Evaluation of Zinc Addition in Cycle 13 at Farley Unit 2

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Technical Report

Evaluation of Zinc Addition in Cycle 13 at Farley Unit 2

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Final Report, August 2000

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REPORT SUMMARY

Previous demonstrations have revealed the value of zinc additions to the PWR reactor coolant system in mitigating radiation fields. This report describes the results of the zinc addition demonstration program during Cycle 13 at Southern Nuclear's Farley Unit 2.

Background

Zinc additions have been made to the reactor coolant system (RCS) of Farley Unit 2 in Cycle 10 (9 months), Cycle 12 (3 months) and Cycle 13 (10 months). Natural zinc acetate was added in Cycle 10. The Cycle 12 experience focused on additions of depleted zinc acetate in which the natural isotope Zn-64—precursor of Zn-65 which adds to radiation dose rates—had been essentially removed. In Cycle 13, approximately 45% of the additions involved depleted zinc acetate remaining from Cycle 12, and the balance was natural zinc acetate. Results of Cycles 10 and 12 as well as non-zinc Cycle 11 have been presented in previous EPRI reports (TR-106358 Vols. 1-2, TR-111349, and TR-107904, respectively). This report documents the experience with 10 months of zinc addition in Cycle 13.

Objective

To demonstrate the corrosion protection and radiation-reduction benefits of zinc addition to Farley Unit 2 RCS during the last 10 months of Fuel Cycle 13.

Approach

The research team monitored coolant chemistry and radiochemistry during operation and shutdown to evaluate the effect of zinc addition. The parameters they monitored included the activities of Zn-65, Co-58, and Co-60 radionuclides as well as the concentrations of zinc and nickel in the coolant. Investigators reduced the zinc concentration from 40 ppb in earlier cycles to 30 ppb to provide margin against precipitation of zinc oxide on fuel cladding. They measured radiation dose rates at standard radiation monitoring point (SRMP) locations and compared them to dose rates from previous cycles, with and without zinc. In addition, they evaluated primary water stress corrosion cracking (PWSCC) data from inspection of hot legs of steam generator alloy 600 tubes. Finally, they conducted poolside fuel surveillance of selected assemblies to monitor cladding corrosion and deposition.

Results

Zinc was detected after only three days of injection, compared to 9 and 11 days in previous cycles. This indicates that zinc in the corrosion films may have approached equilibrium in Cycle 13, offering maximum benefits in terms of corrosion protection and radiation reduction. Zinc addition had no apparent effect on soluble Ni concentration, which remained below 1 ppb. As noted in previous cycles, zinc addition increased Zn-65, Co-58, and Co-60 activities in the coolant. However, the activities at the end of Cycle 13 were significantly lower than those at the end of previous zinc cycles, which is consistent with zinc in corrosion films approaching equilibrium.

The radiation dose rates continued to show a decreasing trend with zinc addition. The dose rates at SRMP locations at the end of Cycle 13 were 25% lower than dose rates at the end of Cycle 12 and nearly 50% lower than pre-zinc dose rates at the end of Cycle 9. Because of inspection uncertainties, it was not possible to interpret the role of zinc in mitigating PWSCC degradation in Farley 2. Fuel surveillance results showed that ZIRLO^{TM}-clad rods experience low corrosion and that the corrosion of improved Zircaloy-4 rods after three cycles of operation is within the normal range for this alloy. Therefore, the presence of zinc during Cycle 13 had no adverse effect on fuel performance.

EPRI Perspective

This work clearly shows the beneficial effect of zinc addition in reducing radiation dose rates at SRMP locations. It also shows that zinc addition had no adverse effect on fuel cladding corrosion. Based on the positive results from the zinc demonstration, Southern Nuclear plans to continue future operation with natural zinc for essentially the full fuel cycle for Farley Units 1 and 2. Similarly, Diablo Canyon Units 1 and 2 are also implementing natural zinc operation for the full cycle. In addition, Palisades is using depleted zinc at a low concentration to mitigate radiation dose rates. EPRI will prepare an overview report on the PWR zinc demonstrations at Farley, Diablo Canyon, and Palisades in early 2001. Additional EPRI reports on the zinc demonstration in PWRs include TR-106357 and TR-113540.

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Keywords
PWR
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Zircaloy
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ABSTRACT

The addition of zinc to the Farley Unit 2 reactor coolant system was resumed during Cycle 13. Zinc additions had previously been made during the last half of Cycle 10 and for three months in the middle of Cycle 12. The Cycle 10 additions had used natural zinc acetate, while the Cycle 12 experience was with zinc acetate in which the natural isotope ^{64}Zn, precursor of ^{65}Zn which adds to the radiation dose rates, had been essentially removed. In Cycle 13, approximately 45% of the additions were made with residual "depleted" zinc acetate left from Cycle 12, and the balance was natural zinc acetate.

This program is a continuation of efforts to demonstrate the benefits of additions of zinc to the reactor coolant system (RCS) of PWRs as a means to reduce general corrosion of the primary system materials and stress corrosion cracking (PWSCC) of Alloy 600. The Cycle 13 program at Farley Unit 2 involved zinc additions to the RCS for the last ten months of the fuel cycle

In addition to close follow of the chemistry and radiochemistry of the coolant during the operating period of Cycle 13, detailed end-of-cycle examinations were performed of the fuel region and the steam generator Alloy 600 heat transfer tubing. Also, measurements were made of component dose rates at standard radiation monitoring locations. This document represents the Final Report for this program.

Southern Nuclear is continuing zinc additions to the RCS at Farley Unit 2 in Cycle 14, and has also completed a first cycle of zinc injection at Farley Unit 1 during Cycle 16.

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INTRODUCTION AND SUMMARY

1.1 INTRODUCTION

Zinc additions have been made to the Farley Unit 2 reactor coolant system (RCS) in Cycles 10 (nine months), 12 (three months), and 13 (ten months). The results of the experiences for the first two of these cycles have been published as EPRI reports (Refs. 1.1 and 1.2). The results for Cycle 13 (injection period from December 1998 through October 1999) are presented in this report. Owing to the availability of depleted zinc acetate from the previous cycle, this chemical was used for approximately the first half of the Cycle 13 injection period; natural zinc acetate was used for the remainder of the injection period.

The chemistry and radiochemistry of the RCS were regularly monitored during the cycle. In addition, at the end of Cycle 13, comprehensive examinations were performed of:

- Chemistry and radiochemistry evolutions associated with the end-of-cycle shutdown,
- The fuel region (visual examinations and measurements of fuel cladding oxide thickness on selected fuel rods in peripheral assemblies),
- The steam generator heat transfer tubing (eddy current examinations of 100% of the hot leg tube ends), and
- The dose rates at standard radiation monitoring locations.

Gamma spectrometry to determine specific radionuclide activities on primary side components had been performed at previous outages, but were not repeated at the end of Cycle 13.

The results and experience from these activities are presented and discussed in this report.

1.2 SUMMARY

A summary of the major observations from the various examinations/evaluations performed is presented below.

Operating Coolant Chemistry/Radiochemistry

- The nominal RCS zinc concentration in Cycle 13 was reduced from 40 ppb in earlier cycles to 30 ppb in order to ensure that zinc oxide precipitation on the fuel cladding did not occur.

- Of the 8.19 kg of zinc added during Cycle 13, 5.88 kg were removed by the CVCS demineralizers, leaving an estimated of 2.31 kg residual.

- Zinc had no apparent effect on the soluble nickel concentration in the RCS, in that the analyzed concentrations were consistently less than 1 ppb.

- The ^{65}Zn activity increased significantly with the resumption of zinc addition, particularly after the use of natural zinc was resumed. Unlike the radiocobalts, the soluble ^{65}Zn activity was dominant.

- The following observations indicate that the zinc in the RCS and in the corrosion films may have reached an equilibrium in Cycle 13:

  - Zinc was detected in the RCS after only three days of injection compared to nine and eleven days in prior cycles.

  - The abrupt increase in radocobalt activities was by a factor of 10 for ^{58}Co and 5 for ^{60}Co, compared to increases by factors of 25 and 8, respectively, in Cycle 10.

  - The ^{58}Co and ^{60}Co “equilibrium” activities at the end of Cycle 13 were significantly lower than those at EOC 10 and EOC 12.

  - The zinc injection rate was decreased three times in the last 100 days of the cycle to maintain the nominal concentration.

Dose Rates/Radiation Levels

- Dose rates continued to exhibit a decreasing trend with zinc addition. Overall, from the initial use of zinc in Cycle 10, the dose rates at the SRMP locations decreased by a factor of nearly two by the end of Cycle 13 compared to the pre-zinc dose rates at the end of Cycle 9.

- Dose rates are lower by an average of 12% after hydrogen peroxide additions during shutdown. For non-zinc plants the corresponding decrease is about 5%, suggesting that zinc is altering the ex-core corrosion films such that the activity is more easily removed after hydrogen peroxide addition.

- In Cycle 13, a cumulative zinc exposure of 300 ppb-month led to a reduction of approximately 25% in dose rates. Data from other plants, including Diablo Canyon, suggest a similar reduction may be achievable with lower cumulative zinc exposures. This variation may be related to design and operational differences between the plants.

- There were no unusual dose rate increases at non-SRMP locations (such as those reported for the RHR system at Diablo Canyon Unit 1 that were attributed to an unplanned shutdown that occurred near the end of the cycle).

Shutdown Chemistry/Radiochemistry

- The peak ^{58}Co activity concentration during the acid-oxidizing phase was 3.8 μCi/cm^3, a value similar to that seen at the end of Cycle 12. The subsequent reduction in activity followed a normal purification half-life. The release of ^{60}Co activity mirrored that of ^{58}Co, but the maximum values were less.

- At the EOC 13 outage, 2047 Ci of ^{58}Co were removed by the purification system. This is similar to the ^{58}Co activity removed after Cycles 10 through 12, and about 25% greater than that removed after Cycle 8 prior to zinc addition (see Table 4-1).

- The average amounts of ^{60}Co activity removed at the end of the cycles with zinc addition were about 70% greater than for cycles prior to zinc addition.

- The amount of ^{65}Zn activity removed at the end of the cycles using zinc addition directly reflected the use of natural or depleted zinc during the cycle.

- In the Cycle 13 outage, 3140 grams of nickel were removed by the purification system. This is comparable to the amounts of nickel removed during the EOC 10 through EOC 12 outages and about 50% greater than that removed at the end of Cycles 8 and 9 prior to zinc addition.

- The overall specific activity for Cycle 13 was 0.65 Ci ^{58}Co/g Ni. This value is about 10 to 15% lower than the ratio seen in previous Farley outages after zinc addition (see Table 4-1).

Steam Generator Stress Corrosion Cracking

- The number of tubes repaired for PWSCC increased from sixty-three at EOC 12 to ninety at EOC 13.

- Owing to the changes in inspection practices and the intermittent nature of the zinc injection practice, it is not possible to interpret a role for zinc in the pattern of PWSCC degradation and repair at Farley Unit 2. This intermittent history has also been experienced at Diablo Canyon, although both the Farley and Diablo Canyon plants have plans for future full-cycle zinc injection.

Fuel Region

- The fuel rods were covered with a dark semi-reflective coating, similar to previous observations at Farley 2 following zinc injection.

- The ZIRLO™-clad rods have exhibited low corrosion levels for all burnups experienced to date at Farley Unit 2.

- Corrosion of the Improved Zircaloy-4 clad rods after three cycles of operation is within the normal range for this alloy.

- The presence of zinc in the reactor coolant system during Cycle 13 had no adverse effects on fuel performance.

Future Plans

- Farley Units 1 and 2 plan on future operation with zinc injection for essentially the full fuel cycle.

References

1.1 Evaluation *of Zinc Addition to the Primary Coolant of PWRs*, EPRI, Palo Alto, CA, and Southern Nuclear Operating Co., Birmingham, AL,: 1996. TR-106358-V1.

1.2 *Evaluation of Zinc Addition in Cycle 12 at Farley Unit 2*, EPRI, Palo Alto, CA, and Southern Nuclear Operating Co., Birmingham, AL,: 1998. TR-111349.

2

CYCLE 13 OPERATING COOLANT CHEMISTRY

2.1 INTRODUCTION

Primary coolant chemistry and radiochemistry data were collected during Cycle 13 for use in assessing the effect of resuming the addition of zinc acetate to the RCS for the last ten months of the cycle. Zinc had previously been added to the RCS during Cycle 10 for about nine months, discontinued during Cycle 11, and added for three months during Cycle 12. Therefore, the Cycle 13 data reflect the chemical and radiochemical behavior after operating cycles with varying periods with and without zinc addition. Moreover, natural zinc acetate was used during Cycle 10 and depleted zinc acetate was added during Cycle 12. During Cycle 13, depleted zinc acetate was used for about the first half of the zinc addition period and natural zinc acetate for the latter half of this period. Information associated with full power operation during Cycle 13 is discussed in this section. Where appropriate, data associated with previous Farley 2 Cycles 8 through 12 are compared to these data.

2.2 CYCLE 13 CHEMISTRY

2.2.1 Primary Coolant pH Control

The monthly average boron and lithium concentrations for Farley 2 for Cycle 13 are shown in Figure 2-1. For Cycle 13, as for the previous four cycles, the plant followed a “modified” coolant chemistry mode of operation. Modified coolant chemistry entails coordination of the boron-lithium concentrations such that an at-temperature pH (pH_T) of 6.9 is maintained early in the cycle when the RCS boron concentrations are high. When the lithium concentration reaches 2.2 ppm it is maintained at that level; hence, the pH_T gradually increases as the boron concentration is reduced. When the pH_T reaches 7.4, the lithium is again reduced to maintain that pH value throughout the remainder of the cycle.

The RCS chemistry was controlled throughout the Cycle 13 operating period with the monthly average boron and lithium concentrations falling within the control bands, with the exception of a single value early in the cycle when the average lithium concentration was slightly below the band.

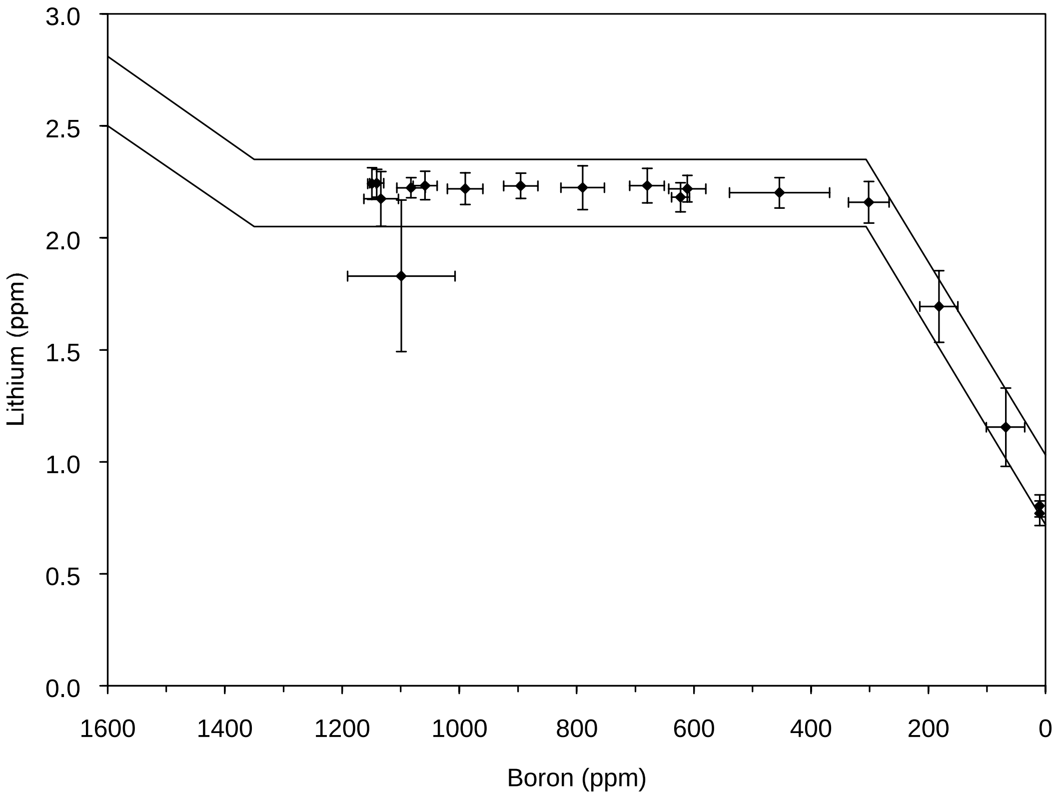

Figure 2-1
Monthly Average Boron and Lithium Concentrations During Cycle 13
[The bars indicate standard deviations for each set of data taken.]

2.2.2 Zinc Injection During Cycle 13

During Cycle 13 the target zinc concentration was reduced to 30 ppb from the 40 ppb value used in prior cycles. This action was based on an evaluation of additional laboratory studies of the solubility of zinc species in water at elevated temperatures. The results were interpreted with reference to PWR coolant conditions (Ref 2.2). These studies concluded that, to be conservative, the zinc concentration should be kept below 40 ppb to minimize the possibility of zinc oxide precipitation on fuel surfaces.

Zinc injection using depleted zinc acetate was initiated on December 9, 1998 at 09:00 and continued until April 15, 1999. Thereafter, natural zinc acetate was injected until October 14, 1999 at 20:00, essentially one day before the EOC on October 16 at 01:00. The period of zinc “exposure” time was 309 days. Subtracting the time when the injection system was shut down for either leak rate tests or reactor trips, the injection time was 274 days. Depleted zinc was added for 126 days, about 40% of the injection time. During Cycle 13, the injection flow rate was initially at 1.0 to 1.2 gph for the first six days and then varied from 0.5 to 0.8 gph for most of the remainder of the cycle. For the last month, it was decreased to about 0.3 to 0.4 gph. The zinc concentration in the feed solution was about 600 ppm during most of the cycle. The typical mass injection rate was about 2 g/h.

Figure 2-2 shows the zinc concentration in the coolant and the injection flow rate of the zinc acetate solution. Zinc was first detected (i.e., a concentration >10 ppb) in the coolant on December 12; three days after initial injection. This time for the initial appearance of zinc is shorter than the nine days observed for Cycle 12 and eleven days found for Cycle 10, (Ref. 2.1), and may suggest that the sites for the incorporation of zinc in the corrosion product film are being saturated as zinc injection continues.

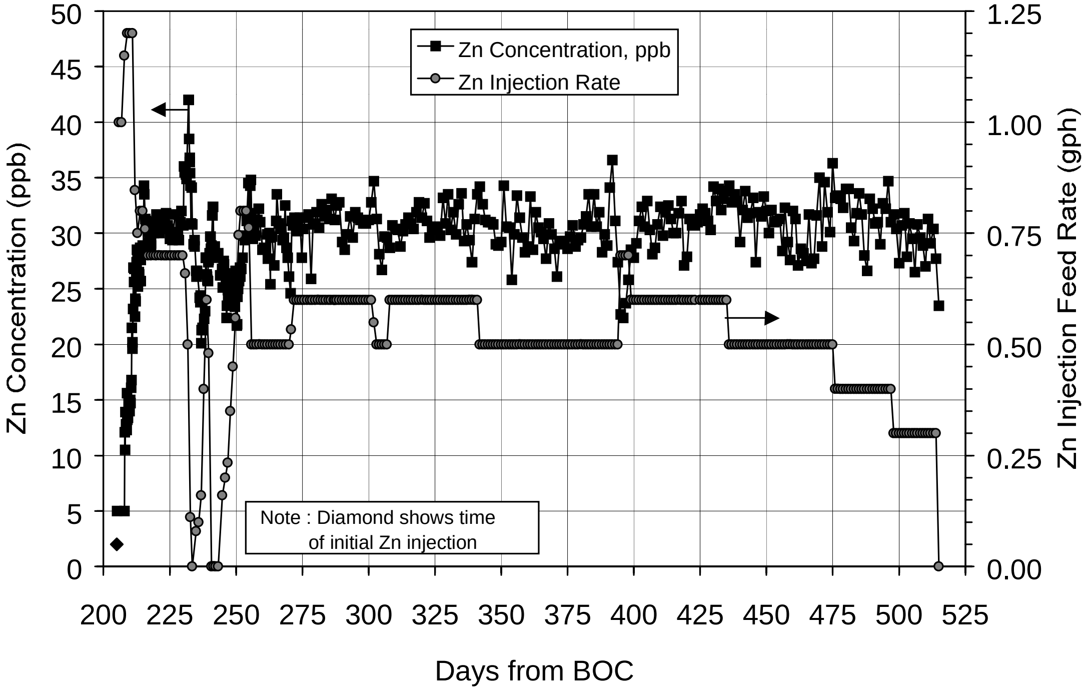

Figure 2-2
Cycle 13 RCS Zinc Concentration and Injection Flow Rates

The zinc concentration in the coolant increased rapidly to about 30 ppb corresponding to an initially high injection rate, and then oscillated between 20 and 42 ppb for about 30 days while the injection feed rate was adjusted to obtain the target value of 30 ppb.

