Evaluation of Constant Elevated pH Demonstration at Comanche Peak Steam Electric Station

Technical Report

Evaluation of Constant Elevated pH Demonstration at Comanche Peak Steam Electric Station

1003408

Interim Report, March 2005

Cosponsor
TXU Power
Comanche Peak Steam Electric Station

EPRI Project Manager
J. Deshon

Electric Power Research Institute • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

THIS DOCUMENT WAS PREPARED BY THE ORGANIZATION(S) NAMED BELOW AS AN ACCOUNT OF WORK SPONSORED OR COSPONSORED BY THE ELECTRIC POWER RESEARCH INSTITUTE, INC. (EPRI). NEITHER EPRI, ANY MEMBER OF EPRI, ANY COSPONSOR, THE ORGANIZATION(S) BELOW, NOR ANY PERSON ACTING ON BEHALF OF ANY OF THEM:

(A) MAKES ANY WARRANTY OR REPRESENTATION WHATSOEVER, EXPRESS OR IMPLIED, (I) WITH RESPECT TO THE USE OF ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT, INCLUDING MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE, OR (II) THAT SUCH USE DOES NOT INFRINGE ON OR INTERFERE WITH PRIVATELY OWNED RIGHTS, INCLUDING ANY PARTY'S INTELLECTUAL PROPERTY, OR (III) THAT THIS DOCUMENT IS SUITABLE TO ANY PARTICULAR USER'S CIRCUMSTANCE; OR

(B) ASSUMES RESPONSIBILITY FOR ANY DAMAGES OR OTHER LIABILITY WHATSOEVER (INCLUDING ANY CONSEQUENTIAL DAMAGES, EVEN IF EPRI OR ANY EPRI REPRESENTATIVE HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES) RESULTING FROM YOUR SELECTION OR USE OF THIS DOCUMENT OR ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT.

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

TXU POWER
WESTINGHOUSE ELECTRIC COMPANY, LLC

ORDERING INFORMATION

Requests for copies of this report should be directed to EPRI Orders and Conferences, 1355 Willow Way, Suite 278, Concord, CA 94520, (800) 313-3774, press 2 or internally x5379, (925) 609-9169, (925) 609-1310 (fax).

Electric Power Research Institute and EPRI are registered service marks of the Electric Power Research Institute, Inc. TOGETHER…SHAPING THE FUTURE OF ELECTRICITY is a service mark of the Electric Power Research Institute, Inc.

Copyright © 2005 Electric Power Research Institute, Inc. All rights reserved.

CITATIONS

This report was prepared by

TXU Power
Comanche Peak Steam Electric Station
Glen Rose, TX 76043

Principal Investigator
John Bosma
Deborah Farnsworth
Jim Stevens

Westinghouse Electric Co., LLC
5801 Bluff Rd
Columbia, SC 29209

Principal Investigator
Jonathan Nilsson
Jayashari Iyer

This report describes research sponsored by EPRI and TXU Power

The report is a corporate document that should be cited in the literature in the following manner:

Evaluation of Constant Elevated pH Demonstration at Comanche Peak Steam Electric Station, EPRI, Palo Alto, CA and TXU Power, Glen Rose, TX: 2005. 1003408.

PRODUCT DESCRIPTION

Laboratory data and limited field experience suggest that constant elevated pH, when optimized, will reduce the release of corrosion products from ex-core PWR surfaces and therefore the amount transported and deposited on fuel assemblies. However, the impact of elevated pH and higher lithium concentrations required to achieve the desired pH must first be evaluated and then demonstrated prior to widespread industry application. This interim report summarizes the results of operating the reactor coolant at a constant pH_t 7.3 during Cycle 7 at Comanche Peak Steam Electric Station (CPSES) Unit 2.

Background

The EPRI Fuel Reliability Program formed an initiative to reduce the amount of crud depositing on PWR fuel rods by modifying reactor coolant chemistry. The intended goal was to reduce ex-core radiation fields and reduce susceptibility to axial offset anomaly (AOA). Historically, plants have been limited in their ability to operate with elevated pH due to the high lithium requirements needed to achieve the desired pH level. Concerns regarding fuel clad corrosion and primary water stress corrosion cracking (PWSCC) of construction materials were the main impediments to raising lithium above the industry experience base. TXU Power teamed with the EPRI Fuel Reliability Program in an effort to evaluate operation with an elevated constant pH program. The initial evaluation of the constant elevated pH demonstration (EPRI report 1006282) was performed by CPSES's nuclear steam supply system (NSSS) supplier and fuel vendors. This evaluation provides the basis for going forward with the current elevated and constant pH demonstration.

Objectives

- To evaluate the initial phase of elevated and constant pH_t operation.
- To verify predicted results, identify any adverse or unexpected conditions, and provide the basis for planned chemistry conditions for the subsequent cycle.

Approach

This phase of the demonstration included detailed monitoring of chemistry, radiochemistry, and core performance parameters during the operating cycle with comparisons to prior cycles of the same unit. The Refuel 7 shutdown chemistry results and radiation field measurements were also compared to prior cycle results to capture any discernable changes. Fuel inspections were performed, including oxide measurements and visual examinations. Investigators examined fuel cladding from both Framatome-ANP Optimized Zircaloy-4 and Westinghouse ZIRLO™ fuel assemblies and compared results to pre-exposure baseline measurements taken during Refuel 6.

Results

Reactor coolant lithium was operated above 3.5 ppm for about the first 125 days of Cycle 7. Operating cycle chemistry evaluations identified crud stability as a possible improvement factor. Shutdown chemistry was more informative, with lower metals removed, reduced specific activity, and significantly lower curies removal than recent outages. These results should be tempered somewhat by a late cycle cold shutdown; nevertheless, the data suggest a potential effect on source term reduction and/or less crud residence on the core. The total outage dose during Refuel 7 was significantly less than prior outages and appears to be partly explained by radiation field reduction, based on EPRI steam generator standard radiation monitoring points (SRMP) measurements. Visual examinations of the fuel confirmed similar or less crud on the fuel assemblies when compared to previous examinations. Minor non-uniform crud deposition was more noticeable on higher duty assemblies, particularly on spans 5 to 7. Eddy-current examinations of fuel revealed no discernable increase in oxide thickness due to operation with elevated pH. Overall, this phase of the elevated pH demonstration was judged successful and results supported the recommendation for constant pH_t 7.4 operation in Cycle 8, as planned.

EPRI Perspective

This report documents observations and results from the first cycle of elevated and constant reactor coolant pH at Comanche Peak Unit 2. Longstanding concerns regarding the corrosive effects of elevated lithium levels required to achieve beginning-of-cycle pH in the range of 7.3 - 7.4 are being evaluated as part of this demonstration. Results from the first leg of the demonstration suggest no apparent acceleration of cladding corrosion after one cycle of constant pH_t 7.3 chemistry. Similarly, crud observations on the fuel suggested either similar or reduced loadings compared to previous cycles. While mid-cycle shutdowns complicate a definitive chemistry assessment, no adverse chemistry aspects were noted and some encouraging signs may have been present during the operating cycle and at shutdown. The aggregate of these observations prompted TXU Power to continue with the demonstration. Unit 2 is currently operating Cycle 8 at a constant pH_t 7.4, with an anticipated end-of-cycle shutdown in spring 2005. It is anticipated that two or more cycles of elevated and constant pH will be required to make a definitive assessment on the prospects of this pH regime. A similar assessment to that contained in this document will be published following Cycle 8.

Keywords

Axial Offset Anomaly
AOA
PWR Primary Water Chemistry
Elevated pH
Lithium
Elevated Lithium
PWR Fuel

ABSTRACT

In recent years, the nuclear industry has placed a high priority on developing solutions to reduce crud on PWR fuel. The Comanche Peak Steam Electric Station demonstration of constant elevated pH is a key initiative of the EPRI Fuel Reliability Program for this specific purpose. This initiative seeks to verify the expected benefits (and absence of adverse observations) of operating at fully optimized conditions of constant pH_t 7.4. This interim report summarizes the results for the first cycle of elevated and constant pH at CPSES U2C7. It also serves as the basis for deciding to continue the demonstration in Cycle 8.

Assessment of operational data revealed minimal movement of corrosion products during power transients compared to similar transients in previous cycles. While the results must be tempered somewhat by a late cycle cold shutdown, the shutdown chemistry data provided more direct evidence of a positive pH effect, particularly in reduction of crud specific activity. Additional evidence may have included a sustained reduction in radiation fields, as well as a significant reduction in total outage exposure during Refuel 7.

Fuel cladding oxide measurements suggested no enhancement of corrosion for the fuel assemblies under examination. Visual examinations revealed a clean state with limited deposits in upper spans where local sub-cooled nucleate boiling is predicted. Crud deposits were comparable or less than the baseline inspections.

A final evaluation of the fuel inspection and chemistry data after operation at pH_t 7.3 prompted the decision by TXU Power to continue the demonstration in Cycle 8 at a constant pH_t 7.4. The absence of any negative results or evidence of an unanalyzed condition was a prerequisite to this decision.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1

INTRODUCTION

1.1 Background of Investigation

The EPRI Fuel Reliability Program and TXU Power co-sponsored the initiative to operate at an elevated constant pH at Comanche Peak Steam Electric Station (CPSES). The initiative is primarily directed at developing solutions to reduce corrosion product deposits (crud) from forming on PWR fuel.

The benefits of operating PWR reactor coolant at elevated pH have been studied extensively, with radiation field reduction as the primary focus. Successful programs involving higher pH operation have been reported by Ringhals in Sweden [2]. Both research results and plant experiences [6] have shown consistent trends of less fuel crud deposits as the at-temperature pH or pH_t is increased. These data further suggest that constant elevated pH_t of 7.4 may be more optimum for this objective. The technical basis includes the prediction that the solubility coefficient for iron based crud deposits becomes positive with higher axial rod elevations (higher temperature) for this operating condition [2], as illustrated in the EPRI PWR Primary Chemistry Water Guidelines [4,7].

Historically, the primary reason elevated pH control ($pH_t > 7.2$) has not been implemented in the U.S. has been due to lithium constraints associated with the high boron requirements for extended fuel cycle operation. Eighteen and 24 month cycles have become standard and beginning-of-cycle (BOC) boron can be 1800 ppm or higher for a 24 month cycle. With the aid of burnable poisons in the core design, these boron values can be reduced by 200 to 300 ppm. Still, for CPSES to achieve pH_t 7.4, calculated lithium concentrations needed to be raised to 6 ppm, which were appreciably outside the operating experience base.

Additionally, a concern and what separates CPSES and many modern PWRs from older units is the newer units are operating with higher RCS operating temperature and higher relative “fuel duty”. Because of these attributes and prior to program implementation, extensive literature reviews were performed using EPRI and other domestic sources in the area of fuel and balance of plant materials to assess the potential effects of operating under the proposed elevated pH/Li environment. Literature reviews were also performed on European plant operation and chemistry programs, research conducted by AECL in Canada, and Nuclear Steam Supply System (NSSS) vendor reports.

TXU Power and fuel vendors (Westinghouse and AREVA) conducted safety evaluations addressing the impact of increasing lithium on three types of fuel cladding; Zircaloy-4, ZIRLO™ and Optimized Zircaloy-4; as well as balance of plant materials. The evaluations concluded that the impact of lithium would be minimal on fuel cladding corrosion for the proposed CPSES Unit

2 Cycle 7 and Cycle 8 core designs, and the effect on balance of plant materials would also be small [2].

1.2 Purpose of Demonstration Project

The elevated pH demonstration project is best described by a review of the task specific to each phase, beginning with the pre-demonstration assessment activities. Each phase of the demonstration and post-operation assessments is then reviewed, as follows:

- Assess the influence of elevated pH_t 7.4 with a maximum lithium concentration of 6 ppm on fuel cladding oxide growth relative to the plant specific core design, limiting power histories, and vendor specific fuel cladding.
- Assess the influence of elevated pH_t 7.4 with a maximum lithium concentration of 6 ppm on primary system materials susceptibility to primary water stress corrosion cracking (PWSCC).
- Demonstrate one cycle (U2C7) of operation at constant pH_t 7.3 and perform interim evaluation of both operating cycle data and refueling outage (2RF07) inspection results. Provide results in interim report.
- Demonstrate one cycle (U2C8) of operation at constant pH_t 7.4, assuming expected results during U2C7, and perform evaluation of both operating cycle and refueling outage (2RF08) inspection results. Provide final project report.
- Demonstrate a second cycle (U2C9) of operation at constant pH_t 7.4. Refueling outage inspections are anticipated to capture results of higher burnup on ZIRLO™ fuel cladding. Not included in the current project scope.

Two major assessment tasks were performed to evaluate the potential impact of the specified chemistry conditions on expected performance of nuclear fuel and reactor coolant system materials. Results of the pre-demonstration task were supportive of the proposed pH program and no significant issues or risks were identified [2].

The potential for minor increases in susceptibility to PWSCC was identified, particularly for the CPSES Unit 1 Alloy 600MA steam generator tube material (Unit 2 has Alloy 600TT tubes). The assessment conclusions found, at most, a minor effect of the proposed chemistry changes. TXU Power judged these to be acceptable and low risk.

While the risks were judged to be low, it was decided to implement the proposed chemistry changes at Unit 2 in two steps, starting with the first operating cycle at a constant pH_t 7.3 and a maximum lithium concentration of 5 ppm. Assuming expected results, the pH program for the next operating cycle would be revised to constant pH_t 7.4 and a lithium limit of 6 ppm.

Each phase of operation included a detailed task for chemistry monitoring and fuel surveillance to verify expected conditions, evaluate results and to capture lessons learned. Some of these tasks were directed at secondary objectives and chemistry parameters that were considered relevant indicators of changes in crud behavior.

Impact of elevated constant pH on radiation fields has been a long-term interest to the industry and capturing these effects is a key objective of the demonstration. Due to the decay of radionuclides in existing ex-core deposits, it is expected that trends may not reach a new equilibrium or dose plateau until after three or more cycles at the optimum pH.

Post demonstration fuel surveillances were planned to capture the effect of elevated pH and higher lithium concentrations on cladding corrosion for both Framatome-ANP Zircaloy-4 and Westinghouse ZIRLO™ fuel rods. Full height fuel surface visual inspections were also planned. Further details are provided in Section 4 of this report.

2
PRIMARY COOLANT CHEMISTRY

2.1 Introduction and Background Information

The overall objective behind the CPSES Unit 2 elevated and constant pH demonstration is to minimize corrosion product release, transport, and deposition on the fuel clad surface. TXU Power's strategies for plant startup, operation, and shutdown chemistry have evolved over the years, especially after the AOA experience at Unit 2 during Cycle 3. Some of the more significant changes in chemistry practices at Comanche Peak Steam Electric Station are described:

- Unit 2 transitioned from modified chemistry (pH_t 6.9-7.4) to coordinated pH_t 7.1-7.2 immediately following the Cycle 3 AOA experience. The vendor approved lithium limit was 4 ppm.
- Startup chemistry controls were modified to minimize crud decomposition during the heat-up evolution and to more rapidly promote crud stabilization. This practice included minimizing excess hydrazine additions during heat-up, delay of hydrogen introduction until after lithium addition, and prompt addition of lithium after terminating RHR operation. More recently, sufficient lithium has been added to assure slightly alkaline, $pH_{t,}$ conditions during heat-up.
- Shutdown chemistry controls have emphasized reducing conditions to enhance crud decomposition and nickel metal removal at higher temperatures. These controls include maintaining high hydrogen during initial cooldown, and minimizing oxygen in the boric acid tanks. In addition, soluble cleanup of released iron has been stressed and more recently, operation of 3 reactor coolant pumps (RCPs) has been maintained during cleanup to minimize ex-core deposition of particulate crud.

TXU Power credits these chemistry practices to have significantly contributed to improved cycle chemistry, enhanced removal of nickel and ^{58}Co during shutdown and reduced times for crud cleanup during startup. Crud observed on fuel assemblies during visual inspections has been characterized as light in comparison to some industry experiences. Also contributing to this latter observation has been a reduction in fuel duty since U2C3.

2.2 Operating Cycle Evaluation

Separating the influence of individual factors on the behavior of corrosion product transport or reactor physics trends (read AOA) is often difficult and the complexity depends, in part, on the number, extent and types of changes that took place for the specific cycle being evaluated. Also contributing to the uncertainty is whether any (and how many) events (e.g. shutdowns) transpired during the cycle. A key objective of this evaluation was to discern any trends that may be associated with influence of elevated and constant pH. Some of the key competing factors considered in this evaluation are reviewed for relevance to the observed results and trends.

2.2.1 CPSES Cycle Assessment

2.2.1.1 Fuel Duty

The core design, specifically the fuel duty, is known to influence the extent of sub-cooled nucleate boiling taking place on the clad surface which has a direct impact on the mass (and often the composition) of crud on the fuel rods [3]. For example, cores with high sub-cooled nucleate boiling are likely to have nickel-rich deposits, which include nickel oxide, nickel metal and in severe cases, bonaccordite, at these locations. Such deposits can exhibit greater mobility during transient conditions than lower duty cores with less sub-cooled nucleate boiling. Therefore, limiting deposits by reduction of sub-cooled nucleate boiling may have a similar effect on chemistry trends as limiting deposits through pH changes.

The High Duty Core Index (HDCI) is used as a preliminary screening criterion for AOA risk assessment [1] and is also used to determine the propensity for a core to deposit crud on fuel surfaces [4]. The HDCI history for CPSES Unit 2 is shown in Table 2-3 and Figure 2-19 for all operating cycles. The HDCI is a gross measure of the fuel duty, and all CPSES Unit 2 operating cycles fall in the “high duty” category.

A more detailed assessment of fuel duty is obtained by comparing steaming rate produced by the BOA code [5] for a crud-free rod surface. The steaming rates for the last three operating cycles at Unit 2 are shown in Figure 2-20. Upon review of the steaming rate trends, it is observed that the core design for U2C7 was similar to recent cycles at BOC, but generally lower duty at mid- and end-of-cycle. Therefore, with all other conditions being equal, one would expect less crud to form on the fuel during U2C7 than in either U2C5 or U2C6.

Figure 2-21 depicts the measured axial offset trend during the cycle versus the nuclear code predicted value. The Cycle 7 CPSES-2 trend is typical for a PWR. No AOA was present during the cycle.

2.2.1.2 Boron, Lithium and pH Control

CPSES Unit 2 is typical of modern PWR operation where the boron requirements have been increased with the transition to 18 month operating cycles. The operating temperature of Unit 2 is relatively high with a hot-leg, T_{hot}, temperature of 618 °F (325.6 °C). The pH control target is based on reactor average temperature, T_{avg}.

