuel rods or assembly components exposed under representative, high-duty conditions out to burnups close to, or above, currently licensed limits. Data also may be obtained by conducting root-cause (hot cell) examinations in cases of fuel failures with potential industrywide implications.

Description
This program will provide failure root-cause evaluations, including hot cell examinations, on important fuel failure mechanisms with potential industrywide implications, as well as information to assess operating margins under modern operating conditions. This program also will assess margins in fuel assembly components (for example, spacer grids, guide tubes, water rods, and channels) and related core components (for example, pressurized water reactor control rod and boiling water reactor control blade

lifetimes). General fuel performance and reliability information (for example, failure root causes, fuel reliability statistics, and good operating practices) will be collected in EPRI's fuel reliability database (FRED) to ensure the information is readily accessible. This project also will acquire basic fuel property data through highly leveraged, internationally sponsored programs (for example, Halden and Nuclear Fuel Industry Research). This program will drive the development of advanced, nondestructive poolside inspection capabilities and enhanced hot cell examination techniques.

Value

- Assess operating margins under limiting conditions
- Determine advances needed to reach the zero fuel failure goal and provide a substantial fraction of the information required for EPRI's technical guidelines
- Engage fuel suppliers to share costs in most activities and ensure results are available for the supplier to improve subsequent fuel reloads
- Apply the results collected to improve fuel reliability in other areas, including licensing for extended exposure, dry cask storage, and transient safety-related issues
- Supports the Institute of Nuclear Power Operations (INPO) 2010 zero fuel failure goal established by industry nuclear executives

How to Apply Results

Many of the results can be applied directly (for example, various guidelines, performance of alternate fuel designs, and control rod lifetimes.). Other results are used by a member's fuel supplier or service provider to improve products and services offered to the member.

2009 Products

Product Title & Description	Planned Completion Date	Product Type
Hot Cell Examination of GNF Channel Coupons from the Monticello BWR: Monticello is the first "D" lattice boiling water reactor plant that has experienced control blade interference from channel bow. Hot cell examination will characterize Global Nuclear Fuel channel coupon materials to assess hydrogen distribution and oxide thickness on coupons with differing levels of shadow corrosion. The objective is to determine whether fluence gradient or shadow corrosion-induced bow is responsible for the excessive distortion in the affected cell.	5/31/2009	Technical Report
Areva Assessment Report of the Hot Cell Examination of North Anna M5 Clad Fuel: Assessment of the hot cell examination of high-burnup M5 clad fuel rods from North Anna. Fuel rod examination at Idaho National Lab and mechanical testing at Argonne National Lab.	3/31/2009	Technical Report

Future Year Products

Product Title & Description	Planned Completion Date	Product Type
Evaluation of Margins of Optimized ZIRLO Fuel at High Burnup: Examination of up to six fuel rods from the Catawba reactor at Oak Ridge National Laboratory. The fuel rods are from Westinghouse Robust Fuel Assembly and Next Generation Fuel assemblies and will include both Zirlo and Optimized Zirlo clad material up to burnups of approximately 55 GWd/MTU. Both nondestructive and destructive exams will be performed to characterize fuel performance.	2010	Technical Report

Product Title & Description	Planned Completion Date	Product Type
Hot Cell Examination of Westinghouse SVEA channels from a US BWR Channel coupons extracted from Westinghouse channels from a boiling water reactor (either Hope Creek or Columbia Generating Station) will be examined to quantify hydrogen and corrosion performance to better understand excessive channel bow and determine the distortion mechanism.	2010	Technical Report
Root Cause Investigation of Browns Ferry Corrosion-related (Unit 2) and duty related (Unit 3) fuel failures in GE13/14 fuel.: Hot cell examination of Global Nuclear Fuel fuel rods from Browns Ferry to better understand the large-scale corrosion-related failures in 2003 as well as determine the failure mechanism of the duty-related failures in Unit 3.	2010	Technical Report

BWR Corrosion & Crud Control (061376)

Issue

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 (NMCA). Many are now considering changing again to online NMCA. Zinc injection has been widely adopted for shutdown dose rate reduction, but also has implications for crud on the fuel.