After the first 30 days, the concentration was fairly well maintained at the 30 ppb target value during the rest of the cycle. The variation at about 390 days was due to a reactor trip and five-day shutdown of the injection system. Note that the injection rate was decreased three times the last 100 days of injection to maintain the target concentration. This suggests that the exchange of the zinc in the coolant with that in the oxide films may be approaching an equilibrium condition.

The net amount of zinc in the RCS was estimated from the difference between the amount injected and that removed by the letdown system. The mass of zinc injected into the RCS was calculated from the injection flow rate, time of injection and concentration in the feed tank. The amount removed by the letdown system was calculated using the letdown flow rate, the concentration of zinc in the RCS and by assuming 100% removal of the zinc by the system demineralizers. The time that the zinc injection system or demineralizers was out of service was accounted for in the calculations. Table 2-1 shows the results of the calculations and the estimated inventory of zinc remaining in the RCS at the EOC 13. Data from Farley 2 Cycles 10 and 12 and Diablo Canyon 1 Cycle 9 are included for comparison (Refs. 2.3 and 2.4).

The data in Table 2-1 show that the net zinc added to the RCS during Cycle 13 was about 60% of that added during Cycle 10, and about 80% of the amount added to Diablo Canyon 1 in Cycle 9.

Table 2-1
Comparison of Zinc Input and Removal in Farley 2 Cycles 10, 12 and 13 and Diablo Canyon 1 Cycle 9

Plant/Cycle	Zinc Exposure Time, Days	Zinc Inj. Time, Days.	Zinc Injected, kg	Zinc Removed, kg	Net Zinc into RCS, kg
Farley 2/10	272	239	10.89	7.06	3.83
Farley 2/12	90	90	4.06	3.03	1.03
Farley 2/13	309	274	8.19*	5.88	2.31
Diablo Canyon 1/9	228	180	5.85	3.05	2.80

*Approximately 3.67 kg, or 45% of the total injected, was depleted zinc.

2.2.3 Coolant Chemical Analyses

Because of a concern for a potential impact of zinc addition on Axial Offset Anomaly (AOA), coolant chemistry samples were analyzed weekly to obtain concentrations of soluble nickel in the coolant. If two consecutive analyses indicated soluble nickel concentrations greater than 6 ppb, additional actions and analyses were required to better quantify whether or not the risk of AOA had increased, and whether it was necessary to suspend zinc injection (Ref. 2.5). The samples were obtained by filtering 0.1 liter of the coolant through a 0.45 µm filter paper, acidifying the filtrate, and analyzing for nickel using a graphite furnace atomic absorption technique. The intent of this sampling was to aid in defining any changes that zinc addition might have had on the concentration of soluble nickel in the RCS.

The results of the chemical analyses indicated that, with the exception of five isolated analyses, the nickel concentrations were all below the limits of detection (<1 ppb) for essentially the entire cycle. There was no apparent change in the concentration during the ten months of zinc injection with the exceptions noted, during which time the nickel never exceeded 2.4 ppb. Since these variations were minor, it is concluded that there is no significant effect of zinc addition on the concentration of soluble nickel.

2.3 CYCLE 13 RADIOCHEMISTRY

2.3.1 Coolant Analyses

Primary coolant activity concentrations for the radiocobalts and ^{65}Zn during Cycle 13 were determined from small volume (0.1 liter) primary coolant samples taken weekly from the RCS hot leg and from 1 liter samples taken every other week from the same location. The 0.1-liter samples represent the total unfiltered coolant activity. The 1 liter samples provide data on the amount of activity in the insoluble and soluble portions of the coolant since the samples were filtered through a 0.45 µm filter paper and the two fractions analyzed separately. Thus the sum of these two fractions represents the total unfiltered activity.

2.3.2 Coolant ^{65}Zn Trends

Figure 2-3 illustrates the variation in the total RCS ^{65}Zn concentration with operating time for the period from Cycles 10 through 13. The decrease in ^{65}Zn activity noted during Cycle 11 with no zinc addition continued during Cycle 12 to a nominal "equilibrium" value of about 5 x 10^{-6} µCi/ml. After zinc addition was re-started, the ^{65}Zn activity concentration immediately increased by a factor of 40 to 2 x 10^{-4} µCi/ml and gradually decreased to approximately 6 x 10^{-5} µCi/ml. Although natural zinc was used for the Cycle 10 addition, depleted zinc was used in Cycle 12. Since the amount of the parent isotope for ^{65}Zn - i.e., ^{64}Zn - is reduced by a factor of about 50 in depleted zinc, the increase observed in the ^{65}Zn activity in Cycle 12 indicated that some of the depleted zinc had exchanged with the natural zinc and ^{65}Zn activity in surface deposits. The fact that the ^{65}Zn concentration generally declined during the 3-month period of zinc injection also suggests that the natural zinc was being replaced by the depleted zinc.

During the initial months of Cycle 13, the ^{65}Zn concentration oscillated around 4 x 10^{-5} µCi/ml until the resumption of zinc addition. Similar to Cycle 12, the ^{65}Zn concentration quickly increased after the resumption of zinc addition although by not as great a factor, i.e., by about a factor of 13 compared to a factor of 40 in Cycle 12. The effect of continuing to use depleted zinc for four months is seen in that the concentration remained at about 5 x 10^{-4} µCi/ml for that time period. After the changeover to natural zinc, the concentration increased to an "equilibrium" of about 2 x 10^{-3} µCi/ml, about half the "equilibrium" concentration of 4 x 10^{-3} µCi/ml reached at the EOC 10, reflecting the combined use of natural and depleted zinc during Cycle 13. The "equilibrium" concentration of 4 x 10^{-3} µCi/ml reached at the EOC 10, reflecting the combined use of natural and depleted zinc during Cycle 13. The "equilibrium" concentration of 4 x 10^{-3} µCi/ml reached at the EOC 10 was essentially identical to that observed in the Diablo Canyon 1 plant after natural zinc injection for a somewhat shorter exposure time of zinc injection, i. e., 7.5 months vs. 9.0 months (Ref. 2.4).

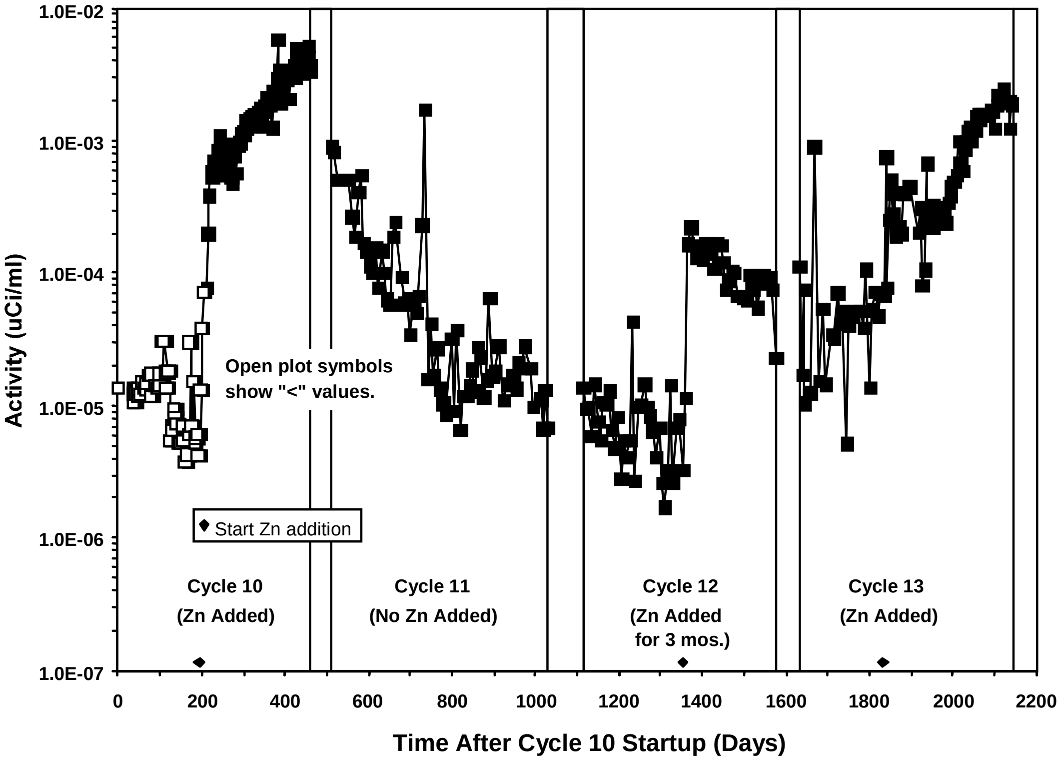

Figure 2-3
^{65}Zn Activity in the RCS During Cycles 10 through 13

2.3.3 Coolant Radiocobalt Trends

The total activity concentrations of ^{58}Co and ^{60}Co versus operating time during Cycles 8 through 13 are presented in Figures 2-4 and 2-5, respectively. Cycle 8 data are included to illustrate the activity trends for the two operating cycles before zinc addition was initiated in Cycle 10.

The ^{58}Co trend shows a clear effect of zinc addition starting in Cycle 10 in that the activity concentrations increased from on the order of 10^{-4} µCi/ml to about 3 x 10^{-3} µCi/ml near the end of the cycle. (The peaks in the last few months are attributed to plant shutdowns rather than to a true increase.) Recovery to pre-zinc levels did not occur in Cycle 11 while zinc injection was suspended, although some recovery was noted at the beginning of Cycle 12.

After zinc was injected during Cycle 12, a similar increase in ^{58}Co activity concentration was noted except that the increase continued after zinc injection was stopped. Considering a final activity concentration of about 10^{-2} µCi/ml during the last month of operation, the value reached was about three times that attained during the last month of Cycle 10, and about a factor of 50 higher than nominal values for cycles prior to zinc addition. During Cycle 13, the ^{58}Co activity

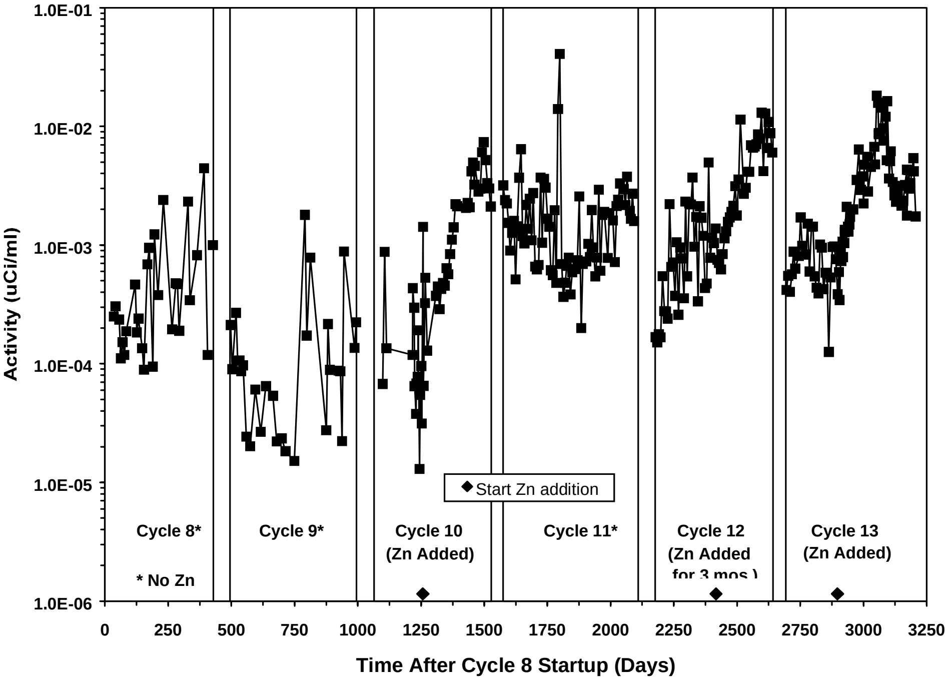

Figure 2-4
^{58}Co Activity in the RCS During Cycles 8 through 13

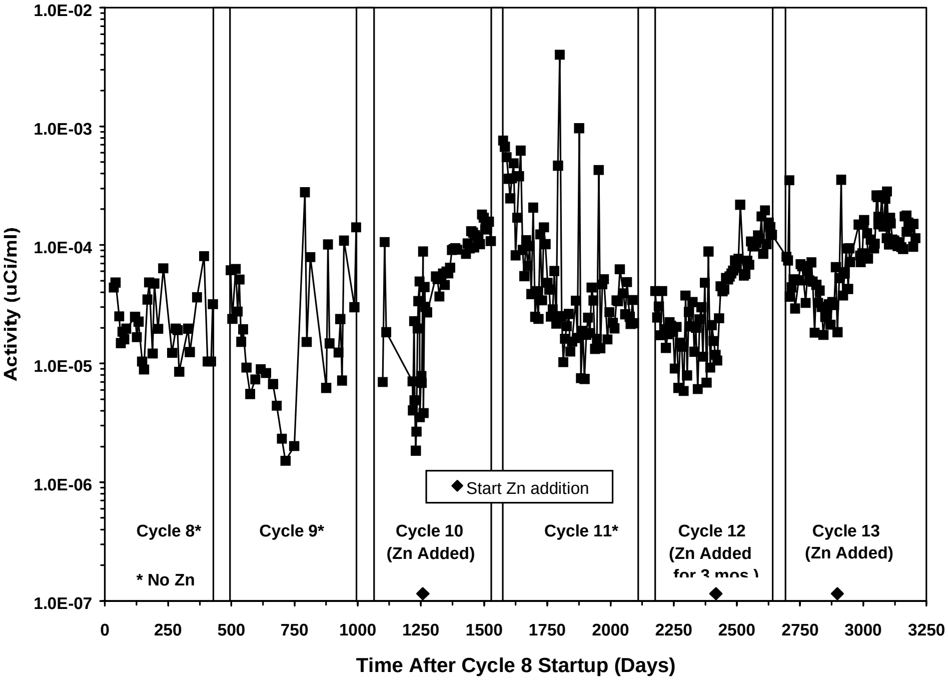

Figure 2-5
^{60}Co Activity in the RCS During Cycles 8 through 13

concentration started slightly higher than that observed at the start of Cycle 12 and then increased after zinc addition was resumed by a factor of 10 to about 1 $x10^{-2}$ μCi/ml, essentially the same concentration reached during Cycle 12. Subsequently, the concentration decreased to an “equilibrium” concentration of about 4 $x10^{-3}$ μCi/ml at the EOC. This decrease suggests that the exchange of zinc with nickel (and ^{58}Co) in the plant corrosion product oxides may have reached an equilibrium condition.

The ^{60}Co activity trend is somewhat different from the ^{58}Co trend in that the concentration initially declined in Cycle 11 and then leveled off in Cycle 12 at a value about equal to the pre-zinc concentrations. The ^{60}Co activity concentration in Cycle 12 increased after zinc injection was re-initiated and, similar to the ^{58}Co activity, continued to increase even after termination of zinc addition. However, it increased only to about the levels found near the EOC 10, i.e., 10^{-4} μCi/ml. Considering a base pre-zinc value of 1×10^{-5} μCi/ml, the ^{60}Co activity increase attributable to zinc is on the order of a factor of ten, or somewhat less than that seen for ^{58}Co. During Cycle 13, the ^{60}Co activity concentration initially decreased as was seen during Cycle 12, and then increased after the resumption of zinc addition by a factor of about five to 1.5×10^{-4} μCi/ml. Similar to ^{58}Co, the concentration then decreased somewhat to 1.0×10^{-4} μCi/ml. This decrease again, as for ^{58}Co, suggests that the exchange of zinc with cobalt (and ^{60}Co) in the ex-core oxide films may have reached an equilibrium condition.

The fact that the ^{60}Co concentration increases after zinc addition are somewhat less than the ^{58}Co increases suggests that zinc addition effects a relatively greater release of nickel than cobalt from the ex-core corrosion films.

2.3.4 ^{58}Co/^{60}Co Activity Ratios

The ^{58}Co/^{60}Co activity ratio in the RCS for Cycles 8 through 13 was also reviewed to define trends during zinc addition. Figure 2-6 shows these trends.

Observations based on an inspection of the data in Figure 2-6 include:

- In general, the ^{58}Co/^{60}Co ratio increases during the cycle. After the start of zinc addition, the trend of this increase was more prominent.

- During Cycle 9, the ratio varied between values of 2 and 10 (the low value reflects the unusually low ^{58}Co value in Cycle 9). However, the ratio was in the range from about 5 to 40 during Cycles 8 and 10, and from about 5 to 80 in Cycles 11, 12 and 13.

- The ratio appears to decrease rather dramatically at the onset of zinc addition and tends to increase with time thereafter. From an inspection of the data in Figures 2-4 and 2-5, this trend appears to be related to a relatively large increase in ^{60}Co activity at the start of zinc addition followed by a period where the ^{60}Co activity concentration increases at a slower rate than the ^{58}Co activity.

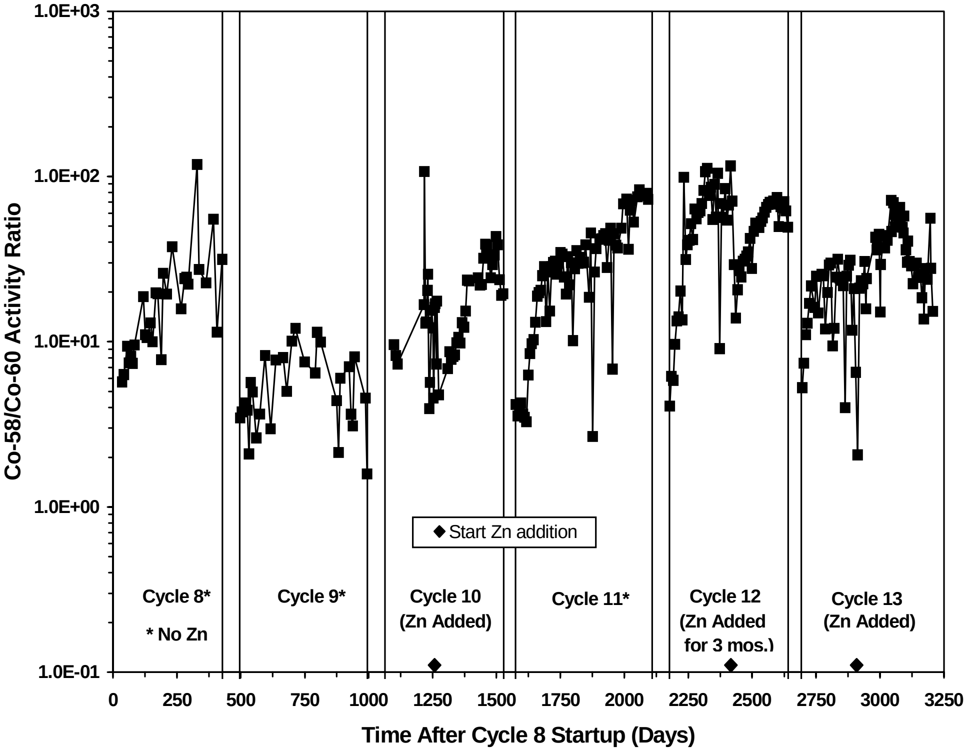

Figure 2-6
The ^{58}Co/^{60}Co Activity Ratio in the RCS for Cycles 8 through 13

2.3.5 Distribution of Insoluble and Soluble Activities

The distribution of activities in the insoluble and soluble portions of the reactor coolant for ^{65}Zn and the radiocobalts for Cycles 12 and 13 are shown in Figures 2-7 through 2-9. [“Less than” values are not shown on the figures. Most of the “less than” values were in the ^{60}Co and ^{65}Zn insoluble concentrations.] Inspection of these data suggests:

- After zinc addition, the soluble ^{65}Zn activity became measurable and equal to or greater than the insoluble activity. This had also been noted during Cycle 10 after zinc addition. The distribution did not change after zinc addition was terminated during Cycle 12, indicating a residual effect of zinc. However, during Cycle 13 the difference between the insoluble and soluble portions was greater than in Cycle 12, indicating the enhanced effect of the zinc addition. The predominance of the ^{65}Zn activity in the soluble portion of the coolant had also been observed in Diablo Canyon 1 after zinc addition (Ref. 2.4).