Boron and lithium concentrations for U2C7 are shown in Figure 2-3 and Figure 2-4. The boron concentration behavior was typical of recent CPSES Core designs with Framatome-ANP fuel with fixed burnable absorbers. Typical full power critical boron concentration for CPSES units is ~1425 ppm which decreases somewhat linearly with cycle exposure.

Lithium concentrations shown in Figure 2-2 illustrate the implementation of the constant elevated pH program. Initial cycle operation was consistent with expectations and nearly 5 ppm lithium concentration was maintained to achieve the target elevated pH_t 7.3 condition (Figure 2-2). As expected, the lithium concentration followed a similar linear pattern as boron to maintain a near constant pH_t condition throughout the cycle. CPSES U2C7 operated approximately 1/4 of the cycle above the industry experience base of 3.5 ppm lithium concentration.

2.2.1.3 CPSES Operating History

Plant operational events such as power reductions, trips and low temperature shutdowns can range from having a small to dominating effect on corrosion product behavior during the cycle. The degree of the impact on chemistry trends depends on both the frequency and severity of the transient and is generally more pronounced for higher duty core designs.

The operating power history for CPSES U2C7 is shown in Figure 2-1, along with the power histories from U2C5 and U2C6. Analysis of the radio-chemistry trends will be influenced by the operating power history due to the influence on crud mobility

CPSES U2C7 operation was marked by more power transients than U2C5 and U2C6, complicating the analysis of the radio-chemistry trends. The plant experienced an early cycle shutdown, as well as two late cycle shutdowns.

2.2.1.4 Iron and Nickel Monitoring

Iron and nickel concentrations were initially monitored daily after startup and weekly for the balance of the cycle. These samples were analyzed by ICP. Prior to U2C7, nickel and iron analyses were not performed routinely for an entire cycle. The detection limits are 1 ppb. The samples are taken in conjunction with daily RCS samples.

U2C7 iron trends are presented in Figure 2-12 and exhibit higher than expected concentrations, particularly at the BOC. These measured results were consistently above the solubility limit (~2 – 5 ppb) for iron. Also, the variability between samples was high and independent of other measured parameters. For example, ^{58}Co and ^{60}Co, Figure 2-96 and Figure 2-7, respectively, did not follow the same trends as iron. The cause for the high measured iron values and variability in the data is not certain, but may have been influenced by sample line effects. Note however, that the ^{59}Fe trend early in cycle did also display some variability, but not on the scale or for the duration of the elemental iron trend. Similarly, ^{54}Mn (from ^{54}Fe(n,p) reaction) did not display the same trend as for iron. The possibility of an out-of-core iron release was considered, but appeared less likely to be the source due to the other trends that were monitored.

U2C7 nickel trends are presented in Figure 2-11 and most of the measured samples were below the 1 ppb detection limit for the analysis. Due to the fact that nickel was quite low, it was not possible to observe any correlation between nickel and ^{58}Co mobility except during power transients. However, the absence of strong nickel movement is considered consistent with relatively low ^{58}Co variability and limited response to transients.

2.2.2 Chemistry Data Assessment by Operating Phase

2.2.2.1 Startup Chemistry Conditions

Startup chemistry control for U2C7 was according to normal CPSES practices. Oxygen control was established with vacuum fill and addition of hydrazine. Immediately following removal of RHR from service, lithium addition was performed and hydrogen control was subsequently established.

Some difficulty was initially observed with stabilizing lithium as result of higher than normal ammonia concentrations from the hydrazine additions. The lithium-ammonia equilibrium for the lithiated mixed bed demineralizer was cyclic until stabilized after full power operation was achieved.

2.2.2.2 Beginning of Cycle Chemistry Indicators (<150 EFPD)

CPSES Unit 2 experienced a power reduction immediately after startup and was followed by a plant trip approximately one month later. Following the trip, movement of activated corrosion products was minimal. This positive indicator may be partly explained by several factors:

- Effective shutdown and observed clean state of fuel,
- Startup chemistry minimized further decomposition of crud,
- Limited time for activation of freshly deposited metals,
- Possible influence of elevated BOC pH to minimize crud on reload assemblies

Only minor crud mobility was observed in response to a 25% power reduction at approximately 30 EFPD. There were minor crud movements at approximately 75 and 125 EFPD that were not explained by operating transients. These events appeared to delay the positive trend of cleanup, although the extent of the activity increases was very small.

Nickel remained near detection limits except during the reactor trip, as shown in Figure 2-11. The fluctuations in ^{58}Co were small, <10X, and remained on a relatively constant downward trend during this phase of the cycle. The high measured concentration of iron was unexpected and was subject to large fluctuations. The absence of similar trends for ^{54}Mn and to a lesser extent for ^{59}Fe suggests that some of these fluctuations were result of sampling line contribution.

2.2.2.3 Middle of Cycle Chemistry Indicators (~150 to 350 EFPD)

While ^{58}Co concentrations cycled by a factor of ~7X, nickel remained below detection limits. Iron concentrations were more “normal” during this period and smaller fluctuations in the data indicated less influence of possible sample line contributions than experienced at BOC. ^{59}Fe appeared stable and was sometimes below the detection limit.

Beginning with the slight power reduction at ~170 EFPD, introduction of oxygen into the coolant was indicated by a slight and steady increase in ^{41}Ar activity. There was also an increase in ^{58}Co and ^{51}Cr while other isotopes remained relatively stable. The cause of these increasing radioisotopic trends was determined to be oxygen ingress from the in-line H_2/O_2 monitor. The in-line probe is on constant purge from the letdown line and is returned to the volume control tank. After the H_2/O_2 probes were repaired, the upward corrosion products trend reversed and radioisotope activities decreased to previous levels.

A similar occurrence of oxygen intrusion at ~ 275 EFPD was attributed to a use of temporary hydrogen bottles for the Volume Control Tank (VCT). The increase in corrosion product ratios coincident with these incidents of oxygen intrusion suggests the source of the crud may have been from incore surfaces. These experiences offer some confirmation that trace oxygen levels can affect crud mobility, since the effect was also confirmed during steady power conditions.

2.2.2.4 End of Cycle Chemistry Indicators (~350 to 500 EFPD)

In general, crud movement and elevated radioisotope activity are expected to be higher during late cycle power transients, principally due to a greater crud inventory and higher activation (due to longer residence time). Power transients did have a marked effect on the corrosion product trends during this period in U2C7. The ^{58}Co increases were on the order of ~100X, but the ^{58}Co/Ni ratios during this period were less than might be expected for EOC transients. These observations might be explained by a reduced crud inventory or reduced residence time on the fuel.

2.2.3 Operating Cycle Chemistry Comparisons to Prior CPSES Cycles

This operating cycle was typical of prior cycle chemistry experience in many regards. However, there were off-normal operational conditions that appear to have impacted the chemistry results. U2C7 was the first cycle in which oxygen ingress was identified during steady-state operations by radioisotopic trends that was not attributed to boric acid addition. The in-leakage identified at the inline H_2/O_2 meter is confirmation that low level dissolved oxygen ingress can have an effect on corrosion product transport. In addition, the number of trips during U2C7 was above average and further contributed to crud mobility. In spite of these events, the overall mobility of crud was less than some cycles and compares well to the spiking behavior during U2C6. During U2C5 & U2C6 only one significant power transient occurred; U2C6 at 250 EFPD. Crud movement during that power transient was comparable to trips much later in U2C7.

During start-up, ^{58}Co, ^{60}Co, and ^{51}Cr all decreased at a greater rate during U2C7 than during U2C5 & U2C6. The initial concentrations for these isotopes were comparable in U2C6 & U2C7; the initial levels were lower in U2C5. Figure 2-6 through 2-8 demonstrate more stable trends during Cycle 7 than either of the previous two cycles, which saw pH transitions from 7.1 to 7.2 take place between 125 and 150 EFPD.

2.3 Shutdown Chemistry

This section will detail the results of the shutdown chemistry, radiation field trends and dose during the outage.

2.3.1 2RF07 Shutdown Chemistry

The CPSES shutdown chemistry program is an aggressive high temperature nickel ferrite decomposition and dissolution process. During the initial stages of the shutdown, plant chemistry is controlled in an alkaline-reducing environment, then transitions to acid-reducing, and finally to acid-oxidizing with the addition of hydrogen peroxide. The combined use of higher hydrogen, low pH and controlled RCS temperature drives the decomposition and dissolution process to optimize shutdown chemistry with minimal schedule impact.

Figure 2-13 illustrates the events and results for 2RF07. Unit 2 shut down to Mode 3 on October 4, 2003 at 11:27. The goal for shutdown chemistry is to minimize particulate releases and condition the coolant for effective removal by the cleanup system. RCS temperature, hydrogen and pH are used in combination to support optimal release and soluble cleanup.

Reactor coolant cleanup and lithium reduction occurs using the Boron Thermal Regeneration System (BTRS) demineralizer. The demineralizer was loaded with forty cubic feet of cation resin overlaying thirty cubic feet of mixed H-OH resin. Rapid boration to > 2400 ppm combined with lithium reduction, prior to 500 ºF, facilitated transitioning from alkaline-reducing to acid–reducing conditions before reaching Mode 4 temperature. TXU Power's strategy of high temperature acid reducing chemistry is to promote nickel ferrite decomposition early in the shutdown to minimize ECP effects of low level oxygen ingress that can occur during RHR operation and pressurizer fill. Combined with temperature and pH, the strongly reducing conditions facilitate the decomposition of nickel ferrite to support optimal release and cleanup.

On completion of rapid boration, the plant was cooled down to Mode 4 and temperature held at approximately 325 ºF to evaluate decomposition and material solubility. The goal for coolant hydrogen was to maintain > 22 cc/kg with RCS temperature > 300 ºF (149 ºC) to support optimal decomposition. RCS hydrogen was reduced to19 cc/kg during the plant cooldown and boration, but had minimal impact on plant chemistry.

Unit 2 reached 160 ºF on October 5, 2003 at 05:01. Only one reactor coolant pump was secured prior to Mode 5 entry, which effectively minimized particulate deposition during the temperature reduction. Chemistry staff injected peroxide at 20:00. Cobalt-58 peaked at 3.25 uC/mL and nickel peaked at 5480 ppb. The remaining three reactor coolant pumps were secured on October 6, 2003 at 11:20 after corrosion product solubility targets were verified.

CPSES continued cleanup until the CVCS was shut down for maintenance on October 9, 2003 at 03:40. A total of 2.85 kg nickel, 0.40 kg of iron, and 1594 Ci of ^{58}Co were removed.

2.3.1.1 Acid Reducing Phase

Unit 2 achieved acid reducing conditions between 7-8 hours after entering Mode 3. The coolant remained acid reducing for approximately 24 hours before injecting peroxide. The majority of the iron removed during Refuel 7 occurred during this period. Decomposition of the nickel ferrite began [theoretically] at the same time acid reducing was achieved. About 0.35 kg of iron was removed during the acid reducing phase.

The specific activity for iron (^{59}Fe/Fe) was below 0.02 Ci/g on average. This is less than experienced in previous outages and suggests a reduced iron mass and/or residence time in the core, which is an expectation of elevated pH operation. Hydrogen was maintained between 19 and 40 cc/kg through the majority of the phase, thus contributing to the decomposition of the nickel ferrite compounds. The slope of the iron cleanup curve was less than theoretical indicating some continued release throughout the acid-reducing phase. The transition of iron to insoluble state occurred at ~250 ºF during cooldown. However, iron remained in suspension for cleanup due to continued operation of 3 RCPs until after peroxide injection. TXU Power believes this strategy limits particulate contribution to shutdown radiation fields, as well as transportable contamination.

The outage schedule called for peroxide injection 29 hours after entering into Mode 3. However, it did not occur until 32 hours after Mode 3 entry. This was still significantly less than experienced in any other outage at CPSES. In 2RF06, the time from Mode 3 entry to peroxide addition was 61 hours.

2.3.1.2 Acid Oxidizing Phase

Twenty-one liters of hydrogen peroxide were added to the coolant at approximately 20:00 on October 5, 2003. An additional 7 liters were added to compensate for residual hydrogen and support a dissolved oxygen residual.

^{58}Co and nickel peaked at 00:05 on October 6, 2003. ^{58}Co peaked at 3.25 uci/mL and nickel peaked at 5.48 ppm. Specific activity for Nickel was 0.5 Ci/g, which was lower than previous experience.

Corrosion products trended similar to past outages. ^{58}Co and ^{60}Co peaked following the peroxide add. ^{54}Mn, ^{51}Cr, and ^{59}Fe all peaked with nickel ferrite decomposition following cooldown from 500 ºF. Corrosion product clean-up appeared consistent with predictions, Figure 2-16.

After drain down, corrosion products cleaned up faster as expected for the lower volume of RCS and at a consistent high letdown rate. In previous outages, letdown was limited to 65 gpm compared to 118 gpm for 2RF07. Reactor Cavity flood up occurred about twelve hours before originally scheduled. Water clarity for fuel movement was excellent and did not impair fuel movement.

2.3.2 Comparison of Outage Indicators for 2RF05, 2RF06, and 2RF07

A review of the 2RF05, 2RF06, and 2RF07 data allows a preliminary assessment of the effect of operating coolant at a constant pH_t 7.3. A stronger assessment is anticipated after two or more cycles of elevated pH operation. Only minor changes have been made in the manner TXU Power manages shutdown chemistry, so reasonable comparisons between 2RF05, 6, & 7 can be made. A couple noteworthy differences are noted:

- The shutdowns during 2RF06 & 2RF07 had 3 reactor coolant pumps runnning through the acid oxidizing stage, while only two were used in 2RF05. This difference can improve the percent removal of released activity and have some impact on radiation fields.

- The reduction of time in acid reducing conditions (~50%) in Refuel 7 will impact the total release, particularly for iron-based compounds and associated radionuclides. Accounting for this difference quantitatively is difficult, but can be approached by comparison of released activity versus time in acid reducing conditions.
- One indicator of operational chemistry, obtained during shutdown, is the specific activity of Nickel, ^{58}Co/Ni. Nickel specific activity is expected to decrease in a higher pH environment, thus providing a lower dose environment for released material. During 2RF06 specific activity averaged ~0.90 Ci/g, while 2RF07 specific activity was lower at ~0.56 Ci/g.

As reactor coolant pH_{tave} increases, the solubility of iron increases as the coolant ascends up the core. Therefore, higher pH is expected to decrease the amount of iron depositing on the fuel and potentially its residence time. This can be evaluated by assessing the ^{59}Fe/Fe ratio. This ratio for 2RF07 versus 2RF06 was 0.033 and 0.018 respectively; a ~40% reduction. A similar comparison between 2RF05 & 2RF06 and 2RF07 ^{60}Co/Fe ratios showed 2RF05 & 2RF06 were higher than 2RF07. This same comparison for ^{54}Mn/Fe ratio provides nearly identical results as for the ^{60}Co/Fe ratio; a ~50% reduction from the 2RF06 results. This supports one of the objectives of the elevated pH program.

The specific activity for nickel was nearly half in 2RF07 than 2RF06. The average ^{58}Co/Ni was ~0.90 Ci/g during 2RF06, while it was ~0.56 Ci/g during 2RF07.

Overall, if one includes the forced outage inventory removal (165 Ci ^{58}Co, 0.50 Kg Ni, 0.08 Kg Fe), the amount of corrosion products removed was less for 2RF07 than either 2RF05 & 2RF06 (see Table 2-2). The reduced amount of metals removed is consistent with the clean condition of fuel observed during post shutdown visual inspection and supports the objectives of the elevated pH program. Table 2-2 only contains removal amounts from the refueling outages. It should be considered that some of the difference between 2RF06 and 2RF07 is due to less time spent in acid reducing conditions, as discussed above.

In summary, the most compelling evidence of a beneficial effect of constant elevated pH is found in the reduced specific activities for both iron and nickel. Drawing stronger conclusions from the shutdown results are premature and several cycles of elevated pH may be required to make definitive conclusions.

2.4 Outage Dose Rates and Dose Accrued

One of the primary objectives of the elevated pH program was to reduce plant radiation fields. The primary indicator of successful radiation field management is dose rates and total dose received during the outage. During 2RF07 the total dose was 55 person-rem, the lowest dose recorded for any CPSES refueling outage. Figure 2-17 represents the ALARA goals and actual values for all outage activities. It is noted that the outage scope was smaller than previous outages. However, the dose projected, even for the smaller scope was 40% greater than the actual dose received. A portion of the dose savings can be attributed to the shorter times taken to perform some of the activities and a portion is credited to the reduction in radiation fields.

EPRI Standard Radiation Monitoring Points (SRMP) are evaluated from outage to outage and compared to industry trends. Overall dose rates were comparable or lower than previous CPSES outages. Due to alternating inspection cycles for the steam generators, CPSES only has information for certain points every other outage. The missing points are interpolated to assist in trending the dose rates.

EPRI SRMP data are represented by Figure 2-18 for all Unit 2 outages. Due to variances in data between steam generators the overall average is generally used to determine the trend for all components collectively. The average for Unit 2 steam generator dose rates, SRMP points 2 & 10, decreased for 2RF07 by more than 30% from 2RF05 & 2RF06. During U2C3 CPSES experienced AOA, which resulted in higher radiation fields. However, dose rates have been decreasing overall after 2RF03 in response to reduced fuel duties, as well as operating chemistry changes and improved shutdown and startup practices. Therefore, it is difficult to judge whether the reduction observed during 2RF07 was due to a continued downward trend, or to one cycle of pH_t 7.3 operation.

