Dose Rate and Coolant Chemistry Data at PWRs Operating with Alternative Primary Coolant Chemistry

Technical Report

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Interim Report, July 2000

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REPORT SUMMARY

Some US PWRs have changed from operating in the “modified” coolant chemistry regime to operating with relatively high pH levels of 7.1 to 7.2 early in the fuel cycle. This latter regime is preferred from a crud transport and deposition perspective. Dose rate and coolant chemistry measurements at the lead plants confirmed the benefits of operating in this new regime, and no adverse effects were observed. The largest dose rate reductions occurred at plants where modest axial offset anomaly levels were observed in the previous fuel cycle.

Background

One goal of controlling PWR primary coolant chemistry is to minimize corrosion product release and its subsequent activation. In the “modified” coolant chemistry regime, lithium and boron are coordinated to maintain pH at 6.9 until the lithium concentration decreases to 2.2 ppm; the pH is then permitted to increase to pH 7.4 while maintaining lithium at a constant 2.2 ppm. In a newer regime, pH is kept at a relatively high level of 7.1 to 7.2 early in the fuel cycle. Operation with high pH early in the fuel cycle leads to more uniform pH levels over the cycle and was expected to result in less crud deposition and activity transport. It was also believed that operation with high pH could alleviate the adverse effects that accompany the axial offset anomaly (AOA). This project was designed to evaluate this hypothesis at a number of plants that switched to the new operating regime.

Objectives

- To collect shutdown dose rate data from Westinghouse-designed PWRs operating with high pH early in the fuel cycle.
- To monitor coolant chemistry and radiochemistry during normal operation and during startup and shutdown of these plants.
- To use the CORA code to assist in analyzing these effects.

Approach

Researchers obtained shutdown dose-rate data from standard radiation monitoring point (SRMP) locations at PWRs that operated with high pH early in the fuel cycle. They also collected and compiled information about primary coolant chemistry and used primary coolant boron and lithium concentrations to determine the coolant pH. The researchers evaluated coolant activity concentrations of ^{59}Co, ^{60}Co, ^{54}Mn, and ^{51}Cr and compiled chemistry and radiochemistry data for the fuel cycle prior to and during the fuel cycles with high beginning-of-cycle (BOC) pH operation. They reviewed activity and nickel releases during plant refueling shutdowns.

Results

Dose rates at the plants that operated with high pH at BOC decreased by 1% to 28%. At one site that operated with a second cycle of high pH at the BOC dose rates decreased another 5%. High dose rate reductions were found in the plants that experienced AOA and/or abnormal coolant pH conditions during prior operating cycles. A positive correlation was found between steam generator dose rates and one indicator of fuel boiling duty. Coolant radiocobalt and ^{54}Mn activity levels decreases by 20% to 32% after changing to high pH at BOC operation. The ^{58}Co releases during shutdown at the end of cycles with high pH at BOC operations are consistently less than was released during prior cycles. CORA predictions of out-of-core activities for the high pH at BOC regime are about the same as predictions for operation with the modified chemistry regime. The observed reductions in radiation fields following conversion to high pH at BOC chemistry tend to be greater than those predicted by the model.

EPRI Perspective

This report focused on plants with PWRs operating with high pH early in the fuel cycle. One motivation for operating in this regime is to get better control of corrosion product transport as utilities pursue operational strategies that impose more demanding conditions on PWR fuel. The expected reductions in shutdown fields were confirmed by these measurements, and no adverse side effects were observed. It was encouraging to see the benefits persisted at the one plant that operated with high pH at BOC for a second cycle and that the greatest benefits were seen at plants that earlier had experienced moderate levels of AOA. One plant that participated in the study (Comanche Peak 2) intends to pursue this concept further and operate an entire fuel cycle at a constant pH of 7.4. Zinc injection is also proving to be an effective dose reduction technique for PWRs (EPRI reports TR-111349 and TR-113540). Promising results with lower levels of zinc additions are being seen at Palisades. Operating in these new chemistry regimes will help PWRs meet industry-established exposure goals and can also lead to lower operation and maintenance costs and an improved environment for workers.

EPRI established the SRMP in 1977 to collect shutdown radiation field data at Westinghouse-designed PWRs. Data from these monitoring points are compiled and analyzed periodically to identify the main factors that contribute to radiation fields. The most recent comprehensive report in this series, EPRI report TR-107566, was issued early in 1997.

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Keywords

Radiation exposure management
PWRs
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ABSTRACT

Based on previous studies, solubility-related nickel ferrite precipitation in the core is expected to be minimized at a coolant pH_{Tave} of 7.4 and operation with primary coolant chemistry maintained at a constant pH of 7.4 during the fuel cycle is generally preferred from a crud generation and transport viewpoint. Operation with this coolant chemistry should result in lower plant dose rates as compared to current "modified chemistry" control programs. However, more recent evaluations of plant data suggest that pH programs with cycle-concluding pH 7.2 may be as effective as modified pH 7.4 chemistry controls insofar as nickel and activity releases during plant shutdowns are concerned. A number of domestic PWRs have recently changed from operation with a modified (i.e., pH 6.9 increasing to 7.4 over the fuel cycle) program of coolant chemistry to a more coordinated (constant) pH with relatively high BOL pH levels of 7.1-7.2. Potential benefits from a crud transport point-of-view include radiation field reduction and reduced risk of axial offset anomaly (AOA).

Plants that have recently converted to increased BOL pH coolant chemistry programs were evaluated to determine the impact of the change in coolant chemistry on plant dose rates. Operational coolant chemistry and radiochemistry data during power operation, boiling duty information, shutdown activity release, and dose rate data were analyzed.

Decreases were noted in the key areas of

- coolant activity concentrations during plant operation,
- activity releases during shutdown,
- ^{58}Co specific activity of crud released during shutdown, and
- plant shutdown radiation fields

when measurements associated with increased BOL pH chemistry to modified chemistry operation were compared. The observed reductions in plant radiation fields were more than those predicted by the CORA computer model of corrosion product generation and transport.

In addition some positive correlations were noted between coolant activities and operational pH (inverse proportionality), shutdown releases and range in pH during operation, and shutdown dose rates and fuel boiling duty.

Although the results of the evaluation indicated a positive effect of operation with the alternative chemistry program, data for additional cycles should be evaluated to better define and quantify the observed effects and to confirm longer-term benefits.

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G. Gary	-	Callaway
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W. Knowles	-	Comanche Peak Units 1 and 2
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J. Deshon	-	Seabrook (presently at EPRI)
R. Litman	-	Seabrook
R. Sterrit	-	Seabrook
D. Bryant	-	South Texas Units 1 and 2
W. Bullard	-	South Texas Units 1 and 2
D. Crawley	-	Watts Bar
G. Vickery	-	Watts Bar
G. Wallace	-	Watts Bar

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1 INTRODUCTION

1.1 Introduction

A number of domestic PWRs have recently changed from operation with a “modified” coolant pH (i.e., 6.9 increasing to 7.4 over the fuel cycle) program of coolant chemistry to a more coordinated (constant) pH with relatively high BOL pH levels of 7.1-7.2. Such operation results in a constant or near constant pH throughout the complete fuel cycle, as compared to operation with modified coolant chemistry. Based on corrosion product solubility considerations and plant data, this “increased BOL pH” mode of coolant chemistry control may result in less crud deposited on fuel cladding surfaces. The associated potential benefits include plant radiation field reduction and a reduced potential for the occurrence of axial offset anomaly (AOA).

1.2 Purpose

This report provides an assessment of plants that have recently converted to increased BOL pH coolant chemistry programs and evaluates the impact of the change in coolant chemistry on plant dose rates. Operational coolant chemistry and radiochemistry data during power operation and shutdown dose rate data in seven plants that have operated with increased BOL pH chemistry are presented and analyzed. This data, along with fuel boiling duty information, provides insights relative to their effects on plant dose rate trends. This information is intended for use by operating plants in evaluating dose reduction measures and other related improvements in plant operability.

1.3 Background

1.3.1 Operating Plant Coolant Chemistry Regimes

Based on the results of nickel ferrite corrosion product solubility studies and modeling of crud transport in reactor systems, PWR operation at a coordinated pH of 7.4 during a complete fuel cycle would be preferred from a crud transport and deposition viewpoint [1]. Plant operation with this coolant chemistry should result in lower plant dose rates compared to operation at a coordinated pH 6.9. Coordinated pH operation consists of coordinating the boron-lithium concentrations such that a constant pH at temperature is maintained throughout the fuel cycle. However, coordinated pH 7.4 operation for the complete cycle would require operation well above the preferred lithium concentration of 2.2 ppm for a significant portion of the fuel cycle.

Due to concerns about corrosion of materials of construction, modified pH operation had been selected by the industry as a reasonable alternative, with some plant operating experience at lithium levels of up to 3.5 ppm for limited times during extended fuel cycles.

Modified coolant chemistry has been defined as operation in the early stages of a fuel cycle at a coordinated minimum pH of 6.9 until the lithium concentration has been reduced to 2.2 ppm; the lithium concentration is then maintained constant at 2.2 ppm until a pH of 7.4 is reached (i.e., operating at an increasing pH), and then maintaining a constant pH of 7.4 until the end of the cycle. The EPRI PWR water chemistry guidelines document [7] considers pH_{Tave} of 7.4 as the upper operating band in a modified pH control program, recognizing that plant-specific constraints may limit the pH to less than 7.4.

Depending upon the fuel cycle length, many plants operate at pH 6.9 for about three months, at an increasing pH for about nine months, and at a constant pH 7.4 for only the last few months of the cycle. Several evaluations of the effect of this coolant chemistry on plant radiation fields indicate that operation with modified chemistry since plant startup results in dose rates about 20 to 25% lower compared to operation with coordinated pH 6.9 chemistry [2,3].

Recent evaluations of plant data have suggested that pH_{Tave} programs with cycle-concluding pH to 7.4 do not demonstrate an advantage over pH_{Tave} 7.2 programs relative to EOL activity releases [8]. Further, a number of plants, some of which have experienced axial offset anomaly (AOA), have recently changed their operating coolant chemistry from modified pH to an "increased BOL pH" chemistry program. This coolant chemistry is defined as one in which the pH at the beginning of the fuel cycle is greater than 6.9 (e.g., 7.1 or 7.2) and maintained at a constant (or near constant) level throughout the cycle. One of the primary incentives associated with this alternative chemistry regime is that of minimizing the production and transport of crud deposits to the fuel cladding surfaces, thereby reducing the potential for AOA.

It is generally thought that AOA in PWRs is a result of lithium borate precipitation in core crud deposits in areas of the core that are subject to high levels of sub-cooled boiling [4]. Thus, AOA is a symptom of core crud buildup that is exacerbated by sub-cooled boiling. Consequently, if crud transport to the core and/or if the source of crud available for deposition are minimized, there should also be direct benefits associated with the reduction of plant radiation fields.

A possible relationship between AOA occurrence and plant dose rate trends was first observed in an evaluation of the coolant activity in the Millstone 3 plant [5]. It was postulated that a large increase in plant radiation fields that was observed at the end of cycle 4 was the result of a release of an abnormal amount of crud from feed fuel. The enhanced crud deposition and release could have been related to sub-cooled boiling at fuel cladding surfaces as evidenced by AOA during the cycle. However, there were other potential influencing factors that could have led to the radiation field increases including a change from "elevated" to pH 6.9 coordinated chemistry for the cycle, a reactor trip that occurred five months before the end of the cycle, and an increase in pH to about 7.1 - 7.3 during the last two months of the cycle.

1.3.2 Plant Follow Program

The following Westinghouse-designed plants that have operated or were planning to operate with increased BOL pH coolant chemistry were evaluated:

- Callaway
- Comanche Peak Unit 1
- Comanche Peak Unit 2
- Seabrook
- South Texas Unit 1
- South Texas Unit 2
- Watts Bar 1

Several of the plants (Callaway, Comanche Peak 2, and Seabrook) have reported AOA during one or more of their fuel cycles. Comanche Peak 1 and 2, Seabrook, and Watts Bar 1 have operated since startup with modified coolant chemistry.

The following data was obtained and evaluated as part of the plant follow program.

Dose Rates - Dose rate information as available from all of the participating plants at the EPRI standard radiation monitoring program (SRMP) locations from start of operation through 1996. Data since this time and at the end of the cycles after the change to the increased BOL pH chemistry operation was obtained from the plants.

Operational Chemistry Data - The primary coolant boron and lithium concentrations were used in determining the coolant pH trend prior to and during the cycle(s) of the increased BOL pH operation.

Operational and Shutdown Radiochemistry Data - The coolant activity concentrations of ^{59}Co, ^{60}Co, ^{54}Mn, and ^{51}Cr prior to and during the cycle(s) of increased BOL pH operation were evaluated. The activity and nickel releases during plant refueling shutdowns were also reviewed.

Fuel Boiling Duty - The fuel boiling duty for the cycles before and during the cycles of the change to the increased BOL pH operation were assessed using techniques similar to those discussed in [6].

The dose rate data obtained from this program was evaluated by (1) comparison of the data trends for each individual plant from the increased BOL pH operation to trends during the prior cycles of operation, and (2) comparison to trends predicted by the CORA crud transport code. The effect of the various coolant chemistry modes of operation on coolant activity concentrations and shutdown releases was also assessed.

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7. "PWR Primary Water Chemistry Guidelines", Vol. 1, Revision 4, TR-105714-V1R4, March 1999.

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2
DESCRIPTION OF OPERATING PLANT DATABASE

The participating plants provided operational coolant chemistry, radiochemistry, and power level data for the cycle in which the change to the increased BOL pH chemistry was made. In addition, similar data for two cycles preceding the change were analyzed in order to assess the change in data trends.

The coolant pH values during the operating periods were calculated from the boron and lithium concentrations using methodology and a computer program that had been developed by Westinghouse in the 1980s by Lindsay [1]. Since the average (full-power) coolant temperature for the fuel cycles considered in the evaluation were all within 1.7°C of the average value of 308.9°C, a nominal value of 310°C was used in the calculation of pH at full power conditions. The core thermal power data was used in the calculation of coolant temperatures and associated pH values when the reactor was not operating at full power. That is, a linear interpolation of temperature to the zero load temperature was used in determining the pH at reduced power conditions. Comparison of the calculated pH to that calculated using the EPRI **chem*WORKS***™ code[a] indicated that the results were within 0.5% of each other.

Radiocobalt concentrations for 19 cycles of operation were obtained from the participating plants. Data for 18 cycles were obtained for the ^{54}Mn concentration, and ^{51}Cr data for 10 cycles of operation were obtained. Generally, more ^{58}Co data were available from the plants as compared to that for the other nuclides.

Table 2-1 provides relevant parameters regarding sampling of the coolant. In all cases, the coolant samples were unfiltered and thus are representative of the total activity in the coolant. The samples were decayed for either 30 minutes or up to 48 hours prior to counting. The sampling point was either from the Chemical and Volume Control System (CVCS) letdown line or the Reactor Coolant System (RCS) hot leg.

[a] **chem*WORKS***™ is a trademark for a family of computer codes produced by EPRI

Table 2-1
Coolant Sampling Parameters

Plant	Count Time after Sampling	Sample Location
Callaway	48 hours	CVCS
Comanche Peak 1	24 hours	Hot leg
Comanche Peak 2	24 hours	Hot leg
Seabrook	24 hours	CVCS
South Texas 1	30 minutes	CVCS
South Texas 2	30 minutes	CVCS
Watts Bar 1	30 minutes	Hot leg

2.1 Operational Chemistry and Radiochemistry

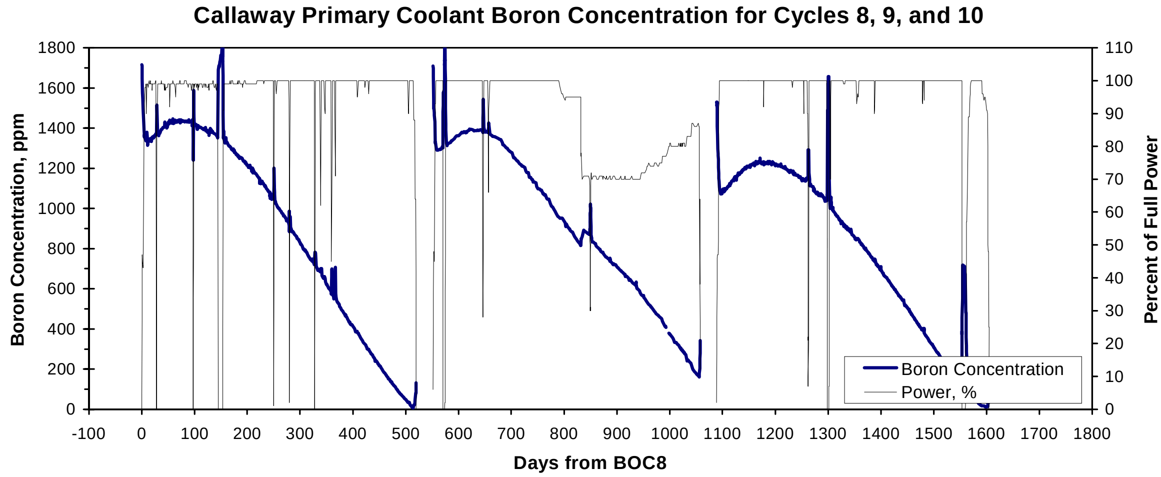
2.1.1 Primary Coolant Chemistry

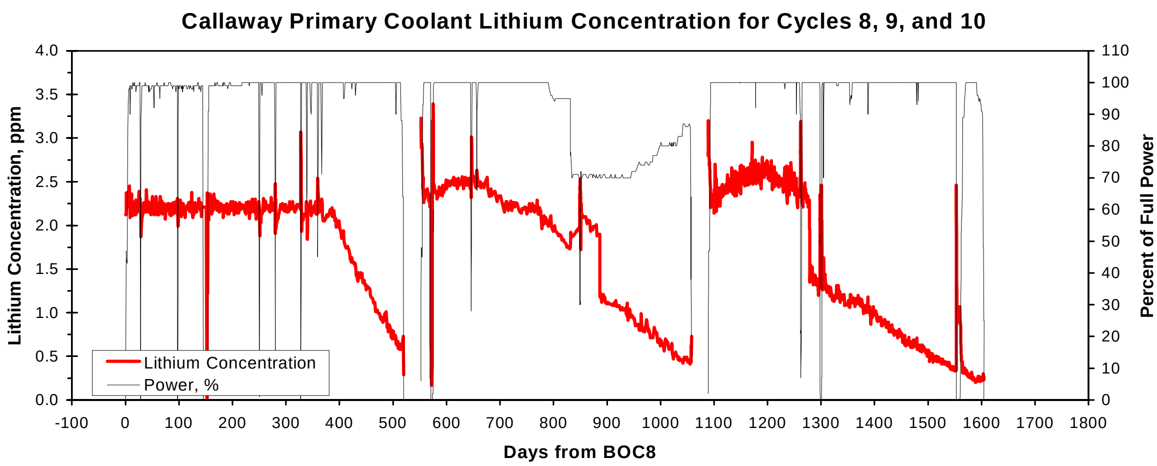
Figures 2-1 through 2-7 show the boron and lithium levels in the primary coolant over the cycles of interest for the participating plants. The corresponding pH, both at temperature, pH_{Tave}, and at 300°C, pH_{300}, are calculated from this data and are also presented. Consideration of the pH based on a fixed temperature; i.e., 300°C, is based on the observation that the temperature dependence of pH is principally controlled by the strong variation of the dissociation constant of water, K_W, with temperature. Using a reference temperature can also facilitate comparison of RCS chemistry environments across different cycles and different plants [2].

All of the plants that were evaluated had operated with modified coolant chemistry before the change in operating chemistry. The increased BOL pH operation did not result in a constant primary coolant pH over the complete fuel cycle at all plants for reasons related to fuel clad corrosion considerations and minimizing the operating time with lithium coolant concentrations above 2.2 ppm. However, three of the plants (i.e., South Texas 1 and 2, and Watts Bar 1) operated with an essentially constant pH and three plants (i.e., Comanche Peak 1, Comanche Peak 2, and Seabrook) operated with a more nearly constant pH operation as compared to that associated with a modified pH program. The plant-specific coolant chemistry controls that were implemented at the participating plants are described below.

2.1.1.1 Callaway Cycles 8, 9, and 10

As shown in Figure 2-1, a modified pH chemistry regime was followed during cycle 8 at Callaway with lithium concentrations in the coolant not exceeding approximately 2.2 ppm. However, the coolant chemistry varied significantly from the other plants in the program during subsequent cycles. Cycle 9 began with a pH_{Tave} of about 7.0, or nearly a tenth of a pH unit higher than the BOL pH for cycle 8 and continued to increase to about 7.1 over the first half of cycle 9. Plant power reductions, reduced lithium levels to less than one ppm, and a drop in pH to an average of approximately 6.95 were then adopted for the remainder of the cycle in conjunction with efforts to control the axial offset anomaly (AOA).





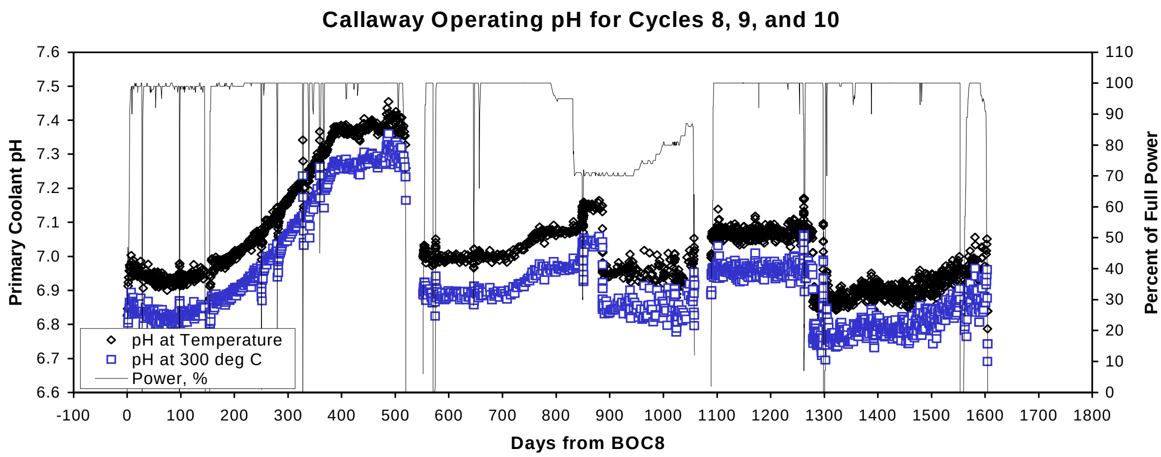


Figure 2-1
Callaway Primary Coolant Chemistry – Cycles 8, 9, and 10

For the first 1/3 of cycle 10, coolant pH was maintained at a nearly constant value of about 7.1. Maximum lithium concentrations in the coolant were approximately 2.5 ppm. However, lithium levels in the coolant were reduced to about 1.5 ppm with a drop in pH to a nominal value of about 6.9 over the next 1/3 of the cycle and a gradual increase from 6.9 to about 7.0 over the last 1/3 of the operating cycle.

This “mix” of operating chemistry regimes, coupled with the existence of the AOA phenomena at Callaway, introduces considerable complexity in the interpretation of the data.

2.1.1.2 Comanche Peak 1 Cycles 5, 6, and 7

Figure 2-2 shows that Comanche Peak Unit 1 operated with a modified pH during cycle 5 and the first 2/3 of cycle 6. Lithium levels were maintained at or below 2.2 ppm during this operating period and the maximum pH_{Tave} was 7.3. About 2/3 of the way through cycle 6 the lithium concentration in the coolant was dropped from 2.2 to about 1.5 ppm and the pH abruptly changed from 7.3 to 7.15 (pH_{300} of 7.2 to 7.05). This change in operating chemistry was associated with a decision to decrease the lithium concentration in both plants at the time of an indication of AOA in Unit 2.

The operating chemistry was changed to a more constant pH during cycle 7 with an initial lithium level of about 3 ppm and a relatively constant pH_{Tave} of about 7.05 over the first 1/3 of the cycle. The lithium concentration was held constant at about 2.2 ppm until about mid-cycle with an associated gradual increase in pH of approximately a pH unit to 7.15. The pH_{Tave} of 7.15 was then maintained over the remainder of the fuel cycle. This change in pH during the cycle results from the fact that lithium levels are held at 2.2 ppm until the maximum pH of 7.15 is achieved. Thus, the operation is basically modified except that that the minimum pH is increased from 6.9 to 7.0 and the maximum pH is decreased from 7.3 to values in the range of 7.1–7.2.

2.1.1.3 Comanche Peak 2 Cycles 3 and 4

Figure 2-3 shows that the plant operated with a modified pH during cycle 3 except for a drop in pH over the last 45 days of the cycle. The pH change is associated with a reduction in coolant lithium levels as a AOA control measure. The operating pH during cycle 4 was consistent with the chemistry control scheme employed in Comanche Peak Unit 1, as described above. That is, the chemistry control program is essentially modified chemistry with the minimum pH increased from 6.9 to 7.0 and the maximum pH decreased from 7.3 to values in the range of 7.1–7.2.