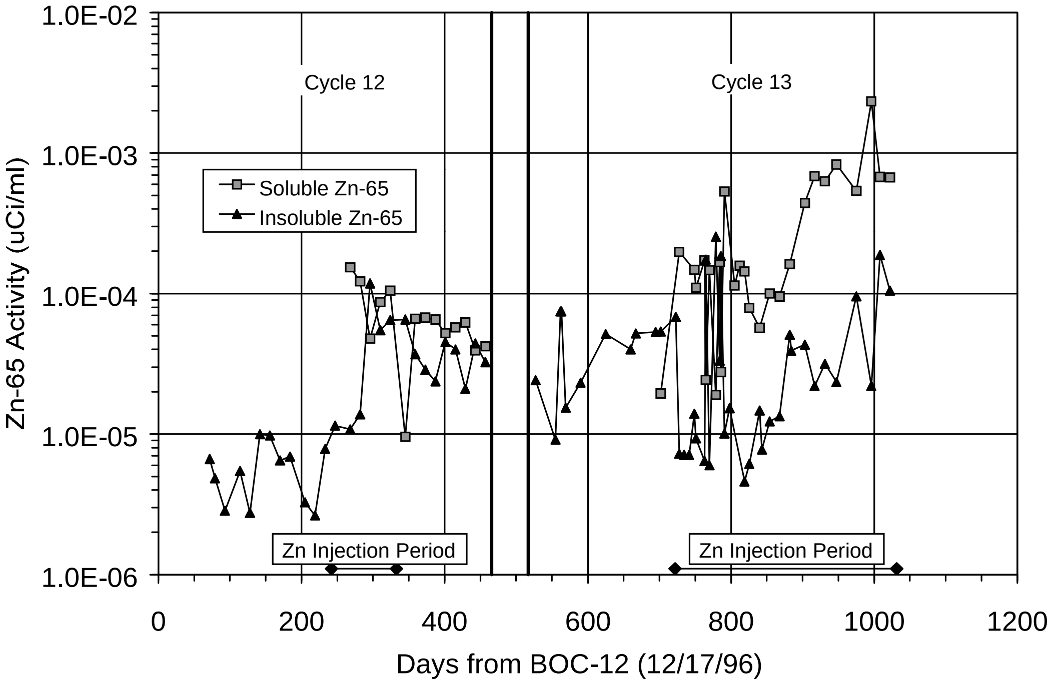

Figure 2-7
Insoluble and Soluble Concentrations of ^{65}Zn During Cycles 12 and 13

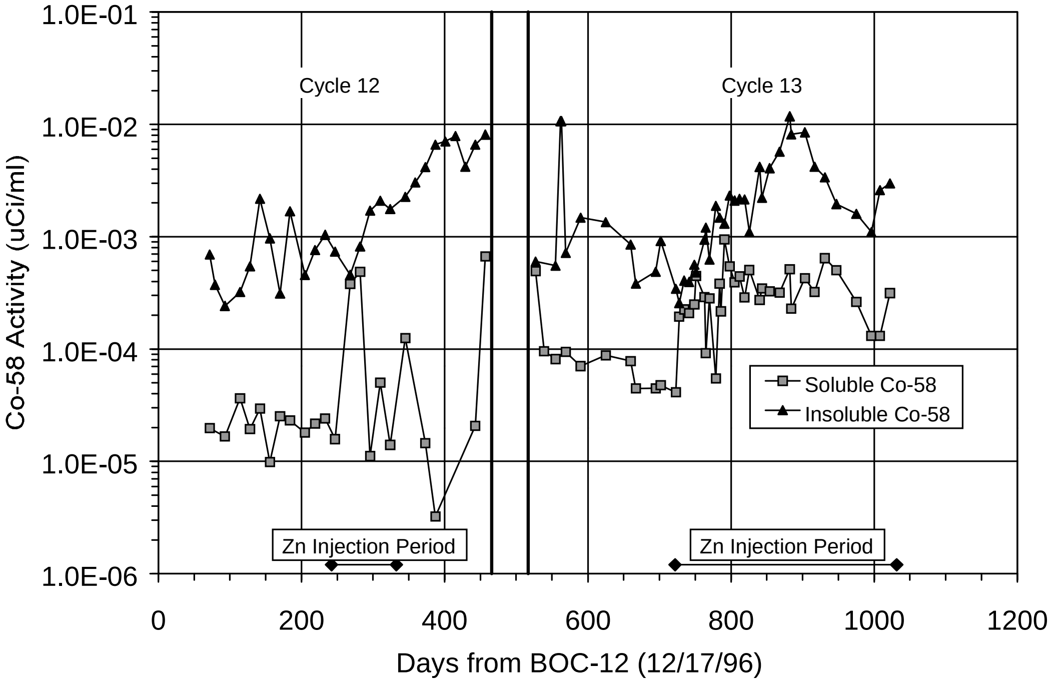

Figure 2-8
Insoluble and Soluble Concentrations of ^{58}Co During Cycles 12 and 13

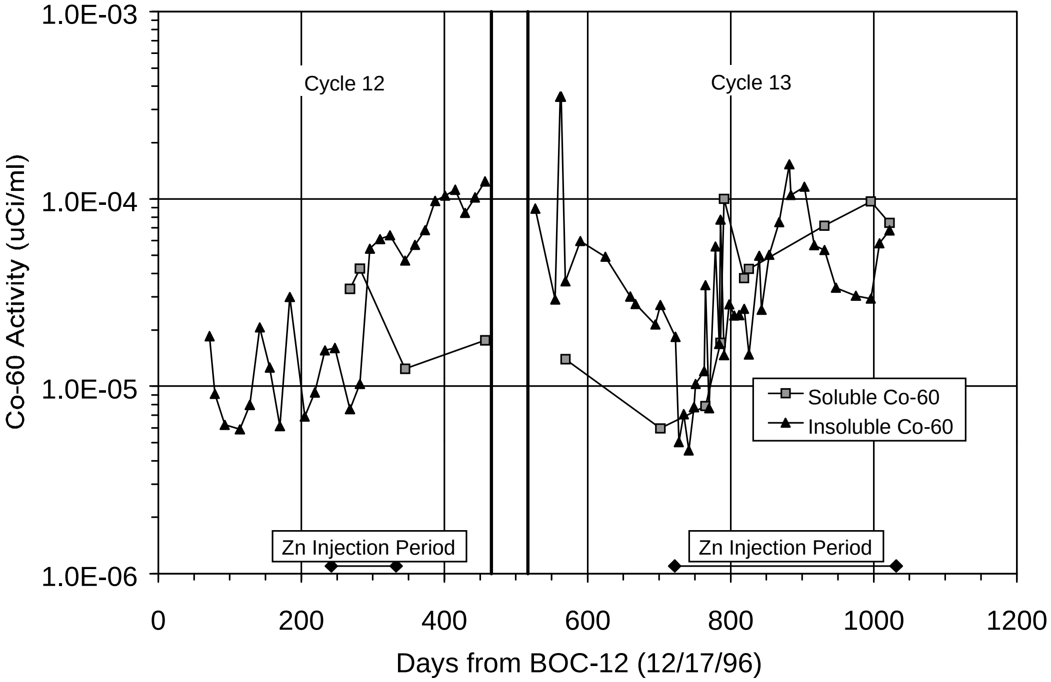

Figure 2-9
Insoluble and Soluble Concentrations of ^{60}Co During Cycles 12 and 13

- For ^{58}Co, most of the activity is in the insoluble form in both Cycles 12 and 13, before and after zinc addition. This was also the case noted in Cycle 10 after zinc addition. Note however that, for a time after the initiation of zinc addition, the soluble activity approached that of the insolubles, suggesting an initial effect of zinc exchanging with the more soluble form of nickel in the corrosion film. Subsequently, the insoluble activity continued to increase whereas the soluble activity tended to level off. The predominance of the insoluble ^{58}Co activity in the coolant was the opposite of that observed in Diablo Canyon 1 after zinc addition (Ref. 2.4).

- Due to the relatively few samples in which soluble ^{60}Co activity was detected, the trend is difficult to assess. However, it appears that the insoluble and soluble trend is similar to that for ^{58}Co, except that the differences between the two are not as great.

2.4 SUMMARY AND CONCLUSIONS

Farley Unit 2 continued to employ a “modified” pH coolant chemistry mode of operation in Cycle 13, as it has for the last four cycles. Zinc addition had no discernible effect on the concentration of soluble nickel in the RCS.

As was observed in Cycle 12, the ^{65}Zn activity concentration quickly increased after the resumption of zinc addition although not as significantly, i.e., by a factor of about 13 compared to a factor of 40 in Cycle 12. The effect of the use of depleted zinc for the first four months of the injection period was seen in that the ^{65}Zn concentration remained at about 5 x 10^{-4} µCi/ml for that time period. After the changeover to natural zinc, the concentration increased to an "equilibrium" of about 2 x 10^{-3} µCi/ml, somewhat lower than the "equilibrium" concentration of 4 x 10^{-3} µCi/ml during Cycle 12.

The trends of the radiocobalt activities in the coolant during Cycle 13 suggest that the exchange of zinc with nickel (and ^{58}Co) and cobalt (and ^{60}Co) in the plant corrosion product oxides may have reached an equilibrium condition.

The target zinc concentration in the RCS was reduced to 30 ppb compared to 40 ppb in prior cycles due to a potential concern for zinc oxide precipitation on the fuel. Zinc was first detected in the coolant three days after injection compared to nine and eleven days in the previous cycles. Over the last four moths of injection, the injection rate was reduced three times from 0.6 to 0.3 gph to maintain the target concentration. This behavior suggests that the zinc in the RCS and that in the oxide films may be approaching an equilibrium condition. Of the zinc additions made in Cycle 13, the residual zinc in the primary system at the EOC 13 was estimated to be 2.31 kg. This compares to a net addition of 1.03 kg in Cycle 12 and a net of 3.83 kg in Cycle 10.

Most of the radiocobalt activity in the coolant is in the insoluble form, both before and after zinc addition; this is true for both the ^{58}Co and ^{60}Co activities. However, the initial response of the radiocobalt activities to zinc addition is an abrupt increase in the soluble activities, suggesting the initial exchange of zinc in the coolant with the ex-core corrosion films effects the release of nickel and cobalt in the soluble form. For ^{65}Zn, the soluble activity was dominant. These soluble-insoluble trends had been noted in previous operations with zinc addition.

A clear change in the trend of the ^{58}Co/^{60}Co ratio is exhibited after zinc addition compared to operation with no zinc addition. The ^{58}Co/^{60}Co ratio decreases at the initiation of zinc addition, followed by a gradual increase.

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3

CYCLE 13 RADIATION LEVELS

3.1 INTRODUCTION

Dose rate and radionuclide concentration measurements of the reactor coolant system (RCS) components were made at Farley Unit 2 at the end of Cycle 9 (EOC 9) as baseline measurements for comparison to those made after the addition of natural zinc to the primary coolant during Cycle 10. These measurements were repeated at the EOC 10 following approximately nine months of zinc addition. During Cycle 11, the addition of zinc was discontinued, but again dose rate and radionuclide measurements were made at the end of the cycle. During Cycle 12, depleted zinc was added to the primary coolant, but only between the ninth and twelfth months of a sixteen-month cycle. Dose rate and radionuclide concentration measurements of the RCS components were subsequently performed at the end of the cycle. These data were used to define the effects on radiation levels and nuclide concentrations due to operation with and without natural and depleted zinc added to the primary coolant (Refs. 3.1 through 3.3).

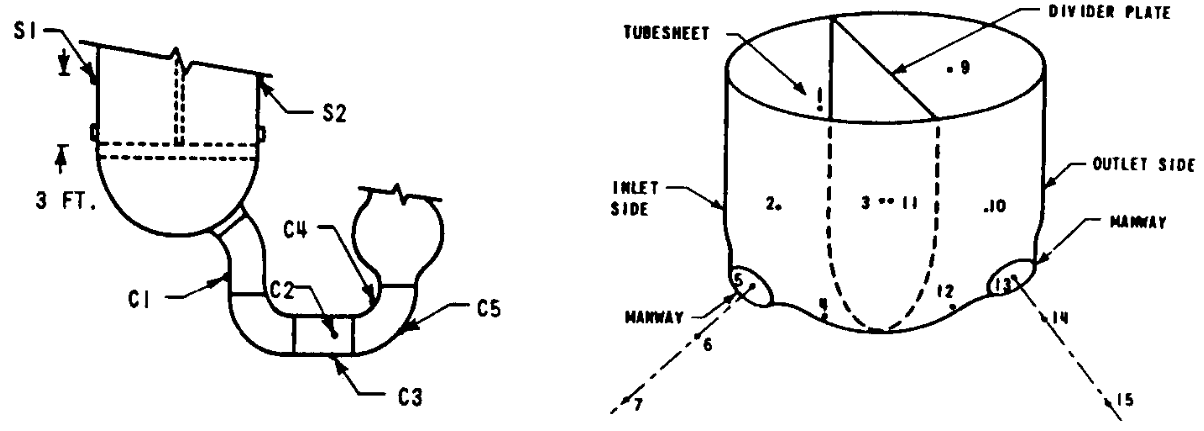
Zinc addition using depleted and natural zinc was resumed for about ten months during Cycle 13. However, only RCS component dose rate measurements were made at the end of the cycle. Radionuclide measurements were not performed. This section presents and evaluates the results of the dose rate measurements; dose rate data for prior cycles are included as appropriate.

3.2 COMPONENT DOSE RATES

3.2.1 EPRI Standard Radiation Monitoring Program (SRMP) Locations

Dose rate measurements were made at the EPRI Standard Radiation Monitoring Program (SRMP) locations shown in Figure 3-1. Measurements on the reactor coolant loop piping and steam generator tubing were made twice during each of the end-of-cycles 9, 10, 11, 12, and 13 refueling outages, i.e., prior to and following hydrogen peroxide addition. In addition, dose rate measurements of the channel head general area following hydrogen peroxide addition were made during each refueling outage using survey instruments and thermoluminescent detectors (TLDs).

As noted above, the dose rate data obtained during the EOC 9 through EOC 12 refueling outages have been presented and discussed in previous reports and are not repeated here. The data taken at the EOC 13 outage are provided in Table 3-1 for the coolant piping and the SG tube bundle; Table 3-2 summarizes the survey data for the SG channel head location.



SG Tubing and Crossover Leg Piping

SG Channel Head

Hot Leg Piping

Cold Leg Piping

Figure 3-1
Locations of EPRI SRMP Measurement Points

Figures 3-2 and 3-3 show the dose rate trends for Cycles 9 through 13 on the RCS piping and outside the SG tube bundle before and after peroxide additions during the shutdown. The piping data reported is the average of points C1-C5, HL1 and CL1 and represent the overall trend of the crossover, hot leg and cold leg piping. This is in contrast to prior reports, in which data from only the crossover piping point C5 was used to represent the piping. The use of all the piping data reduces the effect of variations at individual points. The value for the tube bundle location is the average of points S1 and S2 and is taken to represent the trend for the SG tubing. The SG channel head value is the average of the midpoint of the channel head, points 2 and 10. The piping and tubing data were taken with survey meters.

The SG channel head data are TLD results since these were used in surveys prior to Cycle 9 to track the overall trends since plant startup. Figure 3-4 shows the overall trend of the dose rates in the SG channel head.

Table 3-1
End of Cycle 13 Radiation Survey Summary on the Main Coolant Piping and Outside the SG Tube Bundle

SRMP Location	Survey Meter Dose Rate Readings, mR/h			
	Loop A	**Loop B**	**Loop C**	**Average**
Pre-Peroxide Addition				
C1	85	140*	50	67.5
C2	120	60	50	76.7
C3	160	220	100	160.0
C4	120	260*	80	100.0
C5	50	200*	30	40.0
HL1	100	80	40	73.3
CL1	100	80	60	80.0
S1	7	6.5	8	7.2
S2	9	8.5	8	8.5
Post-Peroxide Addition				
C1	80	100	46	75.3
C2	60	60	44	54.7
C3	120	80	60	86.7
C4	65	60	35	53.3
C5	48	50	43	47.0
HL1	42	40	30	37.3
CL1	52	40	40	44.0
S1	8	9	9	8.7
S2	10	10	10	10.0

*Dose rates affected by Regenerative Heat Exchanger; not included in the average.

Table 3-2
End of Cycle 13 Radiation Survey Summary for the Steam Generator Channel Head

SRMP Location	Loop A	Loop B	Loop C	Average
TLD Dose Rate Readings, R/h				
2	4.1	5.0	4.1	4.40
10	4.7	4.7	4.5	4.63
Survey Meter Dose Rate Readings, R/h				
2	3.7	3.1	3.2	3.3
10	4.2	4.0	3.3	3.8
1	15.0	8.6	6.4	10.0
9	19.2	8.5	7.6	11.8
3	23.0	7.6	6.0	12.2
11	21.0	5.5	6.8	11.1
4	8.0	3.3	3.8	5.0
12	11.0	5.0	4.4	6.8

Notes:

SRMP 2 & 10 - Hot and cold side channel head general area

SRMP 1 & 9 - Hot and cold side tubesheet contact

SRMP 3 & 11 - Hot and cold side divider plate contact

SRMP 4 & 12 - Hot and cold side channel head bowl bottom contact

All points of Loop A except 2 & 10 are suspected as being too high, but were included in the reported average.