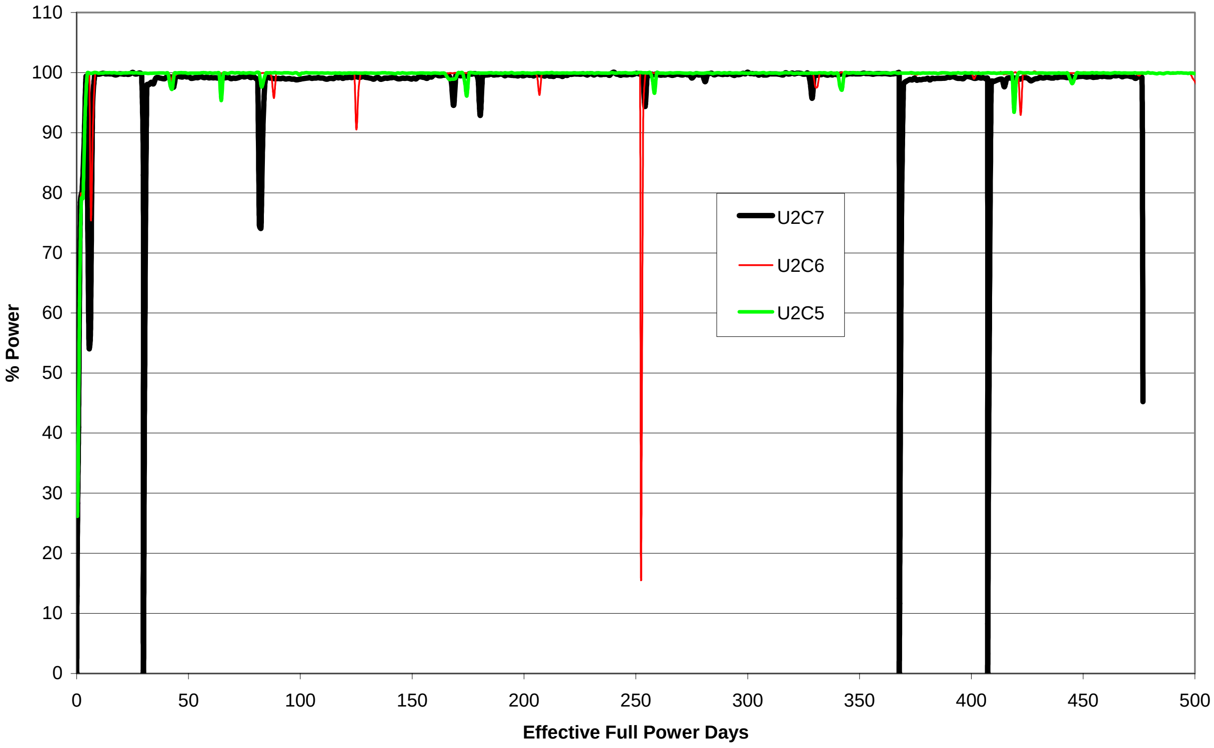


Figure 2-1
CPSES Unit 2 Power

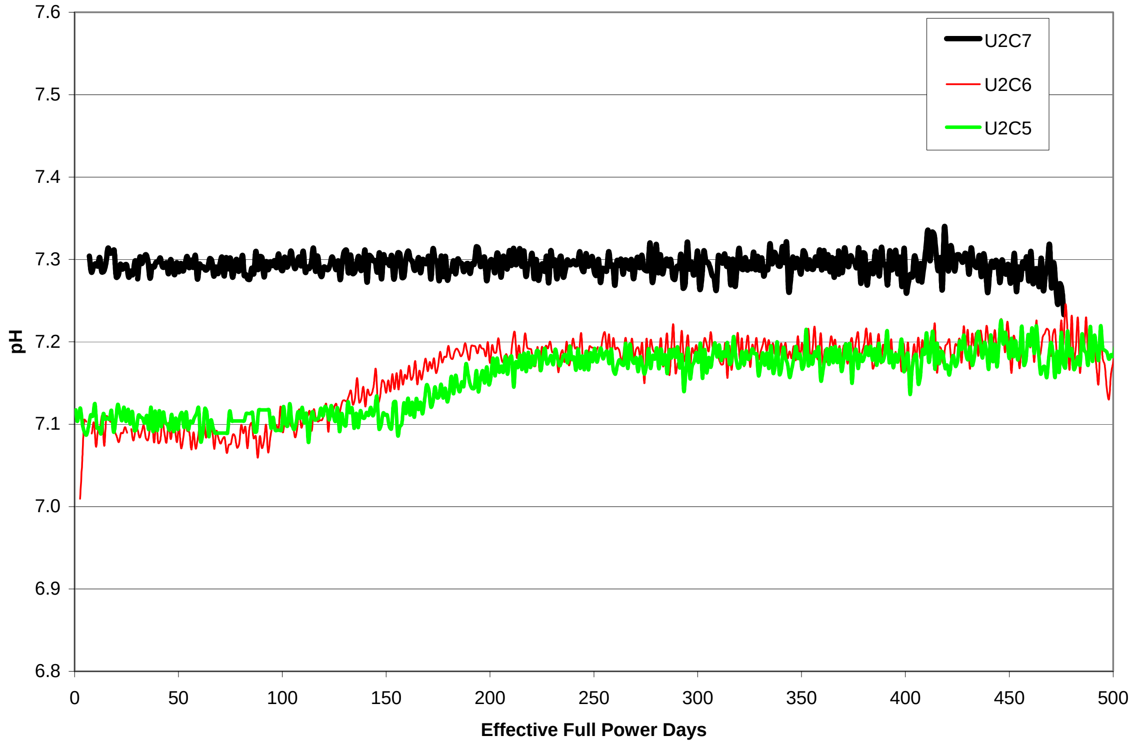


Figure 2-2
CPSES Unit 2 pH at T$_{ave}$

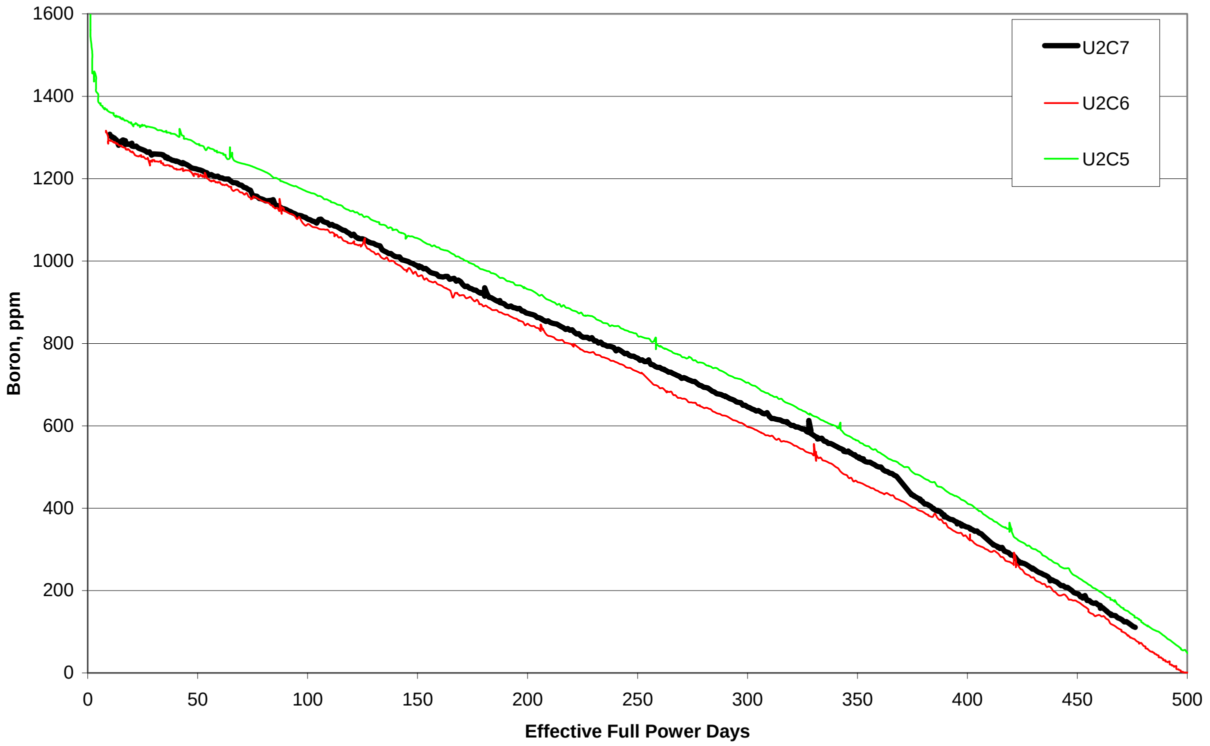


Figure 2-3
CPSES Unit 2 Boron

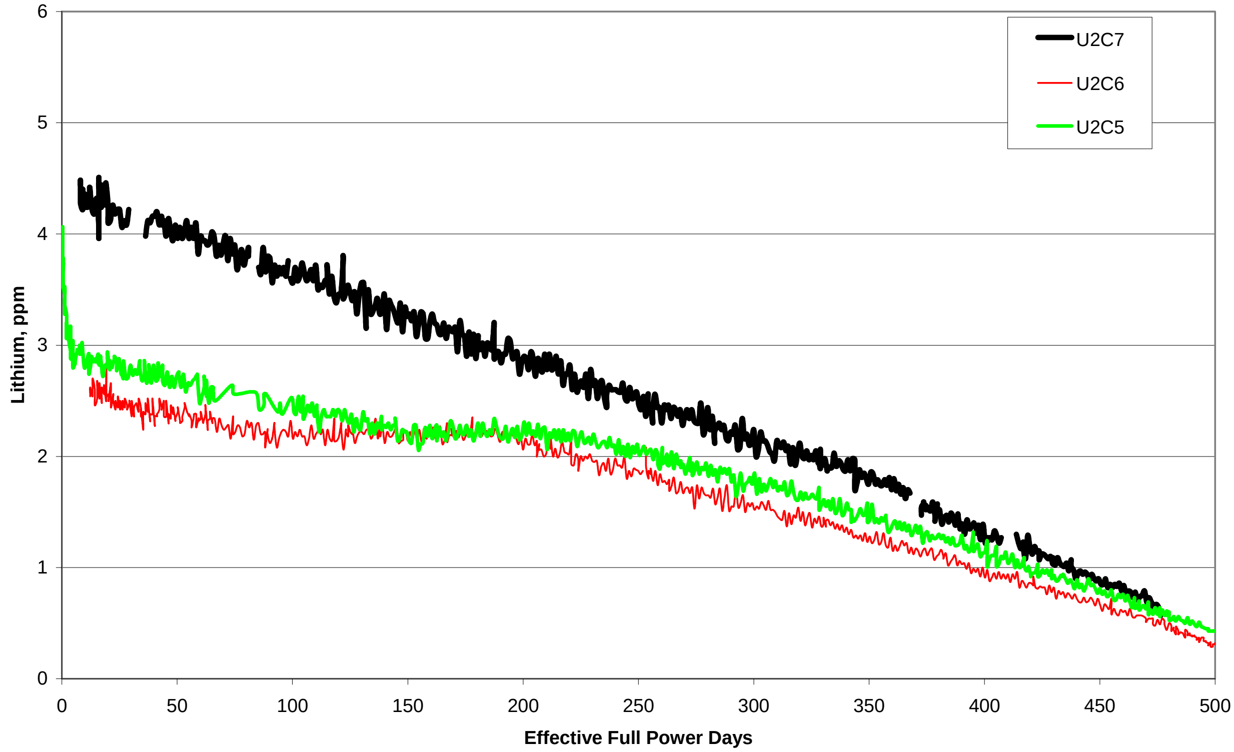


Figure 2-4
CPSES Unit 2 Lithium

Figure 2-5
CPSES Unit 2 RCS ^{41}Ar

Figure 2-6
CPSES Unit 2 RCS ^{58}Co (14 Day Averages)

Figure 2-7
CPSES Unit 2 RCS ^{60}Co (14 Day Averages)

Figure 2-8
CPSES Unit 2 RCS ^{51}Cr (14 Day Averages)

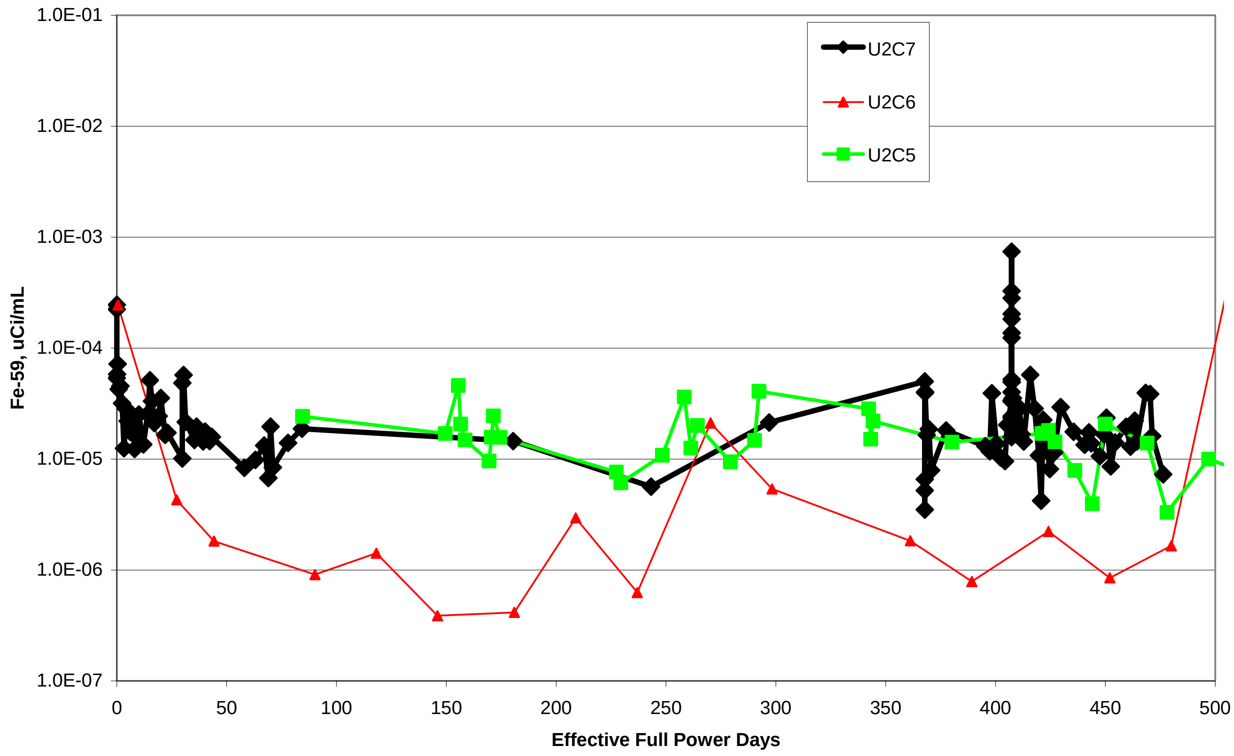


Figure 2-9
CPSES Unit 2 RCS ^{59}Fe

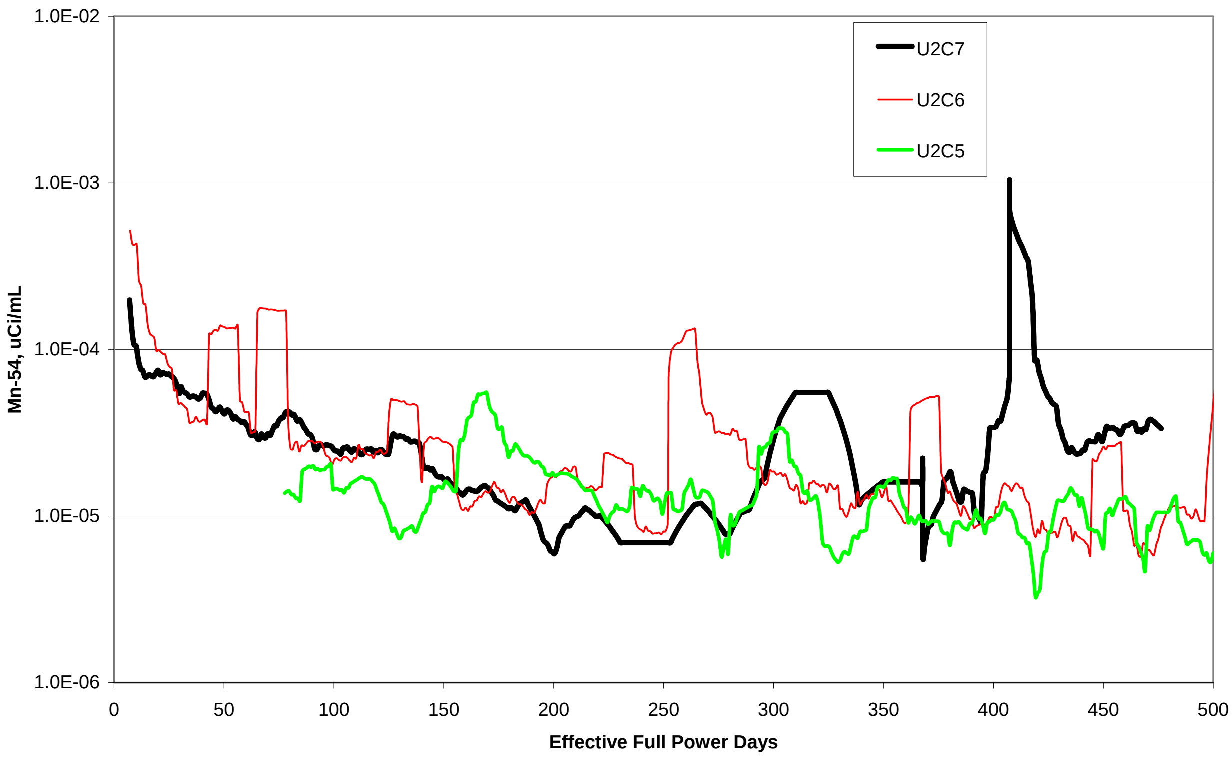


Figure 2-10
CPSES Unit 2 RCS ^{54}Mn (14 Day Average)