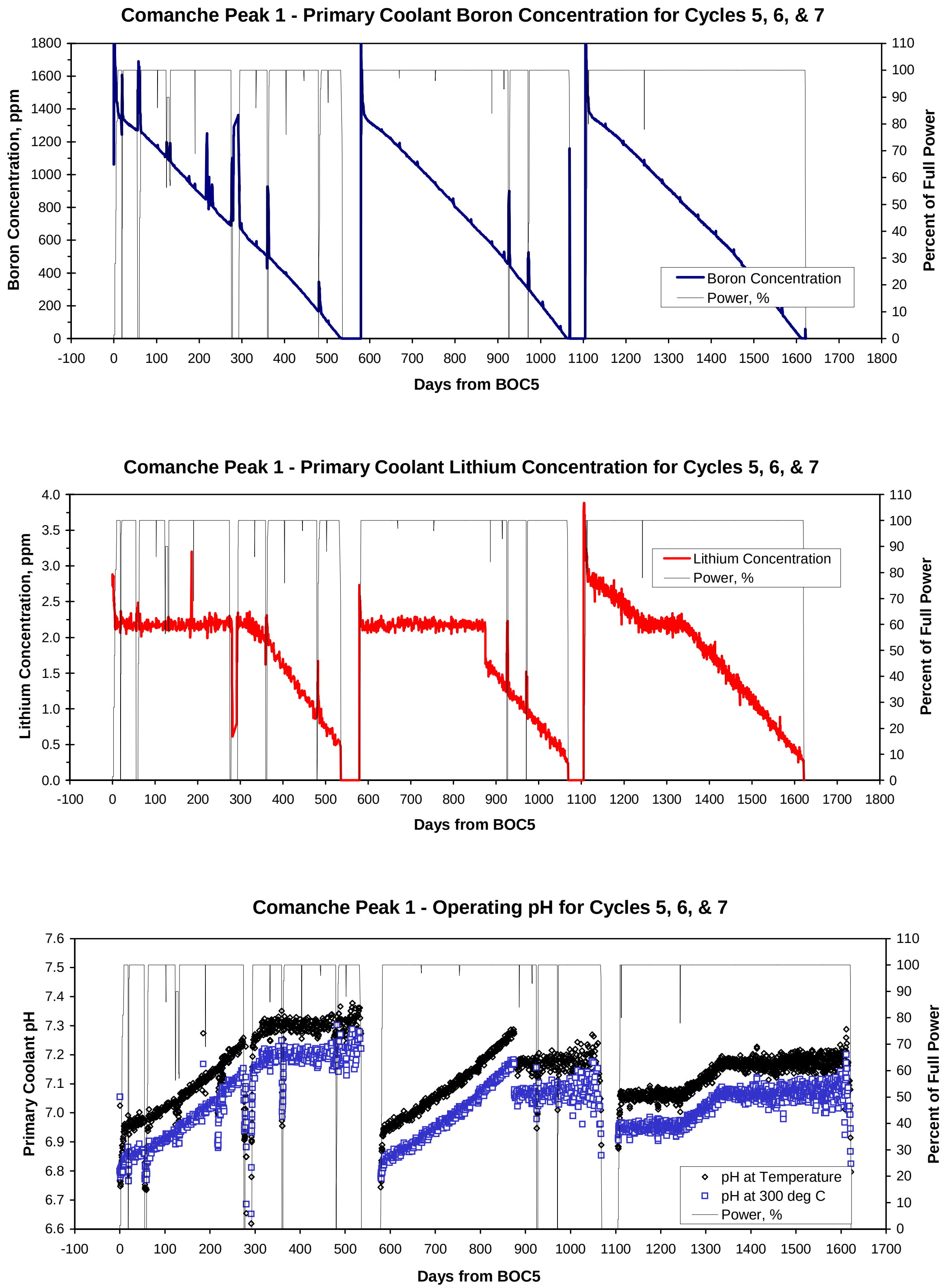
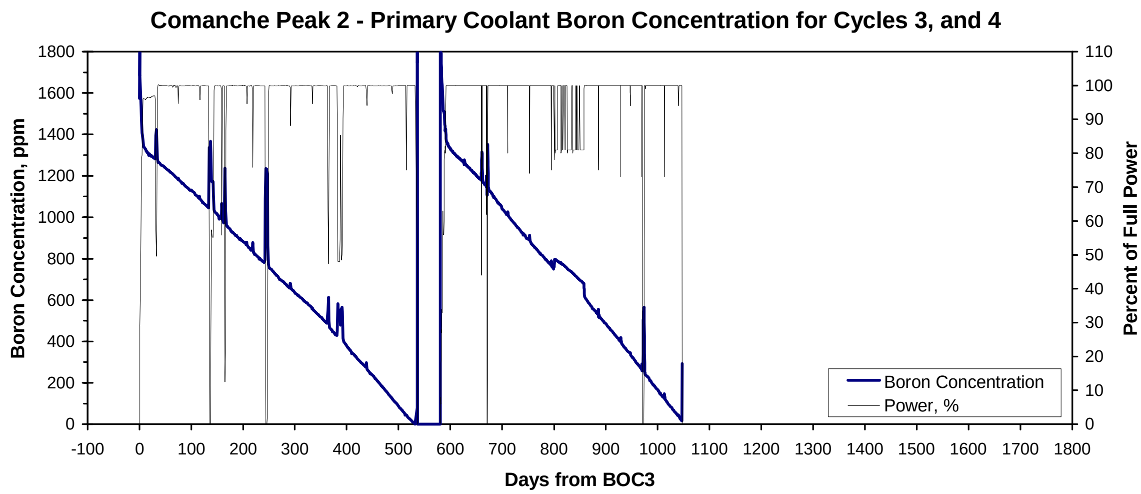
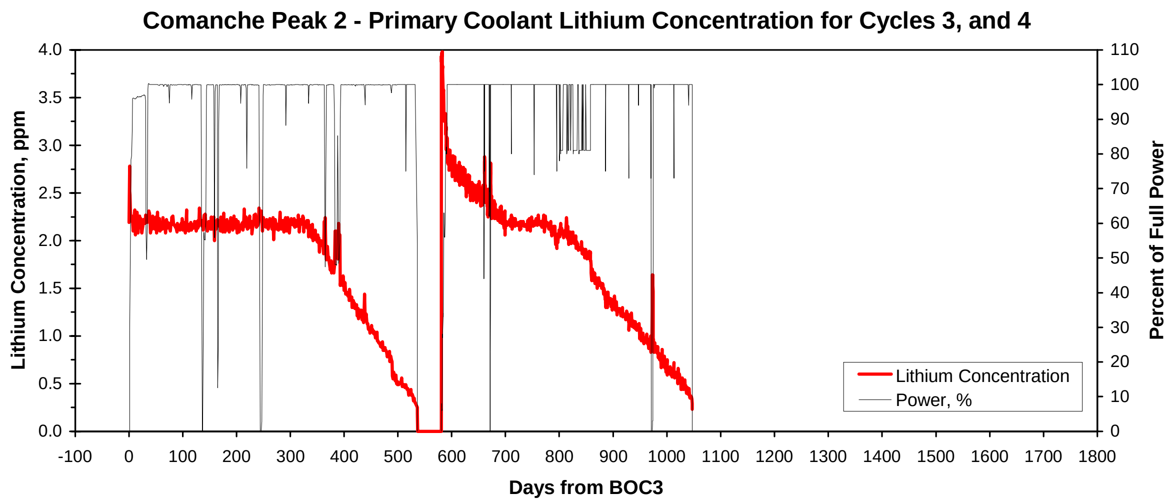


Figure 2-2
Comanche Peak Unit 1 Primary Coolant Chemistry – Cycles 5, 6, and 7





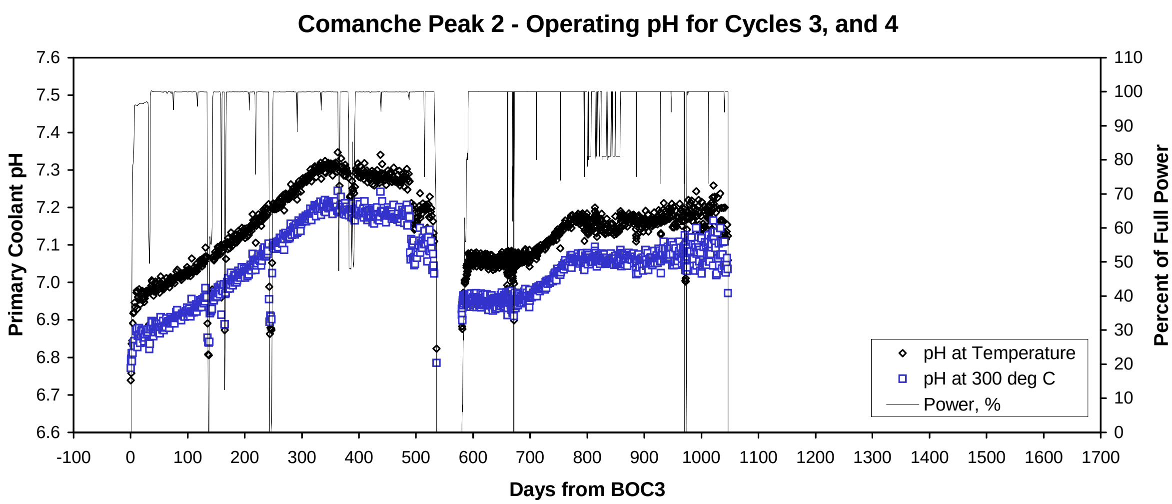


Figure 2-3
Comanche Peak Unit 2 Primary Coolant Chemistry – Cycles 3 and 4

2.1.1.4 Seabrook Cycles 4, 5, and 6

As illustrated in Figure 2-4, Seabrook operated with a modified pH during cycles 4 and 5 preceding conversion to the increased BOL pH chemistry program. The pH_{Tave} during cycle 6 was maintained at a relatively constant value of nearly 7.1 over approximately the first 2/3 of the cycle. The pH was then increased by roughly a tenth of a pH unit to nearly 7.2 over the remainder of the cycle. As in the Comanche Peak plants, this increased pH change during the cycle is a consequence of maintaining lithium levels at 2.2 ppm until the maximum pH is achieved. However, it is noted that, owing to the high initial boron concentration, the initial lithium levels approach 3.5 ppm in order to maintain the elevated BOL pH in the range of 7.0–7.1. Thus, the operation is basically modified with a minimum pH_{Tave} of roughly 7.05 and increasing to a maximum of 7.15.

2.1.1.5 South Texas Unit 1 Cycles 6, 7, 8, and 9 and Unit 2 Cycles 5, 6, and 7

Figures 2-5 and 2-6 show that the two cycles preceding the high BOL pH cycle at both South Texas Units were operated with conventional modified coolant chemistry control programs. The cycles with high BOL pH operated at an essentially constant pH over the entire cycle with maximum lithium levels in the coolant of approximately 3.0 ppm.

For the first high BOL pH cycle, the pH level was maintained at a somewhat higher level in Unit 2 than in Unit 1, i.e., cycle 7 of Unit 2 was operated at a pH_{Tave} in the range of 7.1–7.2 (nominally 7.15) while the pH during cycle 8 of Unit 1 was maintained at about a tenth of a pH unit lower, i.e., in the range of 7.0–7.1 (nominally 7.05). The pH in Unit 1 during cycle 9 was controlled in the same manner as in Unit 2, cycle 7. Note that the initial boron concentrations in the primary coolant are relatively low during these cycles because of the short fuel cycles.

2.1.1.6 Watt Bar 1 Cycles 1 and 2

The first operating cycle at Watts Bar was with modified coolant chemistry and cycle 2 was with the increased BOL pH regime. As noted in Figure 2-7, the relatively low critical boron concentrations for the first cycle of operation result in a high initial pH at the BOL (i.e., pH_{Tave} of between 7.1 and 7.2) and a long operating period (nearly ½ of the cycle) at the maximum pH of 7.4. The subsequent cycle with high BOL pH cycle is similar to the South Texas Unit 2 chemistry regime with a uniform pH_{Tave} of approximately 7.15. Another interesting feature of Watts Bar operation is the relatively long power reduction (coastdown) periods prior to the refueling shutdown as compared to the other plants.

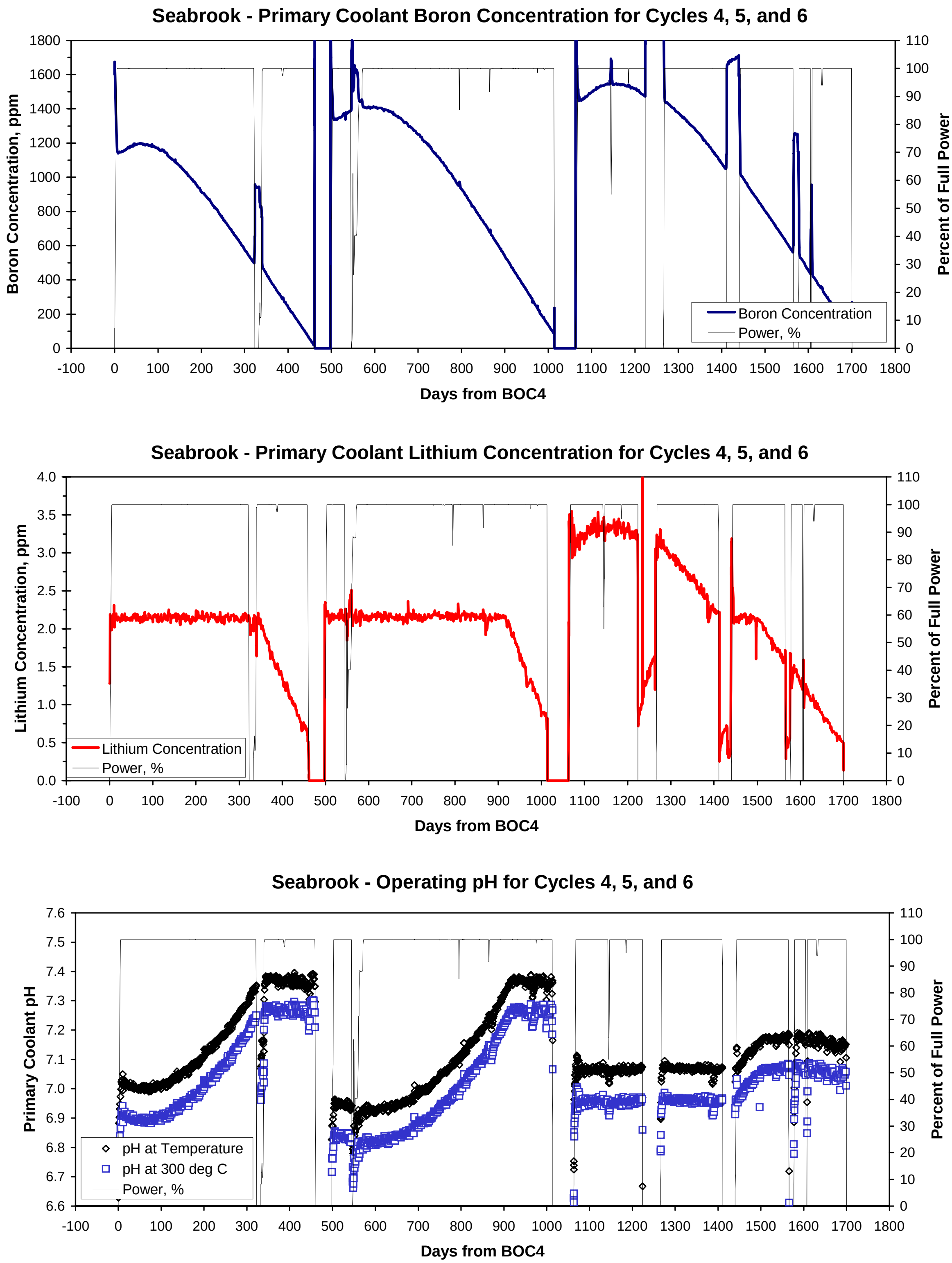


Figure 2-4
Seabrook Primary Coolant Chemistry – Cycles 4, 5, and 6

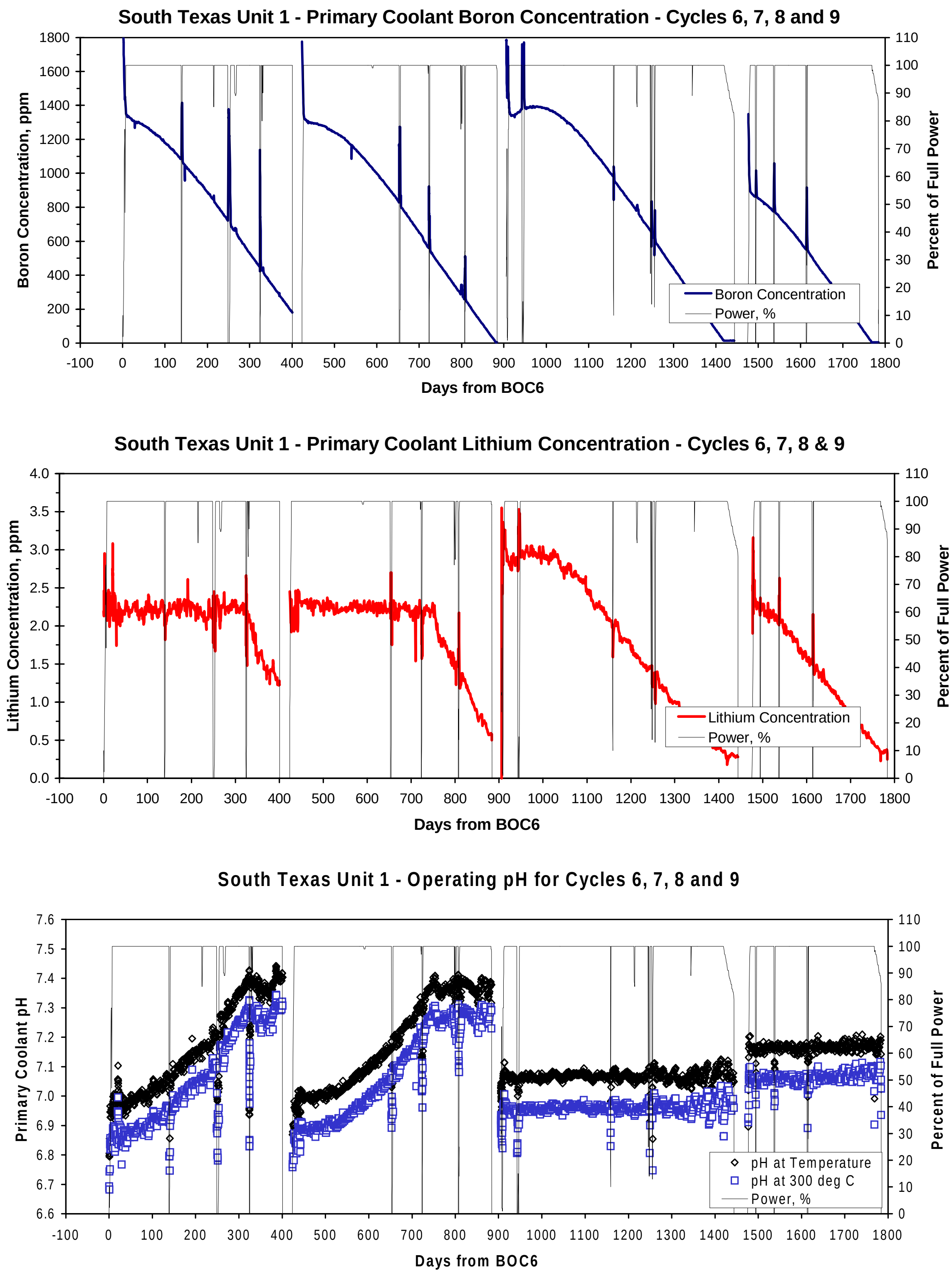
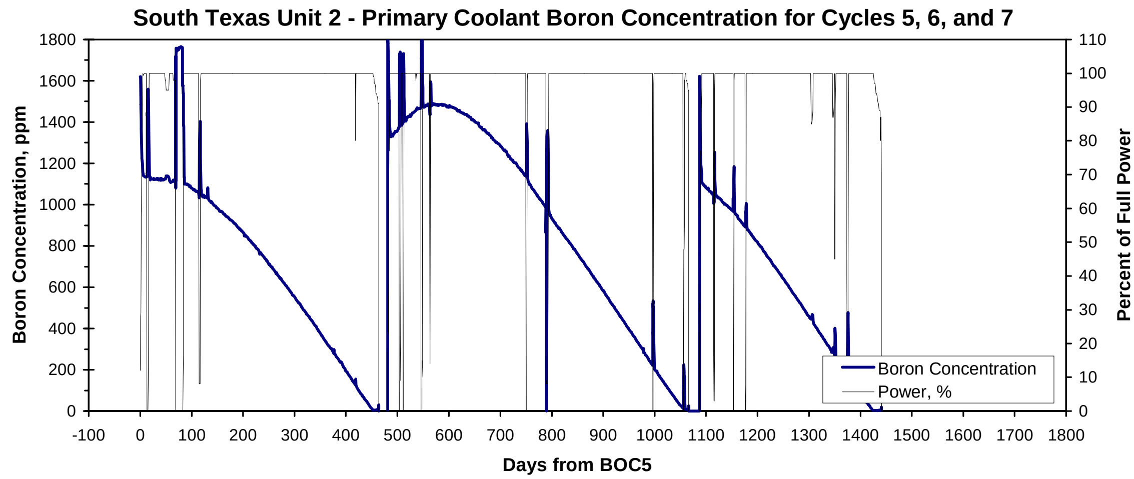
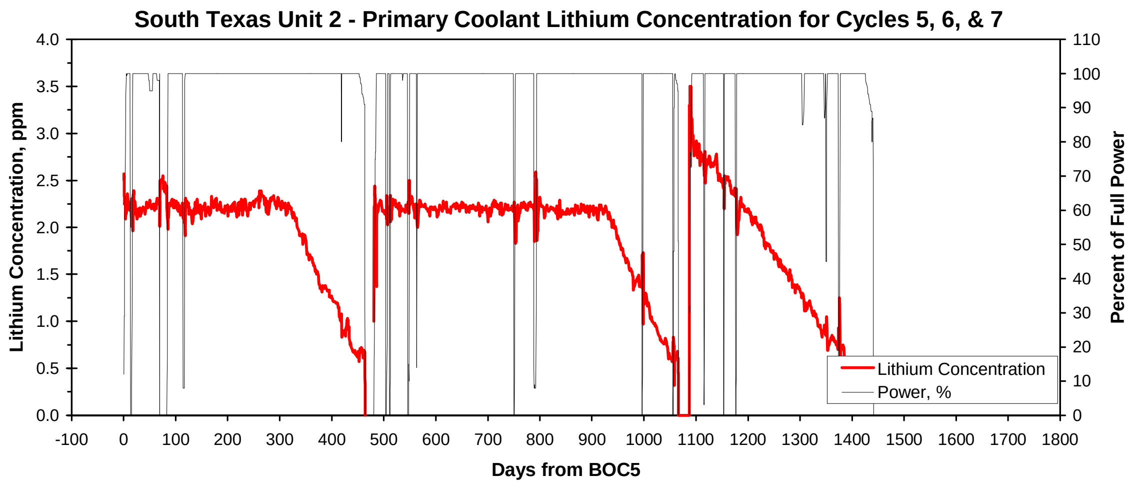