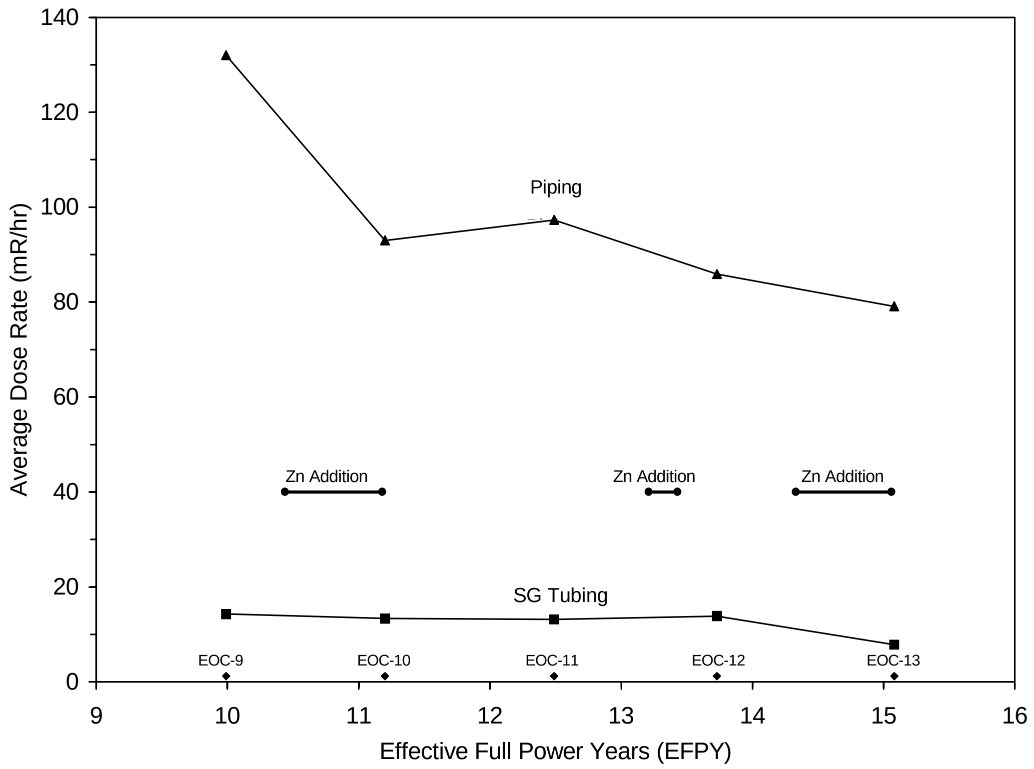


Figure 3-2
Dose Rates at Various Primary System Locations Before H_2O_2 Addition

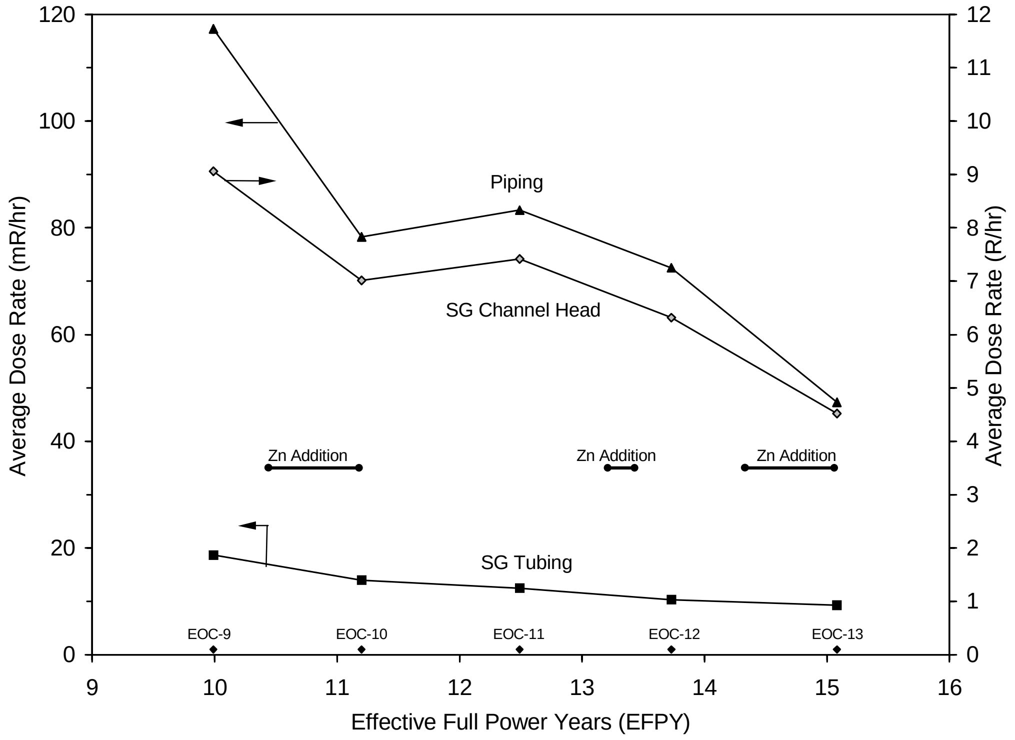


Figure 3-3
Dose Rates at Various Primary System Locations After H_2O_2 Addition

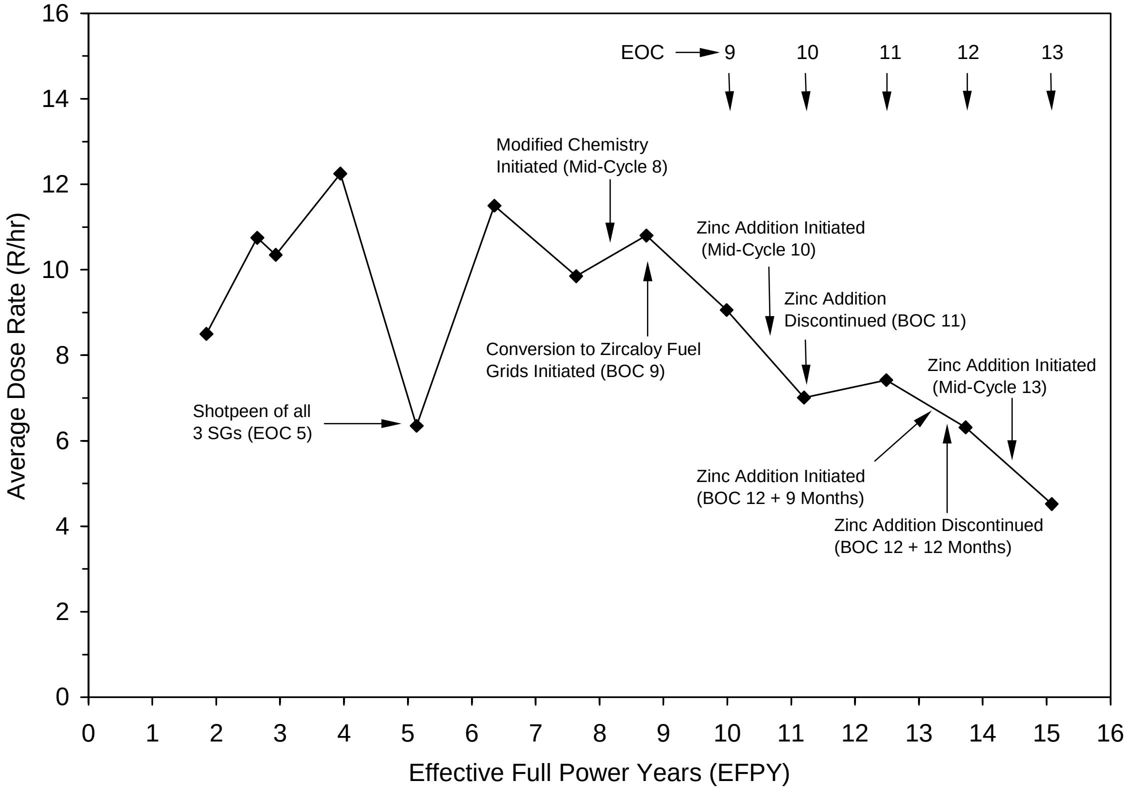


Figure 3-4
Steam Generator Channel Head General Area TLD Dose Rate Trend After Hydrogen Peroxide Addition

Inspection of the trends in the figures shows an overall consistent decrease in the piping and channel head dose rates before and after peroxide addition, with a slight increase occurring after Cycle 11, the cycle with no zinc addition. With the exception of Cycle 13, the SG tubing dose rates before peroxide additions were essentially unchanged. The SG tubing dose rates after peroxide additions decreased during the experience with zinc addition.

Overall, the dose rates at the locations measured decreased by a factor of two over the period of zinc injection in Cycles 10 through 13, compared to the dose rates at the end of pre-zinc Cycle 9.

3.2.2 Non-EPRI-SRMP Locations

Due to an unexpected increase in dose rates at certain non-SRMP locations observed in the Diablo Canyon 1 plant after its initial zinc addition cycle (Ref. 3.4), limited additional dose rate measurements were taken at two locations on the Residual Heat Removal System (RHRS) in Farley 2. Measurements were taken with survey instruments before and after hydrogen peroxide addition during the shutdown process, and with continuously reading electronic dosimeters installed at the same locations. However, only the peak dose rate portion of the dosimeter data was retrieved. Table 3-3 presents the data obtained from the RHRS locations.

The data in Table 3-3 indicate that the dose rate on the RHRS decreased considerably during the shutdown process. However, inspection of the nuclide activity trends during the shutdown process (Section 4.0) shows that by the time the initial pre-peak survey was taken, the coolant activity had reached a significant concentration in the coolant such that it probably contributed to the dose rate on the RHR system piping. This coolant activity contribution would result in a higher dose rate measured at the RHR location before the peak, thus exaggerating the decrease. This effect is considered later in the following section.

Table 3-3
Dose Rates on the RHRS System During the Cycle 13 Shutdown

Location	Dose Rate before Peak, mR/h	Peak Dose Rate, mR/h*	Dose Rate After Peak, mR/h
RHR-A Train	260	1243	100
RHR-B Train	220	1160	60

* Measured with electronic dosimeters; other data taken using survey instruments

3.3 EVALUATION OF DOSE RATE TRENDS

3.3.1 EPRI Standard Radiation Monitoring Program (SRMP) Locations

Dose rate trends at the EPRI-SRMP locations, namely, the midpoint of the SG channel head, outside the SG tube bundle, and outside the piping, were used to evaluate changes from the EOC 9 through the EOC 13 outages. Table 3-4 summarizes the average dose rates at these locations before and after peroxide addition. Note that measurements can not be taken in the channel head before peroxide addition. Also, only the TLD dose rates of the channel head were used in the post-peroxide evaluation, since they are judged to be more accurate than the survey meter values.

Table 3-4
Comparison of RCS Component Dose Rates

Location	Average Dose Rate (1)				
	EOC 9	EOC 10	EOC 11	EOC 12	EOC 13
Pre-Peroxide Addition					
SG Tubing [S1 & S2]	14.3	13.3	13.2	13.8	7.8
Piping Avg. [HL1, CL1, C1-C5]	132.0	93.0	97.3	85.9	80.7
Post-Peroxide Addition					
SG Channel Head [2 & 10](2)	9.06	7.02	7.42	6.32	4.53
SG Tubing [S1 & S2]	18.7	14.0	12.5	10.3	9.3
Piping Avg. [HL1, CL1, C1-C5]	117.3	78.3	83.3	72.7	48.2

(1) Values at locations 2 & 10 in R/h; others in mR/h
(2) Measured by TLD; all others by survey meter

Table 3-5 summarizes the dose rate ratios for the three locations at the end of the five cycles; in each case, the ratios are relative to the pre-zinc addition Cycle 9 values. A comparison of the average dose rate ratios at the available locations shows that the dose rates are lower by an average of 12% after hydrogen peroxide addition. This indicates removal of the out-of-core activity during the shutdown process. This value is greater than the corresponding value of about 5% found in plants that do not use zinc addition (Ref. 3.5) and suggests that zinc has affected the corrosion film activity such that it is more easily removed after hydrogen peroxide addition.

Table 3-5
RCS Component Dose Rate Ratios

Location	EOC 10/9	EOC 11/9	EOC 12/9	EOC13/9
Pre-Peroxide Addition				
SG Tubing [S1 & S2]	0.93	0.92	0.97	0.55
Piping Avg. [HL1, CL1, C1-C5]	0.70	0.74	0.65	0.61
Average	0.82	0.83	0.81	0.58
Post-Peroxide Addition				
SG Ch. Head [2 & 10]	0.77	0.82	0.70	0.50
SG Tubing [S1 & S2]	0.75	0.67	0.55	0.50
Piping Avg. [HL1, CL1, C1-C5]	0.67	0.71	0.62	0.41
Average	0.73	0.73	0.62	0.47

3.3.2 Non-EPRI-SRMP Locations

As noted in Section 3.2.2, the dose rates on the RHR train appeared to decrease during the shutdown evolutions. This is contrary to that observed in plants wherein the dose rates increase after the RHR is put into service due to deposition and/or removal of the nuclides in the coolant on the system walls during the shutdown process (Refs. 3.4 and 3.6). Since the pre-peak dose rates were probably high due to the influence of the nuclides in the coolant, this contribution was estimated normalizing the peak coolant activity concentrations to the dose rate at the measurement location. On this basis, the net dose rate due to the activity in the piping deposits was estimated for both pre- and post-peak surveys. These results are shown in Table 3-6.

The assumptions used to estimate the dose rate changes provide an upper bound. Thus, the “true” actual increase would be somewhat less than that shown in Table 3-6. Nevertheless, the increase is similar to that observed in the Callaway plant (5 to 40 mR/hr) and it is concluded that zinc addition had no effect on the estimated increase at Farley 2.

Table 3-6
Estimated Net Dose Rates on the RHRS During the Cycle 13 Shutdown

Location	Net Dose Rate Before Peak, mR/hr	Net Dose Rate After Peak, mR/hr	Change in Dose Rate, mR/hr
RHR-A Train	40	85	+45
RHR-B Train	14	46	+32

As noted in Section 3.2.2, the dose rate at certain non-SRMP locations in Diablo Canyon 1 increased after the initial cycle (Cycle 9) with zinc addition. These locations included the RHRS, the reactor vessel head area and the letdown line. An evaluation of the increases concluded that increased radiocobalt particulate concentrations in the coolant, which started in a cold shutdown that occurred six weeks before the EOC and continued into the EOC, resulted in an increased deposition of activity in the RHRS. The increase in the vessel head area was also judged to be due to increased amounts of coolant particulates being attracted to the magnetic jacks in the CRDMs. The increase in the letdown line has been observed in other plants without zinc addition and has been attributed to increases in particulates in the coolant, possibly due to a higher pH at the temperature of the heat exchanger (Ref. 3.4).

Because of this occurrence, changes were made to the operational and shutdown process in Diablo Canyon 2, which had also initiated zinc addition in Cycle 9. The changes were effective in that no unusual dose rate increases were observed at the end of the cycle with zinc addition Ref. 3.7).

3.4 RELATIONSHIP BETWEEN ZINC EXPOSURE AND DOSE RATE REDUCTION

Dose rate and other data are available from three Westinghouse-designed nuclear plants (Farley 2, and Diablo Canyon 1 & 2), one Siemens-designed plant (Biblis B), and one Combustion Engineering-designed plant (Palisades) that have performed zinc addition (Refs. 3.8 through 3.11). Since the data from Biblis B (presumably) and Palisades were taken after peroxide addition, only these results were compared. Because the time of zinc injection and the zinc coolant concentrations varied for the plants and cycles, the relationship between the amount of RCS zinc exposure for a cycle and the change in dose rate observed from the beginning to the end of that cycle was investigated.

Zinc exposure is defined for this discussion as the product of the average zinc concentration during the cycle and the time that zinc was in the RCS. The time of exposure was assumed equal to the time of initial zinc injection to the end of the cycle. Even though zinc injection may have been stopped some time during the cycle or towards the end of the cycle, zinc is still in the RCS and thus the system is being exposed to zinc. A measure of this effect is essentially taken into account in using the average zinc concentration during the cycle.

The dose rate reduction for each cycle was calculated using the same points as described above for the three Westinghouse plants; the dose reduction data for the other two plants are based on similar measurement locations. A summary of the dose reduction and zinc exposure data is given in Table 3-7 along with notes regarding the type of zinc acetate added and the percent dose rate due to ^{65}Zn.

The data in Table 3-7 indicate an increasing relationship between zinc exposure and dose rate reduction in the Farley 2 plant. However, it should be noted that, based on CORA evaluations, the reduction at the EOC 10 could be due largely to operational coolant chemistry and design changes that occurred starting in Cycle 8. These changes included operating with a modified coolant chemistry and changeover from Alloy 718 to Zircaloy fuel grid straps. The effect of these changes may continue for several cycles, but it is judged that their incremental effect is minimal by the EOC 13. Because of this possibility, the percent reduction represents a combination of the zinc addition effect and an operational effect. Nonetheless, an increasing dose rate reduction effect with zinc exposure is seen. The Farley 2 Cycle 13 experience suggests that a zinc exposure of 300 ppb-mo resulted in a dose rate reduction of 24%.

Table 3-7
Summary of Zinc Exposure and Dose Rate Reduction Data after Shutdown Chemistry Evolutions

Plant/Cycle	Zinc Added	Approx. Zn Conc., ppb	Zinc Injection Time, mo	Zinc Exposure, ppb-mo	Percent Reduction	% Dose Rate due to ^{65}Zn
Biblis B/17	Depleted	5	10.9	33.6	15.7	--*
Diablo Canyon 1/9	Natural	40-30	7.5	233	29	9
Diablo Canyon 2/9	Natural	30-15	6.2	130	28	--*
Farley 2/10	Natural	40	9.0	310	27	6.6
Farley 2/11	Residual Natural	5-0	7.6**	37.9	0	1.3
Farley 2/12	Depleted	40	3.0	129	15	0
Farley 2/13	Depleted 45% Natural 55%	30	10.3	300	24	--*
Palisades	Depleted	5	6.3	31.5	18	--*

* Gamma spectrometry results for ^{65}Zn contribution not performed or available.
** Zn not injected; injection time equivalent to time when ^{65}Zn concentration in coolant reached equilibrium.

Similar operational and design changes also occurred in both of the Diablo Canyon plants. However, they occurred during the second and third cycles. By the EOC 9, it is judged that their effects should not represent a significant factor in cycle-to-cycle changes. The data in Table 3-7 indicates that a lesser zinc exposure, i.e., 130 to 230 ppb-mo achieved a dose rate reduction similar to that observed in Farley 2 and suggests that a lower zinc concentration may be adequate to effect the dose rate reduction benefit. However, this difference may be related to design differences between the Farley 2 and Diablo Canyon plants. Note also that most of the Farley 2 and Diablo Canyon plant experience has been with natural zinc. Use of depleted zinc would further increase the benefit.

The data from the Biblis B and Palisades plants (Refs. 3.7 and 3.8) also suggests that significant dose rate reductions can be realized with much smaller zinc exposures than in the Farley 2 and Diablo Canyon plants. The relationship between dose rate reduction and zinc exposure using the data from all the plants is given in Figure 3-5. The trend line is a logarithmic fit to the data and indicates that, in general, the greater the zinc exposure, the greater the dose rate reduction. It is noted that the relationships do not take into account any effect of design and operating differences between (and among) the Westinghouse and non-Westinghouse plants.

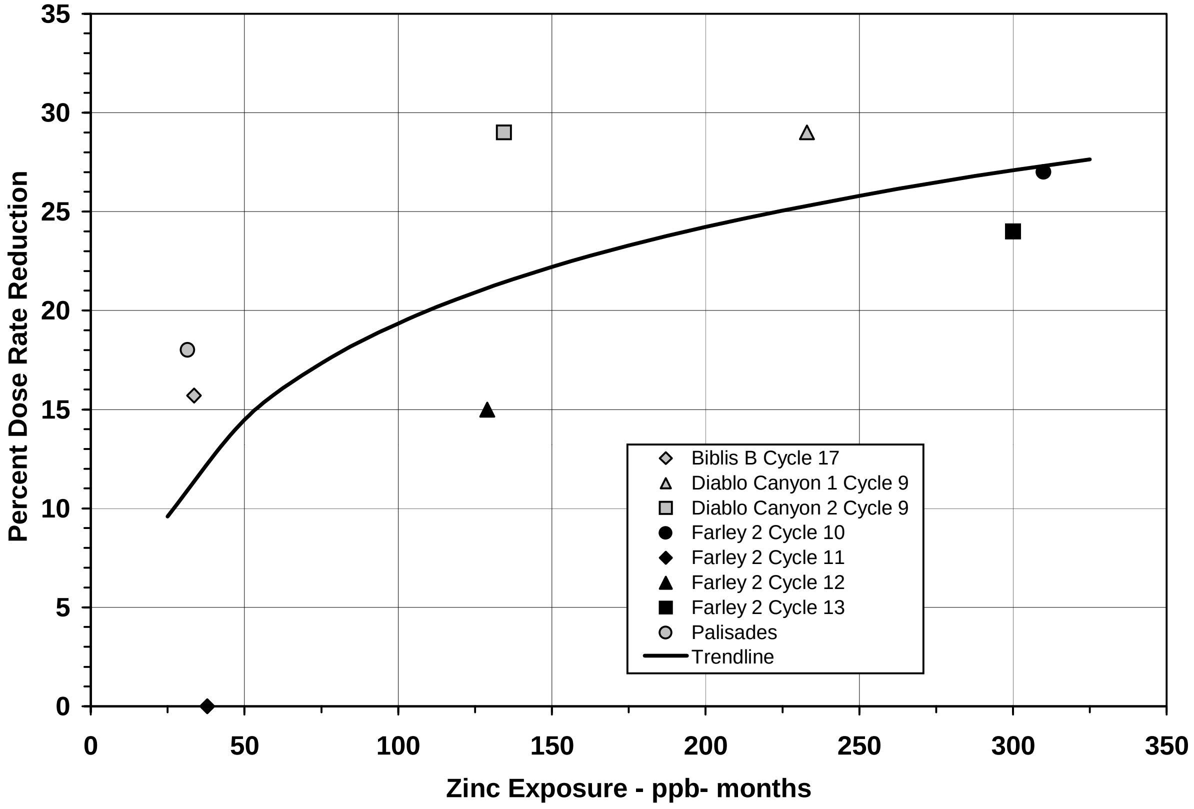


Figure 3-5
Zinc Exposure and Percent Dose Rate Reduction in All Plants

The above observations are based on maximum zinc injection times of 10 to 11 months and a limited data base. For this reason, data from additional longer operating/zinc injection cycles are of interest.

3.5 CONCLUSIONS

The following observations and conclusions result from a review and evaluation of dose rates in Farley 2 during zinc addition and comparison with data from other plants that have added zinc to the primary coolant.

- Dose rates at EPRI SRMP locations in Farley 2 decreased about a factor of two from the EOC 9 through the EOC 13, thus suggesting a dose rate benefit of zinc addition, even when done intermittently or for part of a fuel cycle. The changes by cycle indicated an increasing dose reduction benefit with a longer zinc exposure time. Zinc exposure time is defined as the product of the zinc exposure time and the coolant zinc concentration.

- Based on data from the RHRS, the dose rates at non-SRMP locations did not undergo an unusual increase at the EOC 13. This is in contrast to observations in Diablo Canyon 1 at the end of the initial zinc addition cycle, after an unplanned cold shutdown had occurred shortly before the EOC shutdown.

- A comparison of the average dose rate ratios from cycle-to-cycle indicates the dose rates are consistently lower after hydrogen peroxide addition by an average of 12%. This indicates removal of the out-of-core activity during the shutdown process. This value is greater than the corresponding value of about 5% found in plants that do not use zinc addition and suggests that zinc has affected the corrosion film activity such that it is more easily removed after hydrogen peroxide addition.

- The experience in Farley Unit 2 suggests that an approximate reduction of 24% may be realized for a cumulative zinc exposure on the order of 300 ppb-mo. However, relying on the experience in the Diablo Canyon units, it appears that an equivalent benefit may be attainable with cumulative zinc exposures on the order of 130 to 230 ppb-mo. However, this difference may be related to a plant design effect.

- Zinc addition data from the Biblis B and Palisades plants also suggest that significant dose rate reductions can be attained with much smaller zinc exposures than in the Farley 2 and Diablo Canyon plants. Again, however, it is noted that the relationships do not take into account any effect of design or operating differences between the Westinghouse and non-Westinghouse plants.

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4

EVALUATION OF REFUELING SHUTDOWN CHEMISTRY

4.1 INTRODUCTION

In addition to the usual changes in pH and temperature associated with boration and cooldown, considerable quantities of hydrogen peroxide are added to the coolant during chemical degassing and dissolution of corrosion products. These changes in RCS chemistry have direct impact on radionuclide release characteristics and as such may affect or be affected by the presence of zinc in the RCS.

Zinc was added to the Farley 2 coolant for a ten-month period during Cycle 13. The Cycle 12 shutdown chemistry and radiochemistry data were evaluated in order to discern any possible effects of the presence of zinc in the RCS. A summary of these evaluations is presented in this section. Reference to data and experience from previous Farley Unit 2 refueling shutdowns is made as appropriate.