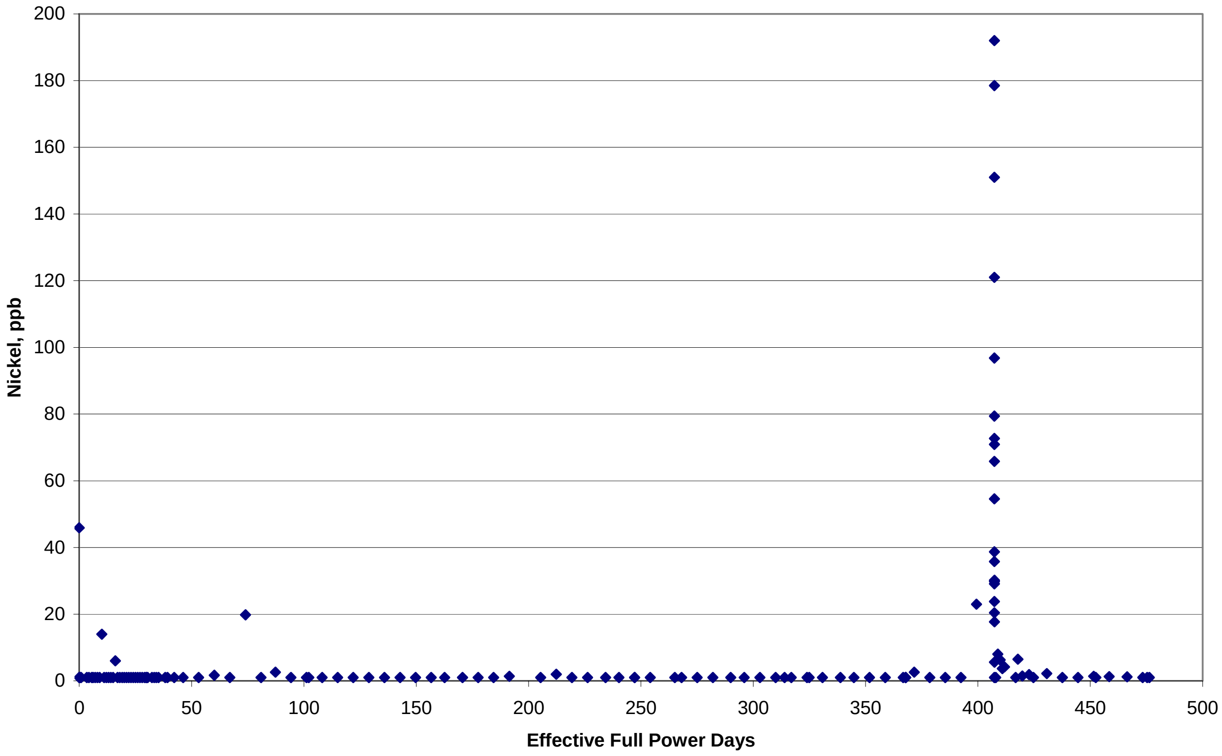


Figure 2-11
CPSES Unit 2 RCS Nickel

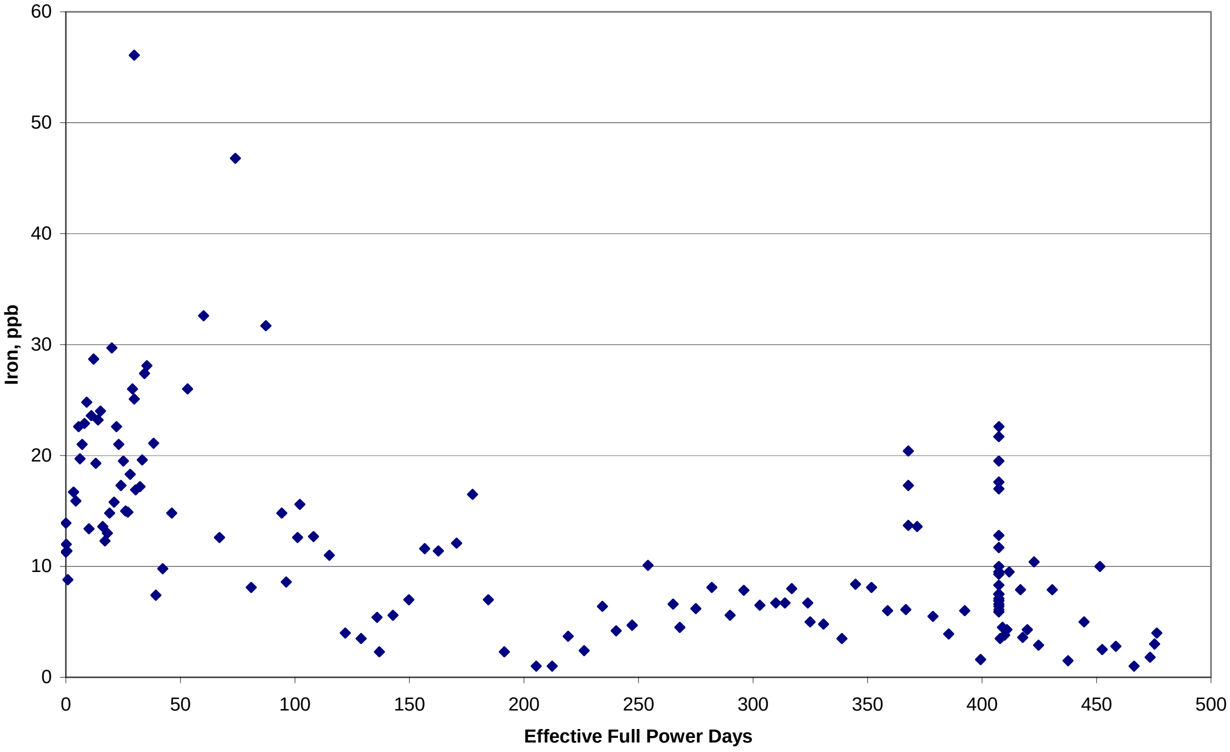


Figure 2-12
CPSES Unit 2 RCS Iron

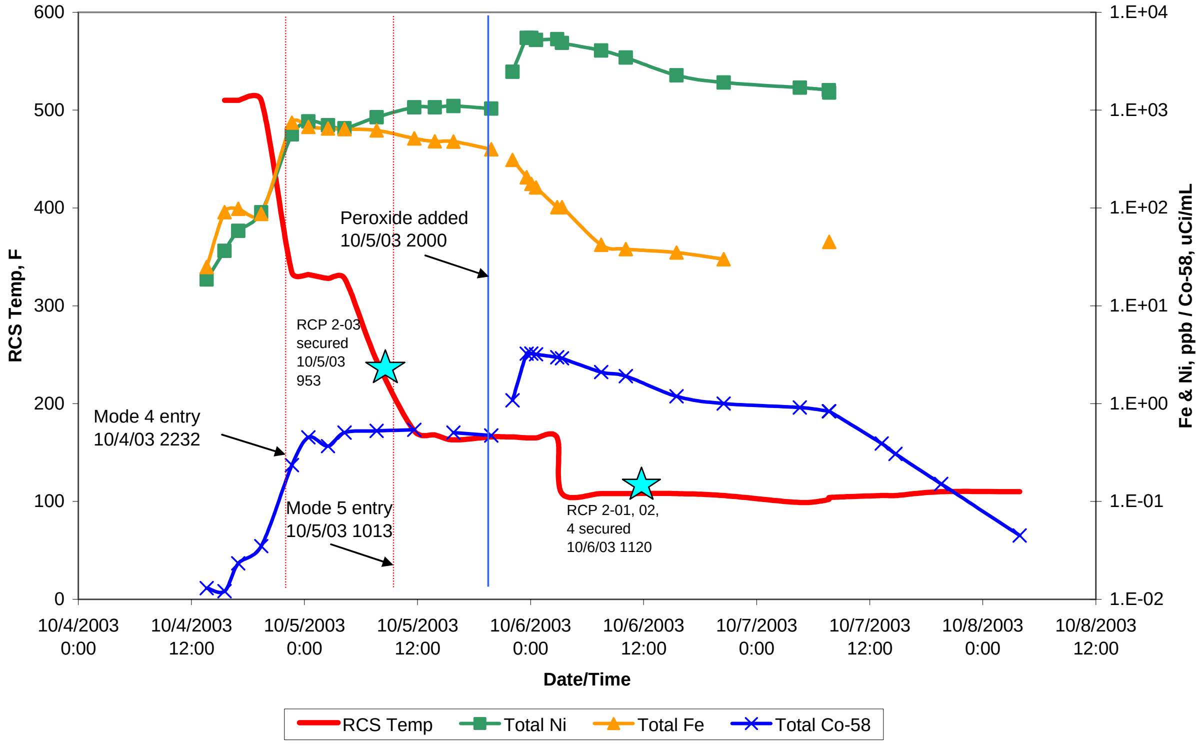


Figure 2-13
CPSES 2RF07 Shutdown Chemistry Indicators

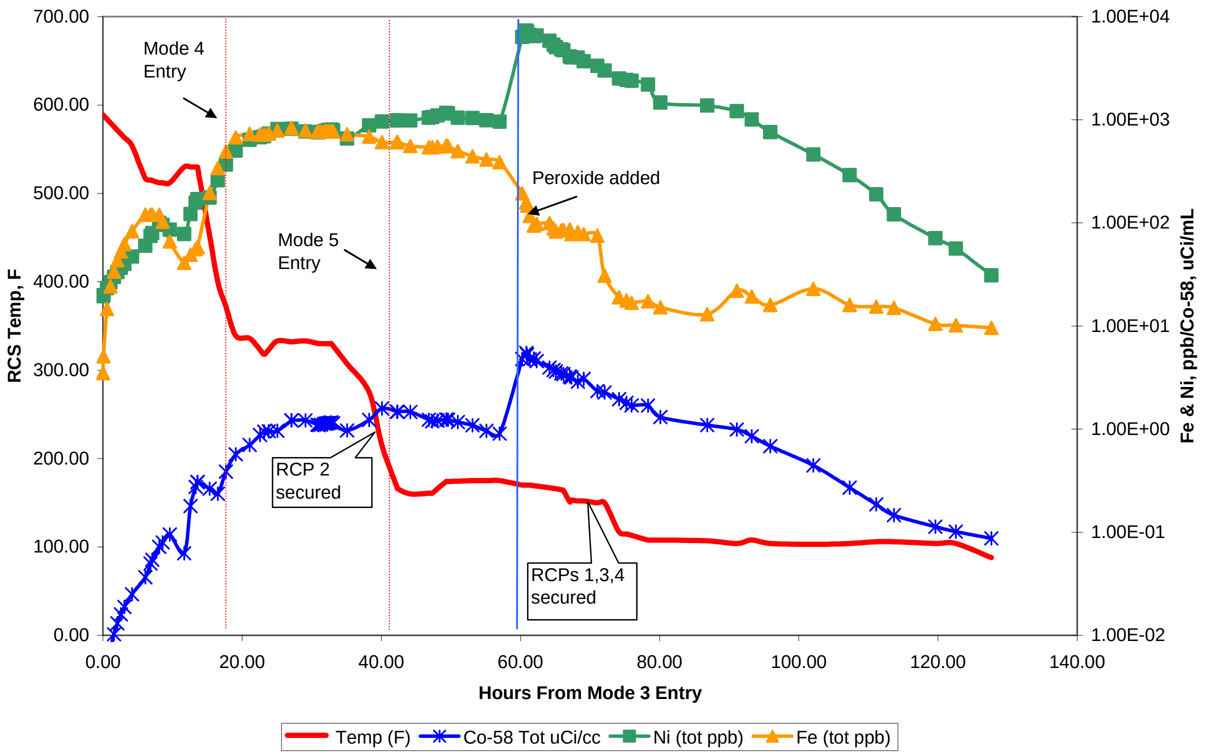


Figure 2-14
CPSES 2RF06 Shutdown Chemistry Indicators

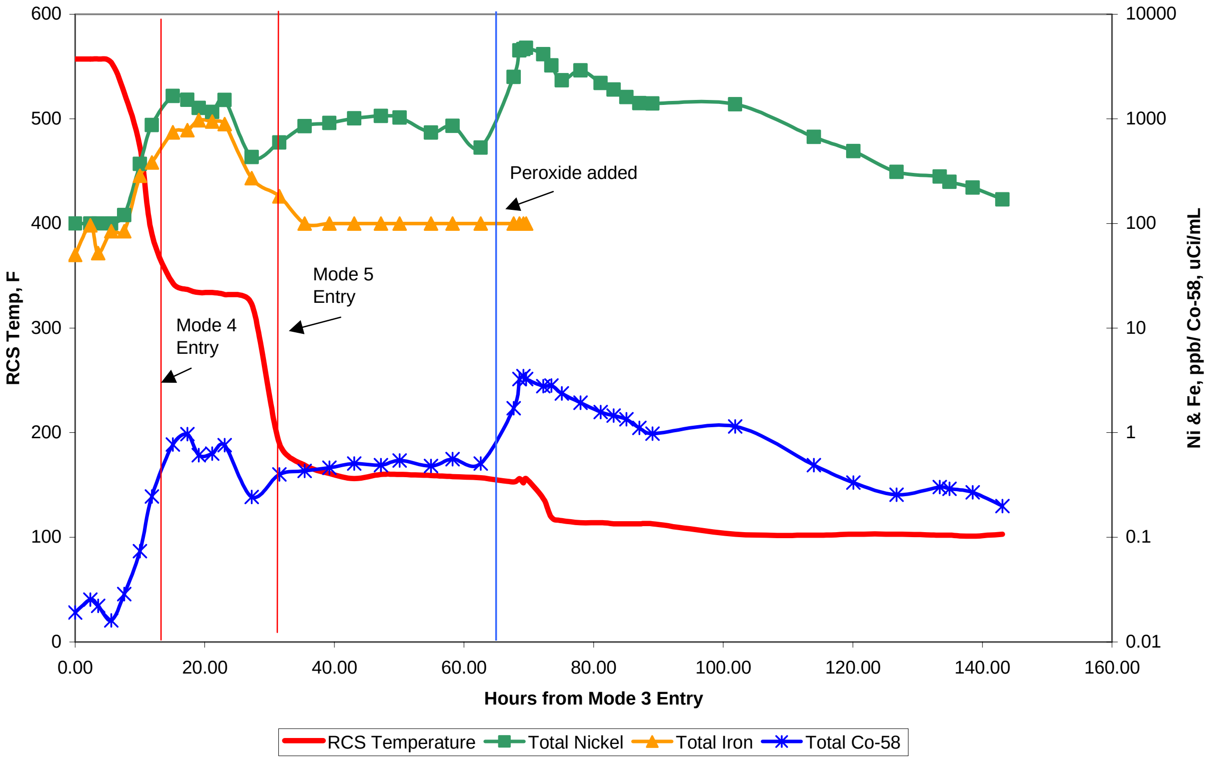


Figure 2-15
CPSES 2RF05 Shutdown Chemistry Indicators

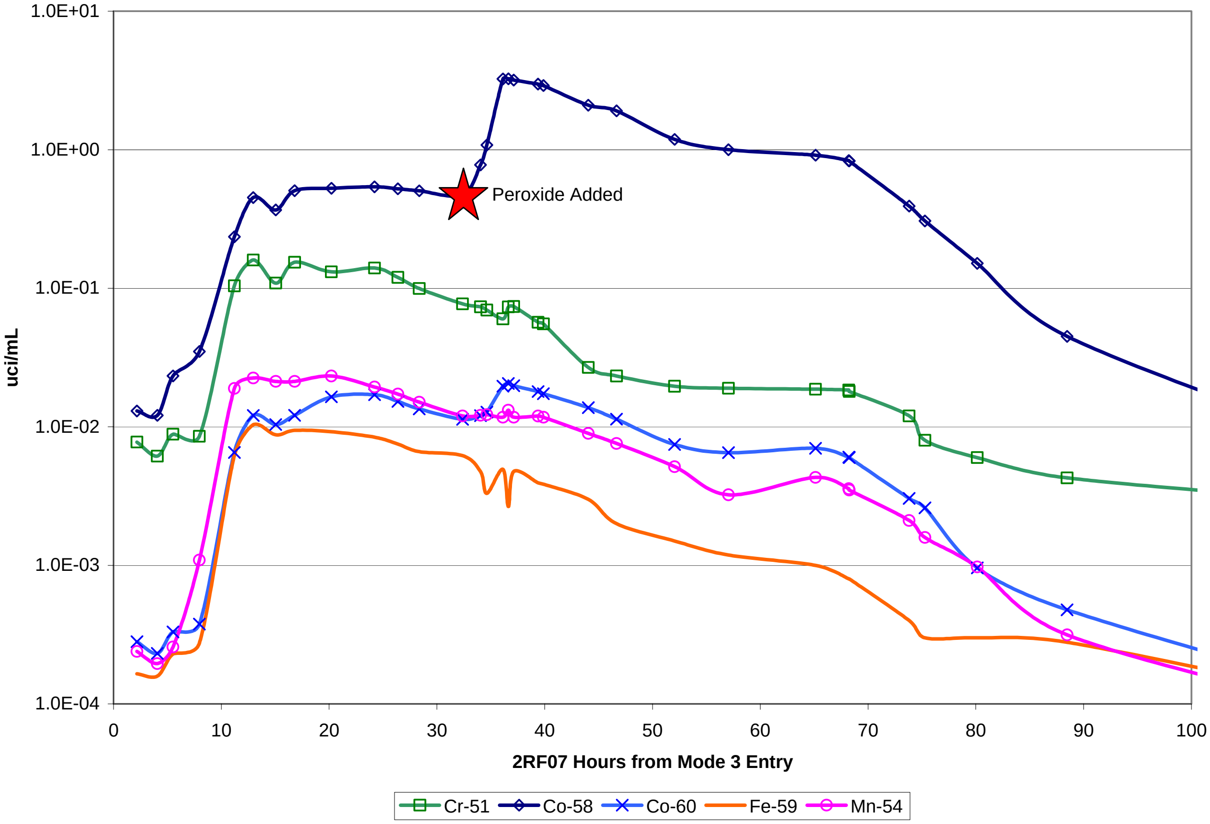


Figure 2-16
CPSES 2RF07 Activated Corrosion Product Concentrations

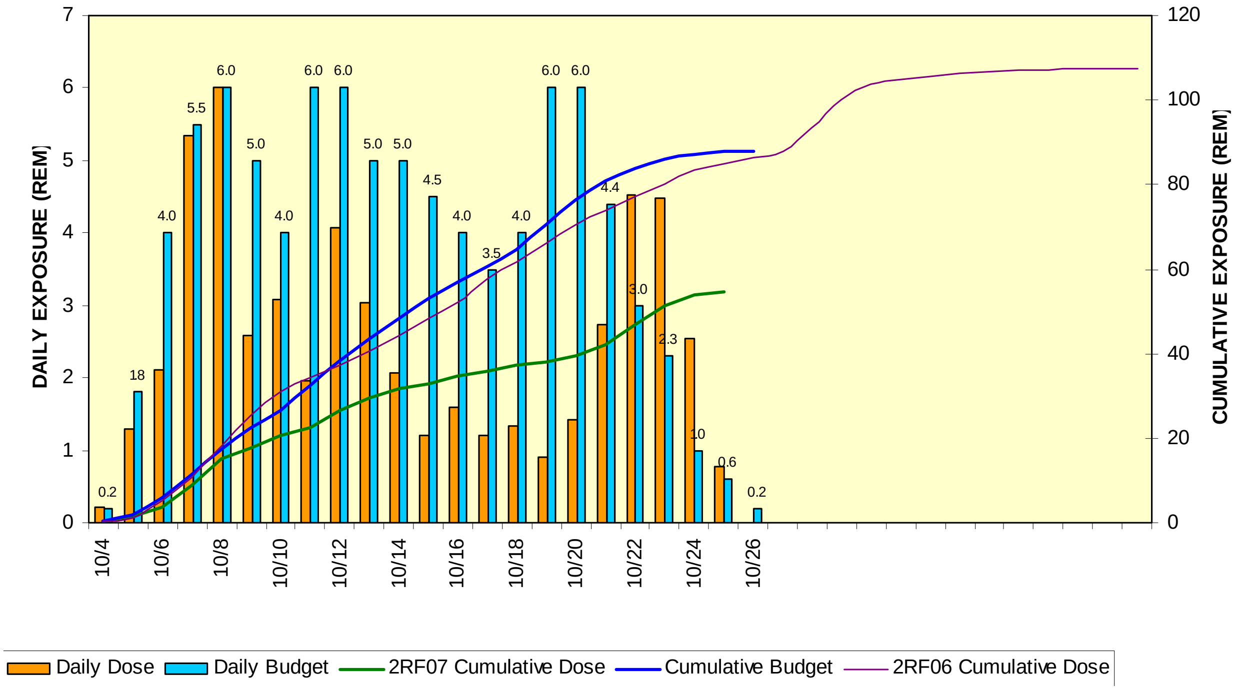


Figure 2-17
CPSES 2RF07 ALARA Exposure Summary

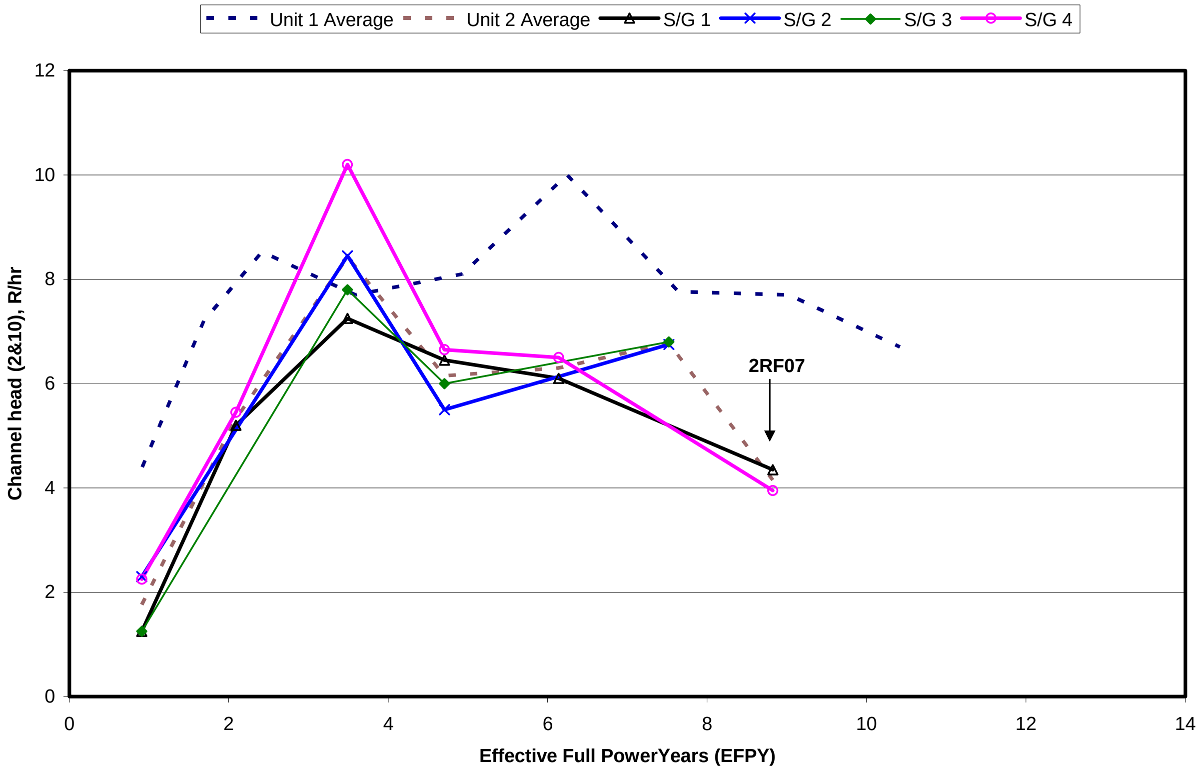


Figure 2-18
CPSES SRMP Steam Generator Data

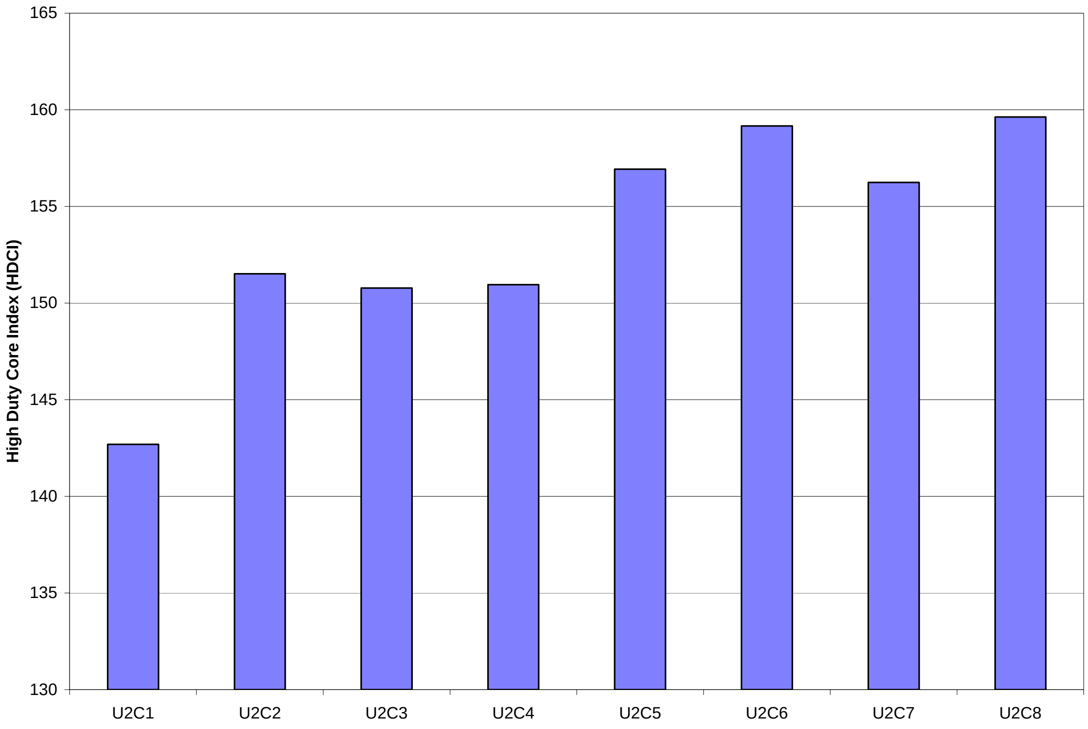


Figure 2-19
CPSES Unit 2 HDCI Values

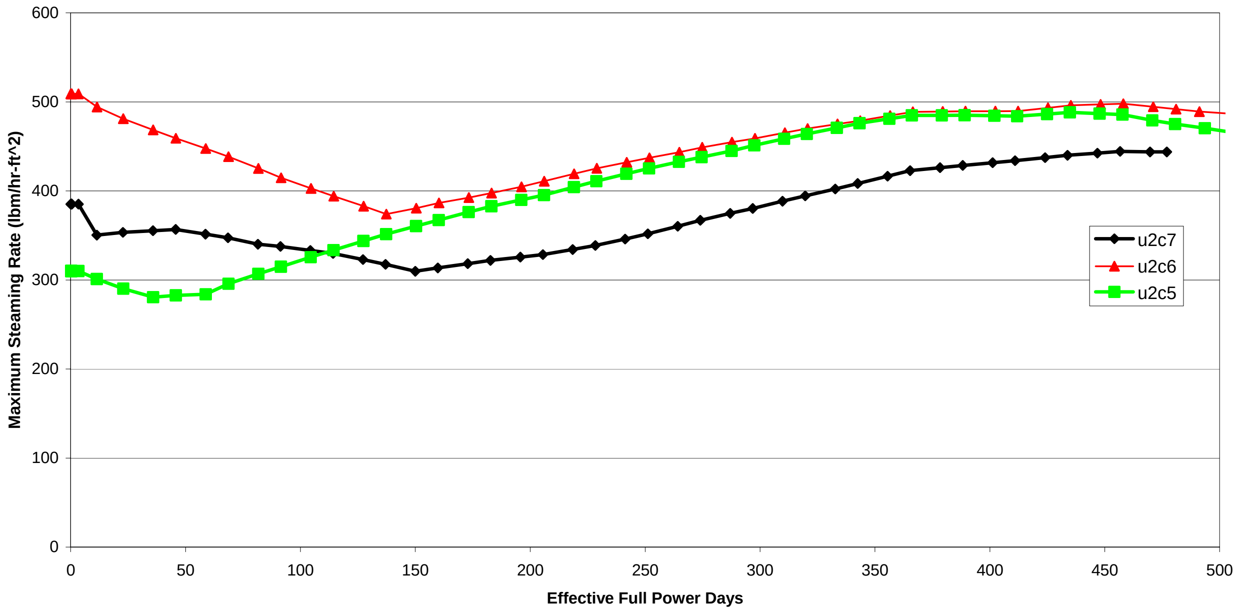


Figure 2-20
CPSES Unit 2 Maximum Steaming Rates

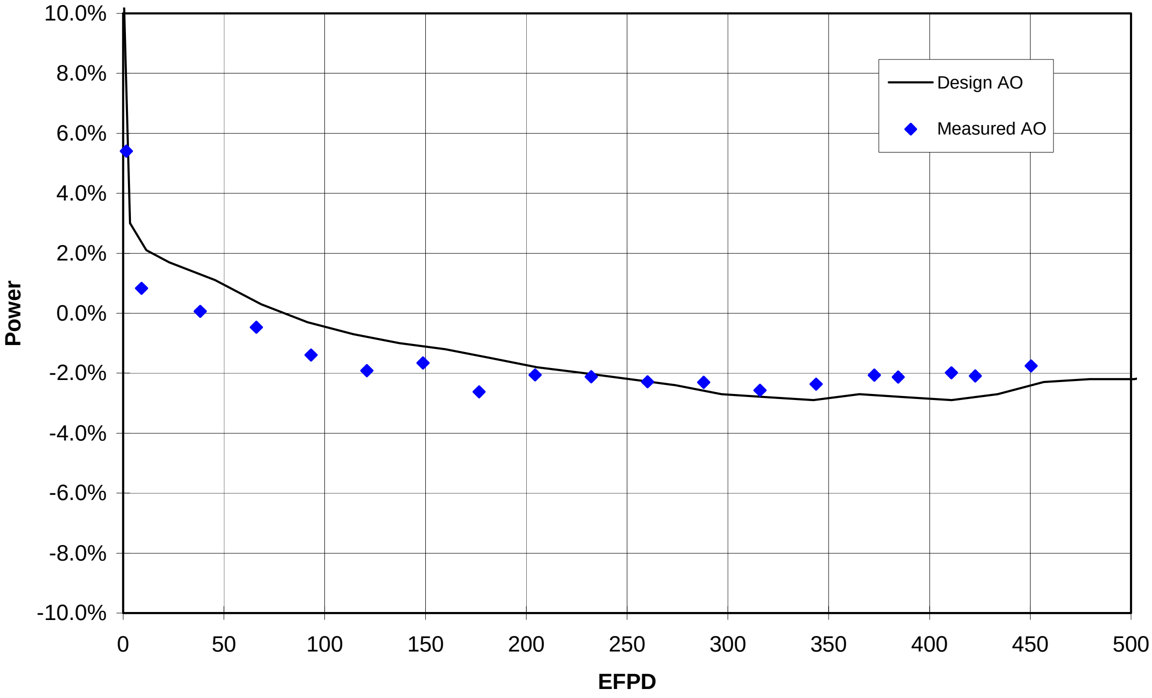


Figure 2-21
CPSES Unit 2 Cycle 7 Axial Offset Trend

Table 2-1
CPSES Shutdown Specific Activity Comparisons

Refueling Outage	^{58}Co/Ni, Ci/g	^{59}Fe/Fe, Ci/g	^{60}Co/Fe, μCi/g	^{54}Mn/Fe, μCi/g
2RF05	0.661	0.023	0.049	0.069
2RF06	0.896	0.033	0.093	0.108
2RF07	0.559	0.018	0.046	0.045

Table 2-2
CPSES Shutdown Removal Amounts

Total CPSES Shutdown Removal Amounts

	Removed, kg		Removed Ci				
Outage	Ni	Fe	^{58}Co	^{60}Co	^{51}Cr	^{54}Mn	^{59}Fe
2RF03	5.26	0.44	1968	----	135	76	----
2RF04	7.14	0.42	2790	----	146	47	----
2RF05	4.32	0.55	2856	27	89	38	13
2RF06	3.98	0.74	3565	69	209	80	25
2RF07	2.85	0.40	1594	18	107	18	7

Acid Reducing Phase CPSES Shutdown Removal Amounts

	Removed, kg		Removed Ci				
Outage	Ni	Fe	^{58}Co	^{60}Co	^{51}Cr	^{54}Mn	^{59}Fe
2RF03	1.41	0.41	860	----	116	67	----
2RF04	0.82	0.33	668	----	117	39	----
2RF05	1.33	0.37	655	15	73	32	11
2RF06	0.92	0.66	1205	37	173	61	20
2RF07	0.57	0.35	265	8	74	11	5

Acid Oxidizing Phase CPSES Shutdown Removal Amounts

	Removed, kg		Removed Ci				
Outage	Ni	Fe	^{58}Co	^{60}Co	^{51}Cr	^{54}Mn	^{59}Fe
2RF03	3.85	0.03	1108	----	19	9	----
2RF04	6.32	0.09	2122	----	29	8	----
2RF05	2.99	0.18	2202	12	17	5	2
2RF06	3.06	0.07	2360	32	36	19	5
2RF07	2.27	0.05	1330	10	33	7	2

Table 2-3
CPSES Unit 2 HDCI Calculations

	Unit 2 Cycle Number						
	U2C1	**U2C2**	**U2C3**	**U2C4**	**U2C5**	**U2C6**	**U2C7**
Number of Loops	4	4	4	4	4	4	4
Number of Fuel Assemblies in Core	193	193	193	193	193	193	193
Fuel Array	17x17	17x17	17x17	17x17	17x17	17x17	17x17
Fuel Rods / Assembly	264	264	264	264	264	264	264
Rod OD (in)	0.360	0.360	0.360	0.360	0.360	0.360	0.360
Core Power (Mwth)	3411	3411	3411	3411	3445	3458	3458
Vessel T-hot (deg F)	616.3	616.3	616.3	616.5	616.8	616.8	616.9
Total Flow (gpm)	419,080	419,080	419,550	415,729	414,940	416,937	415,432
Peak Assembly Power	1.261	1.339	1.334	1.304	1.323	1.335	1.291
HDCIBOL -> 0-6000 (MWD/MTU)	143	152	151	151	158	160	156
AOA Observed?	No	No	Yes	No	No	No	No

3
PERIPHERAL FUEL ROD OXIDE EXAMINATIONS

3.1 Introduction

A peripheral fuel rod oxide exam was performed at Comanche Peak Steam Electric Station Unit 2 during the 6th refueling outage in April 2002. The purpose of this exam was to benchmark cladding corrosion behavior before the start of the elevated pH program and to demonstrate that Westinghouse could accurately measure oxide buildup on Framatome-ANP fuel assemblies.

During 2RF07 in October 2003, peripheral fuel rod oxide measurements were performed following the first cycle exposed to elevated and constant pH.

Full-face camera inspections were performed on all four faces of each assembly examined. Fuel cladding corrosion thickness was measured on the outward-facing surface of peripheral fuel rods. Six peripheral rods were measured on two faces of each assembly. For most of the fuel rods, measurements were performed along all the spans between grids. A high magnification camera recorded visual images of the fuel rods as the oxide measurements were performed.