Figure 2-5
South Texas 1 Primary Coolant Chemistry – Cycles 6, 7, 8, and 9





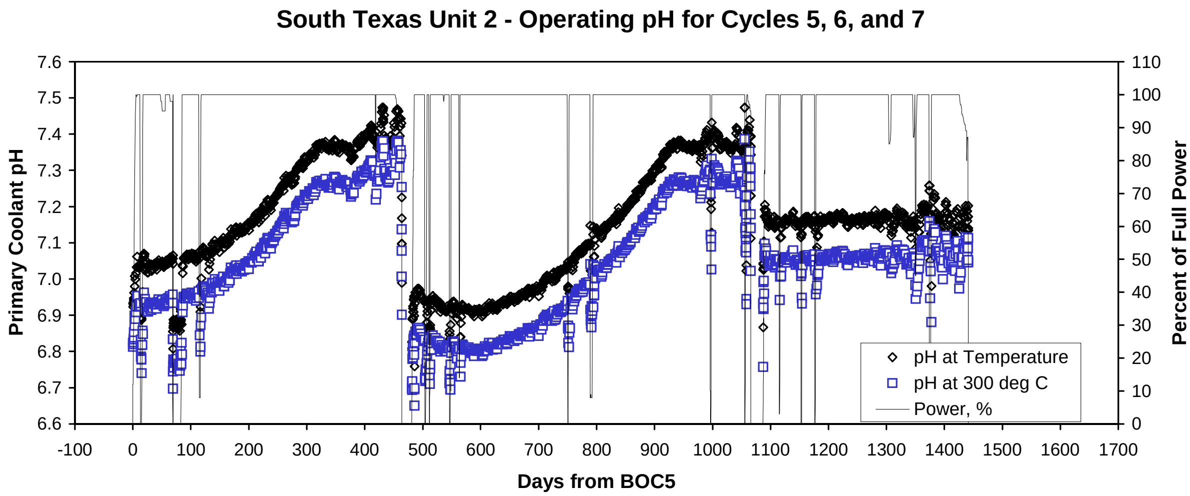


Figure 2-6
South Texas 2 Primary Coolant Chemistry – Cycles 5, 6, and 7

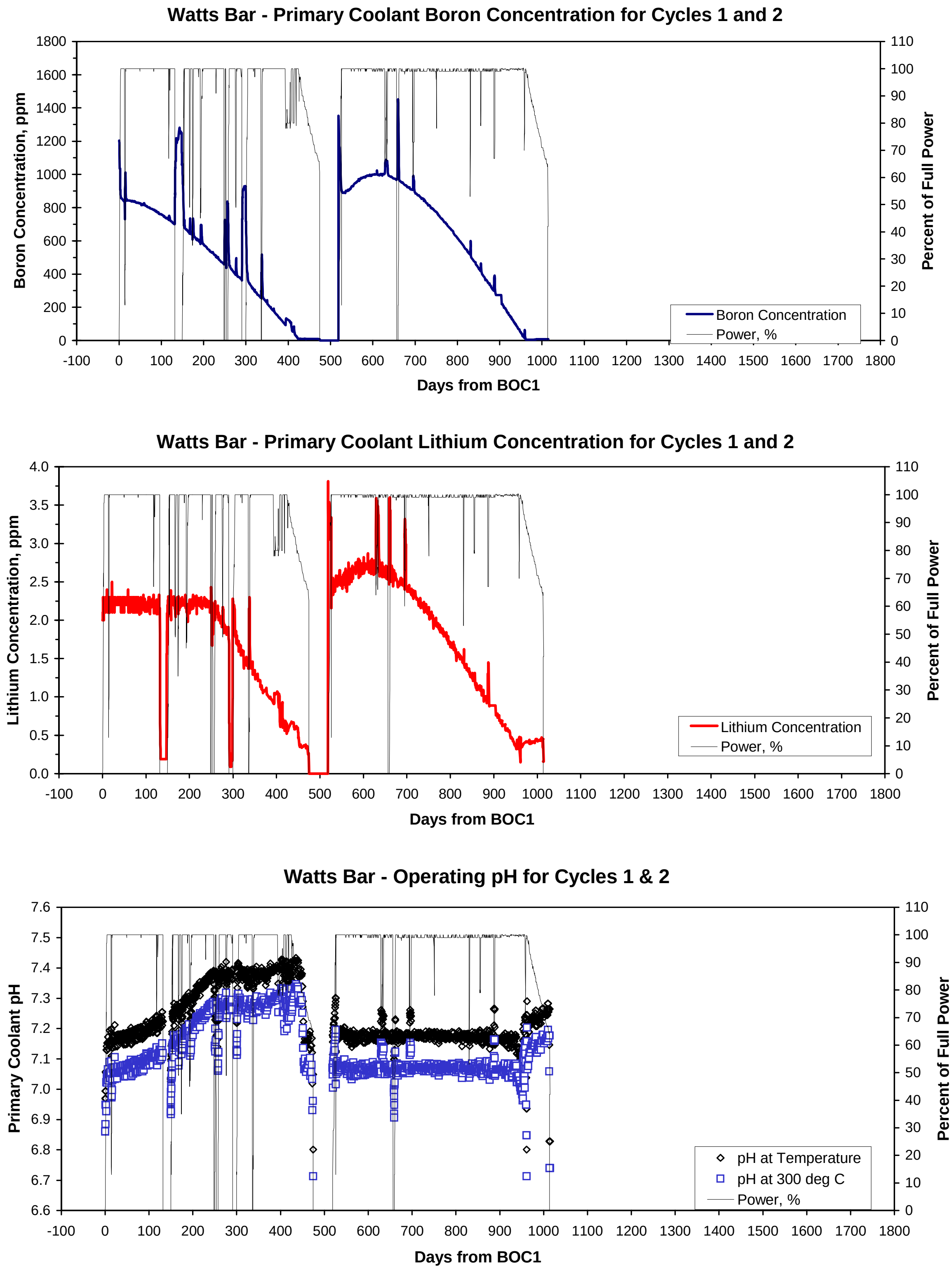


Figure 2-7
Watts Bar Primary Coolant Chemistry – Cycles 5, 6, and 7

2.1.2 Reactor Coolant Radioactivity Levels

Figures 2-8 through 2-21 present the measured radiocobalt, ^{54}Mn, and ^{51}Cr activity concentrations in the plants for the operating cycles of interest. The power history and pH_{300} during the operating cycles are also included at the top of the figures to aid in relating changes in concentrations to these key parameters.

Only the data from the operational cycles is presented in the figures, (i. e., coolant concentrations during refueling shutdowns are not included). For those plants with relatively long power coastdown periods, data is not presented below power levels at which a significant increase in activity levels was observed (generally below about 50-85% of full power for last few days of the cycle). Such increases are considered to be associated with reduced temperature effects on solubility. It is also interesting to note the relatively large range in the number of days associated with power coastdown, that is from 4 to 53 days.

Some general comments regarding trends in corrosion product behavior that have previously been observed at operating plants are discussed below. This is followed by a discussion of the plant-specific data collected from the plants participating in the high BOL follow program.

Coolant Activity Trends for Radiocobalts and ^{51}Cr – In general, activity concentrations for ^{58}Co, ^{60}Co, and ^{51}Cr follow a traditional “bathtub curve” or U-shaped relationship with cycle time. That is, the nuclide concentration is initially high in the early part of the cycle, decreases by a factor of roughly five to ten during the first few months of operation, stabilizes over the majority of the cycle, and then increases by nearly the same factor during the last few months of the cycle. The EOL values are usually the same or somewhat higher than those at BOL. This trend has been observed at a number of plants that have operated with modified coolant chemistry from the beginning to the end of the cycle [3, 4]. The increased activity levels during the last 30 days or so of the cycle could be related to changes in the power distribution of the core during this period.

Coolant Activity Trends for ^{54}Mn – The trend in coolant activity concentrations of ^{54}Mn is generally observed to be somewhat different from that of the other major corrosion product nuclides. Rather than a “bathtub curve” or U-shaped relationship of activity with time, the activity concentrations tend to decrease continuously over the cycle. The final EOL activity concentration is generally observed to be about a factor of three less than the BOL concentration.

Factors That Affect Activity Trends – Shutdowns during the cycle tend to affect the trends in the primary coolant since the activity concentration increases during the shutdown by factors that may be several orders of magnitude higher than normal levels. Thus, the shutdowns tend to disrupt the quasi-equilibrium that has been established in the surface deposits. Such increases are attributed to the solubility changes associated with reduced system temperatures. In many cases, the measured activity concentrations will exhibit significant increases at regular intervals over a core cycle. Such increases are generally attributable to scheduled (quarterly) CRDM movements [5].

The activity measurements reported by the plants participating in the high BOL pH program are discussed below.

2.1.2.1 Callaway Cycles 8, 9, and 10

Figures 2-8 and 2-9 shows the coolant activity trends at the Callaway plant. The ^{58}Co and ^{54}Mn trends for cycle 8 with modified chemistry are noted to be different from the traditional trends discussed above. Rather than a “bathtub curve” relationship with time, the ^{58}Co activity continuously increases throughout the cycle and the ^{54}Mn trend increases rather than decreases at the EOL. However, the ^{60}Co and ^{51}Cr concentrations follow the traditional trends. Since AOA was observed during cycle 8, 9, and 10, it is possible that increased in-core crud deposition which can lead to AOA is a contributing factor to the anomalous behavior.

The activities observed during cycles 9 and 10 also exhibit increasing trends during the cycles. These increases are noted to begin at times that correspond to a significant reduction in pH to 6.9. Since AOA was observed during both of these cycles and high amounts of core crud are considered to be a pre-requisite for the occurrence of AOA, the increased activity levels are attributed to the core crud deposits. The activity levels observed during cycle 10 are higher than those associated with previous cycles and the variability or “scatter” in the data appears to be more severe in cycle 10. The activity concentrations of ^{58}Co approach 1 μCi/g by the end of cycle 10, which is nearly two decades higher than levels typically observed in most operating plants. Further, the ^{54}Mn concentrations during cycle 10 are noted to be one to two orders of magnitude higher than in previous cycles and a significant increase in ^{51}Cr activity concentration coincides with a reduction in pH to approximately 6.9.

2.1.2.2 Comanche Peak 1 Cycles 6 and 7

Figures 2-10 and 2-11 show the activity concentrations in Comanche Peak 1 for cycles 6 and 7. Although the chemistry environment for cycle 5 was included in the previous section, the availability of coolant radiochemistry data for this cycle was limited and is considered to be insufficient for meaningful evaluation. The plant operated with a modified pH during cycles 5 and 6. As shown in the figures, the pH_{300} was abruptly reduced from 7.15 to 7.05 after about 300 days of operation during the sixth cycle. The data indicate that there was no dramatic change in the activity levels immediately after the change to the lower pH. However, it appears that a higher plateau for all the nuclides was established when operation was resumed following a subsequent plant shutdown at about 350 days of operation. The high concentration plateau is presumably related to solubility changes associated with previous reduction in coolant pH; although plant personnel indicated that the increase could be associated with the introduction of oxygen while changing boric acid concentrations (the presence of oxygen was correlated with an increase in ^{41}Ar activity levels).

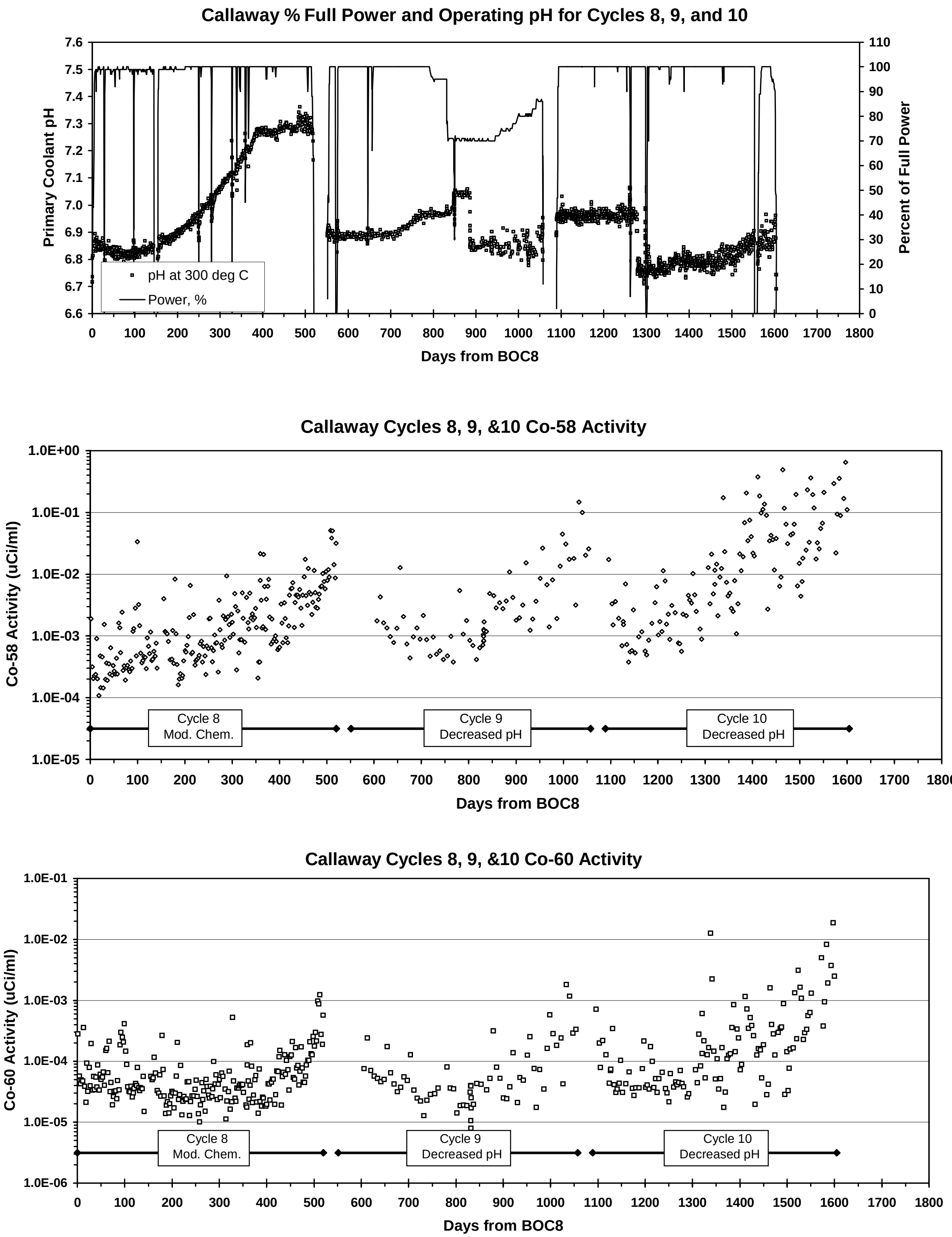


Figure 2-8
Callaway Primary Coolant Radiochemistry – ^{58}Co and ^{60}Co

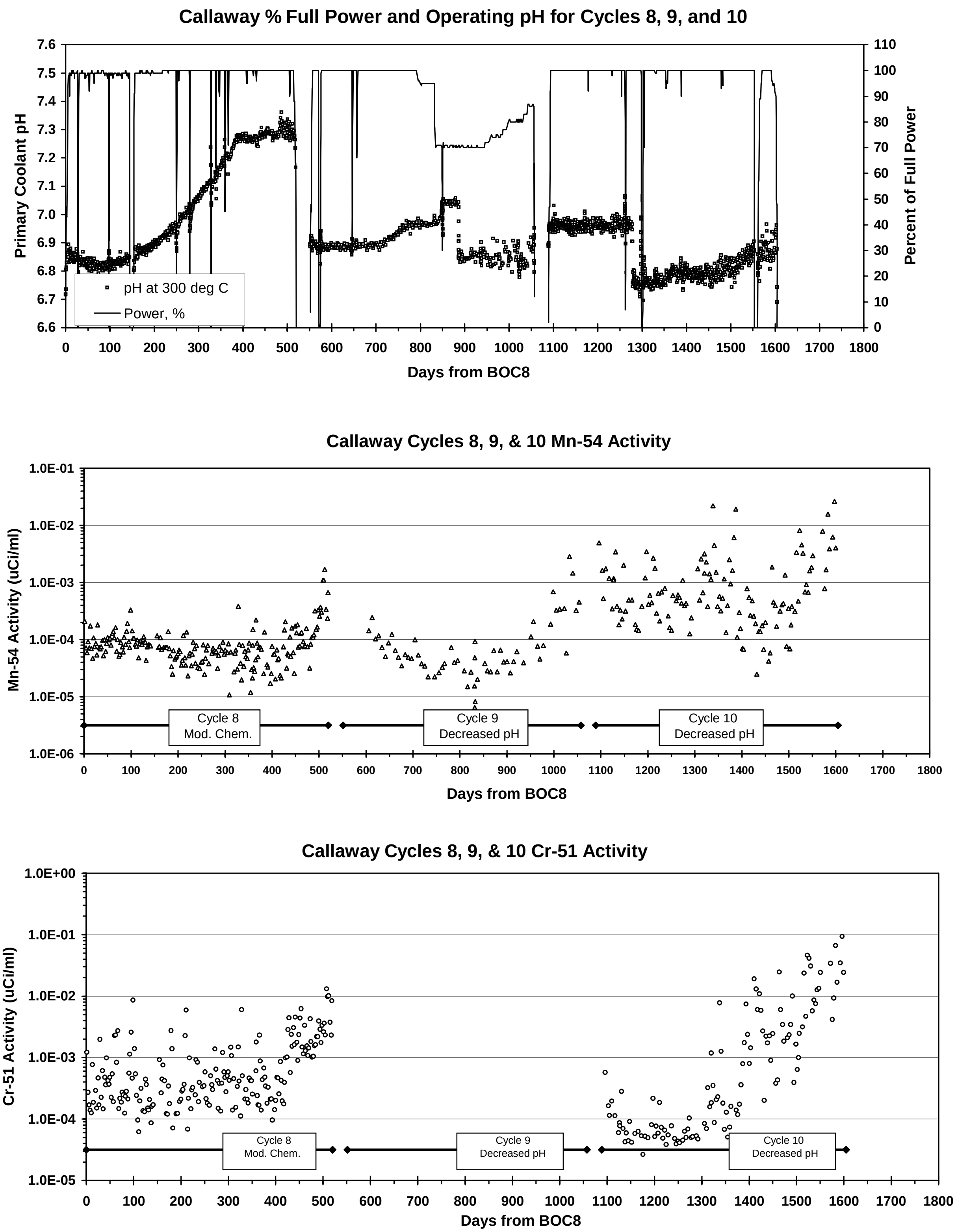
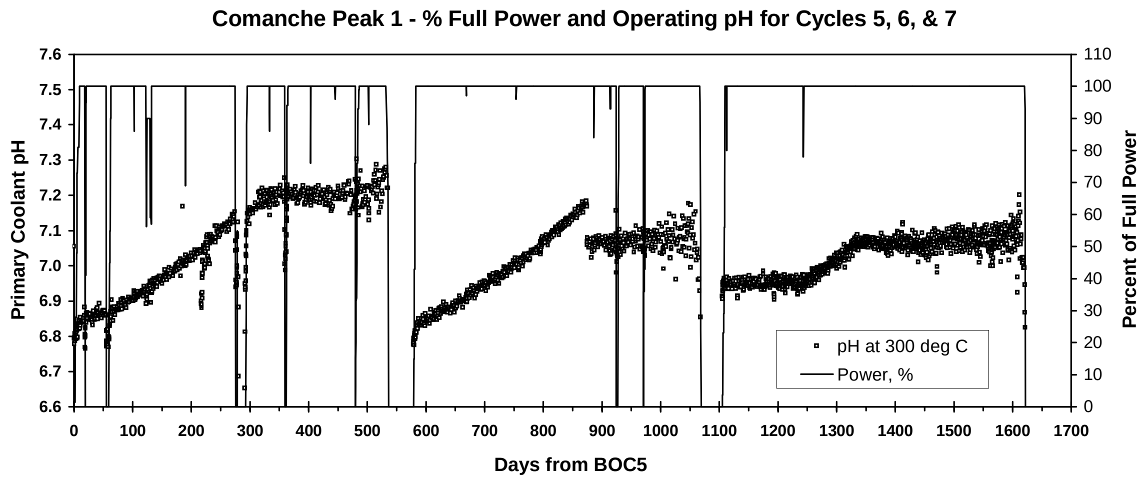
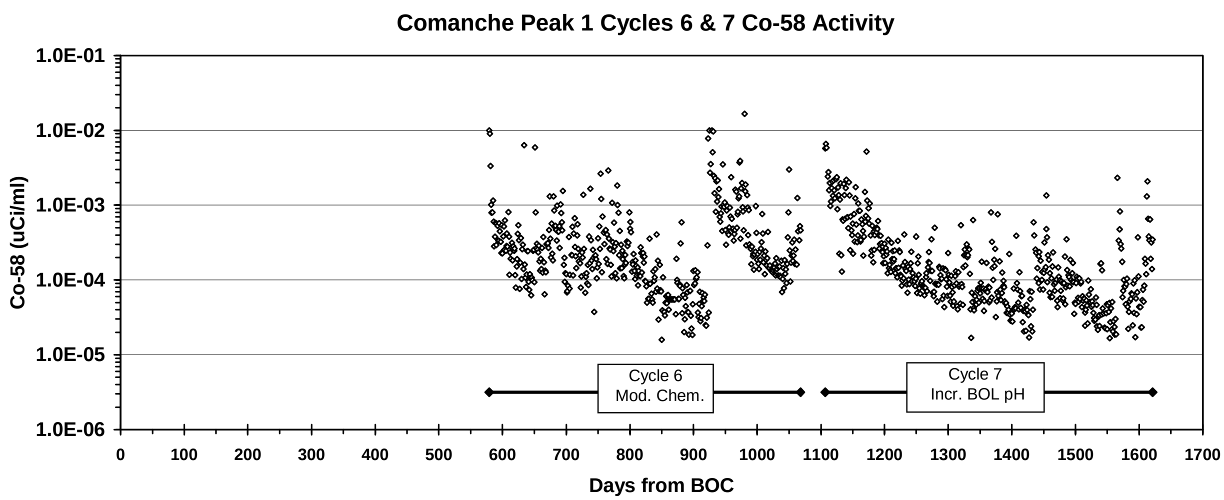


Figure 2-9
Callaway Primary Coolant Radiochemistry – ^{54}Mn and ^{51}Cr





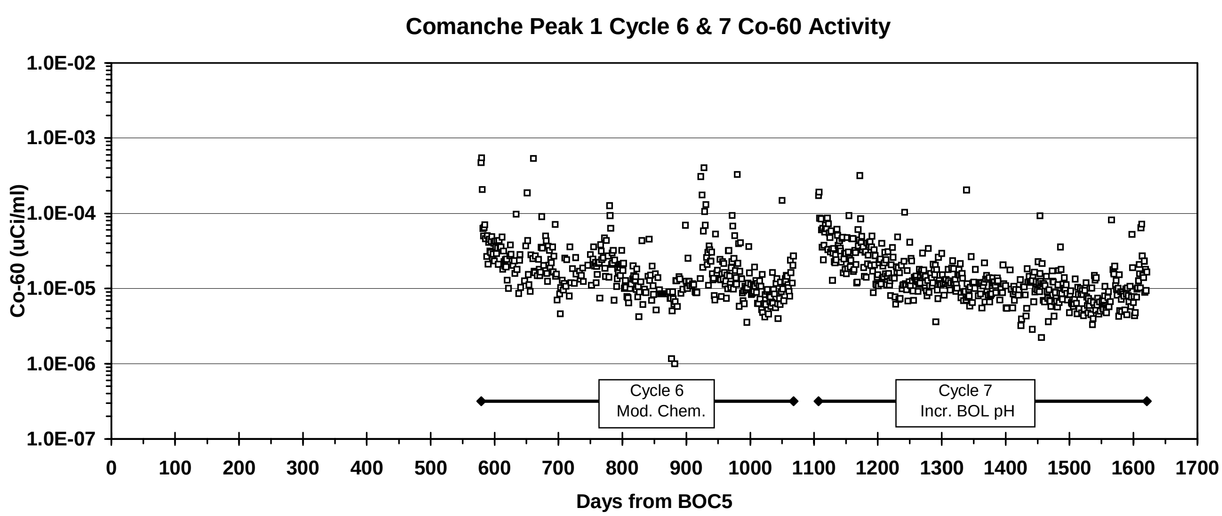
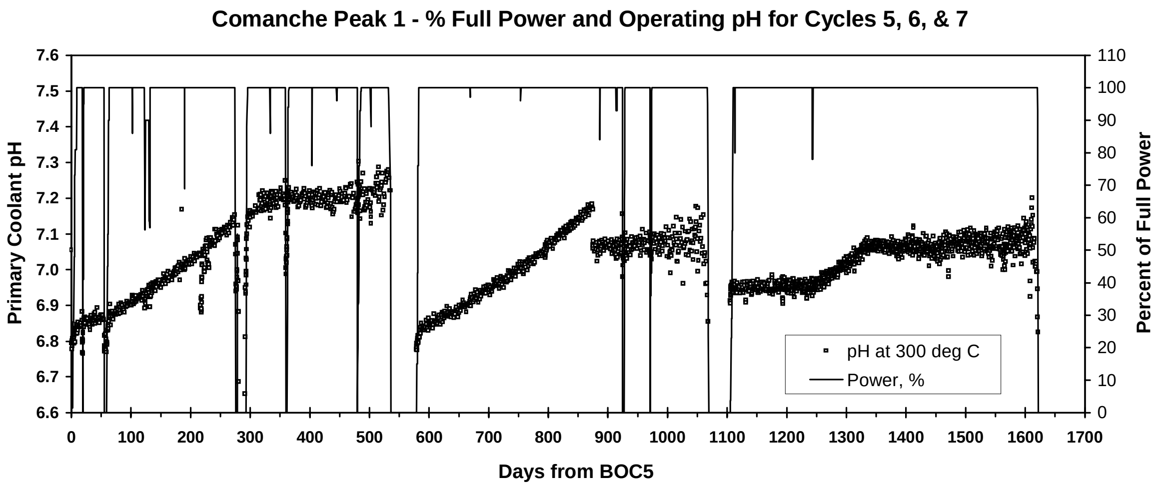
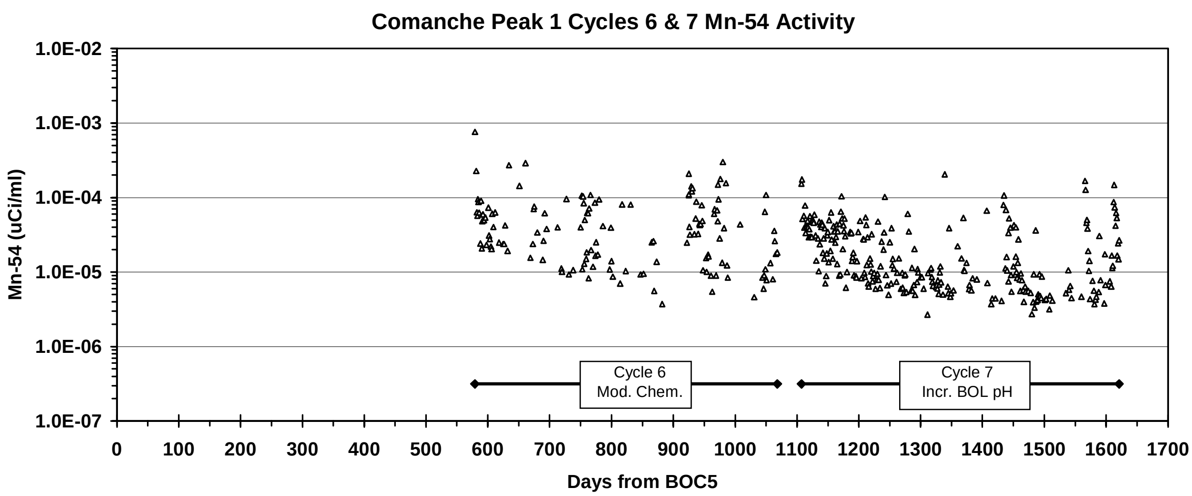


Figure 2-10
Comanche Peak Unit 1 Primary Coolant Radiochemistry – ^{58}Co and ^{60}Co





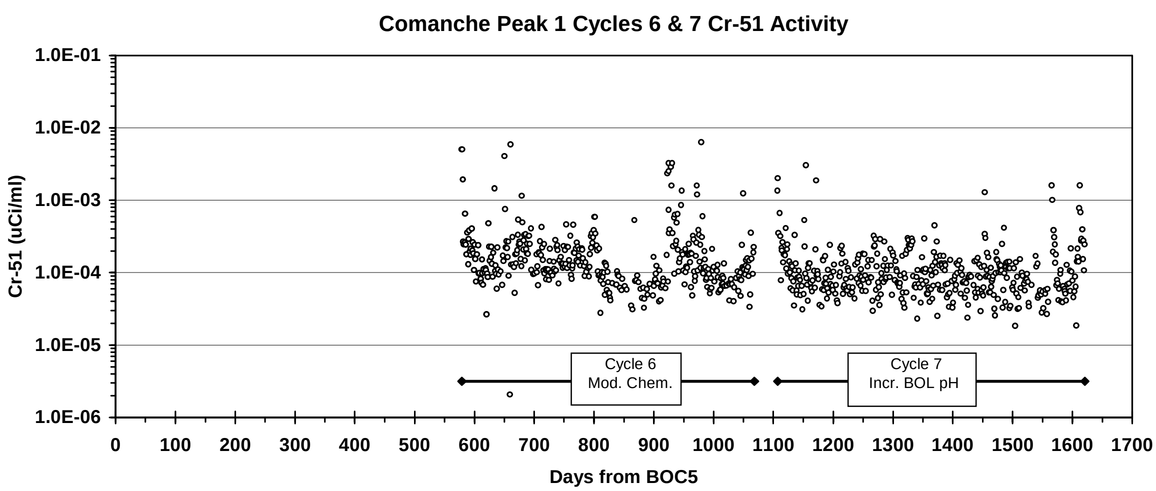


Figure 2-11
Comanche Peak Unit 1 Primary Coolant Radiochemistry – ^{54}Mn and ^{51}Cr

The trend of the activities in cycle 7, with a more constant pH than cycle 6, is not significantly different from that observed in cycle 6. A sharp increase in the ^{58}Co activity concentration after 325 days of cycle 7 operation is noted. The available data does not suggest a particular reason or explanation for the increase, especially since there was no mid-cycle shutdown or power perturbation at the time corresponding to the step increase in activity concentration. Further, the time at which the change in pH occurred during the cycle is much earlier than the observed increasing coolant activity. That is, the pH was increased over about a 60 day period starting after approximately 150 days of cycle 7 operation and reaching the new (higher) pH level at about 210 days of operation; the activity increase occurred at 325 days into the cycle. Another observation is that the activity concentration trends of cycles 6 and 7 are similar, but the magnitude of the concentrations during cycle 7 appear to be slightly lower than those measured during cycle 6, reflecting the more constant pH associated with cycle 7.