4.2 SHUTDOWN CHEMISTRY OPERATIONS

Farley Unit 2 was shut down for the end-of-Cycle 13 refueling outage on October 16, 1999 at 0100[1]. Immediately prior to shutdown, the boron concentration was 46 ppm, the lithium concentration was 0.58 ppm and the RCS hydrogen was approximately 34 cm^3/kg. Within six hours after shutdown, with the system temperature still at 547°F, the boron concentration had been increased to 1692 ppm, lithium had been further reduced to 0.11 ppm, and hydrogen had been mechanically degassed to 14 cm^3/kg. Those conditions resulted in an at-temperature pH_T of 5.42, and established the beginning of the acid-reducing environment (neutral pH at this temperature is 5.67). The boron and lithium concentrations, the RCS temperature, and the pH_T are plotted as a function of time after the start of shutdown in Figures 4-1 through 4-3, respectively. The neutral pH_T is also plotted on Figure 4-3; throughout this period the water chemistry was clearly acidic.

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[1] Since the data plots and the discussion provided in this section are in terms of hours following shutdown, references to the shutdown process are generally described in terms of hours after 0100 on October 16, 1999.

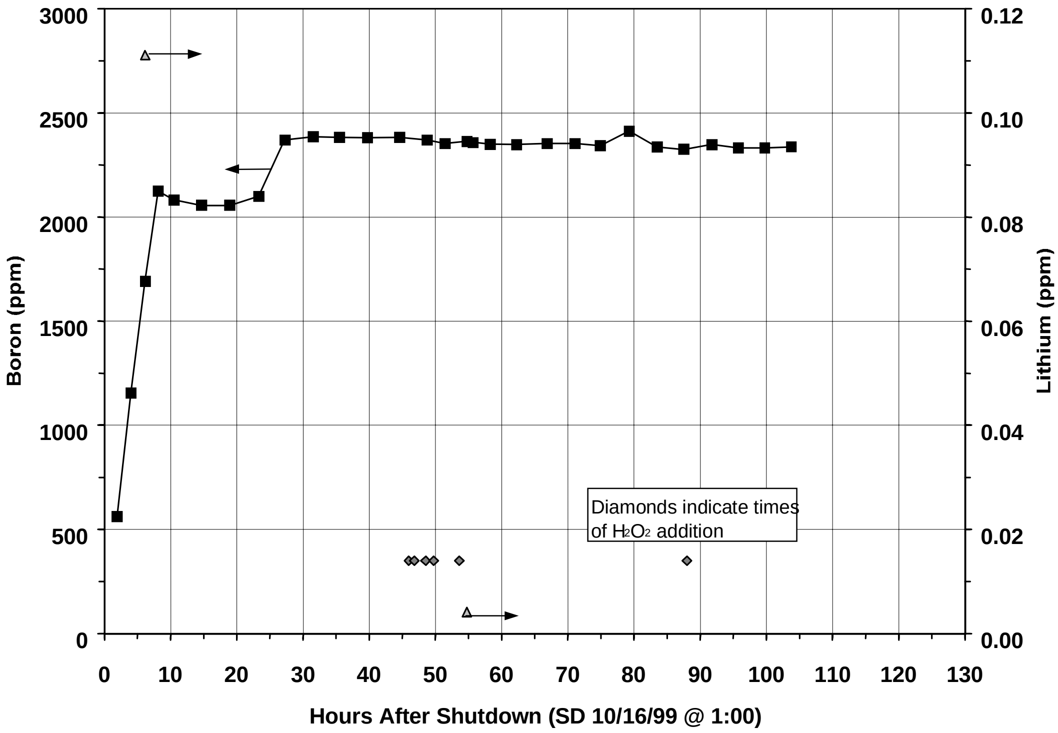

Figure 4-1
Boron and Lithium Concentrations in the RCS During the EOC 13 Shutdown

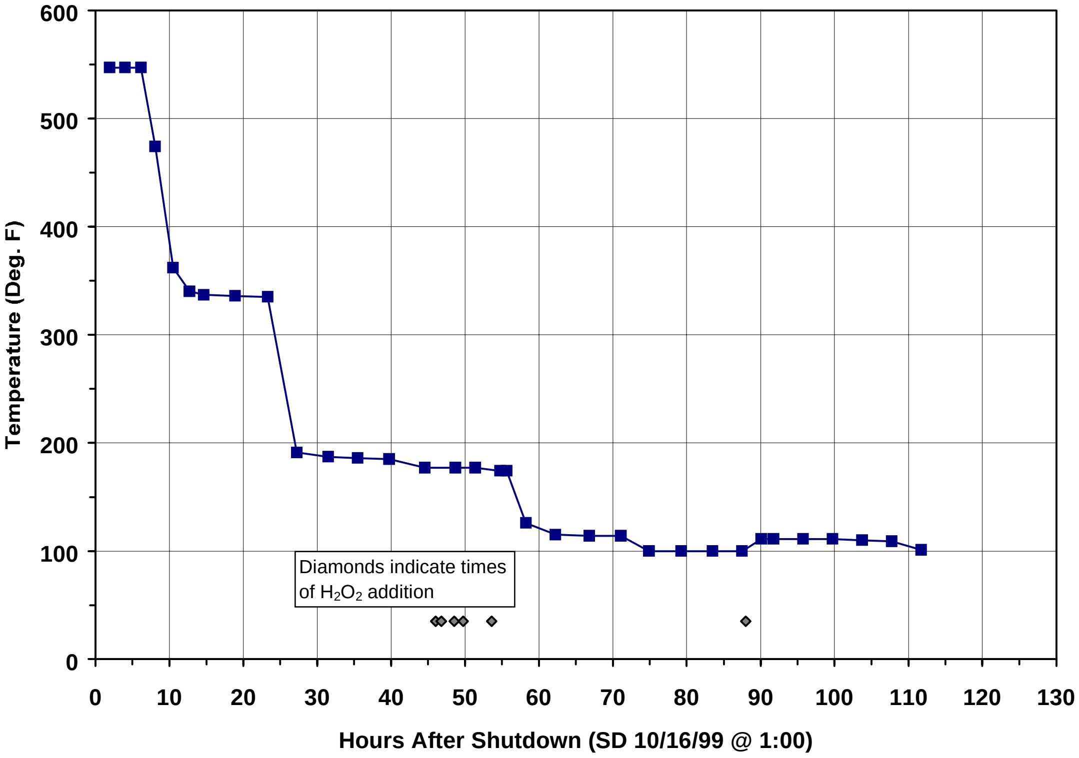

Figure 4-2
Reactor Coolant Temperature During the EOC 13 Shutdown

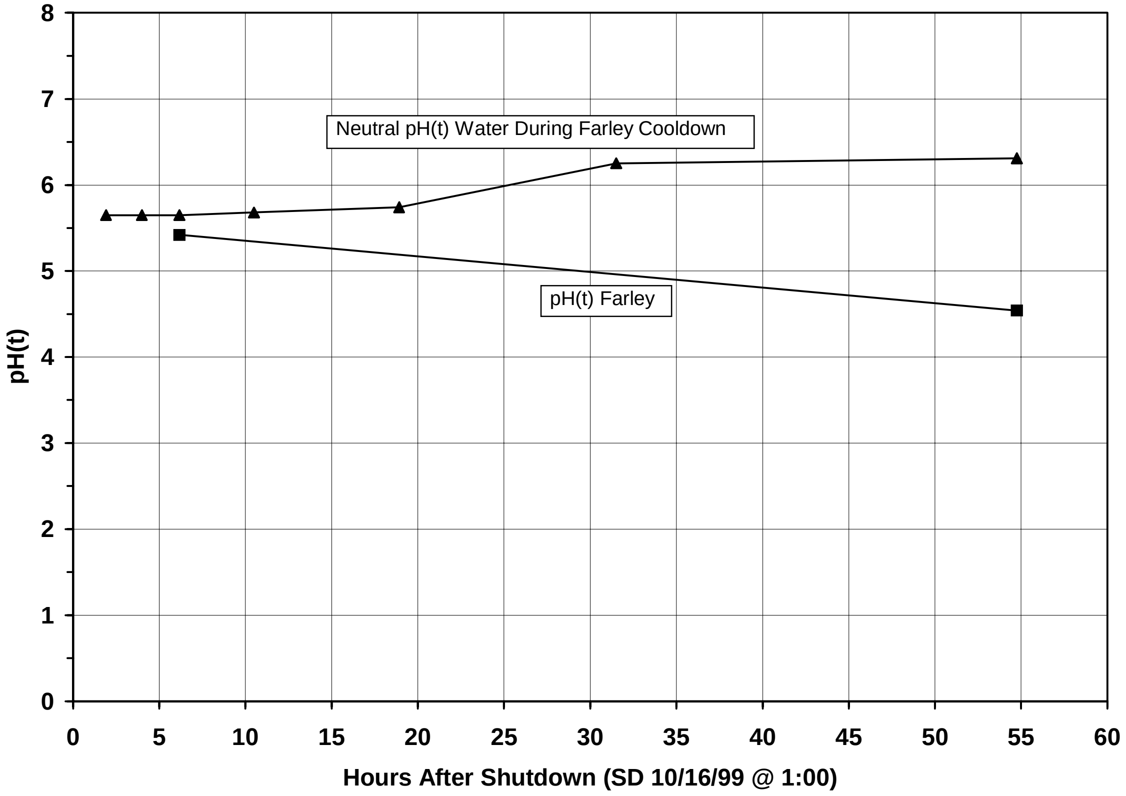

Figure 4-3
At-Temperature pH of the RCS During the EOC 13 Shutdown

The ^{58}Co activity concentration data are plotted as a function of time after shutdown in Figure 4-4[2]. These data show that the water chemistry immediately after shutdown was not sufficient to initiate dissolution of the ^{58}Co. The ^{58}Co activity concentration did not exhibit a sustained rise until 6 hours after shutdown. Shortly after this time, as the temperature was reduced from 547°F to approximately 340°F, and the pH_T was further reduced, the ^{58}Co activity concentration increased from about 4×10^{-2} µCi/cm^3 to $0.4 – 0.5 \times 10^{-1}$ µCi/cm^3 10.5 hours into the shutdown. Additional discussion of radiocobalt dissolution is provided in greater detail in the following subsection.

The shutdown chemistry practice at Farley Unit 2 includes the use of chemical degassing of hydrogen by a hydrogen peroxide treatment. Initial degassing of the RCS hydrogen was accomplished mechanically from a concentration of 34 cm^3/kg prior to the shutdown, to a value of 6 cm^3/kg 19 hours after the shutdown was initiated, Figure 4-5. Approximately 48 hours after shutdown, the hydrogen was measured at 9.6 cm^3/kg. Hence, the hydrogen concentration remained appreciable through a significant portion of the early shutdown period. This extended

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[2] Unless specifically noted otherwise, concentrations referred to in this section are those measured for nonfiltered water samples.

period of exposure of the corrosion products to hydrogen enhances the reduction of nickel oxide to nickel metal, rendering it susceptible to dissolution under the ensuing oxidizing environment.

Chemical degassing of the hydrogen was begun with the addition of 16 liters of 30 wt. percent hydrogen peroxide to the coolant 46 hours after the start of the shutdown.

Over the next 8 hours an additional 59.3 liters of peroxide were added, completing the hydrogen degassing operation and establishing an acid-oxidizing environment.

At the time of the first hydrogen peroxide addition, the total time of the acid-reducing chemistry phase was approximately 49 hours, a time that was similar to the acid-reducing phase (57.5 hours) during the previous Cycle 12 shutdown (Ref. 4.1).

During the shutdown period, the letdown flow was maintained between 120 and 131 gallons/minute throughout the acid-reducing phase, and was ultimately reduced to 80 gallons/minute 62 hours into the shutdown, at which level it was maintained for the remainder of the shutdown, Figure 4-6.

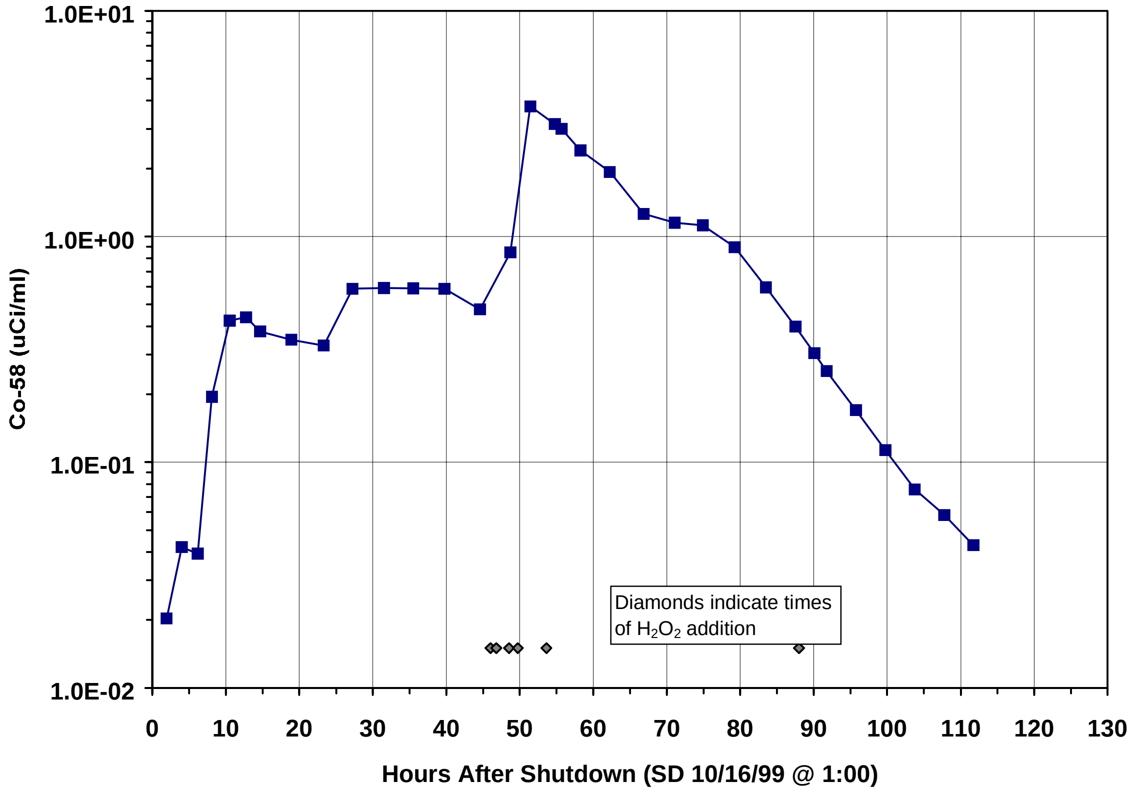

Figure 4-4
The ^{58}Co Activity Concentration in the RCS During the EOC 13 Shutdown

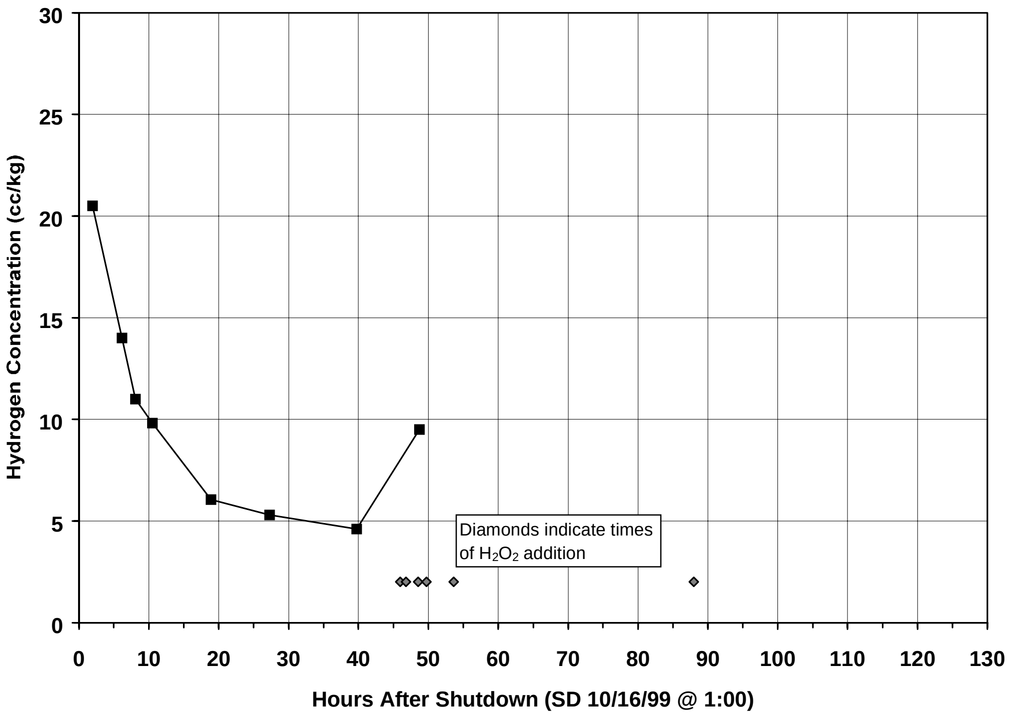

Figure 4-5
Dissolved Hydrogen in the RCS During the EOC 13 Shutdown

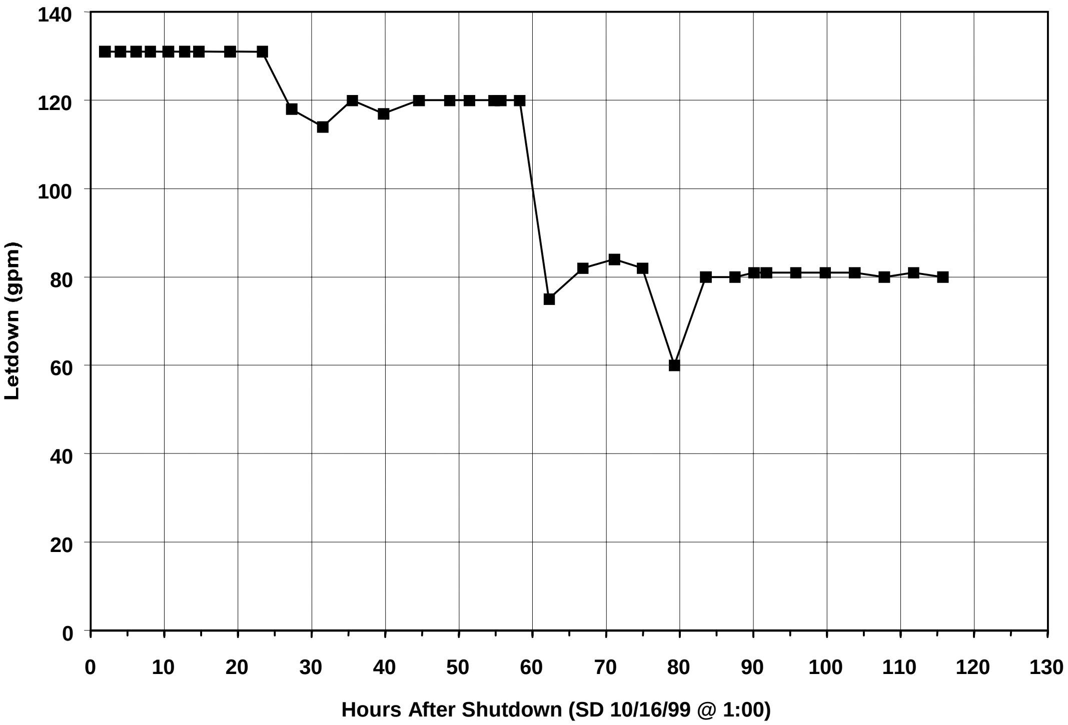

Figure 4-6
Purification System Letdown Flow During the EOC 12 Shutdown

4.3 ^{58}Co DISSOLUTION

On the day prior to shutdown, the ^{58}Co activity concentration in the coolant was measured as 2.12×10^{-3} µCi/cm^3. A sample taken 4 hours after shutdown showed a short spike in the ^{58}Co activity to about 4.2×10^{-2} µCi/cm^3. Such spikes are commonly observed at the start of an outage but are short-lived and do not reflect the initiation of a trend in activity release. The coolant became acid approximately 4 to 5 hours later ($pH_T = 5.42$; neutral $pH_T = 5.67$) and the ^{58}Co activity exhibited some modest fluctuation in the range 3 to 4×10^{-1} µCi/cm^3 before reaching 5×10^{-1} µCi/cm^3 approximately 24 hours after shutdown. The ^{58}Co activity concentration remained at this general level as the RCS temperature dropped to 177°F and the acid-reducing phase continued.

The ^{58}Co dissolution behavior for the remainder of the acid-reducing phase, with very little additional change, demonstrated the limitations in soluble release under acid-reducing chemistry, and showed that an effective rate of release will occur up to approximately 48 to 55 hours. After that, the dissolution begins to slow and is better effected by going to an oxidizing chemistry.