The oxide measuring equipment is an eddy current system. The system is used to electronically process signals from an eddy current probe that is positioned against the fuel rod. Like all similar electronic instruments, the accuracy is diminished at the extreme ends of the operating range. To minimize this phenomenon, the calibration of the instrument is checked periodically throughout the data collection process. Very thin oxide layers (likely less than 5 microns) measured in the bottom assembly spans may sometimes be recorded as negative values. Values of the measured oxide thickness at these levels are considered to be unimportant, compared to the more limiting grid spans at the top of the fuel assembly.

All the measured oxide data have been averaged over a one-inch interval, and the elevations listed are at the centers of these intervals. Approximately 25 data points were taken in each one-inch interval. The elevations are estimated from the bottom of each fuel rod. A dimension stack-up of grid width, span length, and rod length below the bottom grid provides the elevations used in reporting the measured values. Figure 3-1 shows an axial view of the fuel assembly labeled with grid and span dimensions.

The Framatome-ANP fuel assemblies consist of Zircaloy-4 cladding, while the Westinghouse fuel assemblies consist of ZIRLO™ cladding. A characterization of the bias in the measurement of the Framatome-ANP cladding was attempted prior to the oxide inspection by using precisely measured Mylar tape against an unirradiated Framatome-ANP fuel assembly. Previous examinations have also been performed to determine the effect of different materials on the oxide system response. Based on the data obtained from these calibration tests, it is concluded that a bias of +4 microns exists in the measured results. All results in this report for Framatome-ANP fuel assemblies should be reduced by four microns to account for this bias. This correction factor has NOT been applied to any data in this report.

<u>Other Biases</u>

Crud may be present on the fuel rod clad surface. If the crud is light and loosely-attached, the probe will usually pass through unaffected. However, if the crud is thick and dense, the probe will skim over the surface of the crud-affected areas. This will cause the recorded values to have both an oxide thickness component and a crud thickness component. The system utilized has no method for distinguishing between corrosion thickness and crud thickness. Cleaning (by brushing with Scotch-brite pads) and re-measuring the rods can provide some information about the magnitude of any crud component. However, all deposited tenacious crud may not be removed and it is difficult to visually determine the effect of tenacious crud deposits on the oxide data results.

In an attempt to collect some information on the effect of crud on the oxide measurements, brushing was performed on selected spans of selected fuel assemblies. Brushing entailed rubbing Scotch-brite pads along the length of the span in an up and down motion. The pads were secured in a holder that was lowered to the desired position by steel conduit poles. The oxide measurements were then repeated after brushing was complete. The comparison of pre- and post-brushing data provide some indication of crud thickness, but does not necessarily account for all the crud present.

3.2 Fuel Assemblies Examined

Baseline oxide measurements were performed during 2RF06 on eight fuel assemblies in order to characterize oxide growth prior to operation in the elevated pH/lithium environment. The fuel assemblies selected included once, twice and thrice burned Framatome-ANP assemblies with fuel rod burnups nominally covering a range expected for typical assemblies used at CPSES.

In addition, peripheral rod oxide measurements were taken on fuel assembly F10, a previously discharged fuel assembly that had been measured by Framatome-ANP in the past. Oxide measurements were performed on assembly F10 to compare to the previous measurements, and help determine any bias that may exist in the Westinghouse measurement technique when applied to Framatome-ANP Zircaloy-4 clad.