2.1.2.3 Comanche Peak 2 Cycles 3 and 4

The activity concentrations in Comanche Peak 2 for cycles 3 and 4 are presented in Figures 2-12 and 2-13. The figures show that the pH was reduced abruptly about 40 days prior to the end of cycle 3, due to AOA concerns, and that there was a corresponding increase in activity concentrations. However, it is difficult to separate the increase from the typical EOL concentration increases discussed above. The effects of the two shutdowns and two power reductions in cycle 3 are reflected in the corresponding activity increases at these times. Also note that new “equilibrium” levels in the coolant are achieved at about 40 days of constant power operation following these disruptions. Further, a general increase in the new “equilibrium” coolant levels over the course of the cycle is observed, and EOL ^{58}Co activity concentrations are an order of magnitude higher than those at the BOL. Similar trends are observed in the ^{60}Co activities. Activity data for other nuclides was not available to further confirm this apparent behavior. However, the continuous increase is noted to be similar to activity trends observed at the Callaway plant. This suggests an effect of increased crud deposition associated with AOA.

Although there were also a significant number of shutdowns and power reductions during cycle 4, the activity concentration trends in cycle 4 tend to follow the normal “bathtub curve” relationship. The general increasing trend of the new “equilibrium” concentrations as noted in cycle 3 is not observed. Further, the magnitude of the activity increases at shutdowns and power reductions appear to be less during cycle 4 as compared to cycle 3.

The activity concentrations during cycle 4 are generally more consistent and lower than those measured during cycle 3. The lower activity concentrations could reflect the more constant pH associated with cycle 3 and/or the activity levels during cycle 3 are elevated due to operation with AOA during the cycle.

2.1.2.4 Seabrook Cycles 4, 5, and 6

Figures 2-14 and 2-15 illustrate the activity concentration trends in Seabrook cycles 4, 5 and 6. The plant operated with modified pH during cycles 4 and 5 and converted to the more constant pH chemistry in cycle 6. In addition AOA indications were observed at Seabrook during cycles 5 and 6 operation.

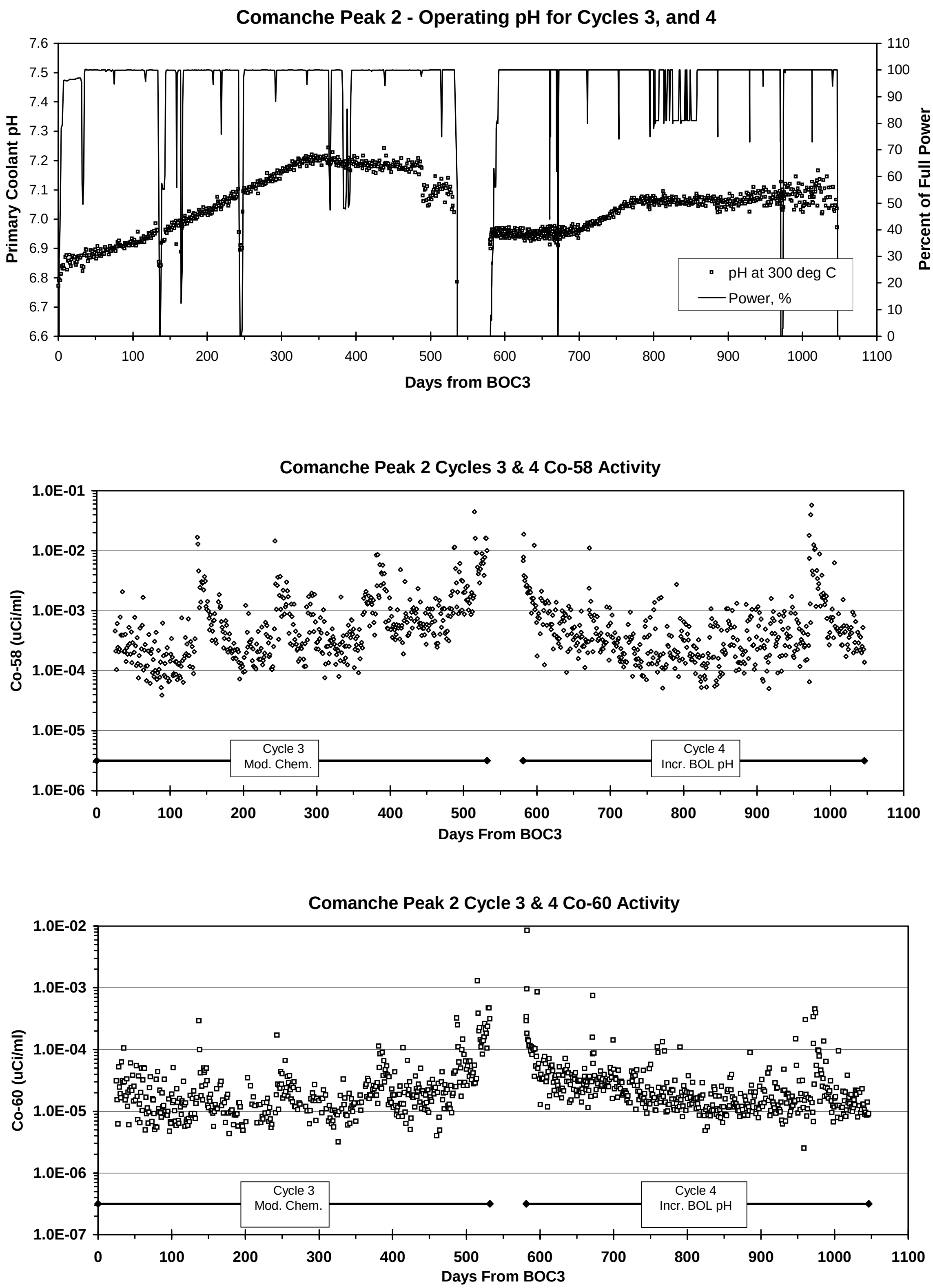


Figure 2-12
Comanche Peak Unit 2 Primary Coolant Radiochemistry – ^{58}Co and ^{60}Co

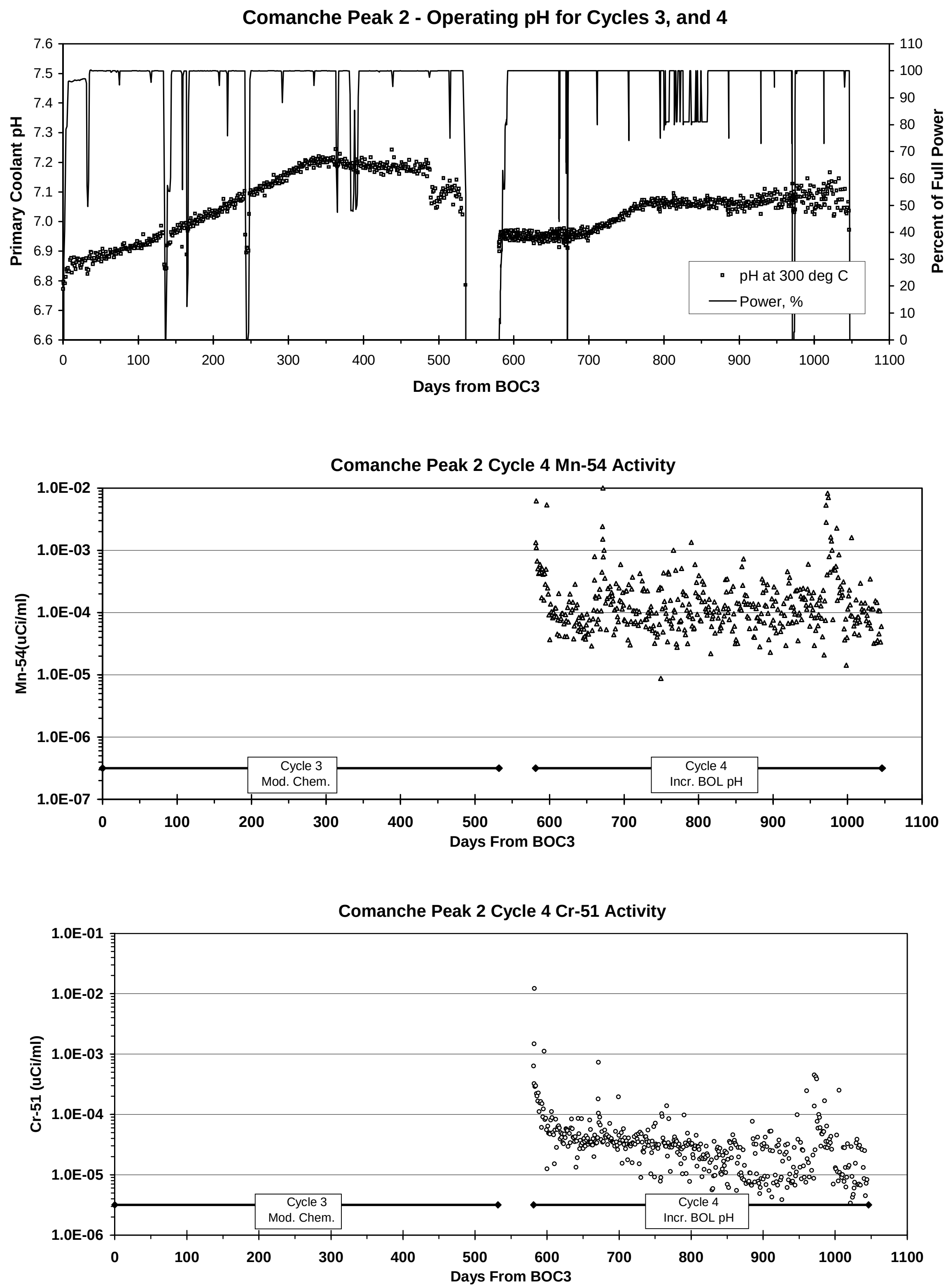


Figure 2-13
Comanche Peak Unit 2 Primary Coolant Radiochemistry – ^{54}Mn and ^{51}Cr

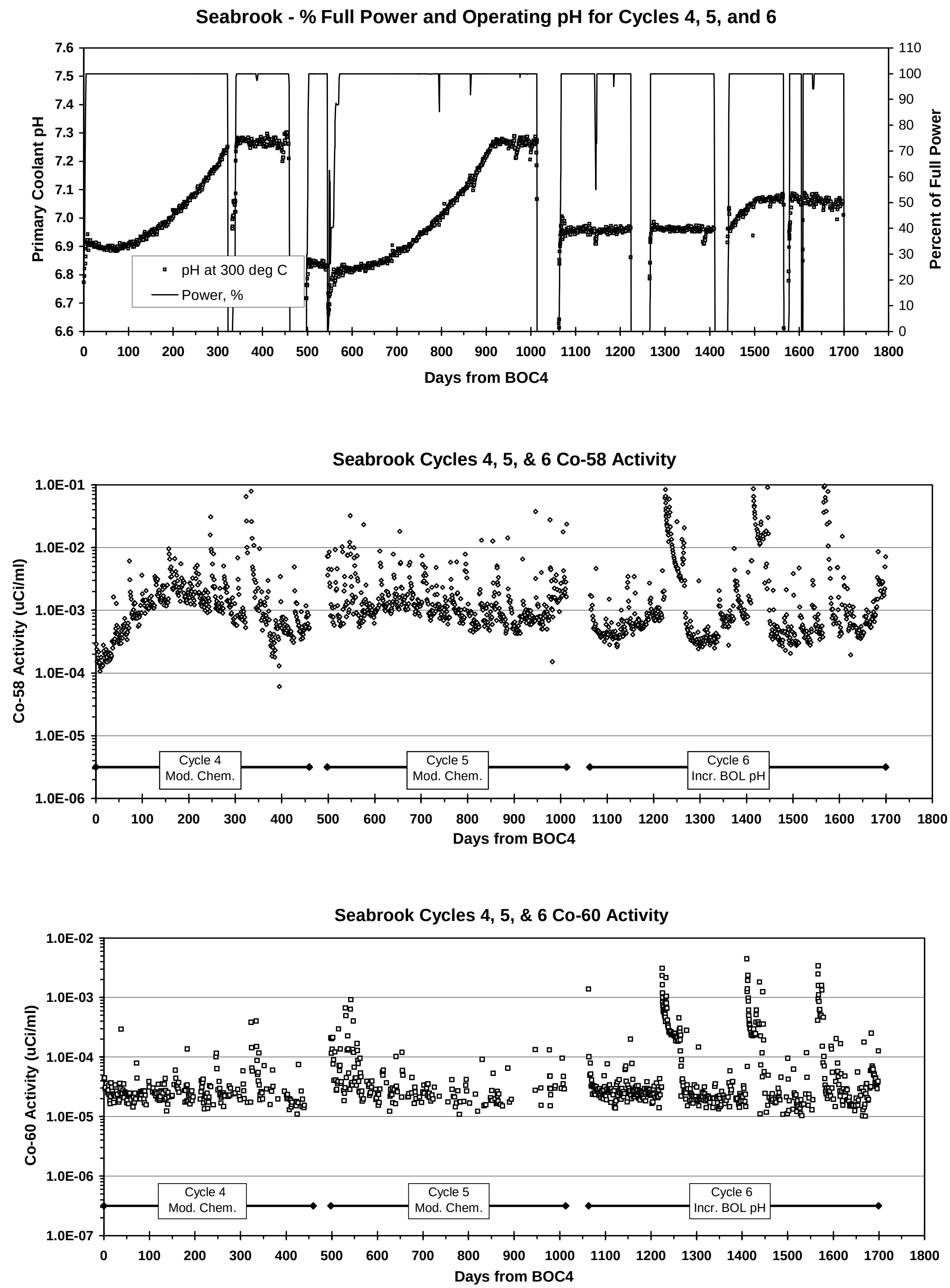


Figure 2-14
Seabrook Primary Coolant Radiochemistry – ^{58}Co and ^{60}Co

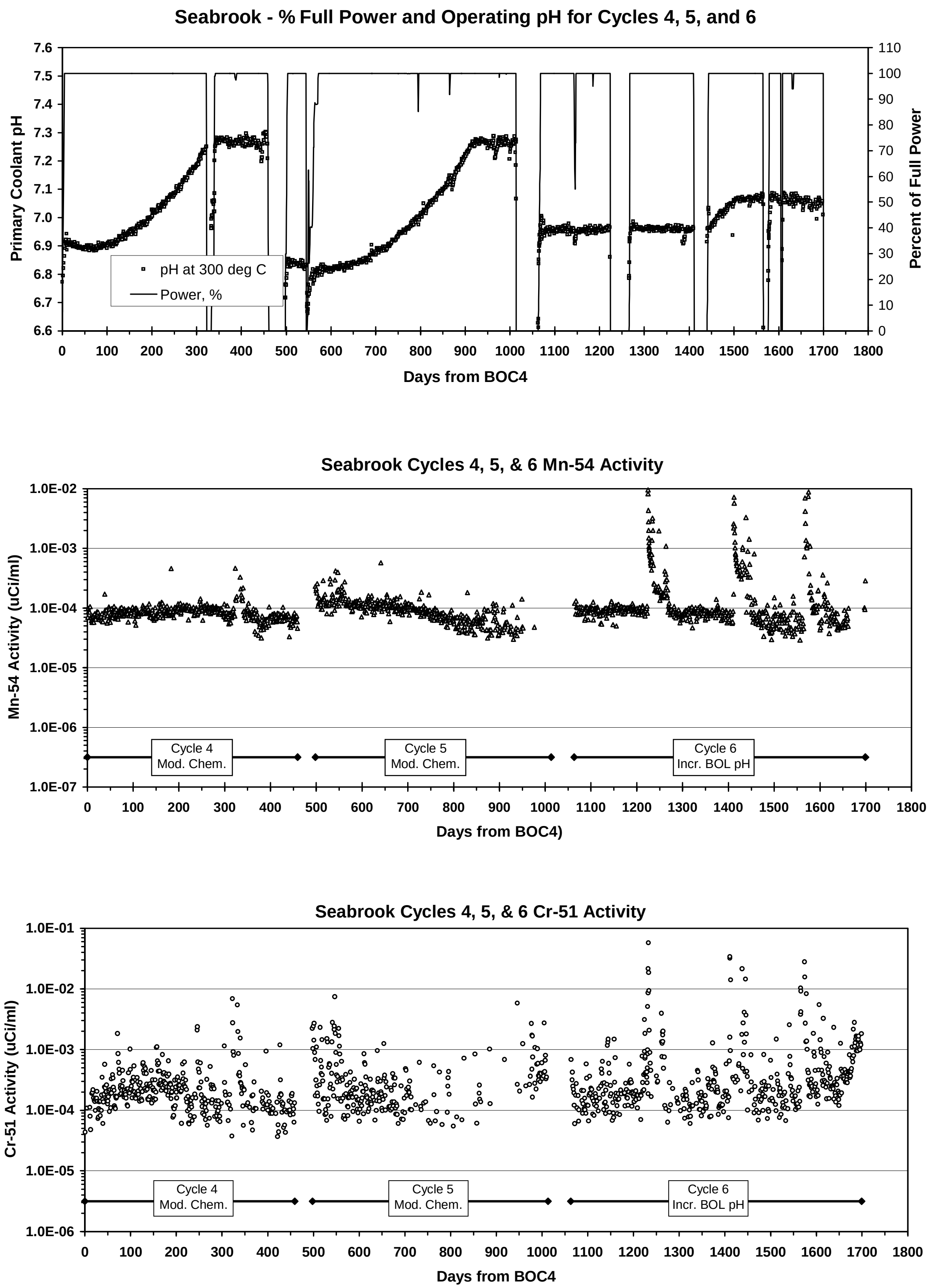


Figure 2-15
Seabrook Primary Coolant Radiochemistry – ^{54}Mn and ^{51}Cr

The activity trends in cycle 4 are atypical in that they exhibit a reverse U shape as compared to a more traditional “bathtub curve” relationship. The decreasing trend over the last half of the cycle appears to continue after the extended shutdown that occurred at about 325 days into the cycle.

The data trend during cycle 5 differs from that observed during cycle 4 in that the ^{58}Co activities increased by about an order of magnitude over the first half of cycle 4 (i.e., from 10^{-4} to 10^{-3} μCi/ml), while the levels during cycle 5 were relatively constant at the higher concentration of about 10^{-3} μCi/ml. Since AOA was observed during cycle 5, this may have been an influencing factor for the activity trend during the cycle.

The activity trends during cycle 6, when the operating chemistry was converted to a more constant pH program, and during which AOA was also experienced, were not significantly different from that associated with cycle 5. The effect of the three extended shutdowns during cycle 6 on the activity trends is illustrated by the large activity increases shown in Figures 2-14 and 2-15. It is also noted that coolant concentrations return to about their pre-shutdown values following return to power operation. As with the activity trends, there is no obvious difference in the magnitudes of the activity concentrations observed during cycle 5 with modified pH and the more constant coolant pH during cycle 6.

2.1.2.5 South Texas 1 Cycles 6, 7, 8, and 9 and South Texas 2 Cycles 5, 6, and 7

Figures 2-16 and 2-17 show the primary coolant activity concentrations at South Texas Unit 1 for cycles 6, 7, 8, and 9. Similar information for South Texas Unit 2 for cycles 5, 6, and 7 are presented in Figures 2-18 and 2-19. These figures show that the both plants operated with modified pH for the two cycles preceding the conversion to the more constant pH operation. The relatively short cycle lengths for Unit 1, cycle 9 and for Unit 2, cycle 7 are due to schedule changes to accommodate the replacement of the steam generators in Unit 1.

The concentrations of ^{58}Co, ^{60}Co, and ^{54}Mn (data for ^{51}Cr was not available) are generally consistent with the aforementioned “traditional” trends for basically all cycles in both plants, with the possible exception of the ^{58}Co trend for Unit 1 cycle 6. The activity concentrations during this cycle exhibit the typical decrease in concentration over the first month of operation and then increase by more than an order of magnitude over the next 3 months of the cycle. Following a plant shutdown at about 140 days, the activity level tends to decrease at a relatively slow rate as compared to typical activity trends that are observed following short shutdowns. After about 100 days the levels are reduced to roughly the minimum levels that were observed during the previous part of the cycle.