On October 17, 46 hours after shutdown, the first addition of hydrogen peroxide was made to initiate the chemical degassing of hydrogen and to begin to establish an acid-oxidizing environment. Over the next 8 hours an additional 59.3 liters of hydrogen peroxide were added to effect the release and dissolution of radiocobalt under the acid-oxidizing conditions. At this time, the ^{58}Co activity concentration spiked upward from ~0.6 µCi/cm^3 to 3.8 µCi/cm^3, and then began to decline under the influence of the CVCS purification letdown flow. The slight change in slope at about 62 to 65 hours into the shutdown may reflect the decrease in letdown flow that occurred at that time.

With the purification flow held steady at about 80 gpm, removal of ^{58}Co activity continued as expected until approximately 112 hours into the shutdown when the ^{58}Co activity concentration had reached 4.2×10^{-2} µCi/cm^3. The short-lived increase that had been observed in the Cycle 10 and Cycle 12 shutdowns (Refs. 4.1 and 4.2) approximately 130 to 140 hours into the shutdown was not observed in the EOC 13 shutdown. [Note: This may be because the EOC 13 shutdown ended after approximately 112 hours.]

The patterns of soluble release and purification of ^{58}Co during both the reducing and oxidizing chemistry environments of this outage were characteristic of plants using combined mechanical and chemical degassing of the coolant.

The overall result of the shutdown chemistry program was the release and removal by ion-exchange purification of 2047 Ci of ^{58}Co. This is slightly less than the release of ^{58}Co activity experienced in the Cycle 12 shutdown (see Table 4.1 in subsection 4.8).

4.4 ^{60}Co DISSOLUTION

The soluble release of ^{60}Co responded to the shutdown chemistry of the Cycle 13 refueling in a pattern nearly identical to that of ^{58}Co, Figure 4-7. All of the influences on dissolution described for ^{58}Co were also effective in ^{60}Co dissolution. The major difference between the behavior of the two radiocobalt activity concentrations was the respective magnitude of the total inventories dissolved. Compared with the 2047 Curies of ^{58}Co dissolved, only 64.4 Curies of ^{60}Co were dissolved and removed from solution. This amount is comparable to the ^{60}Co removed in the Cycle 10 refueling outage, and slightly higher than the amount removed at the end of Cycles 11 and 12 (see Table 4-1 in subsection 4.8).

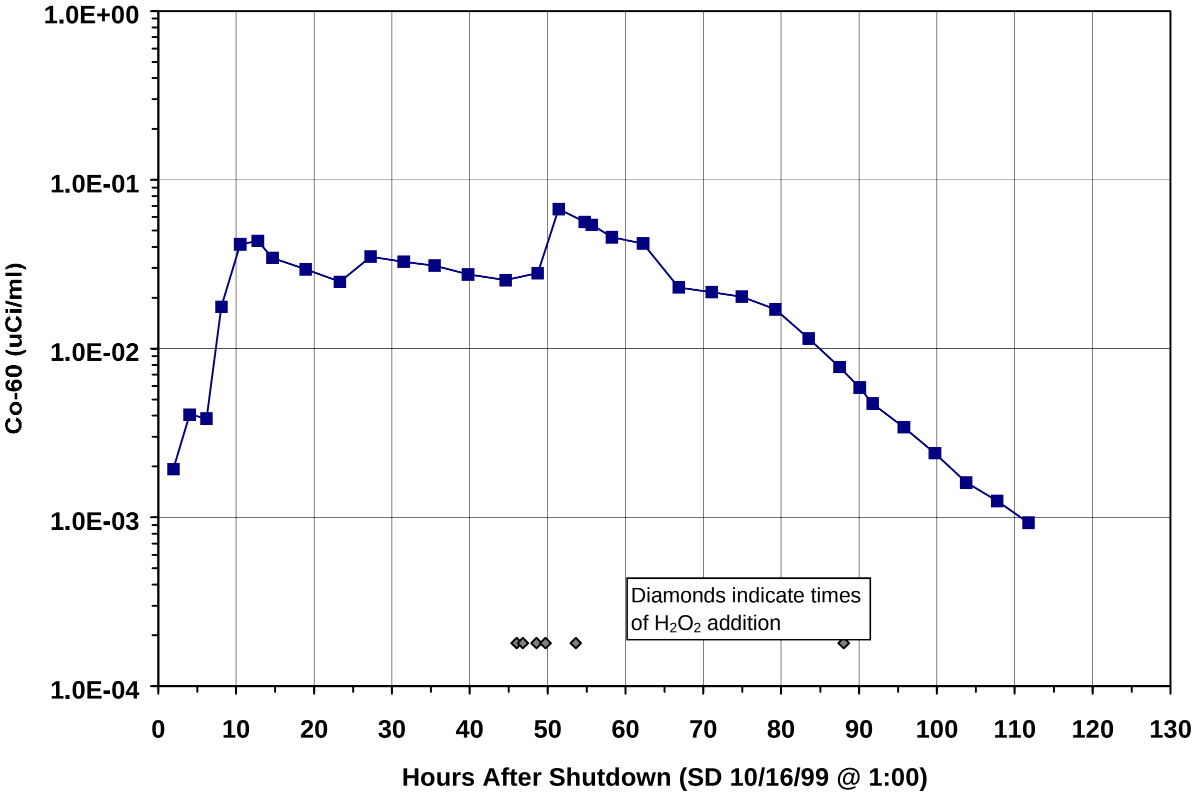

Figure 4-7
The ^{60}Co Activity Concentration in the RCS During the EOC 13 Shutdown

4.5 ^{65}Zn DISSOLUTION

During the Cycle 13 shutdown, the ^{65}Zn activity concentration exhibited a slight increase during the acid-reducing period reaching a peak of approximately 1.7 x 10^{-2} µCi/cm^3. It then decreased slowly through the acid-oxidizing stage to a value of 1 x 10^{-3} µCi/cm^{3}112 hours into the shutdown, Figure 4-8.

The major difference between ^{65}Zn activity dissolution in the EOC 13 outage and that experienced in the EOC 12 outage, during which depleted zinc had been added for only a three-month period, was the magnitude of the dissolution. In the EOC 13 outage, the ^{65}Zn activity concentration was consistently approximately an order of magnitude higher than after Cycle 12. This was true for the initial (start of shutdown) concentration and the final (end of shutdown) values. The final value at the end of the Cycle 12 shutdown was in the low 10^{-4} µCi/cm^3 range (Figure 4-8 in Ref. 4.2).

During the Cycle 13 shutdown a total of 23.4 Ci of ^{65}Zn were dissolved and removed by the purification system. This contrasts with 44 Ci released at the end of Cycle 10, when natural zinc was added, and 6.8 Ci removed in the EOC 12 shutdown following the use of depleted zinc. This lower value in Cycle 13 relative to Cycle 10 almost certainly reflects the use of depleted zinc for the first portion of the Cycle 13 injection period.

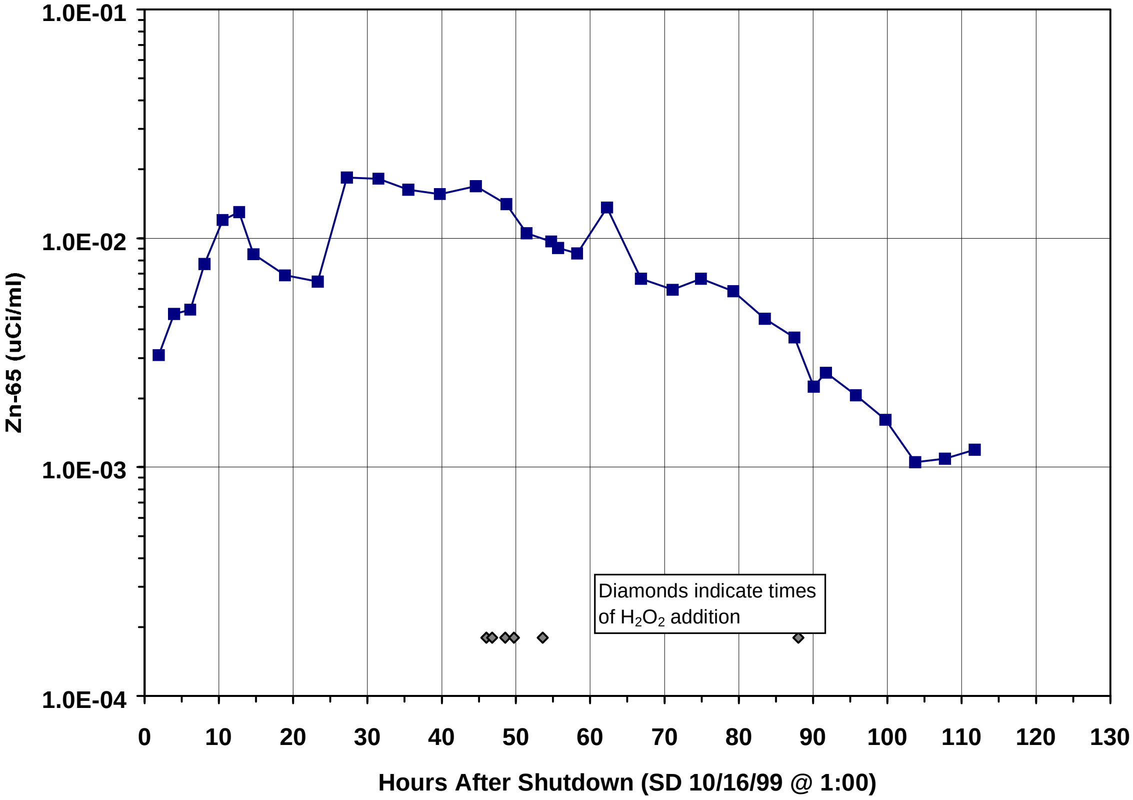

Figure 4-8
The ^{65}Zn Activity Concentration in the RCS During the EOC 13 Shutdow

4.6 DISSOLUTION OF IRON, ZINC AND NICKEL

Iron dissolution was observed during the acid-reducing chemistry phase after cooldown to about 360°F. The iron concentration rose to 311 ppb about 11 hours after shutdown and continued to be detected in the RCS for an additional 29 hours. During that period, it reached a peak of 371 ppb. After a total of 29 hours into the shutdown, prior to the end of the acid-reducing phase, iron was no longer detected in the RCS samples (analyses consistently below 100 ppb).

The concentration of zinc in the RCS as a function of time during the end-of-Cycle 13 shutdown is shown in Figure 4-9. An immediate release of zinc is observed after the start of shutdown, increasing from less than 10 ppb (the nominal lower limit of detection) to a concentration of 130 ppb within ten hours. The RCS zinc concentration then decreased for a short time and ultimately increased to a peak of 189 ppb 27 hours into the shutdown. The concentration decreased continuously through the remainder of the acid-reducing phase and throughout the acid-oxidizing phase except for a single reading of 301 ppb approximately 62 hours into the shutdown (at about the same time a brief increase in the ^{65}Zn activity was observed, Figure 4-8). A total of 226 grams of zinc were removed during the EOC 13 shutdown. This was comparable to the 194 grams of zinc removed at EOC 10 and substantially greater than the 63 grams removed at EOC 12.

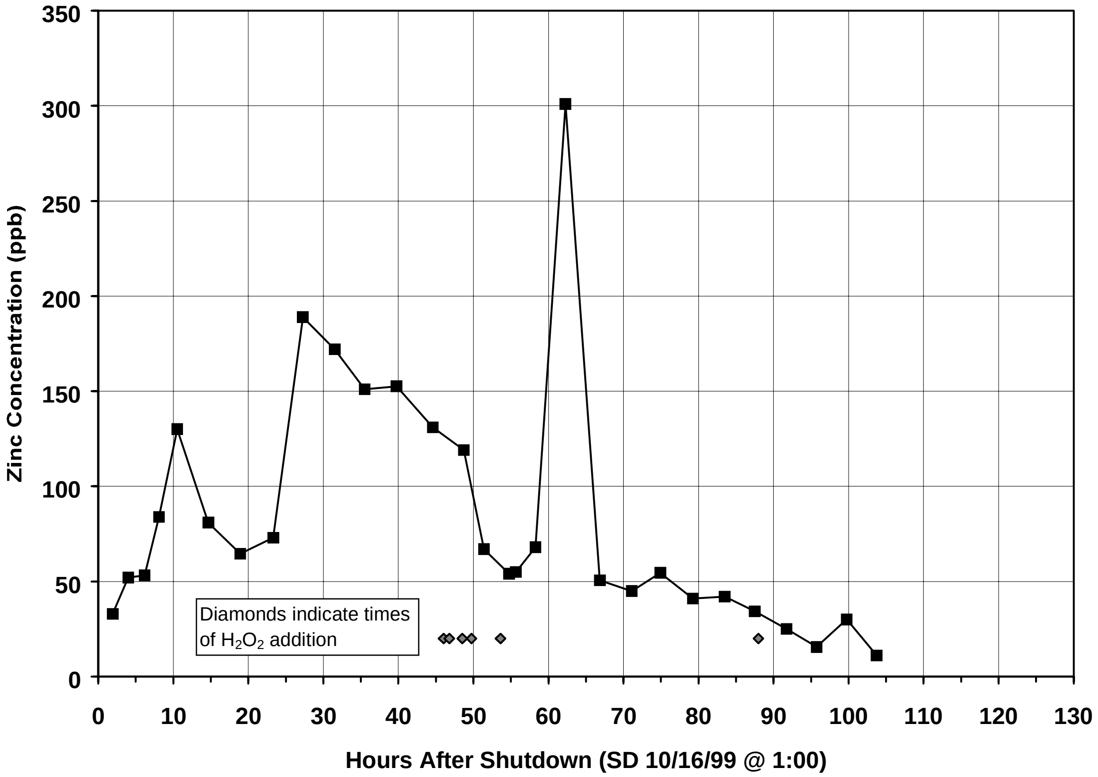

Figure 4-9
Zinc Concentration in the RCS During the EOC 13 Shutdown

The release of nickel occurred as expected, Figure 4-10, paralleling very closely the release pattern of its activation product, ^{58}Co. Each of the influences of coolant chemistry change which were described as having an effect on ^{58}Co dissolution had a similar effect on nickel dissolution throughout the acid-reducing and acid-oxidizing periods. The total inventory of nickel dissolved and removed by ion-exchange purification was 3140 grams, comparable to the mass of nickel released at the end-of-Cycles 10, 11 and 12 outages (Table 4-1 in Section 4.8).

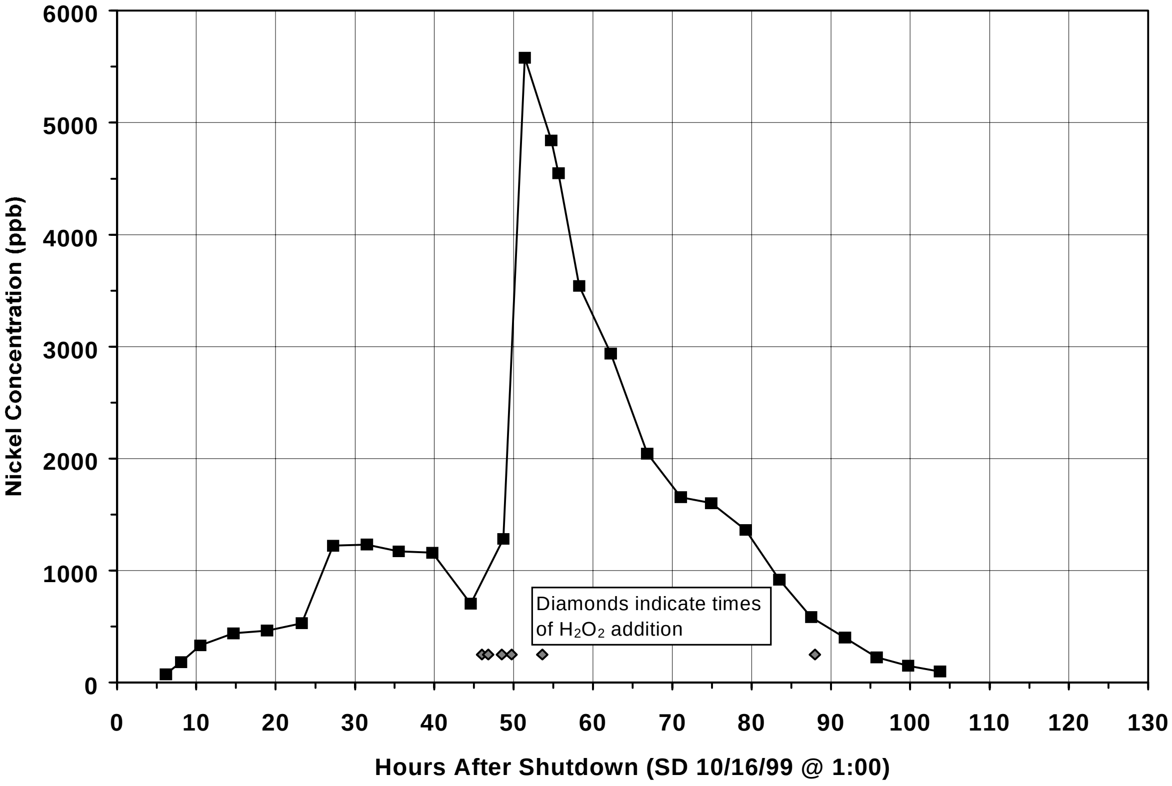

Figure 4-10
Nickel Concentration in the RCS During the EOC 13 Shutdown

4.7 THE SPECIFIC ACTIVITY OF ^{58}Co

The behavior of the specific activity of ^{58}Co (the ratio of Ci of ^{58}Co/g Ni) during the Cycle 13 shutdown was similar to that observed during the Cycle 10 and Cycle 12 shutdowns, but the peak value was somewhat lower. A plot of this value for the Cycle 13 shutdown is presented in Figure 4-11. The specific activity, driven by the large release of ^{58}Co in the first 20 hours of the shutdown, increased from 0.54 six hours after shutdown to a peak value of 1.28 about five hours later. Peak values from 1.6 to nearly 4 had been observed in the previous outages following zinc injection.

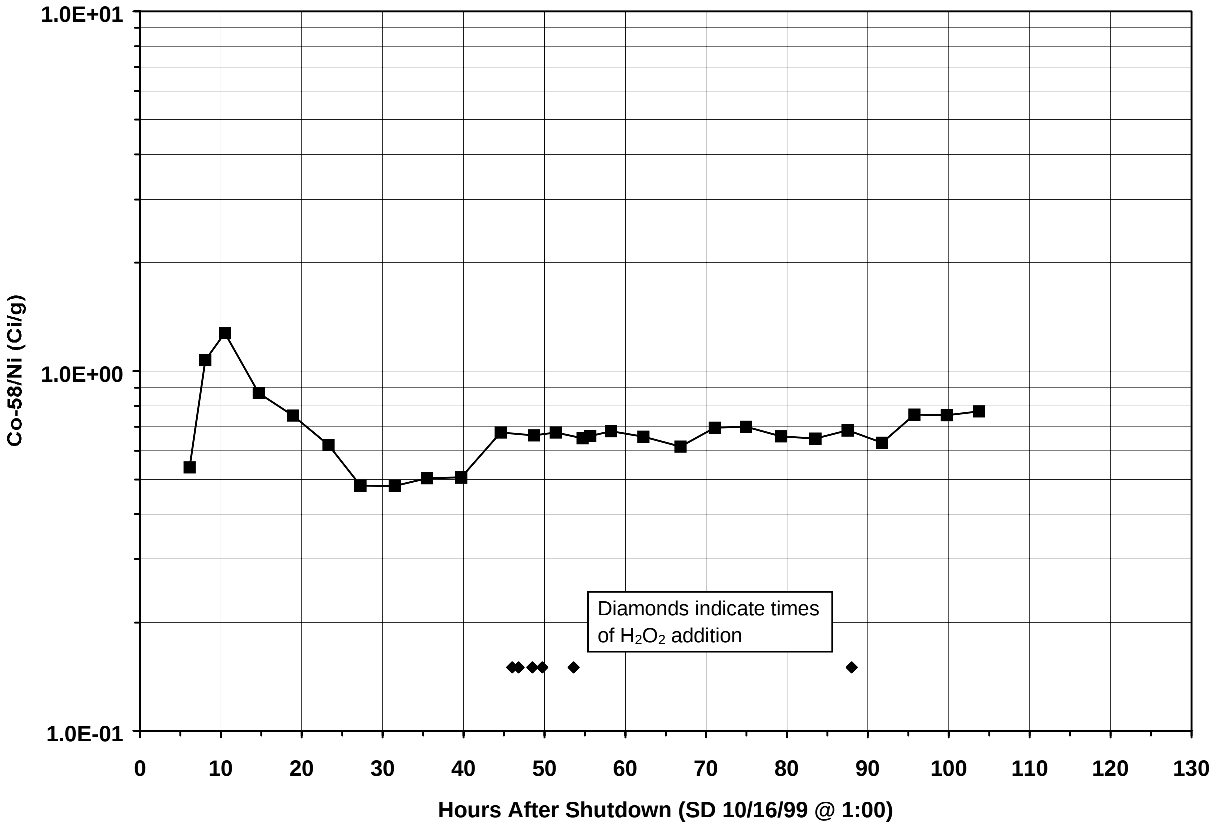

Figure 4-11
The Specific Activity (Ci ^{58}Co/g Ni) in the RCS During the EOC 13 Shutdown

Following the increase to 1.28 the specific activity decreased over the next twenty hours to a value of about 0.5 and remained at that level until forty hours into the shutdown when it increased to about 0.7 – 0.77, where it remained for the remainder of the shutdown. This latter plateau is commonly observed once acid-oxidizing conditions are attained. The overall specific activity for the EOC 13 shutdown, 0.65 Ci ^{58}Co/g Ni, is somewhat below the values seen at the end of Cycles 10 and 12 at Farley Unit 2.