Following U2C7 operation, oxide measurements were performed to determine if a clear and discernible increase in oxide thickness or growth could be identified as a result of chemistry program changes. The 2RF07 measurements were performed on Framatome-ANP fuel assemblies measured during 2RF06 and operated during U2C7 and Framatome-ANP fuel assemblies with similar power histories as those measured during 2RF06. Four Westinghouse lead use assemblies with ZIRLO™ fuel rod clad were also measured during the 2RF07 campaign.

A summary of the fuel assemblies inspected is included as Table 3-1.

3.3 Oxide Measurement Results

Fuel assembly F10 was measured first to compare the results to previous data obtained by Framatome-ANP and provide data to help determine any bias that may exist when using the Westinghouse measurement equipment with Framatome-ANP Zircaloy-4 clad. Six rods on faces 3 and 4 of fuel assembly F10 were measured over all spans and the peak value obtained for each rod is shown in the Table 3-2. The positions of the rods measured in fuel assembly F10 are shown in Figure 3-2.

Figures 3-3 through 3-8 summarize the positions of the rods measured for the other fuel assemblies examined. Table 3-3 summarizes the results of the peripheral rod oxide measurements performed during 2RF06, while Table 3-4 summarizes the results for measurements performed during 2RF07. The peak values reported represent the highest oxide measurement recorded for the axial oxide profile for each rod. Peak values that are thought to include a crud component are noted in the table. The rod burnup represents the average burnup of the fuel rod measured. Figure 3-9 illustrates the data reported in Table 3-3 and Table 3-4.

3.3.1 Comparison of Measurements Before and after Brushing

Visual inspections of several higher burnup assemblies during both 2RF06 and 2RF07 suggested the presence of crud, as shown in Figure 3-10. Selected fuel rods were brushed and another set of measurements was performed. The measurements before and after brushing are shown in Table 3-3 and Table 3-4. In some cases, oxide measurements obtained following crud brushing showed a considerable decrease in maximum oxide thickness as shown in Figures 3-11 and 3-12. However, measurements on other rods after brushing indicated only a small decrease in the measured oxide thickness. This suggests one of two possibilities; either the crud on some the rods was tenacious and was not as effectively removed by brushing, or, crud had only a minimal effect on the oxide measurement. A review of the assembly images that were taken prior to brushing, however, confirms the presence of noticeable crud.

It was concluded that crud had varying effects on the oxide measurements. Following the brushing, some crud was removed but much remained. The impact of brushing on the oxide measurements ranged from only a few microns reduction between before and after results, to as much as a 40 micron reduction in thickness. The rods with the highest measured oxide thickness were also noted to have the most crud present; however, the oxide thickness was reduced by only a few microns after brushing.

3.3.2 Comparison of Symmetric Fuel Rods

Fuel assemblies HH80, HH82 and HH83 operated in symmetric core locations with similar power histories during Cycle 6 and Cycle 7. The measurements performed on symmetric rods are shown in Table 3-5, using data obtained from Table 3-4. The data is presented allowing the symmetric fuel rods to be easily compared. While the measurements on some symmetric rods were consistent, measurements on other rods displayed a large variation in oxide thickness despite the same operating history.

3.4 Fuel Assembly Visual Examinations

Visual examinations were performed on all assemblies on which oxide measurements were taken to determine the overall condition of the fuel clad surface, and, in particular, the nature of any crud deposition on the assemblies. The majority of the assemblies appeared to be in good condition with no indications of significant crud on the clad surfaces. It was noted by the oxide measurement team that the condition of the assemblies, including crud deposition, appeared to be somewhat improved compared to observations made during 2RF06.

On the twice burned high burnup assembly there were indications of streaks of dark crud on several rods. Most of the crud was observed in span 6 of the assembly; however, there were minor indications of crud in some locations on span 5 as well. As discussed previously, several rods were brushed in an attempt to remove the crud and quantify the effect of crud on the oxide measurements.

Evidence of possible oxide blistering was observed in Span 6 of several rods during both 2RF06 and 2RF07 inspections. Oxide blistering has been observed in the industry in Zircaloy-4 cladding with peak oxide thickness in the range of 60-80 microns. The oxide layer is more brittle and resistant than the cladding material. Cracks develop in the oxide layer which join together and delaminate in roughly rectangular patches. The initial stages of the delamination are exhibited by "blisters," "bumps," or "raised oxide surfaces," some of which have become detached from the base material below. There is no general consensus on the mechanism for the cracking but factors that contribute are: rate of oxide formation, oxide volume expansion, thermal gradients, clad strains, coolant chemistry, and clad/oxide alloy chemistry.

During the 2RF07 campaign, assembly HH80, Face 1 showed evidence of oxide blistering on Rod 10, with a maximum measured oxide thickness of 57 microns. Blisters were also observed on Face 2, Rods 7 through 10, 12, and 14. Rods 8, 10, 12, and 14 had peak oxide values of 69, 98, 84, and 71 microns, respectively. Blisters were also observed on assembly HH83, Face 3, Rods 2, 9, 10, 13, and 14. Rods 2, 10, 12, and 14 had peak oxide values of 92, 69, 64, and 46 microns, respectively. Rod 14 had an oxide thickness less than might be expected for oxide blisters; however, oxide blisters were also observed during the 2RF06 inspection campaign on a fuel rod with a peak oxide thickness of 53 microns.

The high magnification visual record showed some evidence of possible oxide delamination. The possible oxide delamination appeared as small crater-like spots that were darker in color than the surrounding surface. The darker color may be indicative of the metal surface or thin layer of oxide remaining after delamination. Brushing of these rods may have caused some of the oxide blisters to be removed. These appeared to be small crater-like spots that are darker in color than the surrounding surface. Evidence of oxide delamination was also observed during the 2RF06 inspection, so this appearance is not unique to Cycle 7.

3.5 Comparison of 2RF06 and 2RF07 Examinations

Once-burned assemblies during 2RF06 (HH39 and HH80) showed some very slight, brownish crud deposition in Spans 4 through 6. This crud was present throughout these spans but was an inconsistent, non-uniform covering. Span 7 had a slightly thicker, uniform light brown cover of crud. The once-burned assemblies during 2RF07 showed evidence of this light brown crud only in Spans 6 and 7. However, a thicker, dark crud was observed on several rods (9 of 408, 2.2%) in Spans 5 and 6. This type of crud was not seen on the once-burned assemblies from Cycle 6.

The low duty, second-burned assemblies from Cycle 6 (GG01 and GG19) showed the same thin, uniform light brown crud on Spans 4 through 6. A thicker layer of this brown crud was observed in Span 7. Thicker, dark crud was also observed on several rods (9 of 136, 6.6%) in Spans 5 and 6. The same type of fuel assembly (HH39) from Cycle 7 showed only the uniform light brown crud in Span 7. No dark crud was observed on this assembly.

The high duty, second-burned assemblies from Cycle 6 (GG54 and GG69) showed light crud accumulation in Spans 5 and 6. A similar, but slightly thicker crud layer was observed in Span 7. Thick, dark crud was observed on three rods (3 of 68, 4.4%) in Span 6. Oxide blistering was noted on several rods in Span 6. The high duty assemblies from Cycle 7 showed the light crud in Spans 4 through 6. It was also present in Span 7 as a slightly thicker layer. The thicker, dark crud appeared on many rods (56 of 204, 27.5%) in Spans 5 and 6. Oxide blistering was also observed on several rods in Span 6.

The third-burned assembly from Cycle 6 (FF41) exhibited the light brown crud in Spans 4 through 7. As in the other assemblies, this crud was most prevalent in Span 7. No thick, dark crud was observed on this assembly. The third-burned assemblies from Cycle 7 showed the light brown crud only in Span 7. However, dark crud was observed on one rod in Span 5 and two rods in Span 6 (3 of 136, 2.2%).

Peak oxide values for fuel rods from Cycle 6 and Cycle 7 with similar power histories are compared in Table 3-6. The first-burned assemblies had fuel rods with peak oxide thicknesses ranging from 9 to 30 microns during 2RF06 and ranging from 10 to 19 microns during 2RF07. Low duty, second-burned assemblies had fuel rods with peak oxide thicknesses ranging from 24 to 30 microns during 2RF06 and ranging from 17 to 22 microns during 2RF07. The high duty, second-burned assemblies had fuel rods with peak oxide thicknesses ranging from 38 to 85 microns (after brushing, no change) during 2RF06 and ranging from 32 to 98 microns (after brushing, 31 to 94 microns) during 2RF07. The third-burned assemblies had fuel rods with peak oxide thicknesses ranging from 22 to 55 microns during 2RF06 and ranging from 26 to 49 microns during 2RF07.

The scatter in peak oxide values for a given assembly face seemed to increase from Cycle 6 to Cycle 7. The largest difference in peak oxide for a face from Cycle 6 was 38 to 75 microns. The largest range on a face from Cycle 7 was 31 to 94 microns.

In general, the oxide thickness measurements performed during 2RF07 were the same or lower than those obtained during 2RF06 for similarly irradiated assemblies. However, oxide measurements on the high burn-up twice burned assemblies were slightly higher than the maximum observed in similar assemblies measured during 2RF06 and showed greater variability in the data.

3.6 Conclusions

Analysis of the data before and after brushing indicated that most of the crud present did not have an effect on the oxide measurements. However, the presence of the localized thick, dark crud that formed axially along the rods in Spans 5 and 6 could affect the oxide thickness results. Several rods were noted to have this type crud present on the upper spans of their peripheral faces (and thus in the probe's path). If brushing was not performed on these rods or the brushing was not effective, then the peak values for these rods are likely to be crud-affected. Only three such rods were identified, and crud-free estimates of peak oxide thickness were determined.

Overall, there seemed to be less of the uniformly deposited, light brown crud present after Cycle 7 than was observed after Cycle 6. The thicker, dark crud consistently appeared in Spans 5 and 6 for both cycles. However, it was observed only on the low and high duty second-burned assemblies in Cycle 6; but was observed on the first-burned, high duty second-burned, and third-burned assemblies in Cycle 7. This type of crud also appeared more often after Cycle 7. Many rods (27.5%) from the high-duty assemblies were affected in Cycle 7, but only a few rods (4.4%) from the high-duty assemblies in Cycle 6 exhibited this type of crud.

Oxide values remained fairly consistent from Cycle 6 to Cycle 7. If anything, there may have been a slight decrease in overall oxide thickness. There was some increase in the peak oxide thickness for the high duty assemblies. Since the increase was only about 10 microns, it is considered within the normal variation to be expected at this level of corrosion. The frequency, magnitude, and location of oxide blistering did not change between Cycle 6 and Cycle 7.

Based on the few changes in crud deposition, oxide thickness, and oxide appearance, and the good performance of the corrosion model, it is concluded the higher pH and increased lithium environment have not had an adverse impact on corrosion performance.

Oxide measurements obtained for Westinghouse and Framatome-ANP assemblies indicate oxide thickness values within the allowable range for the corresponding burnup, and the values compared well with those obtained during 2RF06. Thus, the elevated pH environment (pH_t of 7.3 and lithium concentration up to 5 ppm) did not result in a discernable increase in clad oxide thickness.

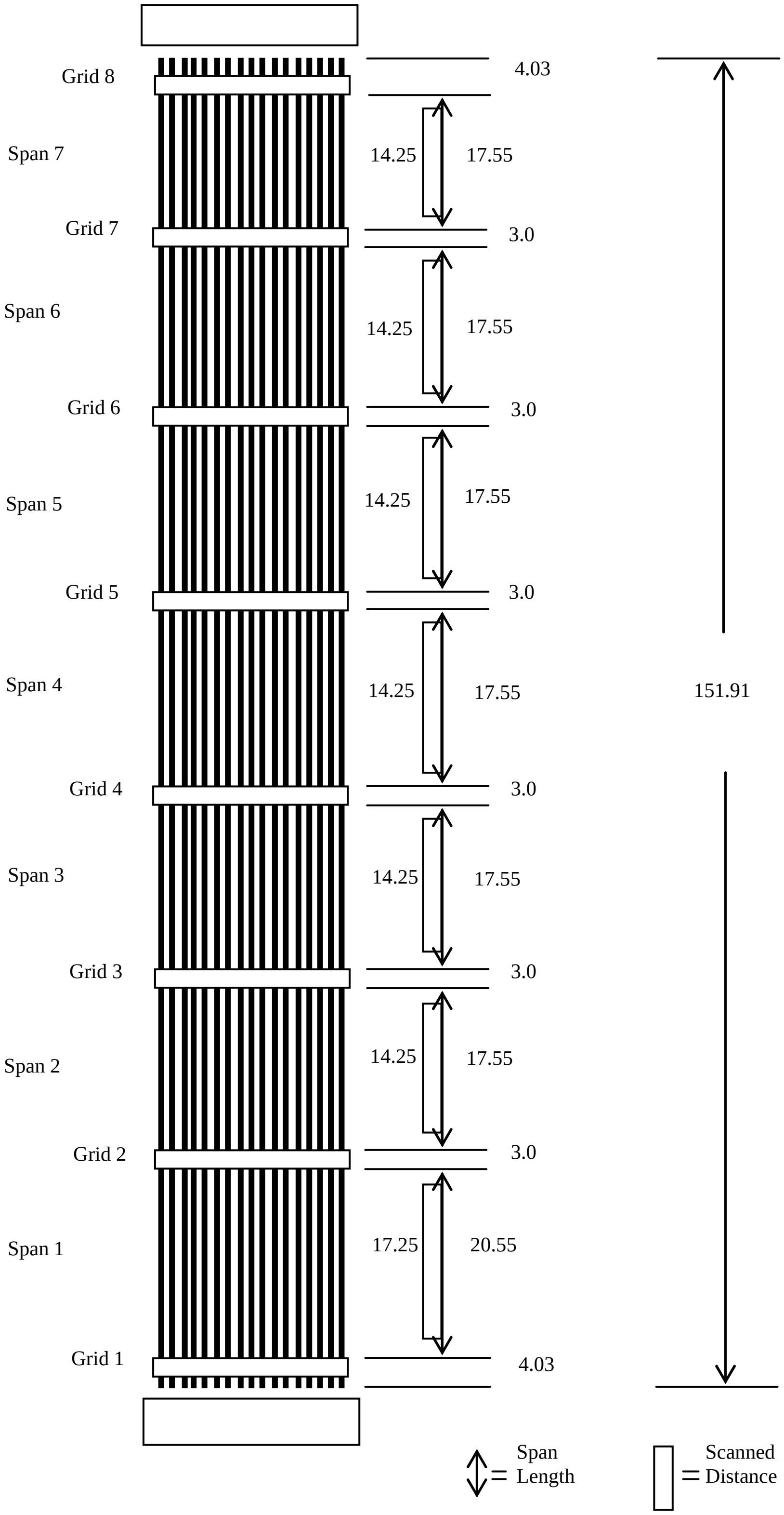


Figure 3-1
Axial View of Fuel Assembly (Dimensions in inches)

Face 1
(Side C)

Face 4
(Side B)

Face 2
(Side D)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
A																	
B	M																
C						T			T			T					
D				T										T			
E																	
F			T			T			T			T			T		
G																	
H	M																
I			T			T			I			T			T		
J	M																
K																	
L	M		T			T			T			T			T		
M																	
N	M			T										T			
O						T			T			T					
P																	
Q	M			M		M		M				M				M	

Face 3
(Side A)

I = Instrument Tube
T = Guide Thimble Tube
M = Measured Fuel Rod Location

Figure 3-2
Fuel Assembly F10, Measured Rod Locations

Face 1
(Side C)

Face 4
(Side B)

Face 2
(Side D)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
A				M		M		M		M		M				M	
B	M																
C						T			T			T					
D				T										T			
E																	
F	M		T			T			T			T			T		
G																	
H	M																
I			T			T			I			T			T		
J	M																
K																	
L	M		T			T			T			T			T		
M																	
N	M			T										T			
O						T			T			T					
P																	
Q																	

Face 3
(Side A)

I = Instrument Tube
T = Guide Thimble Tube
M = Measured Fuel Rod Location

Figure 3-3
Fuel Assembly GG19, GG69 & HH82 Measured Rod Locations

Face 1
(Side C)

Face 4
(Side B)

Face 2
(Side D)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
A																	
B																	
C						T			T			T					
D				T										T			M
E																	
F			T			T			T			T			T		M
G																	
H																	M
I			T			T			I			T			T		
J																	M
K																	
L			T			T			T			T			T		M
M																	
N				T										T			
O						T			T			T					
P																	M
Q		M				M		M		M		M		M			

Face 3
(Side A)

I = Instrument Tube
T = Guide Thimble Tube
M = Measured Fuel Rod Location

Figure 3-4
Fuel Assembly FF41, GG54, HH39, JJ23, JW06 Measured Rod Locations

Face 1
(Side C)

Face 4
(Side B)

Face 2
(Side D)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
A				M		M		M		M		M				M	
B																	
C						T			T			T					
D				T										T			M
E																	
F			T			T			T			T			T		M
G																	
H																	M
I			T			T			I			T			T		
J																	M
K																	
L			T			T			T			T			T		M
M																	
N				T										T			
O						T			T			T					
P																	M
Q																	

Face 3
(Side A)

I = Instrument Tube
T = Guide Thimble Tube
M = Measured Fuel Rod Location

Figure 3-5
Fuel Assembly GG01, HH80, JW01 Measured Rod Locations

Face 1
(Side C)

Face 4
(Side B)

Face 2
(Side D)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
A																	
B	M																
C						T			T			T					
D				T										T			
E																	
F	M		T			T			T			T			T		
G																	
H	M																
I			T			T			I			T			T		
J	M																
K																	
L	M		T			T			T			T			T		
M																	
N	M			T										T			
O						T			T			T					
P																	
Q		M				M		M		M		M		M			

Face 3
(Side A)

I = Instrument Tube
T = Guide Thimble Tube
M = Measured Fuel Rod Location

Figure 3-6
Fuel Assembly HH83 Measured Rod Locations

Face 1
(Side C)

Face 4
(Side B)

Face 2
(Side D)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
A				M		M		M		M		M				M	
B																	
C						T			T			T					
D				T										T			
E																	
F			T			T			T			T			T		
G																	
H																	
I			T			T			I			T			T		
J																	
K																	
L			T			T			T			T			T		
M																	
N				T										T			
O						T			T			T					
P																	
Q		M				M		M		M		M		M			

Face 3
(Side A)

I = Instrument Tube
T = Guide Thimble Tube
M = Measured Fuel Rod Location

Figure 3-3-7
Fuel Assembly JJ83, JW07 Measured Rod Locations

Face 1
(Side C)

Face 4
(Side B)