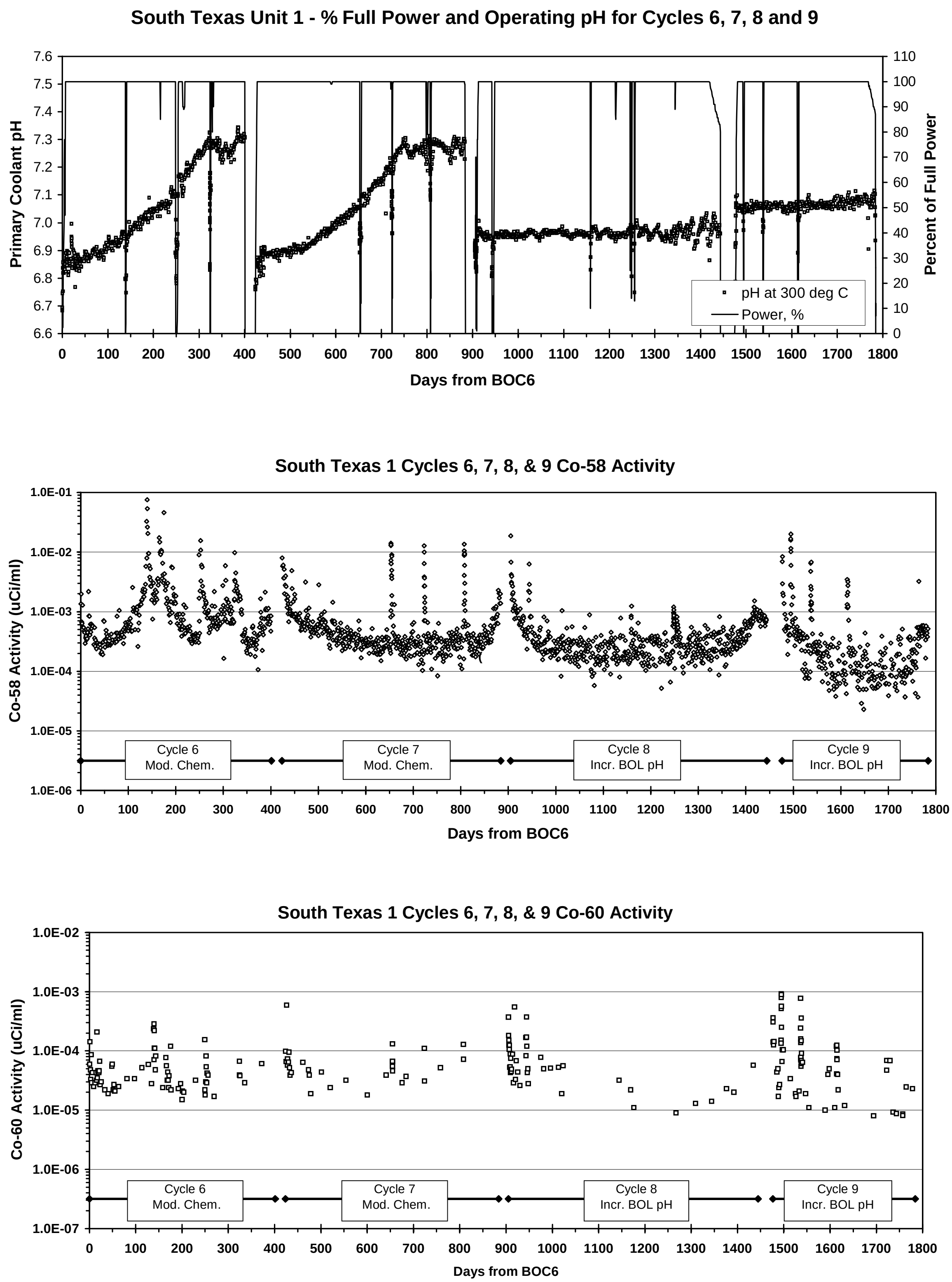
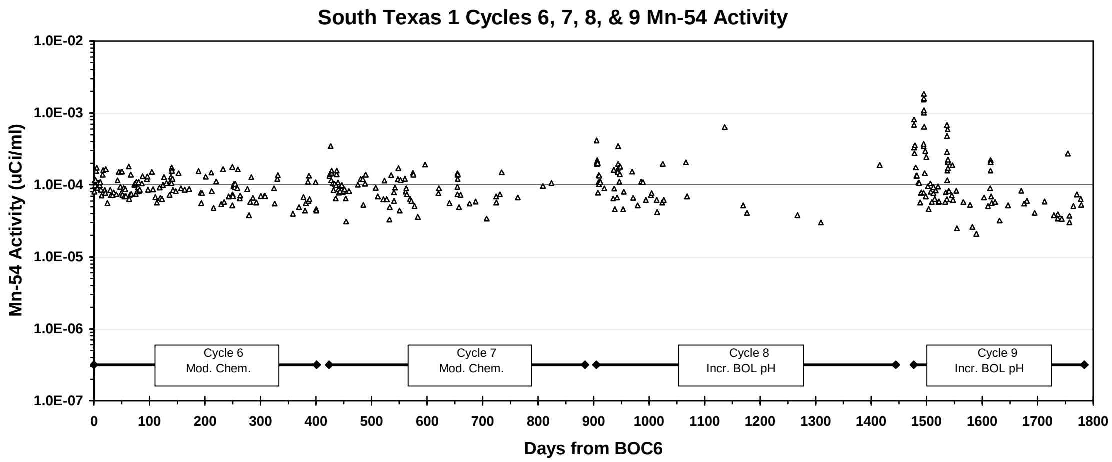


Figure 2-16
South Texas Unit 1 Primary Coolant Radiochemistry – ^{58}Co and ^{60}Co



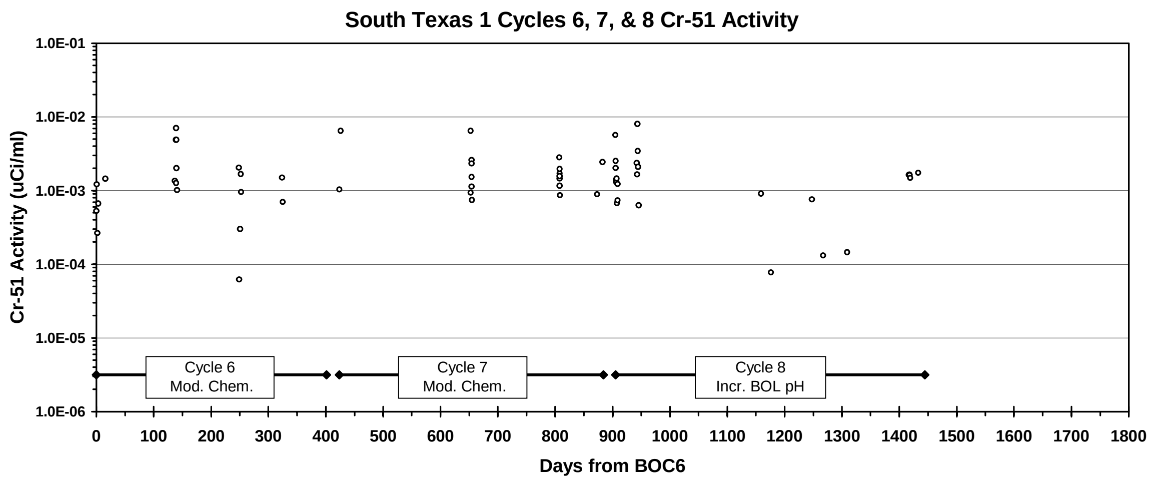
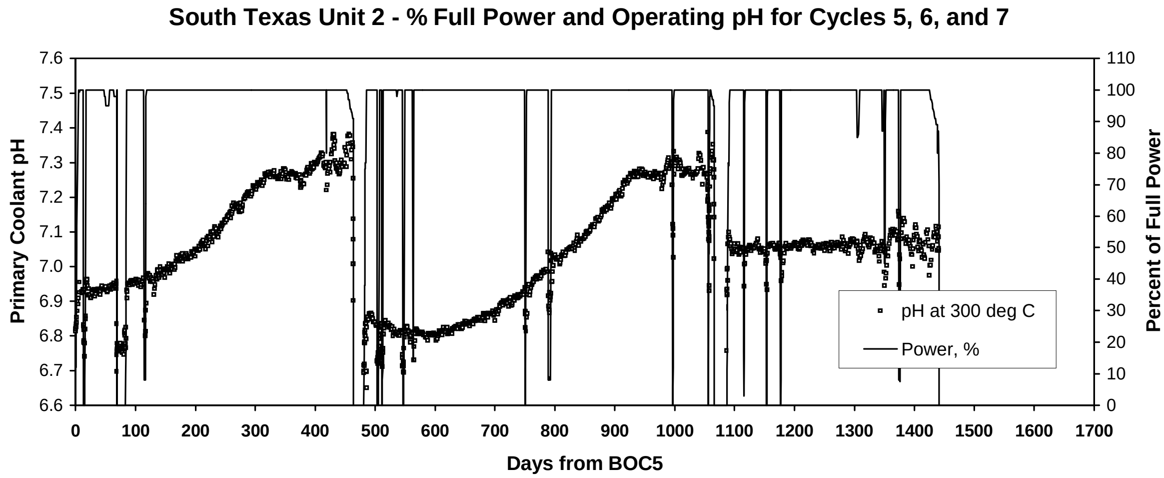
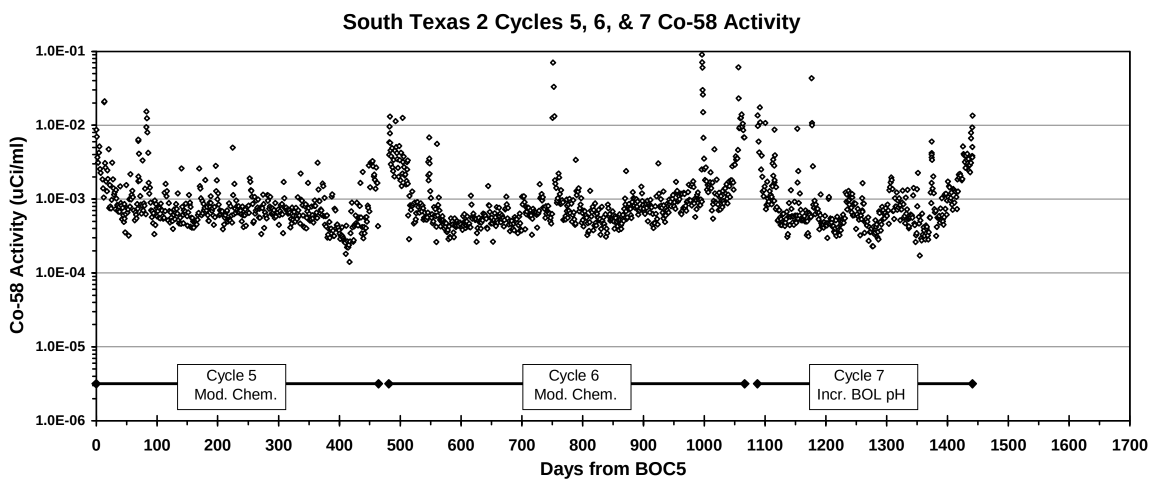


Figure 2-17
South Texas Unit 1 Primary Coolant Radiochemistry – ^{54}Mn and ^{51}Cr





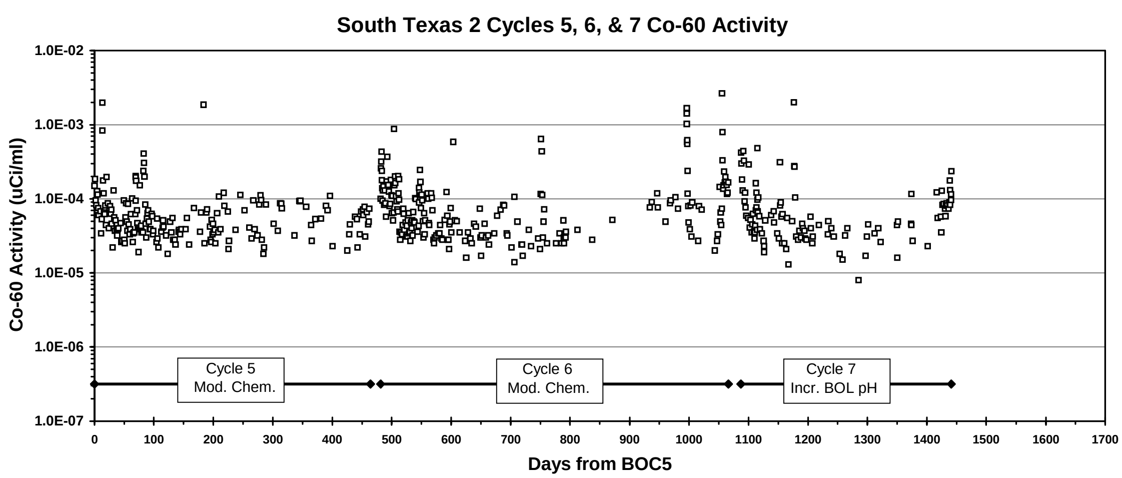
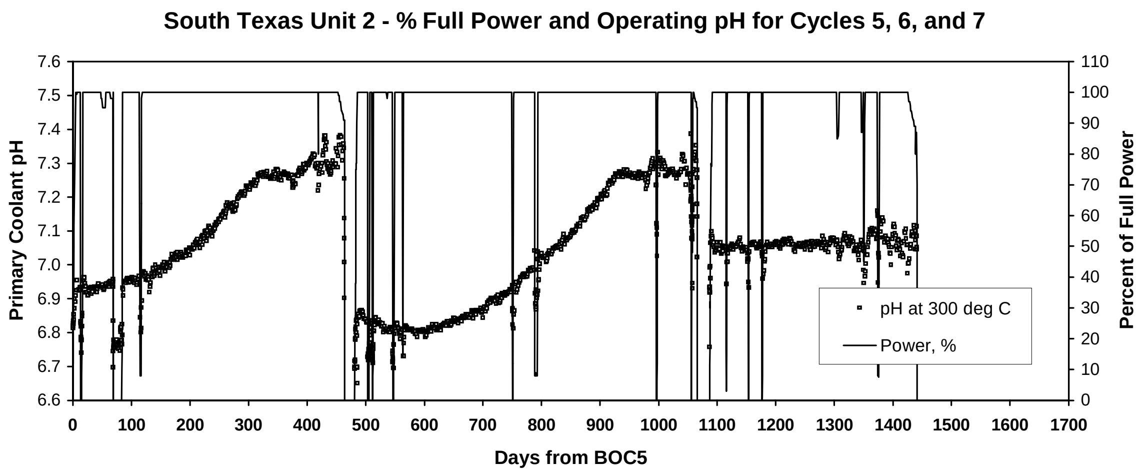


Figure 2-18
South Texas Unit 2 Primary Coolant Radiochemistry – ^{58}Co and ^{60}Co



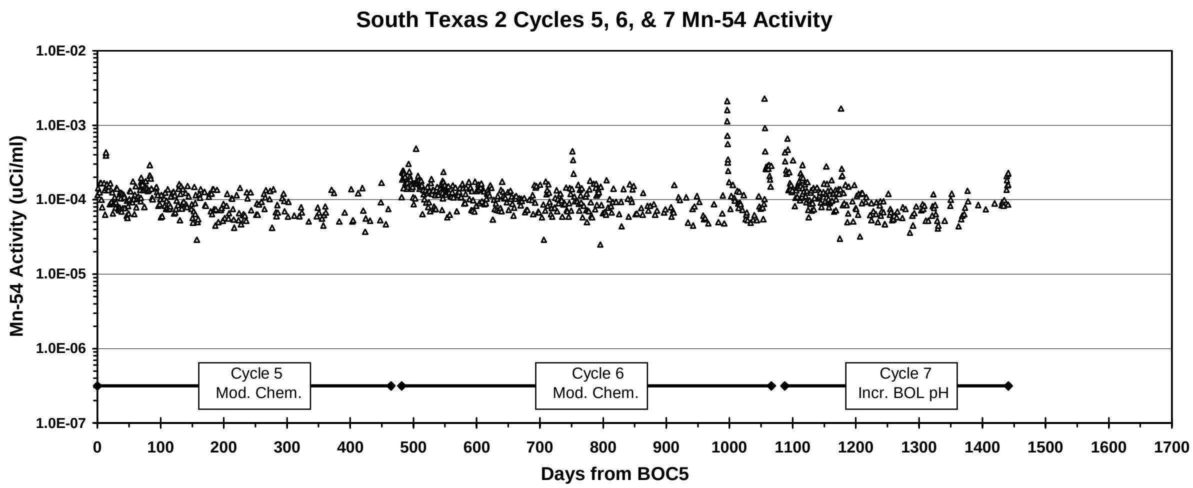


Figure 2-19
South Texas Unit 2 Primary Coolant Radiochemistry – ^{54}Mn

The last two cycles at Unit 1 were operated with the high BOL pH. In general, it appears that activity levels are somewhat lower in these cycles than the two previous cycles that were operated with modified chemistry. Also, the magnitude of the Unit 1 ^{58}Co coolant activity levels during the second cycle with increased pH chemistry control (cycle 9) are somewhat lower than all of the previous three cycles. The activity levels in Unit 2 during the high BOL pH cycle (i.e., cycle 7) and the previous two modified chemistry cycles are very similar. The observation that the activity levels during the second cycle of operation with increased pH chemistry control are somewhat lower than all of the previous cycles suggests that there could be long term benefits with continued operation with the alternative chemistry.

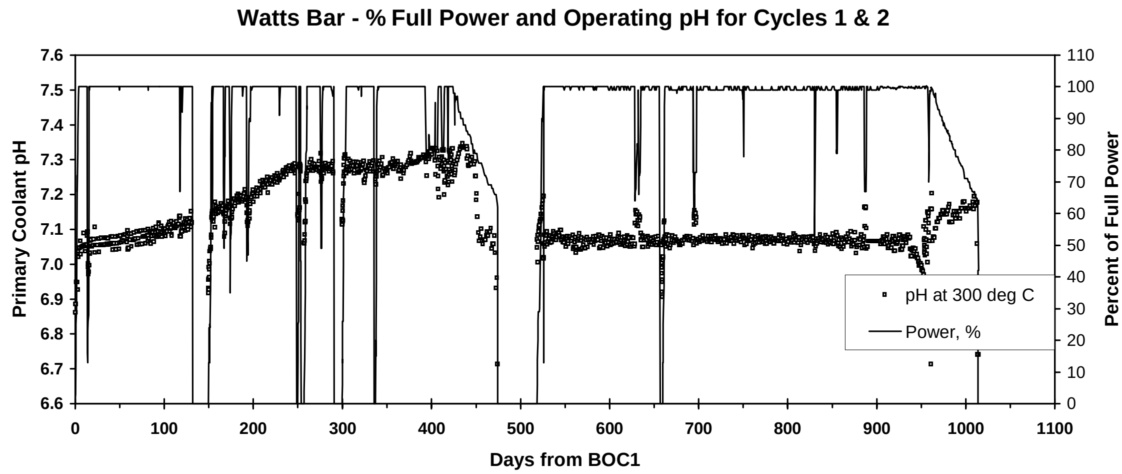
2.1.2.6 Watts Bar 1 Cycles 1 and 2

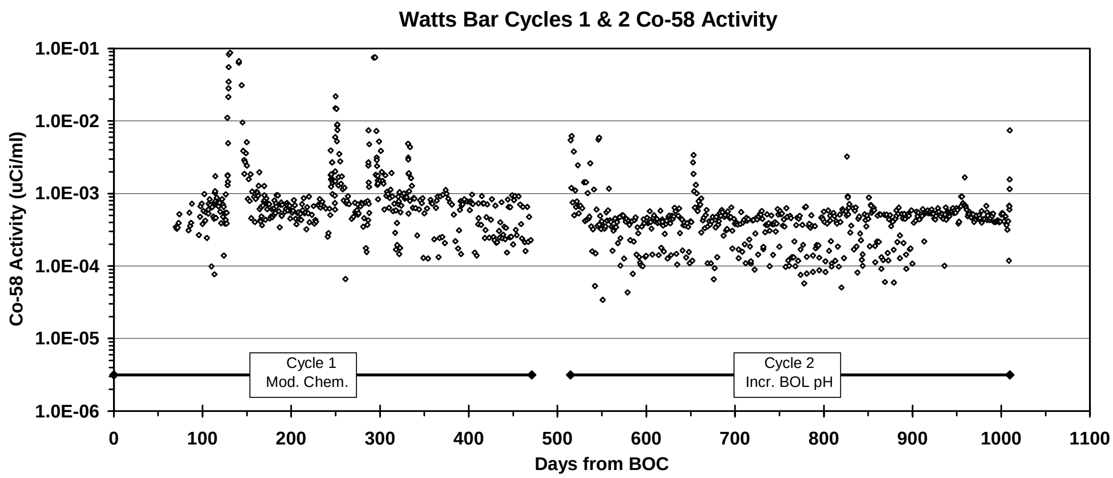
Figures 2-20 and 2-21 show the activity concentrations trends in Watts Bar 1. The plant only had two cycles of operation with the first cycle at a modified pH coolant and the second cycle with a nearly constant pH_{300} between 7.05 and 7.15. The activity data does not indicate any obvious difference in trends between the two types of chemistry operation. However, it should be noted that owing to the relatively low initial boron concentration during cycle 1, the change in pH over the cycle was much smaller at Watts Bar as compared to other operating plants. That is, the other plants in the program generally began modified chemistry cycles with BOL coolant pH_{300} in the range of 6.85-6.95; the lowest pH_{300} at Watts Bar (i.e., at BOL) was approximately 7.1 and the modified pH regime was much more constant than at the other plants.

The activity concentrations tend to be more constant over time during the operating cycles as compared to trends observed at other plants. The activity concentrations during cycle 2 appear to be somewhat lower as compared to that in cycle 1. However, the (albeit limited) ^{60}Co data can be misleading since most of the cycle 1 values were measured during mid-cycle shutdowns. Thus, the cycle 1 concentrations in the range of 10^{-4} to 10^{-2} μCi/g reflect the associated activity increases during shutdown and are significantly higher than expected during normal plant operation.

Further, the interpretation of trends after only two cycles of plant operation is considered to be highly speculative. Additional operating data is desirable to evaluate the impact of increased BOL pH chemistry.

The extended power coastdown periods at the end of cycles 1 and 2 at Watts Bar appears to have an impact on the increasing activity level trends typically observed at the EOL for most plants. In particular, the EOL ^{58}Co concentrations remain relatively constant and do not tend to increase during the last several months of operation as is the trend at most other operating plant. The power coast down period is about 50 days for both cycles at Watts Bar. A similar but less dramatic effect was also noted in the South Texas plants during their relatively long (i.e., about 30 days) power coast-down periods. The amount of available EOL data is limited for the other nuclides and discernible trend could not be established.





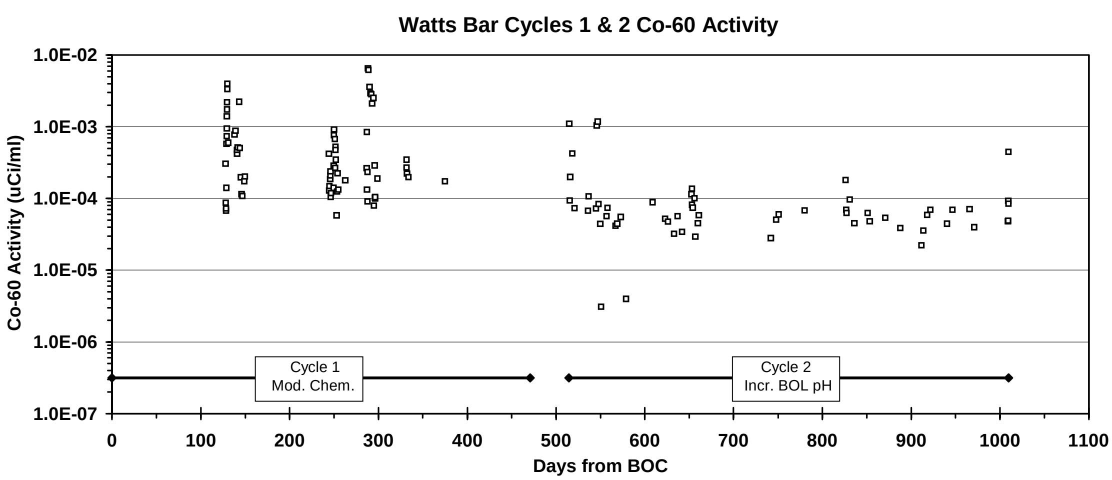
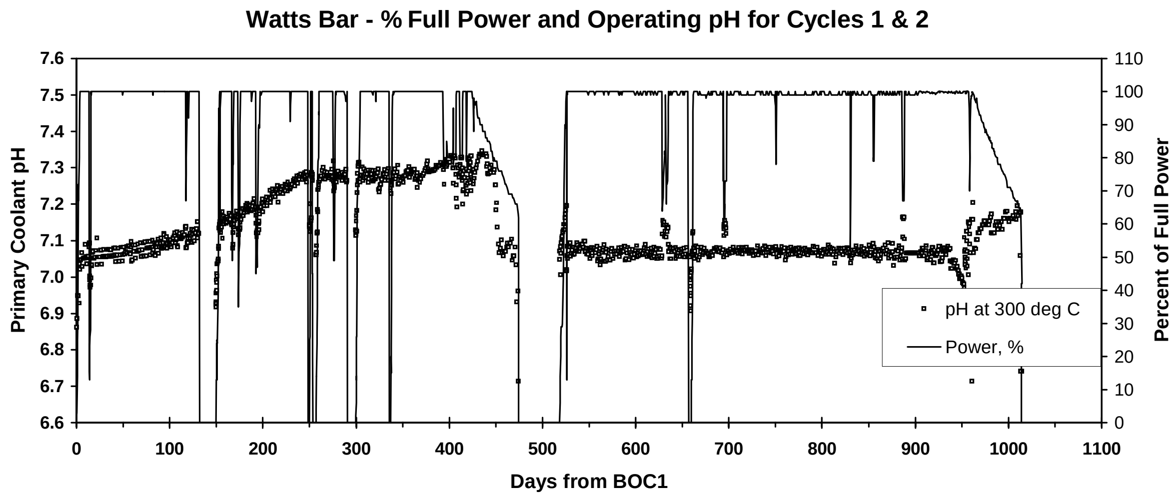
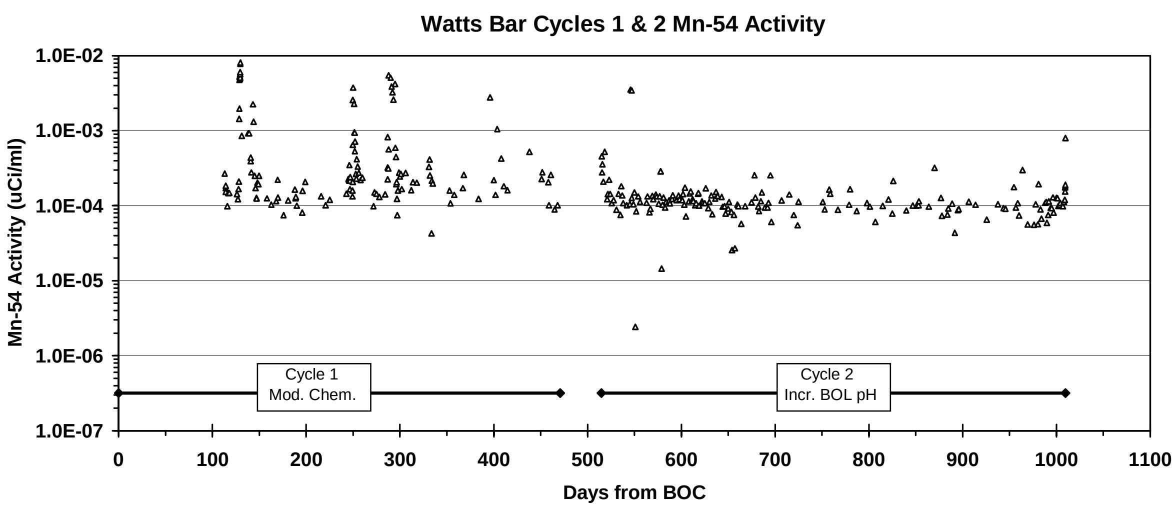