4.8 SUMMARY OF SHUTDOWN RELEASES OF NICKEL AND THE RADIOCOBALTS AT FARLEY UNIT 2

Table 4-1 presents a summary of the total amount of ^{58}Co and ^{60}Co activity, and the mass of nickel, released at Farley Unit 2 during the shutdowns following Cycles 8 through 13. These data cover the period following the adoption of modified pH coolant chemistry operation and early boration during shutdown; hence, the impact of these two operational changes should be consistent. Observe that the total time required to complete the RCS chemistry cleanup varies from 116 hours to 266 hours for the various outages.

Table 4-1
Shutdown Releases for Cycles 8 through 13

Shutdown		Releases, Ci		Ni Release, g	Specific Activity, Ci ^{58}Co/g Ni
EOC	Duration, h	^{58}Co	^{60}Co		
8	150	1692	43.9	2137	0.79
9	123	611	24.9	1944	0.31
10	266	2153	62.5	2959	0.73
11	183	2084	38.7	3040	0.69
12	165	2324	56.2	2904	0.80
13	116	2047	64.4	3140	0.65

The data for these shutdowns are plotted for ^{58}Co, ^{60}Co, and nickel, respectively, in Figures 4-12 through 4-14.

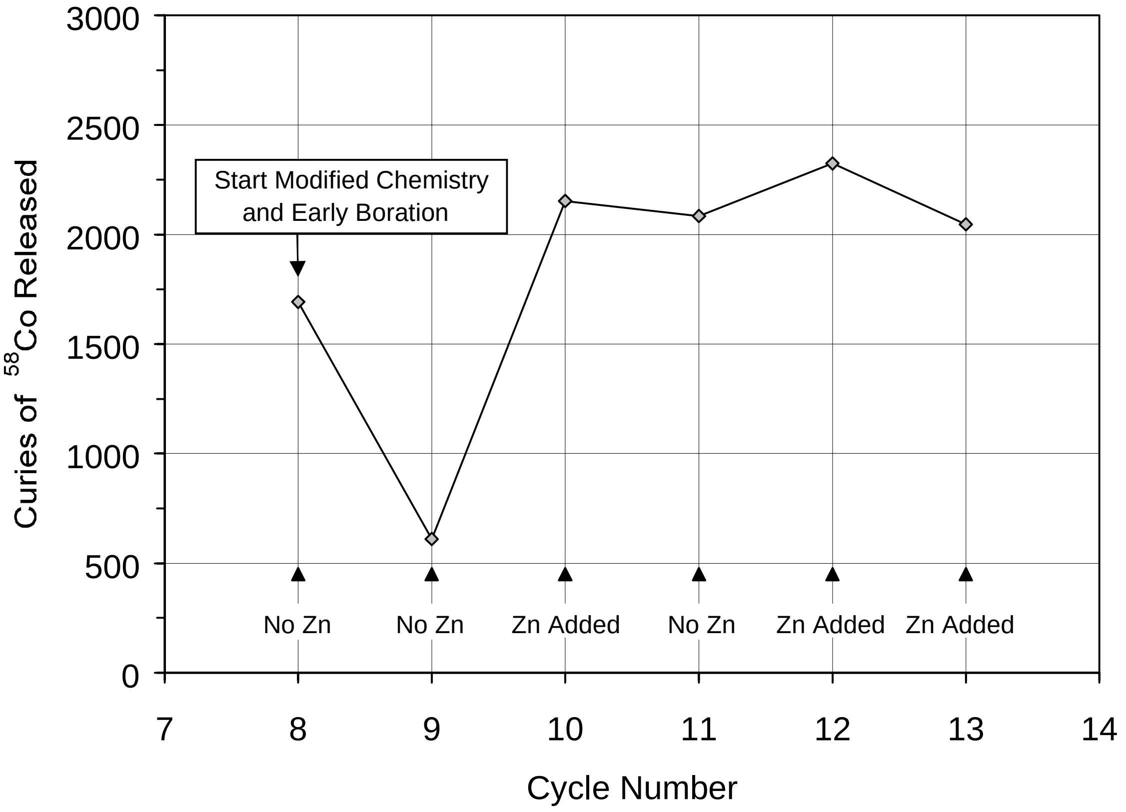

Figure 4-12
Total ^{58}Co Activity Released in the EOC 8 through EOC 13 Shutdowns

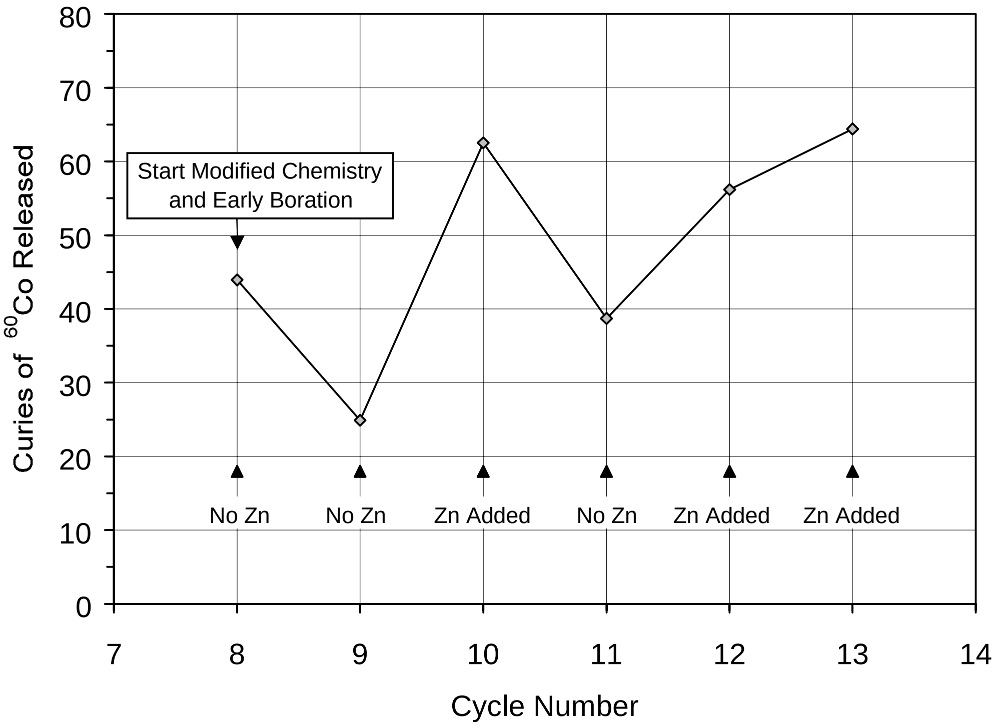

Figure 4-13
Total ^{60}Co Activity Released in the EOC 8 through EOC 13 Shutdowns

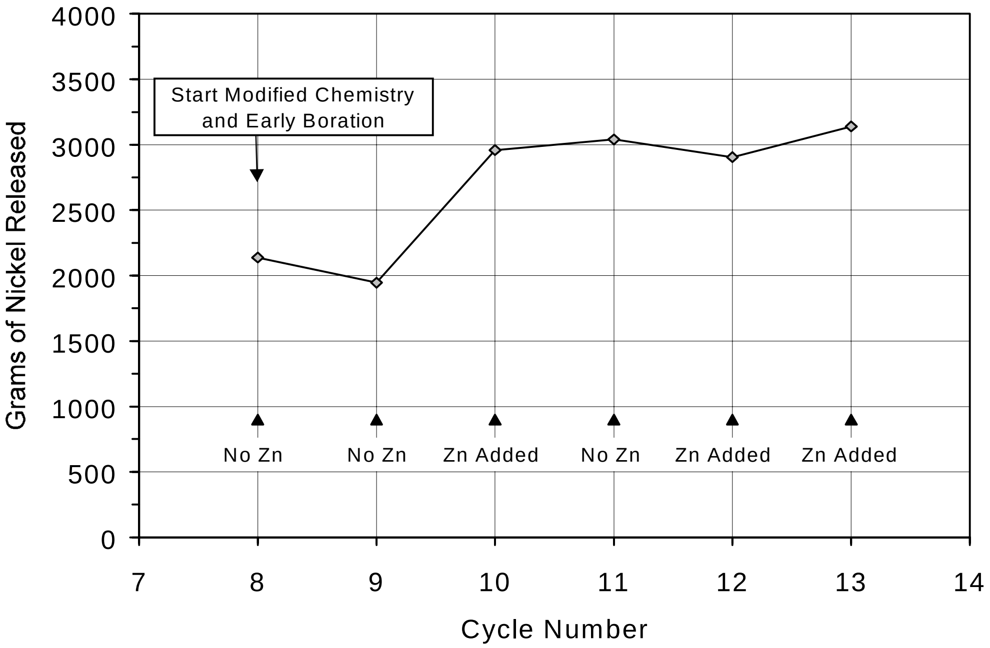

Figure 4-14
Total Mass of Nickel Released in the EOC 8 through EOC 13 Shutdowns

Figure 4-12 shows that, following the use of zinc additions, relatively large releases of ^{58}Co are observed. After Cycle 9, these releases have been in the range from about 2050 Ci to 2300 Ci. In the Cycle 11 outage, following a full cycle without zinc addition, the ^{58}Co release remained relatively unchanged from the EOC 10 outage.

The ^{60}Co activity release appears to be more sensitive than that of ^{58}Co to the amount of zinc in the system. After a significant increase in the Cycle 10 shutdown, the activity of ^{60}Co released in the Cycle 11 shutdown decreased significantly, then exhibited substantial increases after zinc injection was resumed in Cycles 12 and 13.

The specific activity, which is the ratio of the total Curies of ^{58}Co released to the total mass of nickel released, has been in the range from 0.69 to 0.80 for the shutdowns at the end of Cycles 8 and 10 through 13. [As noted previously, the Cycle 9 data for ^{58}Co are unusually low.] The fact that the EOC 8 value is as high as any other specific activity value at Farley Unit 2 opens to question the role that zinc addition may be having on this factor. A similar effect was observed in Cycle 9 at Diablo Canyon Unit 1, where the specific activity was essentially unchanged by zinc addition (Ref. 4.3).

Note that the amount of nickel released during the shutdowns for Cycles 10 through 13 is about 50% greater than that released in the shutdowns after Cycles 8 and 9. A major contributor to this release is judged to be the exchange of zinc for nickel in the ex-core corrosion films.

4.9 SUMMARY OF SHUTDOWN OBSERVATIONS

1. The Cycle 13 refueling shutdown chemistry program included specific procedures for establishing an acid-reducing chemistry environment as early as possible in the outage, combined mechanical and chemical degassing of hydrogen, and the controlled dissolution of radiocobalts by coolant oxygenation using hydrogen peroxide.

2. The coolant became acidic ($pH_T = 5.42$) approximately six hours into the outage. When the at-temperature pH was reduced further, a clear trend of increasing ^{58}Co dissolution was observed signaling the initiation of the acid-reducing environment. The first hydrogen peroxide addition (16 liters) was made approximately 46 hours into the shutdown, thereby effectively ending the acid-reducing phase.

3. During the acid-oxidizing phase, the ^{58}Co activity concentration peaked at 3.8 μCi/cm^3. Subsequent reduction in the activity concentration followed a normal purification half-life for the remainder of the shutdown.

4. A total of 2047 Ci of ^{58}Co were removed from the RCS by dissolution and purification by the CVCS demineralizer system during the outage. This is comparable to that removed during the Cycle 10, Cycle 11 and Cycle 12 outages.

5. The ^{60}Co release responded to each chemistry action that influenced the dissolution of ^{58}Co. A total of 64.4 Ci of ^{60}Co were dissolved and removed from the RCS; this is

comparable to the ^{60}Co activity removed in the Cycle 10 and Cycle 12 outages and substantially higher than that removed during EOC 11.

6. A total of 23.4 Ci of ^{65}Zn activity were removed from the RCS in the Cycle 13 shutdown. This represents a substantial increase from the 7.6 Ci released after Cycle 12, but is considerably lower than the 44 Ci removed after Cycle 10. The EOC 13 release almost certainly reflects the use of depleted zinc for the first portion of the zinc addition period.

7. In the Cycle 13 outage, 3140 grams of nickel were dissolved and removed by the purification system. This amount is comparable to the amounts removed during the Cycle 10 (2959 g), Cycle 11 (3040 g), and Cycle 12 (2904 g) outages.

8. The overall specific activity for Cycle 13 was 0.65 Ci ^{58}Co/g Ni. While the general trend of the specific activity behavior with time during the EOC 13 shutdown was similar to that observed after Cycles 10 through 12, the ratio was somewhat lower than for the earlier shutdowns.

REFERENCES

4.1 *Evaluation of Zinc Addition to the Primary Coolant of PWRs*, EPRI, Palo Alto, CA, and Southern Nuclear Operating Co., Birmingham, AL: 1996. TR-106358, Vol. 1.

4.2 E*valuation of Zinc Addition in Cycle 12 at Farley Unit 2*, EPRI, Palo Alto, CA, and Southern Nuclear Operating Co., Birmingham, AL: 1998. TR-111349.

4.3 *Evaluation of Zinc Addition During Cycle 9 at Diablo Canyon Unit 1*, EPRI, Palo Alto, CA, and Pacific Gas & Electric Co., Avila Beach, CA: 1999. TR-113540.

5

STEAM GENERATOR INSPECTION RESULTS

5.1 INTRODUCTION

An evaluation of the EOC 13 field eddy current data was performed with the intent of characterizing PWSCC in the roll expansion transitions at the top of the tubesheet (TTS) and then relating the results to the zinc addition program. Zinc was first introduced into the primary reactor coolant system during mid-Cycle 10. The zinc injections were discontinued for Cycle 11 and resumed in approximately mid-Cycle 12. Zinc additions during Cycle 12 were continued for approximately 3 months before being discontinued for fuel clad oxide film and gap closure issues not related to the zinc program.

During Cycle 13, zinc was injected into the reactor coolant system from December 9, 1998 to October 16, 1999, when injection was terminated for the end-of-Cycle 13 shutdown. Unlike the previous experience in Cycles 10 and 12 at Farley Unit 2, when the nominal concentration was 40 ppb, the concentration was maintained in the 30 ppb range for Cycle 13.

This section presents a summary of the Farley Unit 2 eddy current inspection data for the current and previous outages, as related to PWSCC in the steam generator tubing.

5.2 EDDY CURRENT INSPECTION HISTORY AT FARLEY UNIT 2

Eddy current data from steam generator tube inspections are available for each outage at Farley Unit 2. Comparisons between the data sets are difficult because of the number of variables, both in terms of the eddy current probes and scopes/procedures used for the various outages over this period. Table 5-1 summarizes the eddy current data for the number of tubes that were repaired (plugged or sleeved) due to reported PWSCC in the hot leg tube ends near the top-of-the-tubesheet (TTS) for all three steam generators.

Farley Unit 2 went critical in May 1981. The first instance of eddy current indications interpreted as PWSCC at the TTS occurred at the EOC 4 (May 1986) inspection after approximately 4 effective full power years (EFPY). The EOC 4 outage included only a partial inspection of the tube bundle with RPC probes to verify the bobbin coil indications.

Table 5-1
Plugging/Repair Actions for PWSCC within F*[1] at the Hot Leg TTS Region in Farley Unit 2

Outage	Reevaluated[2] No. of Rep'd Tubes	Cumul. No. of Rep'd Tubes	Comments on Inspection Data and Significant Plant or Operation Modifications
2R4 (5/86)	39	39	Partial inspection of bundle with RPC to validate bobbin calls. F* not used in this inspection.
2R5 (11/87)	31	70	Partial inspection of bundle with RPC to validate bobbin calls. F* = 1.72 inches. HL shot peening this outage.
2R6 (4/89)	15	85	Partial inspection of bundle with RPC to validate bobbin calls. F* = 1.72 inches.
2R7 (9/90)	305	390	100% inspection of HL side of bundle using RPC probes. F* = 1.72 inches.
2R8 (4/92)	61	451	100% inspection of HL side of bundle using RPC probes. F* = 1.72 inches.
2R9 (10/93)	77	528	100% inspection of HL side of bundle using RPC probes. F* = 1.72 inches.
2R10 (4/95)	151	679	100% inspection of HL side of bundle using RPC probes. F* = 1.72 inches. Zn injected last 9 months of Cycle 10.
2R11 (11/96)	424	1103	100% inspection of HL side of bundle using + Point probes. F* = 1.72 inches. Zn additions suspended in Cycle 11.
2R12 (4/98)	63	1166	100% inspection of hot leg side of bundle using + Point probes. F* = 1.94 inches. Zn injected months 9 - 12 of Cycle 12.
2R13 (10/99)	90	1256	100% inspection of hot leg side of bundle using + Point probes. F* = 1.94 inches. Zn injected last 10 months of Cycle 13.

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[1] F* is a modified plugging criterion based primarily on whether or not the degradation occurs within a distance (F*) below the TTS or below the bottom of the roll transition.

[2] Reevaluation of field eddy current data resulted in revisions to the originally reported data. The reevaluated data used the criteria described in Ref. 5.1.

For both the EOC 5 and EOC 6 inspection campaigns, a limited inspection of the tube bundle was again performed with RPC eddy current probes, primarily as a means to verify bobbin coil indications. However, a new variable was introduced in the EOC 5 outage in that a modified plugging criterion, F*, was used. This plugging criterion is based primarily on whether or not the degradation occurs within a distance (F*) below the TTS (or below the bottom of the roll transition). Tubes with indications below this elevation do not have to be plugged and may remain in service. For each of the outages following Cycles 5 through 11, the F* distance was 1.72 inches. In general, the sensitive rotating eddy current probes used to detect degradation in this roll-expanded area (first used for a full inspection at Farley Unit 2 in the EOC 7 outage) are not used to inspect below F*; hence, degradation below this elevation is not detected or reported.

Another factor that may affect the results is that the hot leg tube ends in all three SGs were shot peened at the end-of-Cycle 5 in the region at the top of the tubesheet to inhibit the initiation and propagation of PWSCC. Hence, the observable decrease (by a factor of 2) in the number of newly repairable tubes in Cycle 6 may be at least partially explainable by the shot peening operation.

Beginning with the EOC 7 outage, the scope of the eddy current inspection was increased to 100% of the hot leg roll transitions, and the reliance on bobbin coils was replaced by the use of rotating pancake coil (RPC) probes which are more sensitive to degradation in the roll-expanded region. Consequently, an abrupt increase (often described as an “inspection transient”) was observed in the number of repairable tubes due to the presence of PWSCC; such an increase is seen in the data for EOC 7 in Table 5-1.

The inspection results for the EOC 8 through EOC 10 outages exhibited a gradually increasing trend, although the numbers for EOC 8 were substantially lower than had been reported for the inspection transient at EOC 7. During Cycle 10, zinc addition to the RCS was started approximately mid-cycle and was continued for the remaining nine months of the cycle. The use of zinc is expected to ultimately reduce the number of tubes with first indications of PWSCC; however, no such effect was seen in Cycle 10, where the number of tubes requiring repair increased by a factor of nearly two.

During Cycle 11, zinc addition was suspended. At the end of Cycle 11, the SG inspection program was performed using Plus-Point (+ Point) probes. Plus-Point eddy current probes have a lower detection threshold for tube degradation than RPC probes. The effect of this change is seen in Table 5-1 where the number of tubes with first indications of PWSCC increased by a factor of nearly three in the EOC 11 outage.

In Cycle 12, a total of 63 tubes were repaired for PWSCC. This represented a substantial decrease from the plugging at the previous outage where Plus-Point probes had been used for the first time.

The plugging data shown in Table 5-1 for the EOC 13 outage are reproduced from Ref. 5.2, and are discussed in the following section.

5.3 EDDY CURRENT INSPECTION RESULTS FOR CYCLE 13

During Cycle 13, zinc injection was performed for approximately the final ten months of the cycle. The 100% hot leg tube end inspections were again performed with Plus-Point probes; the F* distance remained 1.94 inches, unchanged from the EOC 12 outage.