Face 2
(Side D)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
A																	
B	M																
C						T			T			T					
D				T										T			M
E																	
F	M		T			T			T			T			T		M
G																	
H	M																M
I			T			T			I			T			T		
J	M																M
K																	
L	M		T			T			T			T			T		M
M																	
N	M			T										T			
O						T			T			T					
P																	M
Q																	

Face 3
(Side A)

I = Instrument Tube
T = Guide Thimble Tube
M = Measured Fuel Rod Location

Figure 3-8
Fuel Assembly JW05 Measured Rod Locations

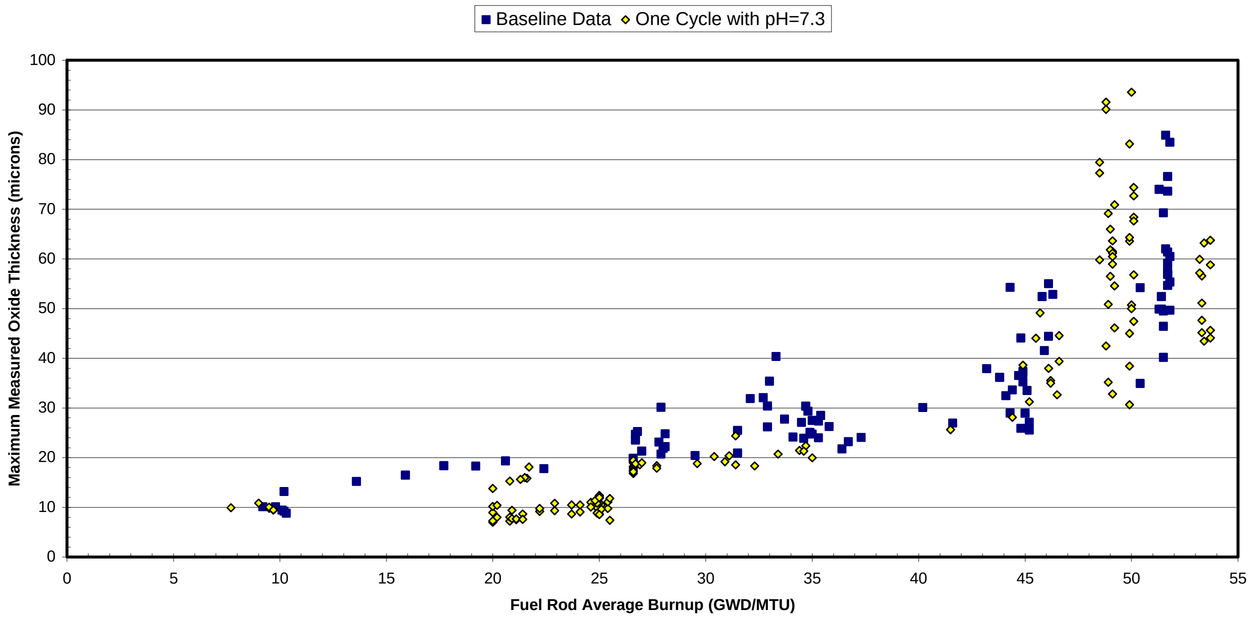
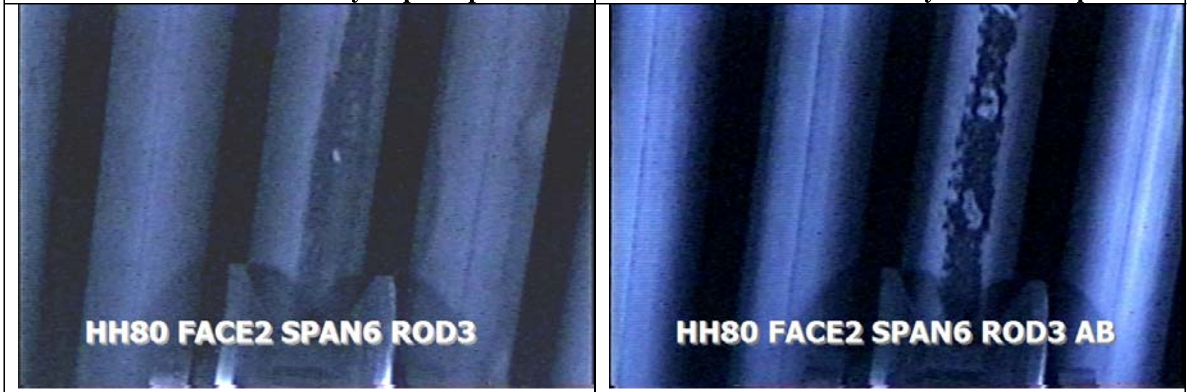


Figure 3-9
CPSES 2RF06 and 2RF07 Oxide Measurement Results

Twice Burned Assembly Top of Span | Twice Burned Assembly Middle of Span



Rod Before Brushing | Rod After Brushing

Figure 3-10
Fuel Assembly HH80 Visual Examination, 2RF07

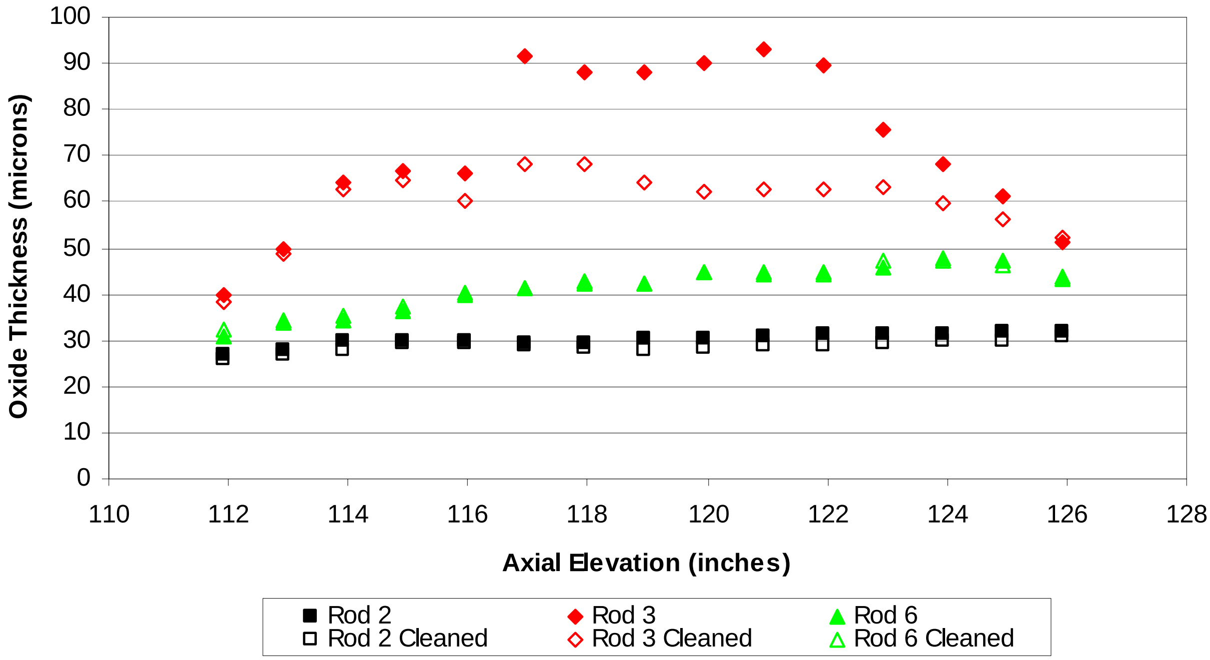


Figure 3-11
Oxide Thickness Measurements, 2RF07, Assembly HH80, Span 6, Rods 2, 3 and 6 Before and After Brushing

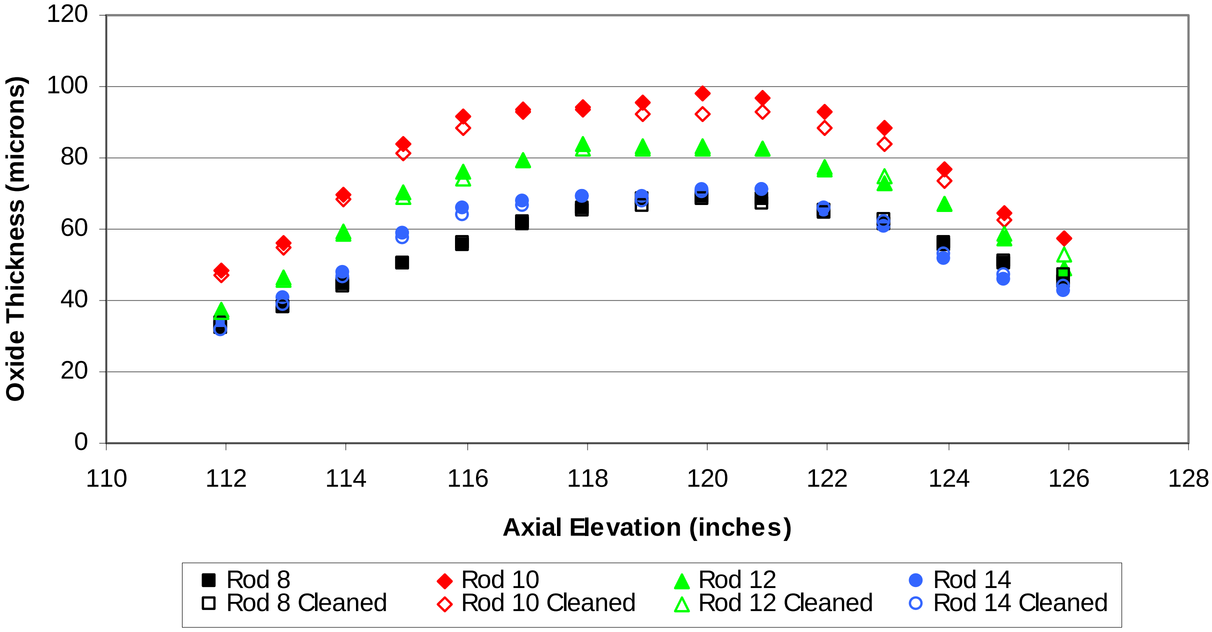


Figure 3-12
Oxide Thickness Measurements, 2RF07, Assembly HH80, Span 6, Rods 8, 10, 12 and 14 Before and After Brushing

Table 3-1
Summary of Fuel Assemblies Inspected

Assembly ID	Outage Measured	Number of Cycles Operated	Fuel Type
F10	2RF06	2nd burn	Framatome-ANP
HH39	2RF06 2RF07	1ST burn 2nd burn	Framatome-ANP
HH80	2RF06 2RF07	1ST burn 2nd burn discharge	Framatome-ANP
GG01, GG19	2RF06 2RF07	2nd burn 3rd burn discharge	Framatome-ANP
GG54, GG69	2RF06	2nd burn discharge	Framatome-ANP
FF41	2RF06	3rd burn discharge	Framatome-ANP
JW01, JW05, JW06, JW07	2RF07	1st burn	Westinghouse
JJ23, JJ83	2RF07	1st burn	Framatome-ANP
HH82, HH83	2RF07	2nd burn discharge	Framatome-ANP

Table 3-2
Summary of Oxide Measurements on Fuel Assembly F10

F/A ID	Face	Rod #	Rod Location	Rod Burnup (MWD/MTU)	Peak Oxide (microns)	Elevation (in)
F10	3	1	Q1	45200	26	119.9
		4	Q4	44400	34	118.9
		6	Q6	44900	37	118.9
		8	Q8	44800	44	118.9
		12	Q12	44900	35	118.9
		16	Q16	44300	29	118.9
	4	2	B1	43800	36	117.9
		8	H1	44900	37	120.9
		10	J1	45000	29	117.9
		12	L1	45100	34	120.9
		14	N1	44600	26	120.9
		17	Q1	45200	27	120.9

Table 3-3
Summary of Baseline Oxide Measurements Performed During 2RF06

F/A ID	Face	Rod #	Rod Location	Rod Burnup (MWD/MTU)	Peak Oxide (microns)	Elevation (inches)	Clean Oxide (microns)	Elevation (inches)
GG19	1	2	A16	31500	21	124.9		
		6	A12	32700	24	117.9		
		8	A10	32900	24	101.4		
		10	A8	33300	26	120.9		
		12	A6	33000	23	125.6		
		14	A4	32100	24	119.9		
	4	2	B1	31500	32	120.9	25	122.9
		6	F1	34100	35	123.9	32	122.9
		8	H1	35300	36	120.9	30	116.9
		10	J1	35800	50	118.9	40	116.9
		12	L1	36700	33	118.9	35	119.9
		14	N1	37300	34	120.9	32	122.9
GG54	2	2	P17	51500	38	113.9	40	125.6
		6	L17	51800	59	116.9	61	121.9
		8	J17	51700	57	115.9	61	115.9
		10	H17	51700	52	113.9	55	112.9
		12	F17	51700	75	119.9	77	119.9
		14	D17	51300	53	98.4	50	119.9
	3	2	Q2	50400	54	123.9		
		6	Q6	51400	50	121.9		
		8	Q8	51600	85	118.9		
		10	Q10	51700	57	119.9		
		12	Q12	51800	83	121.9		
		14	Q14	51500	69	118.9		
GG69	1	2	A16	50400			35	116.9
		6	A12	51300			52	122.9
		8	A10	51500			62	118.9
		10	A8	51700			57	119.9
		12	A6	51800			55	119.9
		14	A4	51500			46	123.9
	4	2	B1	51500			50	118.9
		6	F1	51800			50	122.9
		8	H1	51700			57	116.9
		10	J1	51700			59	118.9
		12	L1	51700			74	120.9
		14	N1	51300			74	118.9

Table 3-3 (continued)
Summary of Baseline Oxide Measurements Performed During 2RF06

F/A ID	Face	Rod #	Rod Location	Rod Burnup (MWD/MTU)	Peak Oxide (microns)	Elevation (inches)	Clean Oxide (microns)	Elevation (inches)
FF41	2	2	P17	44700	37	122.9		
		6	L17	45800	52	119.9		
		8	J17	45900	42	119.9		
		10	H17	46100	55	118.9		
		12	F17	46300	53	119.9		
		14	D17	46100	44	118.9		
	3	2	Q2	36400	22	122.9		
		6	Q6	40200	30	122.9		
		8	Q8	41600	27	120.9		
		10	Q10	43200	38	117.9		
		12	Q12	44100	32	122.9		
		14	Q14	44300	54	120.9		
GG01	1	2	A16	32900	26	120.9		
		6	A12	34800	29	114.9		
		8	A10	35000	25	133.5		
		10	A8	35400	29	119.9		
		12	A6	35300	27	115.9		
		14	A4	34600	24	120.9		
	2	2	P17	33500	24	125.6		
		6	L17	34900	25	105		
		8	J17	35000	28	124.9		
		10	H17	34700	30	114.9		
		12	F17	34500	27	117.9		
		14	D17	33700	28	100.4		
HH39	2	2	P17	10100	9	103.4		
		6	L17	10300	9	144.5		
		8	J17	10200	9	43.3		
		10	H17	10200	13	104.4		
		12	F17	9800	10	105		
		14	D17	9200	10	34.7		
	3	2	Q2	22400	18	100.4		
		6	Q6	20600	19	105		
		8	Q8	19200	18	103.4		
		10	Q10	17700	18	91.4		
		12	Q12	15900	16	116.9		
		14	Q14	13600	15	99.4		

Table 3-3 (continued)
Summary of Baseline Oxide Measurements Performed During 2RF06

F/A ID	Face	Rod #	Rod Location	Rod Burnup (MWD/MTU)	Peak Oxide (microns)	Elevation (inches)	Clean Oxide (microns)	Elevation (inches)
HH80	1	2	A16	28100	25	123.9		
		6	A12	26800	25	117.9		
		8	A10	26700	25	135.5		
		10	A8	26700	24	138.5		
		12	A6	26600	20	84.4		
		14	A4	27000	21	121.9		
	2	2	P17	29500	20	124.9		
		6	L17	28100	22	105		
		8	J17	28000	22	115.9		
		10	H17	27900	30	119.9		
		12	F17	27800	23	125.6		
		14	D17	27900	21	103.4		

Table 3-4
Summary of Oxide Measurements Performed During 2RF07 (pH=7.3 during U2C7 operation)

F/A ID	Face	Rod #	Rod Location	Rod Burnup (MWD/MTU)	Peak Oxide (microns)	Elevation (inches)	Clean Oxide (microns)	Elevation (inches)
GG01	1	2	A16	53300	48	118.9		
		6	A12	53700	59	120.9		
		8	A10	53300	57	120.9		
		10	A8	53200	60	118.9		
		12	A6	53700	44	121.9		
		14	A4	53400	43	120.9		
	2	2	P17	53300	45	117.9		
		6	L17	53700	46	120.9		
		8	J17	53300	51	119.9		
		10	H17	53200	57	120.9		
		12	F17	53700	64	119.9		
		14	D17	53400	63	119.9		
GG19	1	2	A16	41500	26	120.9		
		6	A12	44400	28	101.4		
		8	A10	45200	31	120.9		
		10	A8	46200	36	120.9		
		12	A6	46500	33	119.9		
		14	A4	46200	35	125.9		
	4	2	B1	46100	38	117.9		
		6	F1	46600	45	121.9		
		8	H1	46600	39	116.9		
		10	J1	45700	49	118.9		
		12	L1	45500	44	120.9		
		14	N1	44900	39	124.9		
HH39	2	2	P17	31400	19	118.9		
		6	L17	31400	19	121.9		
		8	J17	31100	18	40.7		
		10	H17	30900	18	41.7		
		12	F17	30400	20	118.9		
		14	D17	29600	17	16.2		
	3	2	Q2	32300	18	122.9		
		6	Q6	34400	22	121.9		
		8	Q8	34700	22	125.9		
		10	Q10	35000	20	119.9		
		12	Q12	34600	21	118.9		
		14	Q14	33400	21	125.9		

Table 3-4 (continued)
Summary of Oxide Measurements Performed During 2RF07
(pH=7.3 during U2C7 operation)

F/A ID	Face	Rod #	Rod Location	Rod Burnup (MWD/MTU)	Peak Oxide (microns)	Elevation (inches)	Clean Oxide (microns)	Elevation (inches)
HH80	1	2	A16	48800	92	118.9		
		6	A12	49100	59	120.9		
		8	A10	49100	33	124.9		
		10	A8	49000	57	119.9		
		12	A6	48900	35	121.9		
		14	A4	48500	77	118.9		
	2	2	P17	49900	32	124.9	31	125.9
		3	O17	49700	93	120.9	68	117.9
		6	L17	50100	48	123.9	47	122.9
		8	J17	50100	69	119.9	68	119.9
		10	H17	50000	98	119.9	94	117.9
		12	F17	49900	84	117.9	83	119.9
		14	D17	49200	71	120.9	71	120.9
HH82	1	2	A16	49900	64	117.9		
		6	A12	50100	74	120.9	(65, crud-free est.)	
		8	A10	50100	57	117.9		
		10	A8	50000	51	114.9		
		12	A6	49900	45	119.9		
		14	A4	49200	55	120.9		
	4	2	B1	48800	43	120.9		
		6	F1	49100	64	120.9		
		8	H1	49100	62	121.9		
		10	J1	49000	62	119.9		
		12	L1	48900	69	119.9	(60, crud-free est.)	
		14	N1	48500	80	119.9		