Figure 2-20
Watts Bar Primary Coolant Radiochemistry – ^{58}Co and ^{60}Co





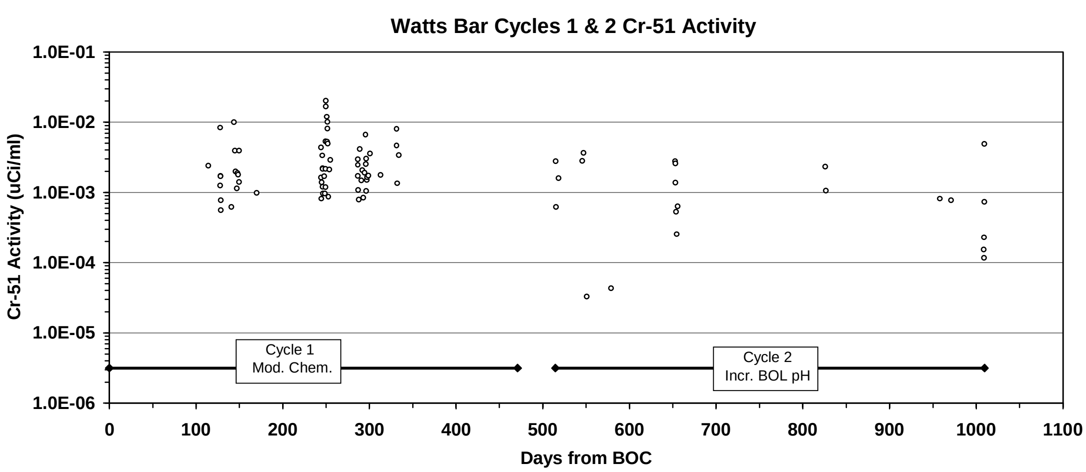


Figure 2-21
Watts Bar Primary Coolant Radiochemistry – ^{54}Mn and ^{51}Cr

2.1.3 Summary of Reactor Coolant Data

A review of the data from nineteen fuel cycles of operation associated with the participating plants results in the following observations:

- The activity concentration trends during each cycle for ^{58}Co, ^{60}Co, and ^{51}Cr generally follow a traditional U shape or "bathtub curve" relationship in plants operating with modified chemistry from the beginning to the end of the cycle. The ^{54}Mn activity concentration trend is somewhat different from that of the other nuclides in that it tends to continuously decrease during the cycle. In general, the trends of nuclide coolant activities over an operating cycle with increased BOL (or more constant) pH operation are similar to those associated with modified coolant chemistry operation. The overall magnitude of the (nominal) ^{58}Co activity concentrations during those cycles of operation with the more constant pH is generally less than the cycles operating with modified coolant chemistry. A similar but less obvious trend is noted for other nuclides.
- The ^{58}Co and ^{54}Mn activity trends in plant cycles with AOA appear to differ from traditional trends that are observed over cycles where AOA is not observed; the trends of ^{60}Co and ^{51}Cr do not appear to be significantly different. Since the parent elements of ^{58}Co and ^{54}Mn are nickel and iron, respectively, this pattern could indicate that nickel and iron deposition on the core is effected by sub-cooled boiling to a much greater extent than cobalt and chromium.
- Shutdowns during the cycle upset coolant activity trends in that the activity increases during the shutdown by factors of one to two orders of magnitude. The activities during power operation following the shutdown are generally higher than the pre-shutdown activity concentration and, depending upon the length of the shutdown, it generally takes from a few days to one to two months for the activity concentration to decrease to the pre-shutdown levels. Such large variation in the time to reach steady-state are possibly related to shutdown/startup procedures.
- Significant increases in activity concentrations are frequently observed at regular intervals over a core cycle. These increases are attributed to scheduled CRDM movements, but are not common to all plants.
- The ^{58}Co activity concentration during long (from about two to seven weeks) power coast-downs remains relatively constant. A similar effect could not be discerned for ^{60}Co and ^{54}Mn concentrations due to limitations in the amount of available data.

2.2 Shutdown Releases

The amounts of radiocobalts and nickel released during EOL shutdown evolutions were obtained from plant personnel or calculated based on shutdown data provided by plant personnel. The results are summarized in Table 2-2 along with other pertinent parameters including,

- Type of operating chemistry preceding the shutdown
- Previous cycle length in effective full power days (efpd)
- Range of pH during the cycle
- Difference in the pH range during the cycle

- Inventories of the radiocobalts released to the coolant during the shutdown
- Mass of nickel released to the coolant during the shutdown
- Specific activity of ^{58}Co in curies per unit mass of nickel (Ci/g)

Activities released during long maintenance or shutdowns were added to the activities released at the end of the operating cycle for both Watts Bar 1 cycle 1 and Seabrook cycle 6. However, the activities released during short shutdowns or power decreases were generally not considered for the other plants since the releases were relatively small.

The pH_{Tave} range was estimated from the figures in Section 2.1.1. This was used to assess relationships between shutdown releases, cycle length, and type of coolant chemistry operation. Results of this evaluation are presented in Section 3.0.

Table 2-2
Shutdown Release Data for Plants Using Increased BOL Chemistry

Plant	Cycle	Type Chemistry	Cycle Length (efpd)	pH_{Tave} Range	Δ pH_{Tave}	Shutdown Release			
						^{58}Co (Ci)	^{60}Co (Ci)	Ni (g)	$^{58}Co/Ni$ (Ci/g)
Callaway	8	Modified	504	6.95-7.40	0.45	1187	13.0	3878	0.31
Callaway	9	Mod-Coord.	448	7.15-6.95	- 0.20	1024	16.6	2986	0.34
Callaway	10	Coord.-Inc. pH	500	7.05-6.90	- 0.15	1947	19.5	4100	0.47
Com. Pk. 1	5	Modified	484	6.95-7.30	0.35	1333	11.1	3182	0.42
Com. Pk. 1	6	Modified	475	6.95-7.20	0.25	4299	37.6	6023	0.71
Com. Pk. 1	7	Increased pH	504	7.05-7.17	0.12	2939	63.5	8800	0.33
Com. Pk. 2	2	Modified	427	—	–	3080	32.6	3728	0.83
Com. Pk. 2	3	Modified	527	6.95-7.28	0.33	2954	90.0	8985	0.33
Com. Pk. 2	4	Increased pH	424	7.05-7.18	0.13	2839	–	7437	0.38
Seabrook	4	Modified	438	7.0-7.37	0.37	2160	23.5	3760	0.52
Seabrook	5	Modified	515	6.93-7.38	0.45	4802	30.6	7160	0.67
Seabrook	6	Increased pH	539	7.05-7.18	0.13	2042	–	7570	0.27
So. Texas 1	6	Modified	387	6.95-7.38	0.43	1984	10.6	3804	0.52
So. Texas 1	7	Modified	449	6.95-7.38	0.43	1700	13.0	4560	0.37
So. Texas 1	8	Increased pH	521	7.05	0.0	900	10.0	2876	0.31
So. Texas 1	9	Increased pH	299	7.15	0.0	415	9.2	2795	0.15
So. Texas 2	5	Modified	438	7.05-7.40	0.35	1487	13.3	3790	0.39
So. Texas 2	6	Modified	565	6.95-7.40	0.45	1404	19.4	3500	0.40
So. Texas 2	7	Increased pH	343	7.15	0.0	1024	9.6	2807	0.36
Watts Bar 1	1	Modified	421	7.15-7.40	0.25	1500	15.5	2160	0.69
Watts Bar 1	2	Increased pH	462	7.17-7.22	0.05	1200	27.0	4550	0.26

2.3 Radiation Fields

2.3.1 Plant Dose Rate Data

Dose rate data were received from the plants in accordance with the requirements established under the EPRI standard radiation monitoring program (SRMP). Figure 2-22 illustrates the location of the survey measurement points, and Table 2-3 gives a description and the rationale for the locations usually chosen as representative of the dose rate trends in the plant.

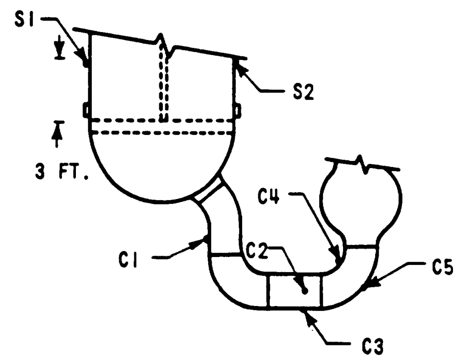
Table 2-3
Description of Dose Rate Measurement Locations

EPRI SRMP Point No.	Description	Rationale
2 and 10	Middle of SG channel head	Historical survey point
C5	Crossover piping below RCP	Represents stainless steel piping
S1 and S2	Exterior of SG tube bundle	Represents Alloy 600 tubing

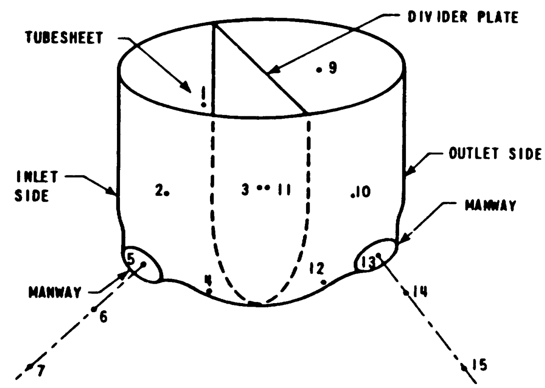
The average dose rate trends (i.e., average of measurements from all loops) at the three locations for the seven plants that were evaluated in the alternative chemistry follow program are presented in Figures 2-23 through 2-25. Indications of AOA in the plants, and the time when the chemistry was changed to increased BOL pH operation are noted in the figures.

Averages of plant radiation field measurements up to 1996 are generally from the last report issued for the SRMP [6]. Subsequent data accumulated for the plants is included in the Appendix. Also included in the Appendix is a tabulation of the values that are presented in Figures 2-23 through 2-25. Additional remarks regarding the data are included in this tabulation and are presented below:

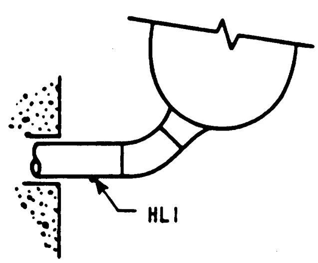
- The South Texas Units 1 and 2 piping data did not include loop B measurements since comments from site personnel indicated that the results from surveys performed at the end of cycles 9 and 7, respectively were suspect.
- Callaway data from survey point C2 loops A and D were used to represent piping trends. No data was taken for point C5 at the end of cycle 10 and data from loops B and C were highly inconsistent.
- Only data from loops B and C for points S1 and S2 were used to establish trends for the last four Callaway outages. Much of the prior data was taken when the steam generator was drained or was regarded as questionable.



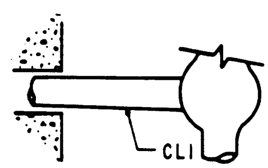
SG Tubing and Crossover Leg Piping



SG Channel Head

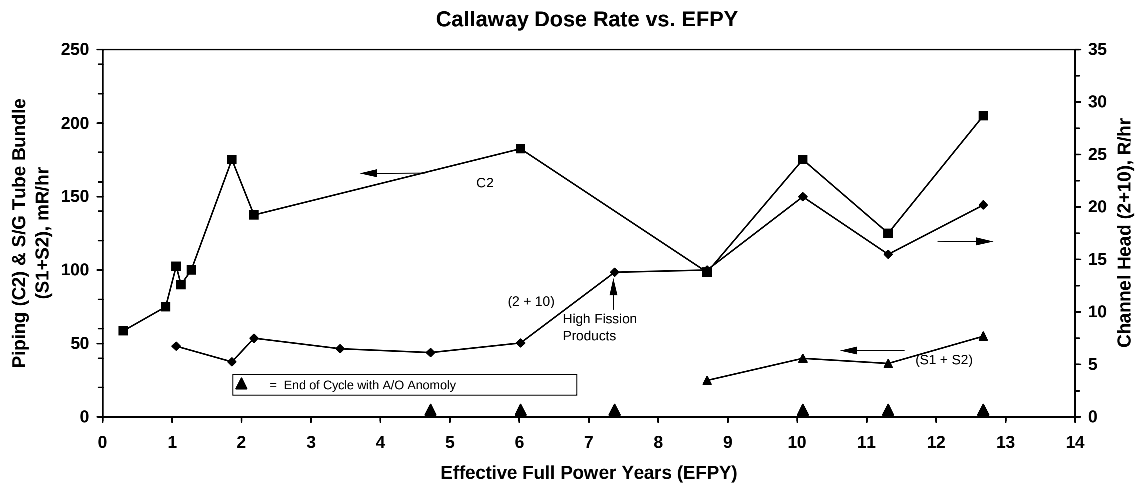


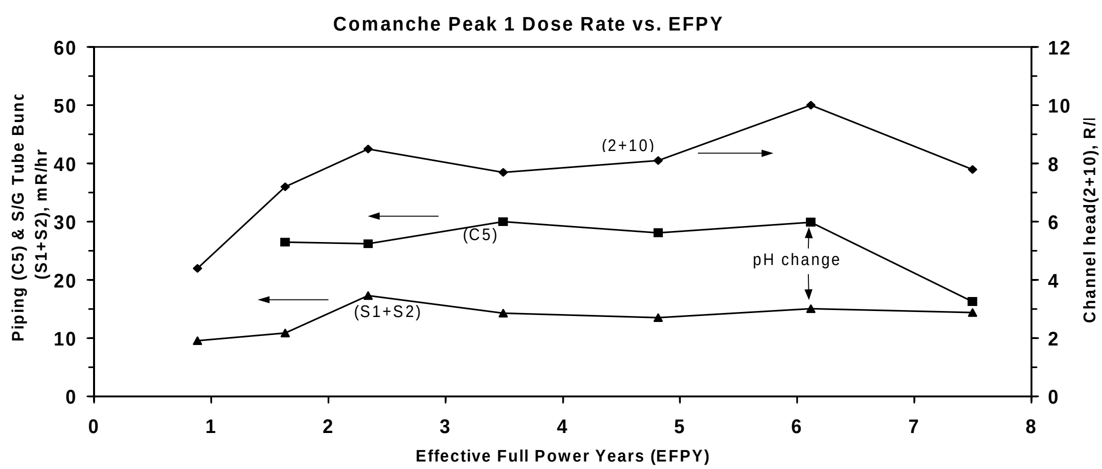
Hot Leg Piping



Cold Leg Piping

Figure 2-22
EPRI SRMP Measurement Locations





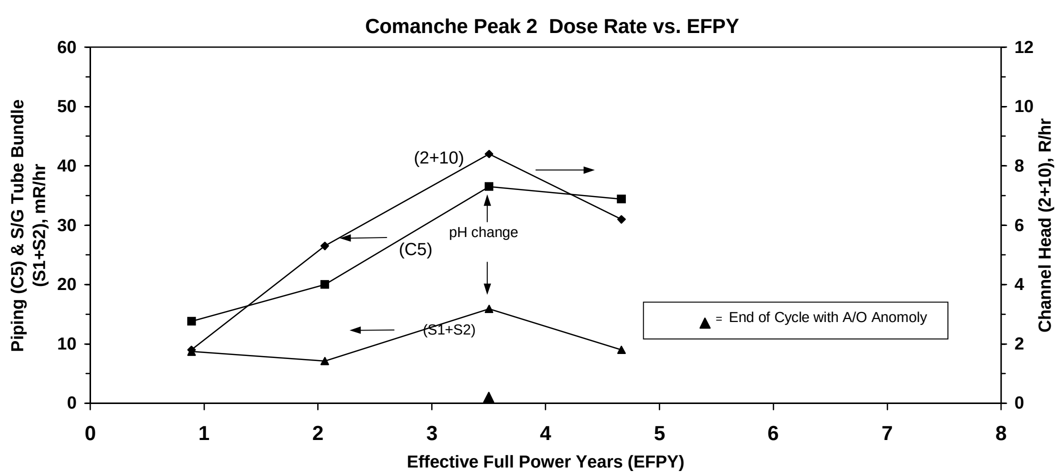
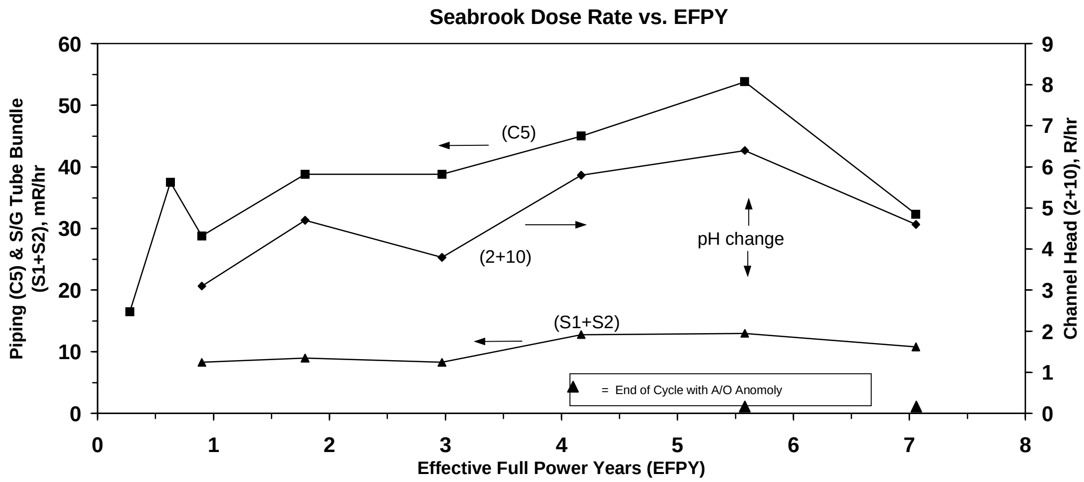
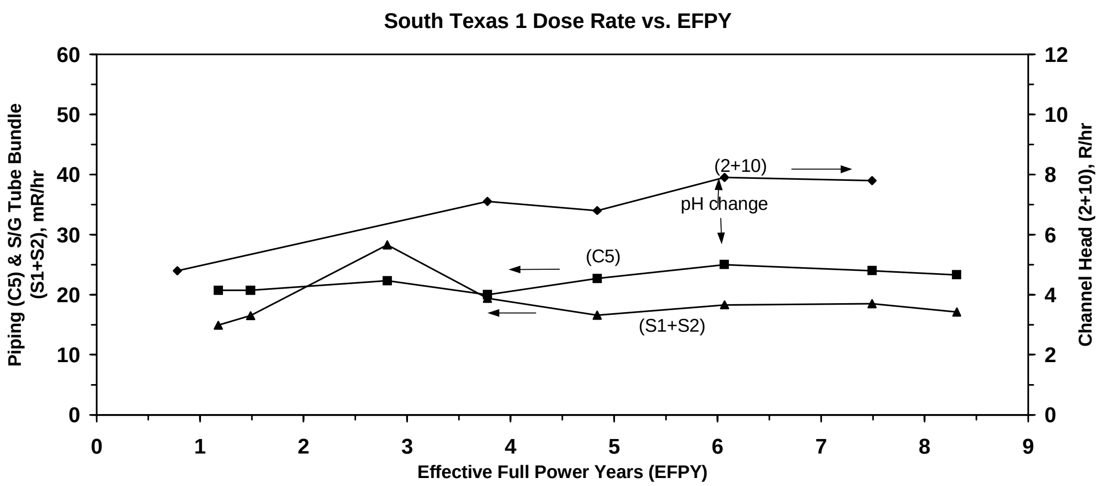


Figure 2-23
Dose Rates at SRMP Locations – Callaway and Comanche Peak 1 and 2





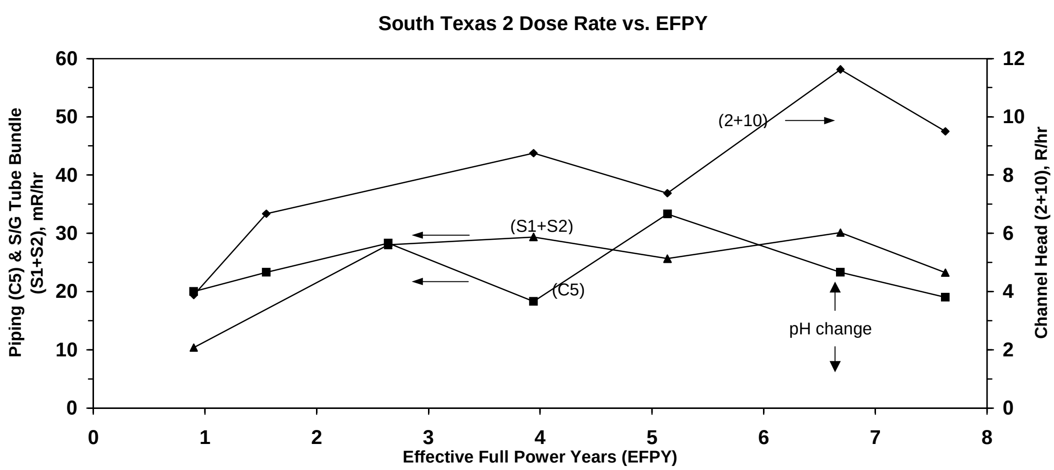


Figure 2-24
Dose Rates at SRMP Locations – Seabrook and South Texas 1 and 2

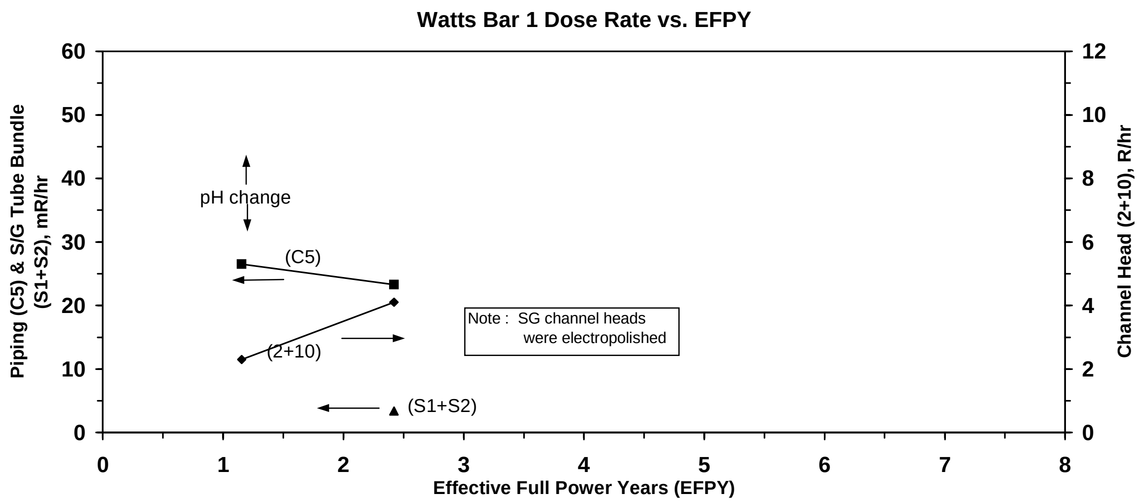


Figure 2-25
Dose Rates at SRMP Locations – Watts Bar

- For a number of plants, the average channel head dose rate included data from all the steam generators, but in some cases the data only reflects the number of steam generators that were inspected during the outage (normally two).
- If one or more surveys were taken during the same plant shutdown, the data were averaged to reflect the piping and steam generator tubing dose rates.

2.3.2 Summary of Radiation Field Data

A review of the radiation field data indicates that:

1. The dose rates approach an equilibrium level rather quickly (i.e., after about 2 to 3 efpy of operation). The dose rates outside of the steam generator and opposite the tube bundle tend to exhibit the least degree of variability in the measurements. The piping and steam generator channel head data are more inconsistent; steam generator channel head measurements vary the most. This trend is considered to be associated with the relative contributions of the major nuclides to the dose rates and indicates that the ^{58}Co activity in the deposits is more variable than the ^{60}Co activity. That is, for an unshielded dose rates inside a steam generator channel head, ^{58}Co is generally the dominant contributor to the measured dose rate. However, if the source is shielded by the pipewalls and/or steam generator lower assembly, the major dose contributor tends to be ^{60}Co. This is due to the fact that ^{60}Co emits gammas of higher energy than ^{58}Co (i.e, 1.17 and 1.3 MeV versus 0.8 MeV) and are not attenuated by shielding as much as the lower energy gamma rays.
2. Callaway, Comanche Peak 2, and Seabrook data trends indicate that dose rates, particularly in the channel head, increase significantly after cycles with AOA indications. This observation has been made in previous studies [7].
3. The dose rates at all locations in five plants that changed to the increased BOL pH operation have decreased after the cycle of the change. The Seabrook and Comanche Peak 2 data

suggest that the magnitude of the change may be related to high core crud levels since AOA was observed during the previous cycle of operation; greater reduction factors are observed at the end of a cycle that follows an operating cycle in which AOA was observed. However, dose rates decreased considerably at South Texas 2 and Comanche Peak 1 following the cycle with increased BOL chemistry even though there was no AOA in previous cycles.