A total of ninety tubes were repaired for PWSCC indications at hot leg TTS locations (eighty-four were interpreted as axial in orientation and six were judged to represent circumferential degradation). This is not significantly different from the EOC 12 plugging (sixty-three tubes) and again represents a substantial decrease from the plugging which occurred at the EOC 11 outage. The number of repaired tubes at the latter two outages are similar to the number of tubes repaired at EOC 8 and EOC 9 after the previous “inspection transient” of EOC 7. In this regard, the slight increase in EOC 13 plugging compared to the EOC 12 plugging parallels the trend observed previously where gradually increased plugging followed the EOC 7 inspection (see the data for outages following Cycles 8 through 10 in Table 5-1).

5.4 DISCUSSION OF RESULTS

As stated previously, it is difficult to compare the eddy current data for the various outages over the operating history of Farley 2 due to the frequent changes that have occurred in the inspection probes, inspection scope, and procedures. Table 5-1 provided a comparison of the number of repaired tubes with hot leg side PWSCC for the EOC 4 through EOC 13 outages.

With respect to the influence of zinc on PWSCC of steam generator tubing, the following is a summary of the Farley 2 experience to date:

Cycle 10

- Zinc was injected for the last nine months; the estimated net accumulation in the RCS was 3.83 kg Zn.
- At EOC 10, the number of tubes repaired for PWSCC increased by a factor of nearly two relative to the EOC 9 outage.
- A steam generator tube pull confirmed efficient incorporation of zinc into ex-core corrosion films, as had been seen in laboratory tests (Ref. 5.3).

Cycle 11

- Zinc addition was suspended pending root cause evaluation of fuel cladding oxidation seen at EOC 10.

- A large increase (by a factor of 2.8 relative to EOC 10) was seen in the number of tubes repaired for PWSCC. This is at least partially attributable to an inspection transient due to the first-time use of Plus-Point eddy current probes.

- A steam generator tube pull indicated residual zinc remained in corrosion films (but less than was found at EOC 10).

Cycle 12

- Zinc was added to the RCS for 3 months in the middle of the cycle; the estimated net mass of zinc added this cycle was 1.03 kg.

- The number of tubes repaired for PWSCC decreased by a factor of 7 relative to EOC 11 (424 to sixty-three).

Cycle 13

- Zinc was added to the RCS for the last 10 months of the cycle; the estimated net mass of zinc added during this cycle was 2.31 kg

- The number of tubes repaired for PWSCC increased from sixty-three at the end of Cycle 12 to ninety at the end of Cycle 13.

There may be a general trend in this data when viewed over the period from the outages following Cycle 7 through the current outage. At the EOC 7 and EOC 11 outages large increases occurred in the numbers of tubes repaired for PWSCC; each of these are believed to reflect the first-time use of more sensitive inspection probes (RPC at EOC 7 and Plus-Point at EOC 11). Following these abrupt increases, the numbers of tubes repaired decreased significantly in the subsequent outage and then slowly increased over the next several outages.

Trying to decipher a potential role of zinc on the degradation observed is not possible from the data available. It must be concluded at this time that the experience with zinc at Farley Unit 2 has not been sufficient to provide unambiguous results from the SG eddy current inspection data. While the several observations that zinc is being incorporated into the ex-core corrosion films are encouraging, more definitive evidence of a positive effect will require additional experience. It is hoped that future cycles with zinc injection will be for longer periods, ultimately approaching full fuel cycles. Perhaps when such experience is accrued it will be possible to reach definitive conclusions about the role of zinc in mitigating PWSCC.

REFERENCES

5.1 *End-of-Cycle 11 Examinations at Farley Unit 2,* EPRI Palo Alto, CA, Southern Nuclear Operating Co., Birmingham, AL: 1997. TR-107904.

5.2 Farley Unit 2: 2R13 Outage October-November 1999. Condition Monitoring & Final/Preliminary Operational Assessment, Westinghouse Electric Company, LLC, November 29, 1999.

5.3 R. J. Jacko, et al., "Loop Experiments with Zinc Additions to Primary Water Coolant - Final Report", report of work sponsored by the Westinghouse Owners Group, Subgroup on Zinc Addition, Westinghouse Electric Corporation, SG-96-05-006, May 1996.

6

FUEL REGION INSPECTIONS

6.1 INTRODUCTION

Beginning approximately the eighth month of Cycle 13, zinc additions to the RCS were resumed at Farley Unit 2. The zinc addition was continued without interruption until the end of the cycle, thereby accruing approximately ten months of operation with zinc in the reactor coolant system.

At the end of Cycle 13, on-site examinations were performed to determine the fuel cladding oxide thickness and to determine any potential impact of the ten months of zinc injection on cladding corrosion. The work scope included measurements of oxide thickness on selected peripheral rods, as well as televisual examinations of these rods and assemblies. In addition, limited efforts were performed to clean the surface of a few rods to verify that significant corrosion product deposits were not compromising the accuracy of the oxide thickness measurements.

Rods from the following eight fuel assemblies were included in this effort:

2N38, 2P08, 2P29, 2P31, 2P32, 2P63, 2R52, and 2R60

The 2N38 assembly had experienced three cycles of operation, the “2P” assemblies contained twice-burned fuel, and the “2R” assemblies had been in the core for a single fuel cycle. The rods in assembly 2N38 were clad with Improved Zircaloy-4; all rods in the 2P and 2R assemblies were clad with ZIRLO™.

6.2 MEASUREMENT TECHNIQUE

A Zetec MIZ-23 data acquisition system was used to electronically process the signal from an eddy current probe which was positioned against the fuel rod. Like all similar electronic instruments, the accuracy of this technique diminishes at the extreme ends of the operating range. To minimize this effect, the calibration of the instrument is periodically checked, and corrected if necessary, throughout the data collection process. The MIZ-23 calibration is checked to oxide references over the range of 5 to 98 µm. The data must be within ± 3 µm for successful calibration.

Because of these inherent physical limitations in the system, very thin oxide layers (5 µm or less) are sometimes recorded as negative values. The absolute value of the measured oxide thickness at these levels is judged to be unimportant in the larger context of evaluating overall cladding corrosion performance for the more limiting grid spans at the top of the fuel assembly.

6.3 OXIDE THICKNESS MEASUREMENTS

A summary of the maximum oxide thickness data for each of the measured rods is provided in Table 6-1 (Refs. 6.1 and 6.2). Included in the table are the magnitude of the peak thickness and an estimate of the burnup for the individual rods. A plot of the peak oxide data as a function of burnup is presented in Figure 6-1.

Figure 6-2 presents a comparison of the oxide data at the end of Cycle 13 with similar measurements made after Cycle 12 (Ref. 6.3). The data for Improved Zircaloy-4 at EOC 12 in the burnup range of 35 to 38 GWD/MTU include measurements made on rods in assembly 2N38 that were remeasured at EOC 13 at burnups ranging from 46 to 47.5 GWD/MTU.

For Region 13 (F/A 2N38), the peak oxide value for the thrice-burned Improved Zircaloy-4 clad rods was below 62 μm, with an average value of 56 μm. For Region 14 (F/As 2P08, 2P29, 2P31. 2P32 and 2P63) the maximum value measured for the twice-burned ZIRLO™-clad rods did not exceed 40 μm, with an average value of approximately 29 μm. The once-burned Region 15 fuel assemblies (2R52 and 2R60) had a maximum value less than 13 μm, with an overall average of about 10 μm. None of these measured values challenged the predicted EOC 13 measurement criteria, Table 6-1.

Since the eddy current probe tends to skim over the surface of dense tenacious deposits, the values recorded by the probe include both the oxide thickness and any contribution due to corrosion product deposits. The videotapes of the oxide measurements were reviewed to identify any locations where surface deposits may have affected the measurements, and spikes in the data that may have been caused by these deposits were adjusted to be linear. The maximum oxide thickness values reported in Table 6-1 are from areas that appear to be relatively free of significant surface deposits.

In order to determine the extent to which corrosion product deposits may have affected the oxide thickness values, selected rods on the once-burned assembly 2R52 were brushed with “Scotch-Brite” over approximately the middle third of each rod in span 6 (span with maximum thickness measurements) and remeasured. Similar brushing and remeasurement was made on two rods of the twice-burned assembly 2P32. A comparison of the oxide thickness measurements, before and after cleaning, is presented in Table 6-2.

Cleaning of the rods in 2R52 resulted in decreases in the 1 to 4 μm range (the oxide measurement system calibration tolerance is ± 3 μm). Decreases on the twice-burned rods in assembly 2P32 were somewhat greater, with a maximum of about 20 μm and an average of about 6 μm in the lower portions of the spans measured.

Table 6-1
Summary of Fuel Cladding Oxide Thickness Measurements

Fuel Ass'y	Rod ID	Cladding Alloy	Max. Oxide, µm	Burnup, MWD/MTU
2N38	7 (A11)	Imp. Zr-4	52	47,564
Face 1	8 (A10)	Imp. Zr-4	55	47,479
	9 (A9)	Imp. Zr-4	56	47,527
	10 (A8)	Imp. Zr-4	57	47,025
2N38	7 (G1)	Imp. Zr-4	57	45,863
Face 4	8 (H1)	Imp. Zr-4	55	45,889
	9 (I1)	Imp. Zr-4	62	46,300
	10 (J1)	Imp. Zr-4	52	46,298
2P08	7 (A11)	ZIRLO™	19	41,100
Face 1	8 (A10)	ZIRLO™	23	41,088
	9 (A9)	ZIRLO™	21	41,335
	10 (A8)	ZIRLO™	15	41,073
2P08	7 (G1)	ZIRLO™	21	41,100
Face 4	8 (H1)	ZIRLO™	25	41,088
	9 (I1)	ZIRLO™	19	41,335
	10 (J1)	ZIRLO™	17	41,073
2P29	7 (A11)	ZIRLO™	24	43,681
Face 1	8 (A10)	ZIRLO™	24	43,635
	9 (A9)	ZIRLO™	26	43,911
	10 (A8)	ZIRLO™	20	43,671
2P29	7 (G1)	ZIRLO™	26	44,548
Face 4	8 (H1)	ZIRLO™	30	44,627
	9 (I1)	ZIRLO™	38	44,980
	10 (J1)	ZIRLO™	27	44,795

Table 6-1 (Cont'd)
Summary of Fuel Cladding Oxide Thickness Measurements

Fuel Ass'y	Rod ID	Cladding Alloy	Max. Oxide, µm	Burnup, MWD/MTU
2P31	7 (A11)	ZIRLO™	37	45,978
Face 1	8 (A10)	ZIRLO™	28	45,890
	9 (A9)	ZIRLO™	30	46,250
	10 (A8)	ZIRLO™	31	45,864
2P31	7 (K17)	ZIRLO™	35	45,818
Face 2	8 (J17)	ZIRLO™	33	45,709
	9 (I17)	ZIRLO™	33	46,076
	10 (H17)	ZIRLO™	27	45,733
2P32	7 (Q7)	ZIRLO™	38	45,978
Face 3	8 (Q8)	ZIRLO™	37	45,890
	9 (Q9)	ZIRLO™	40	46,250
	10 (Q10)	ZIRLO™	33	45,864
2P32	7 (G1)	ZIRLO™	26	45,818
Face 4	8 (H1)	ZIRLO™	34	45,709
	9 (I1)	ZIRLO™	32	46,076
	10 (J1)	ZIRLO™	32	45,733
2P63	7 (K17)	ZIRLO™	36	46,237
Face 2	8 (J17)	ZIRLO™	30	46,122
	9 (I17)	ZIRLO™	34	46,284
	10 (H17)	ZIRLO™	29	45,889
2P63	7 (Q7)	ZIRLO™	30	44,822
Face 3	8 (Q8)	ZIRLO™	32	45,029
	9 (Q9)	ZIRLO™	31	45,580
	10 (Q10)	ZIRLO™	35	45,601

Table 6-1 (Cont'd)
Summary of Fuel Cladding Oxide Thickness Measurements

Fuel Ass'y	Rod ID	Cladding Alloy	Max. Oxide, µm	Burnup, MWD/MTU
2R52	7 (A11)	ZIRLO™	12	26,269
Face 1	8 (A10)	ZIRLO™	8	25,874
	9 (A9)	ZIRLO™	9	26,384
	10 (A8)	ZIRLO™	11	25,838
2R52	7 (K17)	ZIRLO™	10	26,328
Face 2	8 (J17)	ZIRLO™	8	25,963
	9 (I17)	ZIRLO™	11	26,509
	10 (H17)	ZIRLO™	9	25,985
2R60	7 (A11)	ZIRLO™	11	26,471
Face 1	8 (A10)	ZIRLO™	11	26,101
	9 (A9)	ZIRLO™	12	26,632
	10 (A8)	ZIRLO™	8	26,092
2R60	7 (Q7)	ZIRLO™	12	26,595
Face 3	8 (Q8)	ZIRLO™	11	26,251
	9 (Q9)	ZIRLO™	12	26,802
	10 (Q10)	ZIRLO™	13	26,258

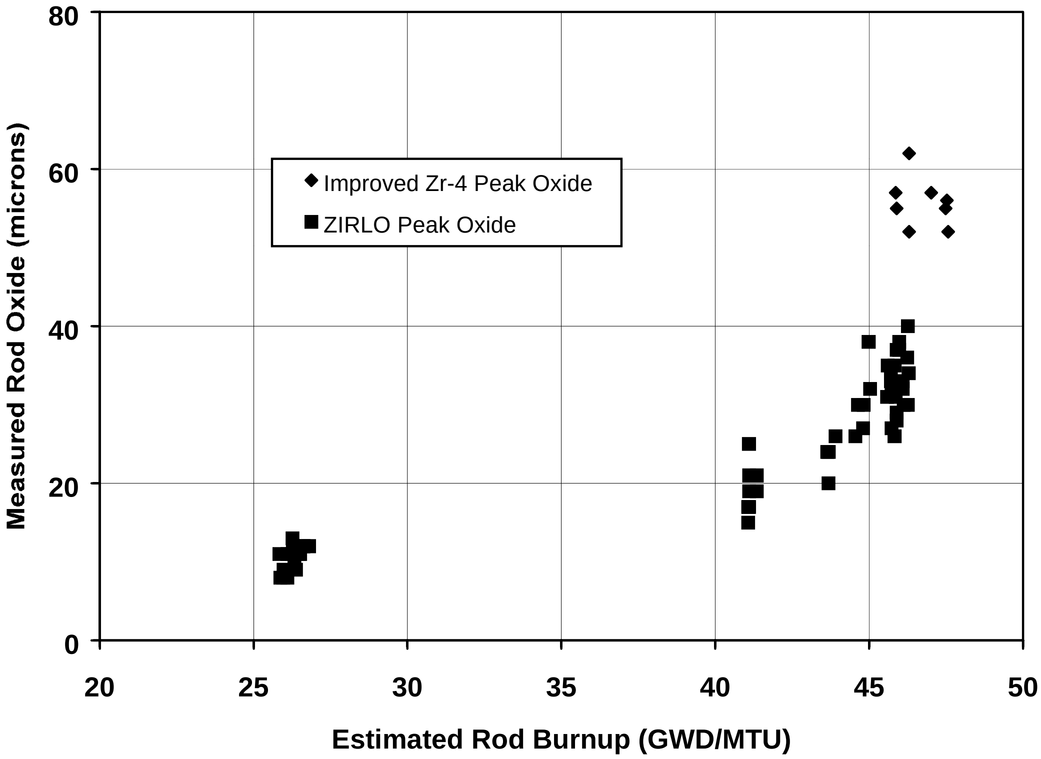

Figure 6-1
Peak Oxide Thickness vs. Rod Average Burnup at EOC 13

6.4 VISUAL INSPECTION RESULTS

Visual inspection of the surfaces of the measured fuel rods/assemblies during the refueling operations indicated that the rods were covered with a dark semi-reflective coating. This coating was similar in appearance to that seen at the end of virtually all fuel cycles following extended operation with zinc injection. This dark, semi-reflective coating is very thin, and has no appreciable effect on the oxide thickness measurements.

6.5 DISCUSSION OF RESULTS

As seen in the data presented in Table 6-1 and Figure 6-1, the ZIRLO™-clad rods exhibit low levels of corrosion for all burnups experienced to date at Farley Unit 2. This is true for both the once-burned feed fuel and also for the twice-burned rods which experienced burnups in the 41 to 46 GWD/MTU range.

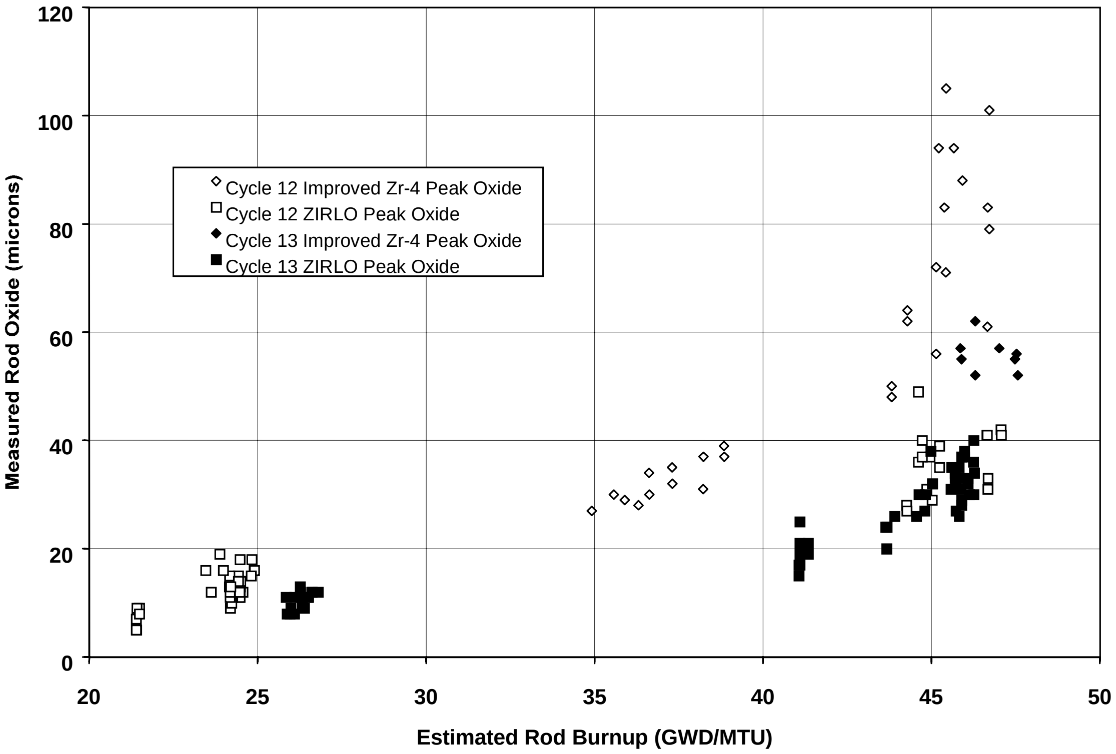

Figure 6-2
Peak Oxide Thickness vs. Rod Average Burnup at EOC 12 and EOC 13

Corrosion of the Improved Zircaloy-4-clad rods after three cycles of operation is well within the normal range for this alloy, and are below values measured previously for this material at equivalent burnups (Ref. 6.3).

Analysis of the Cycle 13 data, and comparison with other data for Improved Zircaloy-4 and ZIRLO™, indicates that zinc additions had no impact on the fuel cladding corrosion. Based on these data it may be appropriate to revisit the decision to impose a 10% corrosion margin requirement for PWRs operating with zinc additions to the RCS. It should, however, be noted that with the widespread use of ZIRLO™ fuel cladding, this additional margin requirement does not limit core design or operation.

Table 6-2
Comparison of Oxide Thickness Measurements for Selected Rods in Assemblies 2R52 and 2P32 Before and After Brushing (All ZIRLO™ Cladding)

Assembly	Rod	Burnup, MWD/MTU	Pre-Clean, µm	Post-Clean, µm
2P32/Face 3	8	45,890	38	26
	9	46,250	46	26
2R52/Face 1	7	26,269	12	10
	8	25,874	8	5
	9	26,384	9	8
	10	25,838	11	6
2R52/Face 2	7	26,328	10	10
	8	25,963	8	4
	9	26,509	11	8
	10	25,985	9	5

REFERENCES

6.1 “Preliminary – Partial Data for Farley Unit 2, EOC-13, Post-Zinc Injection, Peripheral Rod Oxide Examination – Assemblies 2R52 and 2R60,” PPE-99-169, Commercial Nuclear Fuel Division, November 4, 1999.

6.2 “Preliminary – Partial Data for Farley Unit 2, EOC-13, Post-Zinc Injection, Peripheral Rod Oxide Examination – Assemblies 2N38, 2P08, 2P29, 2P31, 2P32 and 2P63,” PPE-99-196, Commercial Nuclear Fuel Division, December 8, 1999.

6.3 *Evaluation of Zinc Addition in Cycle 12 at Farley Unit 2*, EPRI, Palo Alto, CA, and Southern Nuclear Operating Co., Birmingham, AL: 1998. TR-111349.

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