Table 3-4 (continued)
Summary of Oxide Measurements Performed During 2RF07
(pH=7.3 during U2C7 operation)

F/A ID	Face	Rod #	Rod Location	Rod Burnup (MWD/MTU)	Peak Oxide (microns)	Elevation (inches)	Clean Oxide (microns)	Elevation (inches)
HH83	3	2	Q2	48800	92	118.9	90	118.9
		6	Q6	49100	62	118.9	61	118.9
		8	Q8	49100	65	117.9	61	116.9
		10	Q10	49000	69	118.9	66	117.9
		12	Q12	48900	57	121.9	51	120.9
		14	Q14	48500	68	120.9	60	119.9
	4	2	B1	49900	38	122.9		
		3	O1	49700	88	119.9	(70, crud-free est.)	
		6	F1	50100	68	116.9		
		8	H1	50100	73	120.9		
		10	J1	50000	48	122.9		
		12	L1	49900	64	120.9		
		14	N1	49200	46	119.9		
JJ23	2	2	P17	27700	18	121.9		
		6	L17	26600	19	97.4		
		8	J17	26600	18	78.8		
		10	H17	26600	17	104.4		
		12	F17	26600	18	104.4		
		14	D17	26900	19	98.4		
	3	2	Q2	27700	18	101.4		
		6	Q6	26600	18	125.9		
		8	Q8	26600	18	120.9		
		10	Q10	26600	17	124.9		
		12	Q12	26700	19	103.4		
		14	Q14	27000	19	117.9		
JJ83	1	2	A16	21600	16	104.4		
		6	A12	21700	18	99.4		
		8	A10	21500	16	123.9		
		10	A8	21300	16	104.4		
		12	A6	20800	15	105.4		
		14	A4	20000	14	125.9		
	3	2	Q2	7700	10	144.5		
		6	Q6	9000	10	125.9		
		8	Q8	9500	10	112.9		
		10	Q10	9500	10	120.9		
		12	Q12	9700	10	123.9		
		14	Q14	9700	10	93.4		

Table 3-4 (continued)
Summary of Oxide Measurements Performed During 2RF07
(pH=7.3 during U2C7 operation)

F/A ID	Face	Rod #	Rod Location	Rod Burnup (MWD/MTU)	Peak Oxide (microns)	Elevation (inches)	Clean Oxide (microns)	Elevation (inches)
JW01	1	2	A16	25400	10	121.8		
		6	A12	25000	15	139.3		
		8	A10	25000	13	100.2		
		10	A8	24900	12	102.2		
		12	A6	24900	11	122.8		
		14	A4	25100	11	124.8		
	2	2	P17	20800	7	123.8		
		6	L17	22200	9	105.2		
		8	J17	22900	9	103.2		
		10	H17	23700	9	125.8		
		12	F17	24100	11	124.8		
		14	D17	24600	11	105.2		
JW05	2	2	P17	25500	10	135.3		
		6	L17	24900	10	104.2		
		8	J17	24800	10	104.2		
		10	H17	25000	10	124.8		
		12	F17	25000	9	84.7		
		14	D17	25000	8	125.8		
	4	2	B1	20000	7	125.8		
		6	F1	20000	9	105.2		
		8	H1	20200	8	105.2		
		10	J1	20900	9	125.8		
		12	L1	21100	8	125.8		
		14	N1	21400	8	123.8		
JW06	2	2	P17	25400	11	117.8		
		6	L17	25000	11	76.7		
		8	J17	25000	12	113.8		
		10	H17	24900	10	122.8		
		12	F17	24900	9	121.8		
		14	D17	25100	10	122.8		
	3	2	Q2	20800	8	117.8		
		6	Q6	22200	10	119.8		
		8	Q8	22900	11	125.8		
		10	Q10	23700	11	125.8		
		12	Q12	24100	9	83.7		
		14	Q14	24600	10	105.2		

Table 3-4 (continued)
Summary of Oxide Measurements Performed During 2RF07
(pH=7.3 during U2C7 operation)

F/A ID	Face	Rod #	Rod Location	Rod Burnup (MWD/MTU)	Peak Oxide (microns)	Elevation (inches)	Clean Oxide (microns)	Elevation (inches)
JW07	1	2	A16	25500	12	120.8		
		6	A12	24900	11	125.8		
		8	A10	24800	11	140.3		
		10	A8	25000	12	125.8		
		12	A6	25000	12	124.8		
		14	A4	25000	9	124.8		
	3	2	Q2	20000	7	119.8		
		6	Q6	20000	10	119.8		
		8	Q8	20200	8	124.8		
		10	Q10	20900	8	104.2		
		12	Q12	21100	8	123.8		
		14	Q14	21400	8	104.2		

Table 3-5
Comparison of Results for Symmetric Fuel Rods after Cycle 7 Operation

Rod #	Burnup (GWD/MTU)	Oxide (microns)		
		HH80 Face 1	HH82 Face 4	HH83 Face 3
2	48.8	92	43	90
6	49.1	59	64	61
8	49.1	33	62	61
10	49.0	57	62	66
12	48.9	35	60*	51
14	48.5	77	80	60
		HH80 Face 2	HH82 Face 1	HH83 Face 4
2	49.9	31	64	38
3	49.7	68	n/a	70*
6	50.1	47	65*	68
8	50.1	68	57	73
10	50.0	94	51	48
12	49.9	83	45	64
14	49.2	71	55	46

* Crud Free Estimate.

HH80 Face 2, HH83 Face 3 after brushing values reported

Table 3-6
Comparison of Results for Similar Fuel Assemblies

2RF06 Once-Burned Assemblies				2RF07 Once-Burned Assemblies			
Assembly	**Rod #**	**Burnup (GWD/MTU)**	**Oxide (microns)**	**Assembly**	**Rod #**	**Burnup (GWD/MTU)**	**Oxide (microns)**
HH80	2	29.5	20	JJ23	2	27.7	18
Face 2	6	28.1	22	Face 3	6	26.6	18
	8	28.0	22		8	26.6	18
	10	27.9	30		10	26.6	17
	12	27.8	23		12	26.7	19
	14	27.9	21		14	27.0	19
HH80	2	28.1	25	JJ23	2	27.7	18
Face 1	6	26.8	25	Face 2	6	26.6	19
	8	26.7	25		8	26.6	18
	10	26.7	24		10	26.6	17
	12	26.6	20		12	26.6	18
	14	27.0	21		14	26.9	19
HH39	2	22.4	18	JJ83	2	21.6	16
Face 3	6	20.6	19	Face 1	6	21.7	18
	8	19.2	18		8	21.5	16
	10	17.7	18		10	21.3	16
	12	15.9	16		12	20.8	15
	14	13.6	15		14	20.0	14
HH39	2	10.1	9	JJ83	2	7.7	10
Face 1	6	10.3	9	Face 3	6	9.0	10
	8	10.2	9		8	9.5	10
	10	10.2	13		10	9.5	10
	12	9.8	10		12	9.7	10
	14	9.2	10		14	9.7	10

Table 3-6 (continued)
Comparison of Results for Similar Fuel Assemblies

2RF06 Twice-Burned Assemblies				2RF07 Twice-Burned Assemblies			
Assembly	**Rod #**	**Burnup (GWD/MTU)**	**Oxide (microns)**	**Assembly**	**Rod #**	**Burnup (GWD/MTU)**	**Oxide (microns)**
GG01 Face 2	2	33.5	24	HH39 Face 3	2	32.3	18
	6	34.9	25		6	34.4	22
	8	35.0	28		8	34.7	22
	10	34.7	30		10	35.0	20
	12	34.5	27		12	34.6	21
	14	33.7	28		14	33.4	21
GG01 Face 1	2	32.9	26	HH39 Face 2	2	31.4	19
	6	34.8	29		6	31.4	19
	8	35.0	25		8	31.1	18
	10	35.4	29		10	30.9	18
	12	35.3	27		12	30.4	20
	14	34.6	24		14	29.6	17
GG54 Face 3	2	50.4	54	HH80 Face 2	2	49.9	32
	6	51.4	50		6	50.1	48
	8	51.6	85		8	50.1	69
	10	51.7	57		10	50.0	98
	12	51.8	83		12	49.9	84
	14	51.5	69		14	49.2	71
GG54 Face 2	2	51.5	38	HH80 Face 1	2	48.8	92
	6	51.8	59		6	49.1	59
	8	51.7	57		8	49.1	33
	10	51.7	52		10	49.0	57
	12	51.7	75		12	48.9	35
	14	51.3	53		14	48.5	77

Table 3-6 (continued)
Comparison of Results for Similar Fuel Assemblies

2RF06 Thrice-Burned Assemblies				2RF07 Thrice-Burned Assemblies			
Assembly	**Rod #**	**Burnup (GWD/MTU)**	**Oxide (microns)**	**Assembly**	**Rod #**	**Burnup (GWD/MTU)**	**Oxide (microns)**
FF41	2	36.4	22	GG19	2	41.5	26
Face 3	6	40.2	30	Face 1	6	44.4	28
	8	41.6	27		8	45.2	31
	10	43.2	38		10	46.2	36
	12	44.1	32		12	46.5	33
	14	44.3	54		14	46.2	35
FF41	2	44.7	37	GG19	2	46.1	38
Face 2	6	45.8	52	Face 4	6	46.6	45
	8	45.9	42		8	46.6	39
	10	46.1	55		10	45.7	49
	12	46.3	53		12	45.5	44
	14	46.1	44		14	44.9	39

4

CONCLUSIONS

Interim observations support the expected benefits of CPSES operation with elevated constant pH. TXU Power conducted an extensive monitoring program, including a poolside fuel rod oxide measurement campaign. The oxide measurement results were evaluated to determine if any clear and discernible adverse trends were evident when comparing 2RF07 oxide measurements to the baseline 2RF06 oxide measurements. No clear and discernible significant increase in oxide thickness was identified on any fuel assemblies measured during 2RF07.

Fuel visual examinations conducted in conjunction with poolside oxide measurements indicated that the crud observed on the assemblies was equal to or less than crud observed during the 2RF06 inspection campaign.

The shutdown data obtained following U2C7 operation suggest possible improvements attributed to the elevated constant pH program. The specific activities of the corrosion products monitored during shutdown were lower during 2RF07 than previous outages, and the outage dose rates measured at the standard measurement points were also reduced. It is noted that ex-core radiation fields had been trending downward over the previous several cycles.

There were no issues identified that would preclude an increase in coolant pH to 7.4 (maximum 6 ppm lithium) for U2C8 operation. Therefore, operating U2C8 at a constant pH_t of 7.4 was deemed acceptable.

5

REFERENCES

1. PWR Axial Offset Anomaly (AOA) Guidelines, Revision 1, EPRI, Palo Alto, CA: 2004. 1008102.
2. Assessment of Elevated pH Program for Comanche Peak Steam Electric Station, EPRI, Palo Alto, CA and TXU Electric, Glen Rose, TX: 2001. 1006282
3. *Evaluation of Fuel Clad Corrosion Product Deposits and Circulating Corrosion Products in PWRs*, EPRI, Palo Alto, CA, and Westinghouse Electric Company, Pittsburgh, PA: 2004. 1009951
4. Pressurized Water Reactor Primary Water Chemistry Guidelines: Volume 1, Revision 5, EPRI, Palo Alto, CA: 2003. 1002884.
5. Boron-induced Offset Anomaly Risk Assessment Tool, BOA Version 1.0, EPRI, Palo Alto, CA: 2003. 1003211.
6. Analysis Report on 1999-2001 Field Experience with Elevated, Constant pH, EPRI, Palo Alto, CA: 2001. 1003153.
7. Pressurized Water Reactor Primary Water Chemistry Guidelines: Volume 2, Revision 5, EPRI, Palo Alto, CA: 2003. 1002884.

WARNING: This Document contains information classified under U.S. Export Control regulations as restricted from export outside the United States. You are under an obligation to ensure that you have a legal right to obtain access to this information and to ensure that you obtain an export license prior to any re-export of this information. Special restrictions apply to access by anyone that is not a United States citizen or a Permanent United States resident. For further information regarding your obligations, please see the information contained below in the section titled "Export Control Restrictions."

Export Control Restrictions

Access to and use of EPRI Intellectual Property is granted with the specific understanding and requirement that responsibility for ensuring full compliance with all applicable U.S. and foreign export laws and regulations is being undertaken by you and your company. This includes an obligation to ensure that any individual receiving access hereunder who is not a U.S. citizen or permanent U.S. resident is permitted access under applicable U.S. and foreign export laws and regulations. In the event you are uncertain whether you or your company may lawfully obtain access to this EPRI Intellectual Property, you acknowledge that it is your obligation to consult with your company's legal counsel to determine whether this access is lawful. Although EPRI may make available on a case by case basis an informal assessment of the applicable U.S. export classification for specific EPRI Intellectual Property, you and your company acknowledge that this assessment is solely for informational purposes and not for reliance purposes. You and your company acknowledge that it is still the obligation of you and your company to make your own assessment of the applicable U.S. export classification and ensure compliance accordingly. You and your company understand and acknowledge your obligations to make a prompt report to EPRI and the appropriate authorities regarding any access to or use of EPRI Intellectual Property hereunder that may be in violation of applicable U.S. or foreign export laws or regulations.

The Electric Power Research Institute (EPRI)

The Electric Power Research Institute (EPRI), with major locations in Palo Alto, CA, and Charlotte, NC, was established in 1973 as an independent, non-profit center for public interest energy and environmental research. EPRI brings together member organizations, the Institute's scientists and engineers, and other leading experts to work collaboratively on solutions to the challenges of electric power. These solutions span nearly every area of power generation, delivery, and use, including health, safety, and environment. EPRI's members represent over 90% of the electricity generated in the United States. International participation represents over 10% of EPRI's total R&D program.

Together...Shaping the Future of Electricity

SINGLE USER LICENSE AGREEMENT

THIS IS A LEGALLY BINDING AGREEMENT BETWEEN YOU AND THE ELECTRIC POWER RESEARCH INSTITUTE, INC. (EPRI). PLEASE READ IT CAREFULLY BEFORE REMOVING THE WRAPPING MATERIAL.

BY OPENING THIS SEALED PACKAGE YOU ARE AGREEING TO THE TERMS OF THIS AGREEMENT. IF YOU DO NOT AGREE TO THE TERMS OF THIS AGREEMENT, PROMPTLY RETURN THE UNOPENED PACKAGE TO EPRI AND THE PURCHASE PRICE WILL BE REFUNDED.

1. GRANT OF LICENSE

EPRI grants you the nonexclusive and nontransferable right during the term of this agreement to use this package only for your own benefit and the benefit of your organization. This means that the following may use this package: (I) your company (at any site owned or operated by your company); (II) its subsidiaries or other related entities; and (III) a consultant to your company or related entities, if the consultant has entered into a contract agreeing not to disclose the package outside of its organization or to use the package for its own benefit or the benefit of any party other than your company.

This shrink-wrap license agreement is subordinate to the terms of the Master Utility License Agreement between most U.S. EPRI member utilities and EPRI. Any EPRI member utility that does not have a Master Utility License Agreement may get one on request.

2. COPYRIGHT

This package, including the information contained in it, is either licensed to EPRI or owned by EPRI and is protected by United States and international copyright laws. You may not, without the prior written permission of EPRI, reproduce, translate or modify this package, in any form, in whole or in part, or prepare any derivative work based on this package.

3. RESTRICTIONS

You may not rent, lease, license, disclose or give this package to any person or organization, or use the information contained in this package, for the benefit of any third party or for any purpose other than as specified above unless such use is with the prior written permission of EPRI. You agree to take all reasonable steps to prevent unauthorized disclosure or use of this package. Except as specified above, this agreement does not grant you any right to patents, copyrights, trade secrets, trade names, trademarks or any other intellectual property, rights or licenses in respect of this package.

4. TERM AND TERMINATION

This license and this agreement are effective until terminated. You may terminate them at any time by destroying this package. EPRI has the right to terminate the license and this agreement immediately if you fail to comply with any term or condition of this agreement. Upon any termination you may destroy this package, but all obligations of nondisclosure will remain in effect.

5. DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

NEITHER EPRI, ANY MEMBER OF EPRI, ANY COSPONSOR, NOR ANY PERSON OR ORGANIZATION ACTING ON BEHALF OF ANY OF THEM:

(A) MAKES ANY WARRANTY OR REPRESENTATION WHATSOEVER, EXPRESS OR IMPLIED, (I) WITH RESPECT TO THE USE OF ANY INFORMATION, APPARATUS, METHOD, PROCESS OR SIMILAR ITEM DISCLOSED IN THIS PACKAGE, INCLUDING MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE, OR (II) THAT SUCH USE DOES NOT INFRINGE ON OR INTERFERE WITH PRIVATELY OWNED RIGHTS, INCLUDING ANY PARTY'S INTELLECTUAL PROPERTY, OR (III) THAT THIS PACKAGE IS SUITABLE TO ANY PARTICULAR USER'S CIRCUMSTANCE; OR

(B) ASSUMES RESPONSIBILITY FOR ANY DAMAGES OR OTHER LIABILITY WHATSOEVER (INCLUDING ANY CONSEQUENTIAL DAMAGES, EVEN IF EPRI OR ANY EPRI REPRESENTATIVE HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES) RESULTING FROM YOUR SELECTION OR USE OF THIS PACKAGE OR ANY INFORMATION, APPARATUS, METHOD, PROCESS OR SIMILAR ITEM DISCLOSED IN THIS PACKAGE.

6. EXPORT

The laws and regulations of the United States restrict the export and re-export of any portion of this package, and you agree not to export or re-export this package or any related technical data in any form without the appropriate United States and foreign government approvals.

7. CHOICE OF LAW

This agreement will be governed by the laws of the State of California as applied to transactions taking place entirely in California between California residents.

8. INTEGRATION

You have read and understand this agreement, and acknowledge that it is the final, complete and exclusive agreement between you and EPRI concerning its subject matter, superseding any prior related understanding or agreement. No waiver, variation or different terms of this agreement will be enforceable against EPRI unless EPRI gives its prior written consent, signed by an officer of EPRI.

Program: 1003408

Nuclear Power

Printed on recycled paper in the United States of America