4. The limited operating history of the Watts Bar plant does not lend itself to use in establishing representative dose rate trends. Further, the relatively low steam generator channel head dose rates reflect the beneficial effect of pre-operational electropolishing of the channel head bowl which adds an additional variable in the comparison of dose rates at this location to data from other plants.

2.4 Fuel Boiling Duty

Section 1 suggested that one of the potential benefits associated with increased BOL pH chemistry control is a reduction in the production and transport of crud deposits to the fuel cladding surfaces, thereby reducing the potential for the axial offset anomaly (AOA). It is generally recognized that significant crud deposition on fuel cladding is a necessary condition for the occurrence of AOA. Further, plants that are susceptible to AOA appear to be those that have high coolant temperatures, high power feed assemblies, and sub-cooled boiling heat transfer.

Plant experience indicates that cycles with a large amount of sub-cooled boiling in the core are more prone to AOA, but not all plants with the same degree of sub-cooled boiling show the anomaly. This is evidenced by the data tabulated in Table 2-4, which includes the lead channel mass evaporation rate for the plant cycles addressed in this report. The cycles during which AOA was experienced are also specified in the table, along with the maximum AO deviation observed during the cycle. The mass evaporation rate data is also presented in Figure 2-26 for the cycles in which the plant operated with increased BOL pH chemistry and the two cycles preceding this cycle.

The participating plants that observed AOA were Callaway (cycles 8, 9, and 10) and Seabrook (cycle 5), with some indications prior to mid-cycle shutdowns during cycle 6 at Seabrook and possible AOA occurrence at Comanche Peak Unit 2 during cycle 3. As shown in the table and figure, the mass evaporation rates for all three cycles at Callaway and cycle 5 at Seabrook are relatively high. However, the values for all of the operating cycles at South Texas Units 1 and 2 exceed the value associated with the AOA cycle 5 at Seabrook. This confirms the view that the occurrence of AOA cannot be linked to a single parameter. The axial offset anomaly is a complex phenomenon that has received considerable industry attention and research. The presence or absence of AOA was considered in the interpretation of the data gathered for this program, since it is recognized that core crud buildup is necessary for AOA and also influences plant radiation fields.

Table 2-4
Comparison of Mass Evaporation Rate and AOA Experience

Plant	Cycles	Calculated m-dot-e	AOA Observed	Maximum AO Deviation
Callaway	8	307	Yes	-7
	9	320	Yes	-14
	10	267	Yes	-8
Comanche Peak 1	5	179	No	
	6	249	No	
	7	239	No	
Comanche Peak 2	2	224	No	
	3	218	Yes	-3.5
	4	158	No	
Seabrook	4	227	No	
	5	254	Yes	-3
	6	240	Yes	-2
South Texas 1	6	269	No	
	7	269	No	
	8	300	No	
	9	288	No	
South Texas 2	5	266	No	
	6	289	No	
	7	291	No	
Watts Bar	1	196	No	
	2	228	No	

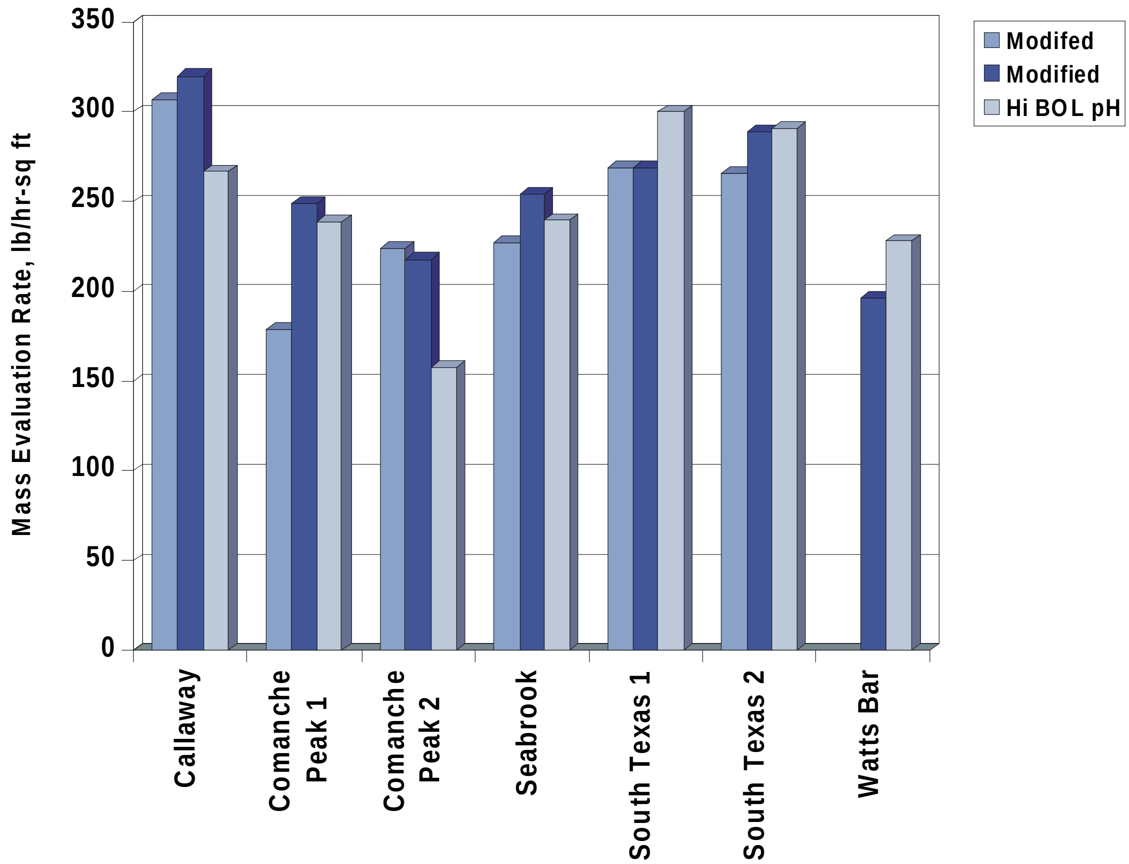


Figure 2-26
Mass Evaporation Rate by Plant and Cycle

2.5 References

1. Lindsay, W. T., Jr., "Computer Program BLITHFPU, and adaptation of program PHBLI," Lindsay and Associates, April 1985.

2. "PWR Primary Water Chemistry Guidelines, Volume 1, Revision 4," EPRI TR-105714-V1R4, March 1999.

3. "Evaluation of Zinc Addition During Cycle 9 at Diablo Canyon Unit 1," EPRI TR-113540, November 1999.

4. "Evaluation of Zinc Addition in Cycle 12 at Farley Unit 2," EPRI TR-111349, December 1998.

5. Riddle, J. M. "Power Operation for High pH Chemistry," paper presented at EPRI PWR Primary Startup and Shutdown Chemistry Workshop, San Antonio, TX, April 2000.

6. Bergmann, C. A. and Bencini, R. L., "Evaluation of PWR Radiation Fields: 1991-1996," EPRI TR-107566, February 1997.

7. Kormuth, J. W. et al, "Preliminary Report on Evaluation of Plant Design and Power Operation Data," Part 1, Rev. 1, March 1999.

3
EVALUATION OF PLANT DATA

3.1 Chemistry/Radiochemistry Considerations

3.1.1 Effect of Increased BOL pH Chemistry on Coolant Activities

As noted in the previous section, the coolant activity tends to be lower during the cycles with increased BOL pH chemistry as compared to cycles operating with modified pH coolant chemistry. This was particularly evident in the South Texas 1 plant (see Figure 2-16). To quantify this trend, the average coolant activities for the radiocobalts, ^{54}Mn and ^{51}Cr were calculated. Only the activity concentrations during operation were considered, and the large activity increases seen during startup, shutdown, and power changes were not included in the averages. The data for the Callaway plant were included in the comparison even though there were deviations from the intended operating chemistry regime due to the onset of AOA. However, the observed changes in concentration with pH changes are of interest and are included in the evaluation of the data.

The average coolant activity data for the seven plants that were evaluated are included in Table 3-1. In most cases the average activity concentration is lower in the cycle with the increased BOL pH operation. Also note the relatively high activities associated with the Callaway plant which also exhibited the most significant axial offset indication (see Section 2.4). The AOA indications would, thus reflect a relatively high core crud buildup.

The ratio of the concentrations in the increased BOL pH cycle to that in the modified pH cycle is given in Table 3-2. The table indicates that the average coolant activity concentrations range from 20% to 32% less after one cycle of increased BOL pH chemistry as compared to the previous cycle with modified chemistry. The results are reasonably consistent (there are only two exceptions), and indicate that the increased pH chemistry results in a lower average coolant activity for all reported nuclides.

Table 3-1
Average Coolant Activities During Operation

Plant	Cycle	Activity Concentration, µCi/ ml			
		^{58}Co	^{60}Co	^{54}Mn	^{51}Cr
Callaway	8	2.9×10^{-3}	7.9×10^{-5}	1.0×10^{-4}	1.1×10^{-3}
Callaway	9	8.4×10^{-3}	1.2×10^{-4}	1.6×10^{-4}	–
Callaway	10	5.2×10^{-2}	6.9×10^{-4}	1.8×10^{-3}	5.4×10^{-3}
Comanche Peak 1	6	4.8×10^{-4}	2.3×10^{-5}	7.9×10^{-5}	9.89×10^{-4}
Comanche Peak 1	7	2.8×10^{-4}	1.8×10^{-5}	2.3×10^{-5}	1.4×10^{-4}
Comanche Peak 2	3	1.0×10^{-3}	3.0×10^{-5}	–	–
Comanche Peak 2	4	6.5×10^{-4}	2.7×10^{-5}	1.8×10^{-4}	3.6×10^{-5}
Seabrook 1	4	1.5×10^{-3}	2.8×10^{-5}	8.3×10^{-5}	2.4×10^{-4}
Seabrook 1	5	2.0×10^{-3}	5.9×10^{-5}	9.8×10^{-5}	4.1×10^{-4}
Seabrook 1	6	1.1×10^{-3}	3.5×10^{-5}	8.9×10^{-5}	3.8×10^{-4}
South Texas 1	6	1.4×10^{-3}	4.2×10^{-5}	9.3×10^{-5}	–
South Texas 1	7	5.2×10^{-4}	4.6×10^{-5}	9.0×10^{-5}	–
South Texas 1	8	3.4×10^{-4}	6.0×10^{-5}	1.1×10^{-4}	–
South Texas 1	9	2.6×10^{-4}	3.4×10^{-5}	8.1×10^{-5}	–
South Texas 2	5	8.4×10^{-4}	6.6×10^{-5}	9.2×10^{-5}	–
South Texas 2	6	1.1×10^{-3}	6.9×10^{-5}	1.1×10^{-4}	–
South Texas 2	7	9.3×10^{-4}	5.7×10^{-5}	1.0×10^{-4}	–
Watts Bar 1	1	6.4×10^{-4}	1.8×10^{-4}	2.3×10^{-4}	2.2×10^{-3}
Watts Bar 1	2	0.44×10^{-3}	10.6×10^{-5}	1.6×10^{-4}	1.5×10^{-3}

Table 3-2
Ratio of Average Coolant Activity – Increased BOL pH / Modified Chemistry

Plant / Cycles	^{58}Co	^{60}Co	^{54}Mn
Comanche Peak 1/ 6 and 7	0.58	0.80	0.29
Comanche Peak 2/ 3 and 4	0.65	0.89	–
Seabrook / 5 and 6	0.58	0.59	0.91
South Texas 1 / 7, and 8	0.65	1.31	1.19
South Texas 1 / 8, and 9*	0.76	0.56	0.76
South Texas 2 / 6 and 7	0.85	0.83	0.94
Watts Bar 1 / 1 and 2	0.69	0.60	0.68
Average	0.68	0.80	0.80

*Ratio of second cycle with increased pH / first cycle with increased pH

Also note that the second cycle of operation with increased BOL pH at South Texas 1 has lower activity levels than those observed during the first cycle, indicating a continuing beneficial effect.

Coolant activity data in several other operating plants were also reviewed to determine if similar activity trends occurred in plants that had not converted to the increased pH chemistry. Available data was limited to that from the Diablo Canyon 1 and the Vogtle 1 and 2 plants [1,2]. The radiocobalt activity concentrations in the coolant during cycles 4 to 8 for Diablo Canyon 1, cycles 6 to 9 for Vogtle 1, and cycles 4 to 7 for Vogtle 2 are presented in Figures 3-1 to 3-3, respectively. Cycles during which AOA was observed at the Vogtle units are indicated on the figures.

The data from Diablo Canyon Unit 1 indicate that both ^{58}Co and ^{60}Co concentrations appear to be somewhat higher in cycles 4 and 5 compared to those in cycles 6, 7, and 8. Similarly, a decreasing trend in radiocobalt activities is observed in Vogtle 1 from cycles 6 and 7 as compared to those in cycles 8 and 9 and in Vogtle 2 from cycles 4 and 5 to those in cycles 6 and 7. However, the differences in the nominal activity levels are relatively small and a sampling of three plants is not considered sufficient to draw definitive conclusions. Also, AOA was detected in both of the Vogtle units in the cycles with the higher concentrations; and the observations from the plants evaluated in this report show that the activity trends are influenced by the accumulation of core crud which can result in AOA.

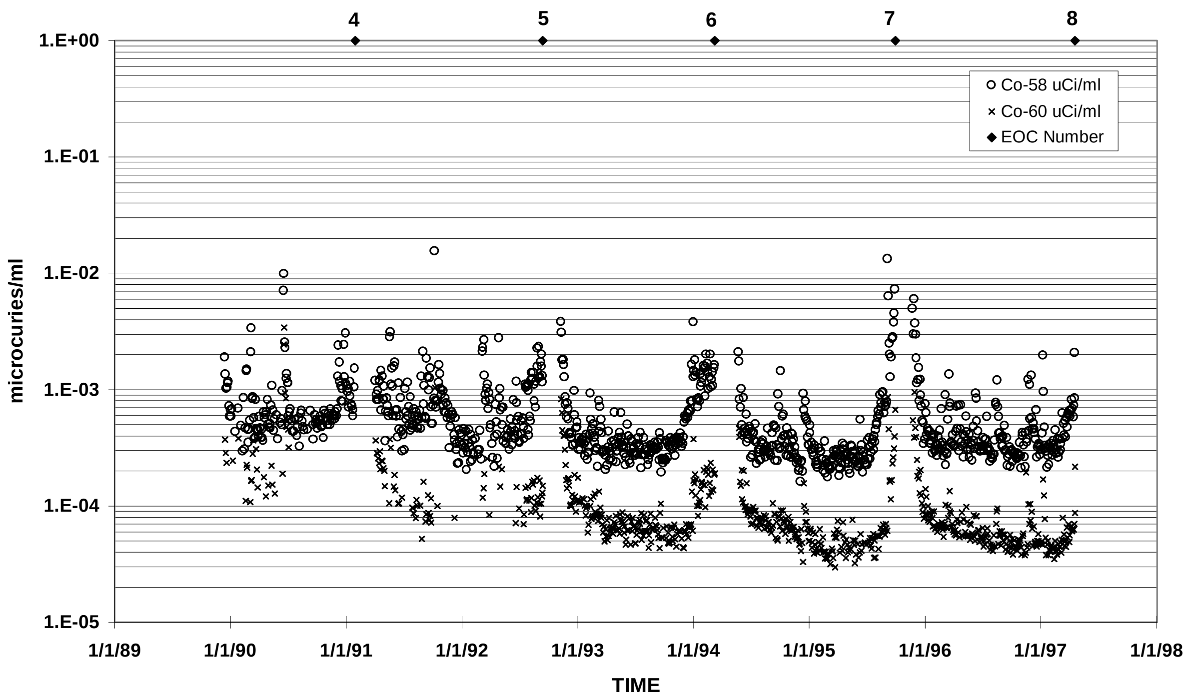
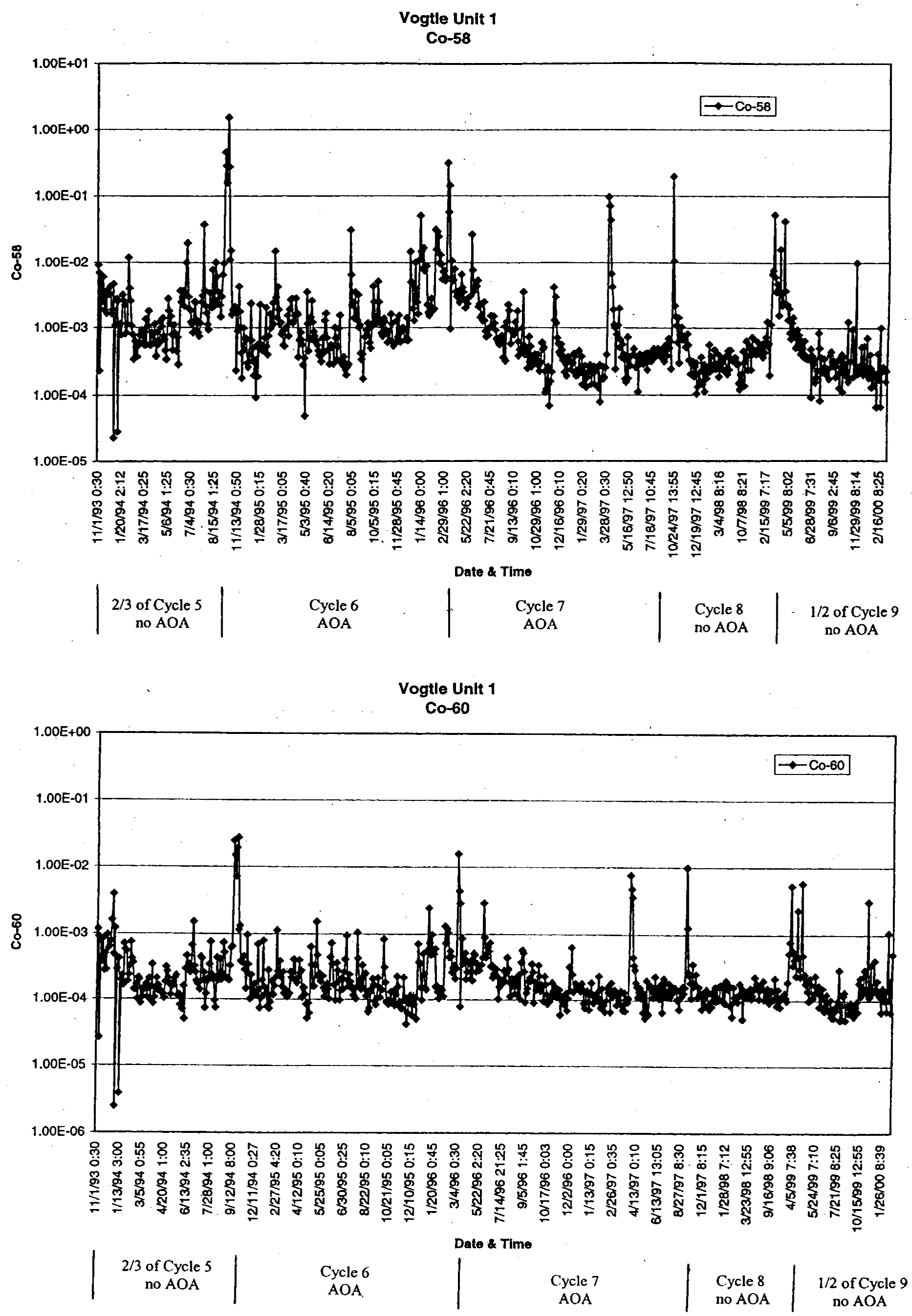


Figure 3-1
RCS Radiocobalt Activities - Diablo Canyon Unit 1–Cycles 4-8



Source: Reference 2

Figure 3-2
RCS Radiocobalt Activities - Vogtle Unit 1–Cycles 5-8

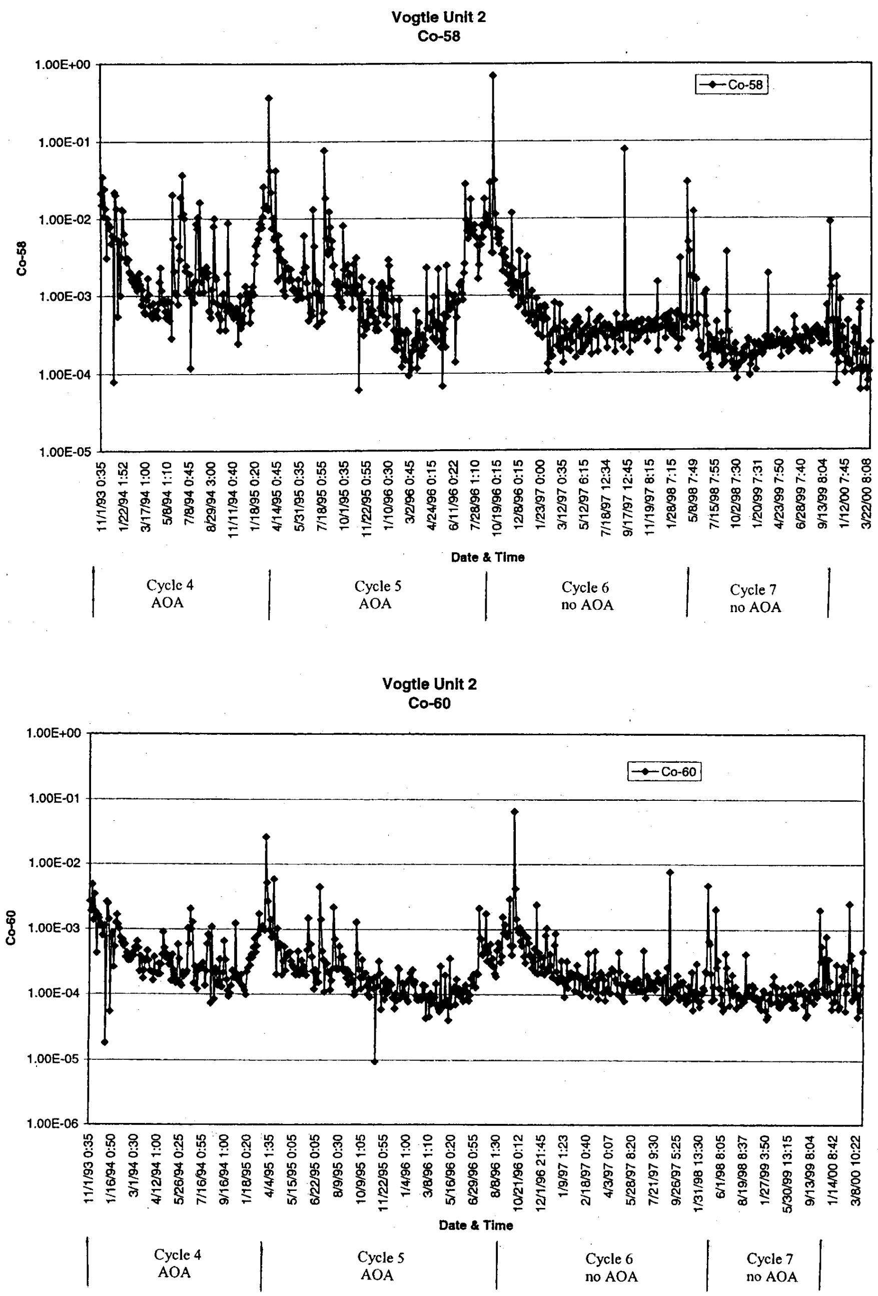


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Figure 3-3
RCS Radiocobalt Activities - Vogtle Unit 2–Cycles 4-7

3.1.2 Relationship of Coolant pH and Activity Concentrations

As noted in Section 2.1.2.1, the coolant activity levels at the Callaway plant begin to increase about mid-way through cycles 9 and 10. Figure 2-1 shows that these increases correspond to the times when the coolant pH_{Tave} decreased from an average of about 7.05 to 6.95 during cycle 9 and from 7.08 to about 6.93 during cycle 10. This increase can be attributed to the effect of the pH change on the solubility of the parent elements of the nuclides. In order to investigate the effect of the reduction in pH in more detail, the average radiocobalt and ^{54}Mn concentrations and average pH values were calculated for the four different periods during the cycles in which pH was held at a nearly constant value. Coolant concentration data from those cycles at South Texas and Watts Bar, where operation was at essentially constant pH for the complete cycle, were also considered. The data is presented in Table 3-3.