Description

This program's objective 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 hydriding 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 SiO2; and 5) develop a predictive capability for crud deposition. This program will collaborate and coordinate its activities closely with the Boiling Water Reactor Vessels and Internals Project (BWRVIP) Mitigation Committee and Water Chemistry program to ensure maximum benefits to members.

Value

- This program will 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 INPO 2010 zero fuel failure goal established by nuclear industry executives.

How to Apply Results

Much of the technology developed here 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.

2009 Products

Product Title & Description	Planned Completion Date	Product Type
Zircaloy Shadow Corrosion Mechanism in BWRs – A Simulation Study: Laboratory tests to evaluate the effects of water chemistry impurities and material variability on corrosion, including shadow corrosion, and associated hydrogen pickup in Zircaloy and alternate zirconium alloys	11/30/2009	Technical Report
Evaluation of Accelerated Hydriding of Zircaloy-2 and Alternate Zr-Alloys Using Electrochemical Approaches	12/31/2009	Technical Report
Effect of Chemical Impurities on Zircaloy Corrosion and Hydriding Autoclave testing to determine the effects of chemical impurities on Zircaloy corrosion and hydriding	12/31/2009	Technical Report
BWR Feedwater Zn and Fe Effects on Fuel Performance at LaSalle -1 and -2: Boiling water reactor feedwater Zn and Fe effects on fuel performance at LaSalle -1 and -2	6/15/2009	Technical Report
Post-Irradiation Examination of GNF Simulated NOBLECHEM and Shadow Corrosion Coupons and ABB Shadow Corrosion Coupons Tested in MITR-II Research Reactor	2/2/2009	Technical Report
BWR Fuel Crud Deposition Mechanism: BWR fuel crud deposition mechanism	6/30/2009	Technical Report

Future Year Products

Product Title & Description	Planned Completion Date	Product Type
Online NMCA 2nd Cycle Fuel Surveillance at a High Duty US BWR	2010	Technical Report

NFIR (058707)

Issue

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, 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.

Description

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

Value

- 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 influence fuel R&D issues with all vendors, not just their own major fuel-supplier.
- With 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, MOX, and advanced fuels

2009 Products

Product Title & Description	Planned Completion Date	Product Type
Fuel Fragmentation Scoping Studies Part 2: Rapid Laser Heating of Unrestrained Fuel Samples	3/31/2009	Technical Report
Hydride Reorientation Studies Part 1: Unirradiated Samples	3/31/2009	Technical Report
NFIR-V Dimensional Stability Project: Final Report	9/10/2009	Technical Report

Fuel Code Enhancement and Maintenance (060410)

Issue

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, 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.

Description
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 (a Nuclear Regulatory Commission requirement for dry storage or spent-fuel disposal) for the most advanced fuel designs.

Value
- 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.

2009 Products

Product Title & Description	Planned Completion Date	Product Type
FALCON Redesign Alpha Release: Redesign of EPRI nuclear fuel performance code, FALCON, to provide more flexibility on code inputs and improved graphics capabilities	3/31/2009	Software

Fuel Regulatory Issues (052391)

Issue
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 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.

Description
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 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 conservatisms in both areas.

Value

- 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.

2009 Products

Product Title & Description	Planned Completion Date	Product Type
Revised Topical Report on Reactivity Initiated Accident Criteria -- Coolability Limit	12/31/2009	Technical Report
Measured distributions of oxygen and hydrogen in post-LOCA cladding samples	6/15/2009	Technical Report
Revised Topical Report on Reactivity Initiated Accident Criteria -- Acceptance Criteria	12/31/2009	Technical Report
Analysis of NSRR RIA Tests in High-Temperature Pressurized Capsule	12/31/2009	Technical Report

Future Year Products

Product Title & Description	Planned Completion Date	Product Type
Topical Report on Proposed Revisions to LOCA Criteria	2010	Technical Report
CABRI Water Loop Design Characteristics and Preliminary Test Results	2010	Technical Report