Table 3-3
Average pH and Activity Concentrations During Constant pH Periods

Plant	Cycle	Time in Cycle	pH_{Tave}	pH_{300}	^{58}Co (µCi/g)	^{60}Co (µCi/g)	^{54}Mn (µCi/g)
Watts Bar	2	Complete	7.17	7.07	4.4×10^{-4}	1.1×10^{-4}	1.6×10^{-4}
So. Tex. 1	9	Complete	7.15	7.06	2.6×10^{-4}	3.4×10^{-5}	8.1×10^{-5}
So. Tex. 2	7	Complete	7.15	7.06	9.3×10^{-4}	5.7×10^{-5}	1.0×10^{-4}
Callaway	10	First third	7.06	6.96	2.9×10^{-3}	8.7×10^{-5}	9.1×10^{-4}
So. Tex. 1	8	Complete	7.05	6.96	3.4×10^{-4}	6.0×10^{-5}	1.1×10^{-4}
Callaway	9	First half	7.01	6.95	2.0×10^{-3}	5.4×10^{-5}	5.3×10^{-5}
Callaway	10	Last 2/3	6.93	6.80	7.8×10^{-2}	1.0×10^{-3}	8.2×10^{-3}
Callaway	9	Second half	6.91	6.85	2.1×10^{-2}	2.5×10^{-4}	3.7×10^{-4}

The activity data in this table is plotted in Figure 3-4, for ^{58}Co, ^{60}Co, and ^{54}Mn. The plots include an exponential fit of the data with reasonable correlation coefficients. Thus, the data suggests an inverse relationship between the coolant concentration and pH for pH_{Tave} and pH_{300} values in the ranges of 6.9 to 7.2 and 6.8 to 7.1, respectively. A similar inverse relationship was noted between the total radiocobalt activities and pH_{300} from the range of 6.83 to 7.25 in the Beznau 2 plant and in the Vandellos 2 plant at pH_{Tave}, in the range of 7.2 to 7.4 for both the insoluble and soluble radiocobalt species [3,4].

However, it should be noted that there are potential influencing factors other than pH associated with the Callaway data that may affect the observed coolant concentrations, e.g., (1) the addition of ammonia to the coolant during the last half of cycle 9 and all of cycle 10, and (2) AOA indications during the cycles.

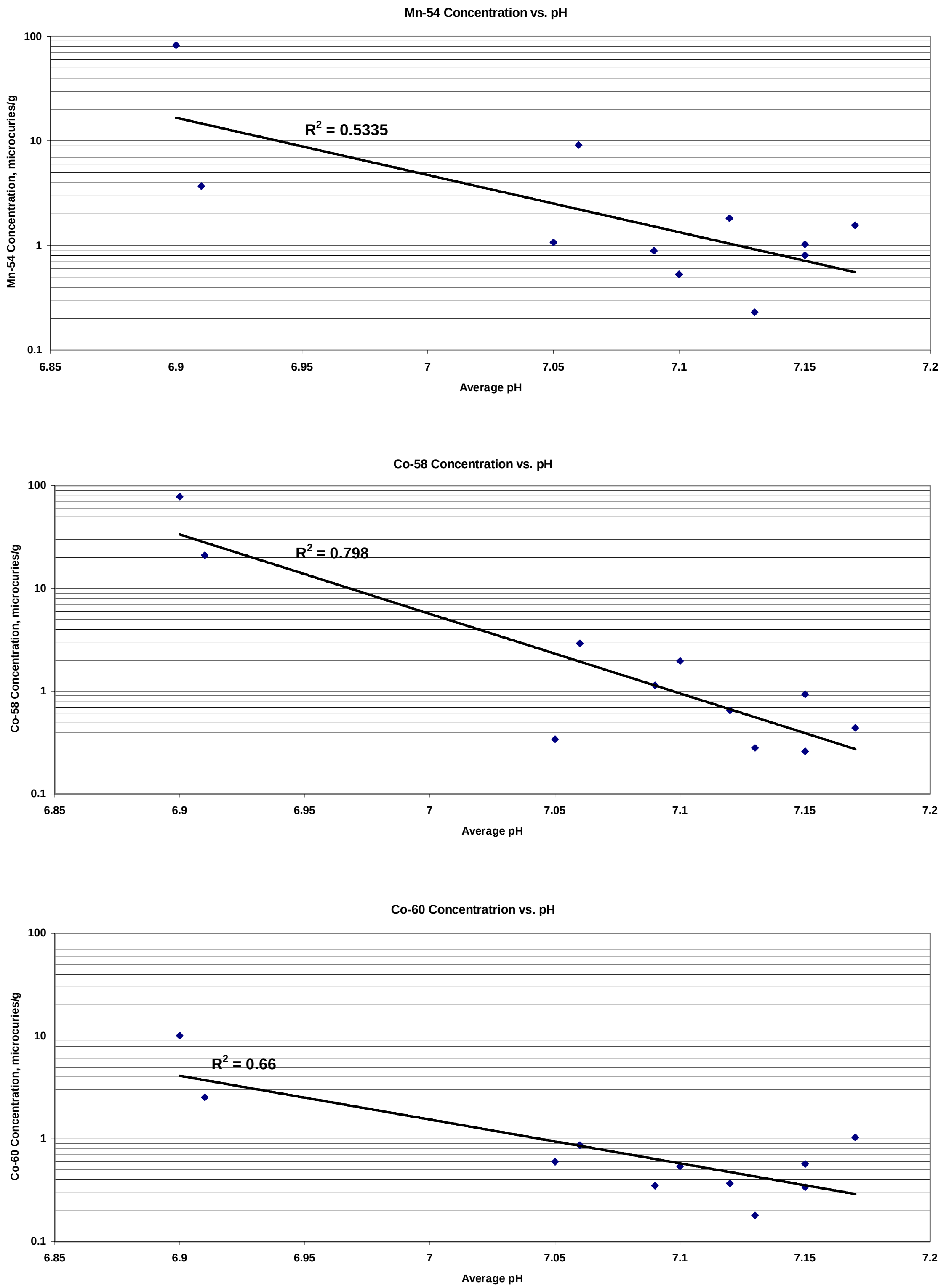


Figure 3-4
Correlations of Activity Concentrations with Coolant pH

3.2 Radiation Field Comparisons

3.2.1 Changes in Radiation Fields with Increased BOL pH Operation

As noted in Section 2.3, the dose rates after the cycle with the increased BOL pH operation decreased compared to those in the prior cycles. The ratio of the dose rates for the two cycles; i.e., before and after conversion to increased BOL pH chemistry, were determined and used as a quantitative measure of the difference. The results are tabulated in Table 3-4, where the data were obtained at the EPRI SRMP measurement locations (Figure 2-22). The dose rate changes in Callaway are not included in this evaluation since the plant did not maintain the increased BOL pH chemistry program over a complete cycle of operation. Watts Bar data has also been excluded owing to the limited operating time (two cycles) of the plant and the associated uncertainties in distinguishing between cycle to cycle changes based on time dependent factors other than pH.

Table 3-4
Ratio of Dose Rates at SRMP Locations

Plant	Cycle	Average Dose Rate at SRMP Location,			Ratio of Dose Rates, Inc. BOL pH / Modified			Ratio
		Avg. C5 (mR/hr)	Avg.S1 and S2 (mR/hr)	Avg. 2 and 10 (R/hr)	C5	S1 and S2	2 and 10	
Com. Peak 1	6	29.9	15.0	10.0				
Com. Peak 1	7	16.3	14.4	7.8	0.54	0.96	0.78	0.76
Com. Peak 2	3	36.5	15.9	8.4				
Com. Peak 2	4	34.4	9.0	6.2	0.94	0.57	0.74	0.75
Seabrook / 5	5	53.8	13.0	6.4				
Seabrook / 6	6	32.2	10.8	4.6	0.60	0.83	0.72	0.72
So. Texas 1	7	25.0	18.3	7.9				
So. Texas 1	8	24.0	18.5	7.8	0.96	1.01	0.99	0.99
So. Texas 1	9	23.3	17.1	–	0.97	0.92	–	0.95
So. Texas 2	6	23.3	30.1	11.6				
So. Texas 2	7	19.0	24.6	9.5	0.82	0.82	0.82	0.82

The results in Table 3-4 show that the change in radiation fields varied from being unchanged in some plants to exhibiting decreases of as much as 28% in other plants, with an average reduction of 17%. Further, the dose rates at South Texas 1 after the second cycle of increased BOL pH operation decreased by another 5%. The largest dose rate reduction was observed in the two plants (Comanche Peak 2 and Seabrook) that experienced AOA in the cycle prior to implementation of increased BOL pH operation. Seabrook also had several long mid-cycle shutdowns during cycle 6, which may have contributed to the lower dose rates. However, the reduction factors in two other plants that did not experience AOA (Comanche Peak 1 and South Texas 2), are similar in magnitude. Possible reasons for the relatively large reductions in their dose rates include operational events that could have resulted in unusually high radiation fields during the outage preceding the one which was operated with increased BOL pH chemistry:

1. At Comanche Peak Unit 1, the pH was reduced during the cycle preceding the cycle with increased BOL pH for reasons related to AOA in Unit 2. This resulted in increased coolant activities and higher EOL dose rates (Table 3-1 and Figure 2-23).

2. As shown in Figure 2-6, the South Texas 2 plant operated for approximately 230 days of cycle 6 (39% of the cycle time) below a pH_{300} of 6.9. Such operation may have caused additional deposition and transport of corrosion products relative to that in other cycles and a corresponding increase in radiation fields (Figure 2-24) [5].

The above considerations suggest the reduction in dose rates to be expected after implementation of the high BOL pH chemistry may be on the lower end of the measured range. However, the results from the second cycle of operation with the increased BOL pH chemistry at South Texas Unit 1 are encouraging in that the high pH chemistry appears to provide a continuing dose reduction benefit. Data from additional cycles of operation data are necessary to confirm this trend and to further define the magnitude of the reductions that can be expected.

3.2.2 Dose Rate and Coolant Activity Relationships

The plant measurements indicate that both the coolant activities concentrations during operation and the shutdown dose rates were lower with increased BOL pH coolant chemistry as compared to that in prior cycles. The average coolant activities were evaluated to determine if a fixed proportionality existed between the activities and the shutdown dose rates.

Since dose rates depend on the energy and magnitude of the gamma emissions from the contributing nuclides, the average coolant activities were converted to a relative gamma source strength and normalized to the values associated with the cycle preceding the cycle of operation with the increased BOL pH chemistry. The following approximation was used in deriving the relative gamma sources:

$$S_{eff} \propto (C_x \cdot E_x + C_y \cdot E_{y\,+} C_z \cdot E_z)$$

where:

S_{eff} = “effective” gamma source for coolant activity

C_x = coolant concentration of ^{58}Co, μCi/g

E_x = gamma energy per disintegration for ^{58}Co = 0.97 MeV/dis

C_y = coolant concentration of ^{60}Co, μCi/g

E_y = gamma energy per disintegration for ^{60}Co = 2.51 MeV/dis

C_z = coolant concentration of ^{54}Mn, μCi/g

E_z = gamma energy per disintegration for ^{54}Mn = 0.84 MeV/dis

The normalized source term and channel head dose rate ratios for the two cycles (i.e., after chemistry change / before chemistry change) are given in Table 3-5. Although both sets of data are less than one, indicating a reduction in dose rates and the activity/source values after conversion to the increased BOL pH chemistry, the values are not consistent. Thus, there does not appear to be a proportional relationship between the dose rates and the coolant activities.

Table 3-5
Dose Rate and Normalized Coolant Activity Ratios

Plant	Cycles	S/G Channel Head Dose Rate Ratio	Ratio of Normalized Primary Coolant Source Term
Comanche Peak 1	6 and 7	0.78	0.57
Comanche Peak 2	3 and 4	0.74	0.81
Seabrook	5 and 6	0.72	0.59
South Texas 1	7 and 8	0.99	0.82
South Texas 2	6 and 7	0.82	0.87

3.2.3 Dose Rate and Fuel Boiling Duty Relationships

The fuel boiling duty and AOA data presented in Section 2.4 are not adequate to support a clear influence of increased BOL pH chemistry on AOA. However, the possible benefits of increased BOL pH chemistry are not expected to manifest themselves after only one fuel cycle, because it requires longer times to change existing crud deposits on RCS surfaces. Further, none of the participating plants that experienced AOA were able to operate with a constant pH for 100% of the cycle. Changes to pH were made at some of these plants in order to minimize lithium to alleviate AOA.

However, the data evaluation does appear to indicate an increasing trend in coolant activities (primarily for ^{58}Co) and subsequent shutdown radiation fields with the incidence of AOA. Further if mass evaporation rate has a correlation with AOA, one might expect a correlation of boiling duty and plant radiation fields. The relevant data is shown in Figure 3-5.

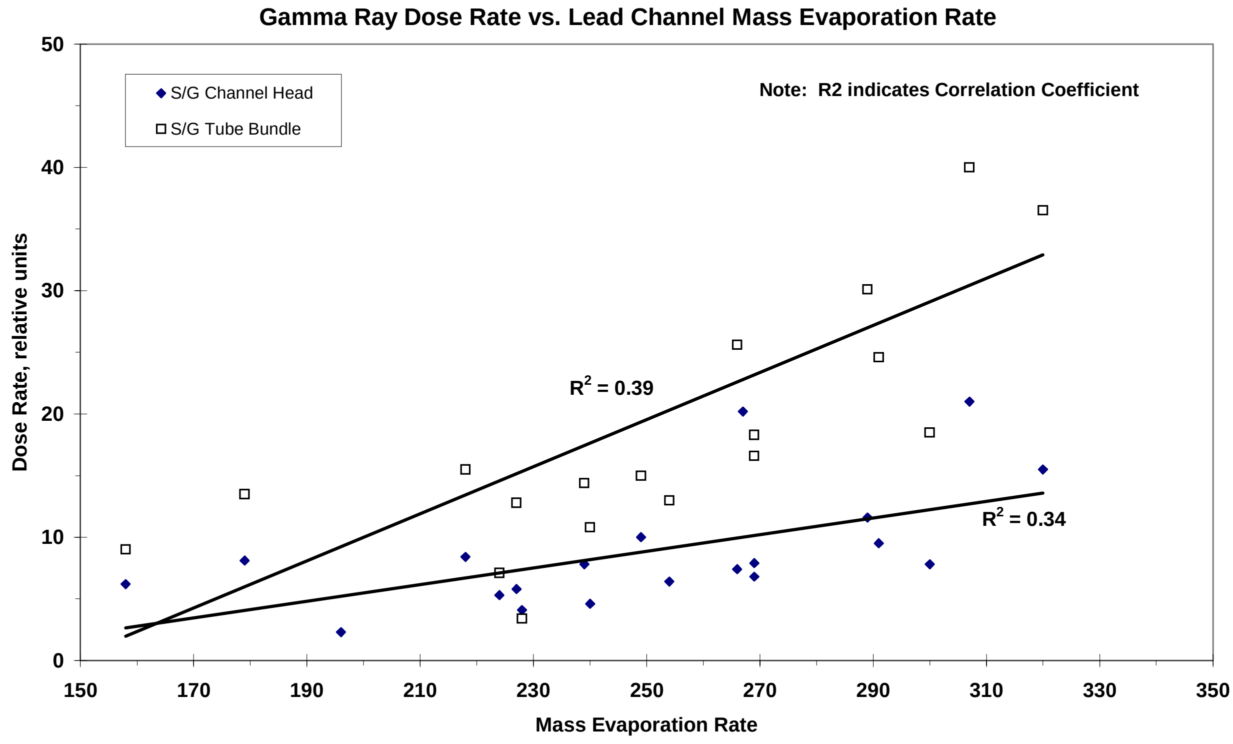


Figure 3-5
Correlations of Radiation Fields and Fuel Boiling Duty

The figure presents a plot relative dose rates for the steam generator channel head general area and dose rates measured outside the steam generator lower assembly (opposite the tube bundle) with mass evaporation rates. Linear fits of the data indicate reasonable correlations with correlation coefficients of about 0.3-0.4. A correlation with RCS piping dose rates was also evaluated, but the correlation coefficient was determined to approach zero (< 0.001) in this case.

The results of the dose rate and fuel boiling duty trends are interesting and worthy of additional investigation. The relatively high correlation coefficients for at least some of the dose rate measurements suggest that radiation fields are a function of parameters related to fuel boiling duty. However, it does not imply that plant radiation fields are a simple function of fuel boiling duty. Just as AOA is a complex phenomenon, crud transport is also extremely complex and is a function of many other influencing parameters.

3.3 Shutdown Releases

The amounts of radiocobalt activity and nickel released during refueling shutdowns were examined with respect to the potential relationship of the releases with the increased BOL pH cycle (and the preceding cycle), the cycle length, and the pH range during the cycle.

3.3.1 Effect of Increased BOL pH on Refueling Shutdown Releases

The shutdown release data (Table 2-2) indicates that the amount of ^{58}Co released during the cycle with increased BOL pH operation is consistently less than that released during the prior cycle with modified pH operation. These values are compared and presented in Table 3-6 as the ratio of inventory released at the end of the increased BOL pH cycle to that associated with the preceding cycle with modified pH. Activities released during long maintenance or shutdowns were added to the activities released at the end of the operating cycle for both Watts Bar cycle 1 and Seabrook cycle 6. However, the activities released during short shutdowns or power decreases were generally not considered for the other plants since the releases were relatively small.

Table 3-6
Shutdown Activity Release Ratios

Plant	Cycles	Ratio of Shutdown Releases at EOL (Inc. BOL pH Cycle / Modified pH Cycle)		
		^{58}Co	^{60}Co	Nickel
Comanche Peak 1	6 and 7	0.68	1.69	1.46
Comanche Peak 2	3 and 4	0.96	–	0.83
Seabrook	5 and 6	0.43	–	1.06
South Texas 1	7 and 8	0.53	0.77	0.63
South Texas 1	8 and 9	0.46	0.92	0.97
South Texas 2	6 and 7	0.73	0.49	0.80
Watts Bar	1 and 2	0.80	1.74	2.11

The table shows the ratio of ^{60}Co and nickel releases is not as consistent as that for ^{58}Co. For ^{60}Co, shutdowns at two plants led to more activity released following the alternative chemistry. Also, more nickel was released at the end of the high BOL pH cycle in three of the seven plants. In the two plants with the most constant pH operation for the cycles of interest, namely South Texas 1 and 2, the reduced release amounts were consistently lower for both ^{58}Co and ^{60}Co, as well as nickel. However, two of the cycles were relatively short which could affect the amount of release during the shutdown. Although not completely consistent, there is some evidence that the higher BOL pH operation results in less activity released during refueling shutdowns. This implies reduced corrosion product deposition and activation on the fuel cladding during the cycles that operated with increased BOL pH chemistry.

3.3.2 Effect of Cycle Length on Shutdown Releases

The effect of cycle length was examined by plotting activity and metals (i.e., nickel) inventories releases during a plant shutdowns versus the previous cycle length for all plants and all cycles of operation. The results for nickel, ^{58}Co, and ^{60}Co are illustrated in Figure 3-6. The figure shows a very statistically weak (correlation coefficient of 0.10 to 0.21) for the relationships between the shutdown activity released and the cycle length. Due to the large variation in the data, it is difficult to quantify the effect of a shorter cycle in a specific plant. However, it is reasonable to expect lower shutdown releases for shorter fuel cycles, as observed at the South Texas plants, due to the shorter activation and crud transport time.

3.3.3 Effect of Cycle pH on Shutdown Releases

The average coolant pH during plant operation was considered in the evaluation of the effect of pH on average coolant activities and shutdown activity and nickel releases. Table 3-7 lists the pH at temperature and at 300°C for all of the cycles considered in the evaluation. The averages do not include the pH during shutdown conditions. The range of pH over each cycle, $\Delta\ pH_{Tave}$, is also included in the table.

There is generally very little difference between the average pH for the modified chemistry operation versus that for operation with increased BOL pH. Thus, the average pH does not provide an indication of the variability of pH over the cycle and is not a good measure of the difference in operating chemistry regimes. A better measure is the average pH over the cycle along with the range over which the pH varied during the cycle. The effect of the average coolant activity during the cycle; as well as the amounts of radiocobalts, amounts of nickel, and specific activity of ^{58}Co (Ci per gram of nickel) released at the end of the plant operating cycles, were evaluated with respect to the cycle pH ranges. The Callaway plant cycles with decreasing pH (i.e., cycles 9 and 10) were not included since mid-cycle changes to their chemistry program prevented them from operating with increased BOL pH throughout the cycle.

The most statistically significant correlations of release data with pH data were those associated with ^{58}Co. The data is presented in Figure 3-7 which plots the release data as a function of the difference between BOL and EOL pH. As noted in the table the magnitude of the pH values considered are in the range of 7.05 to 7.2. The results with ^{60}Co, ^{54}Mn, and nickel activities and releases had extremely weak correlation coefficients of less than 0.007 and no significant relationship was exhibited by the data.

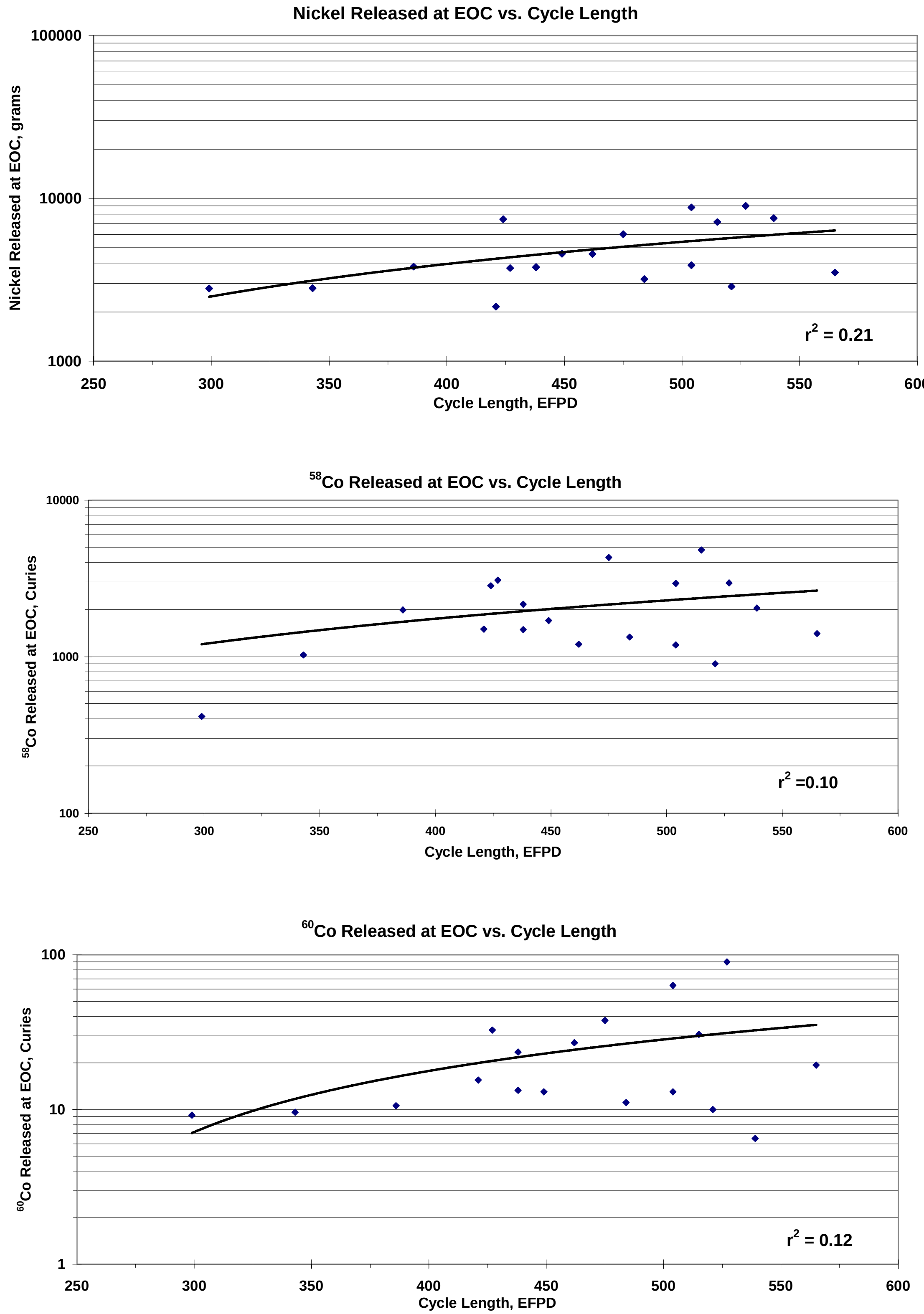
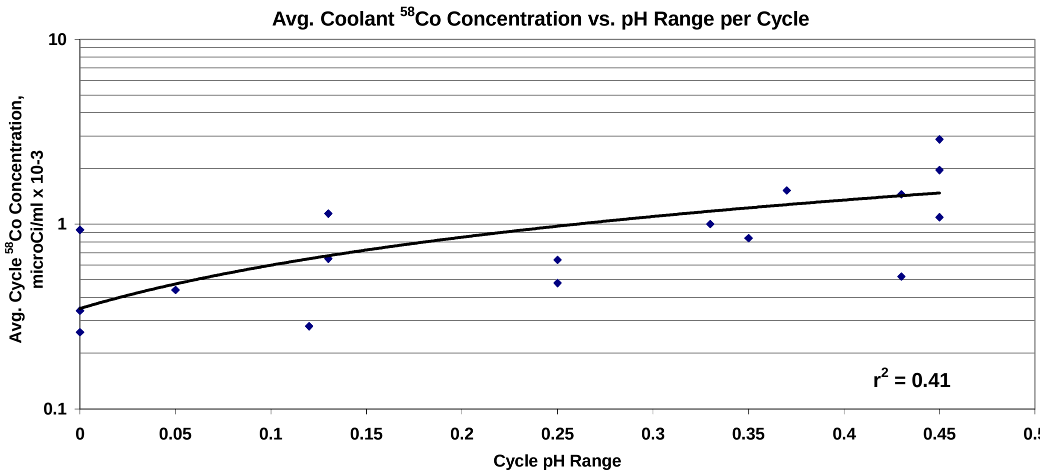


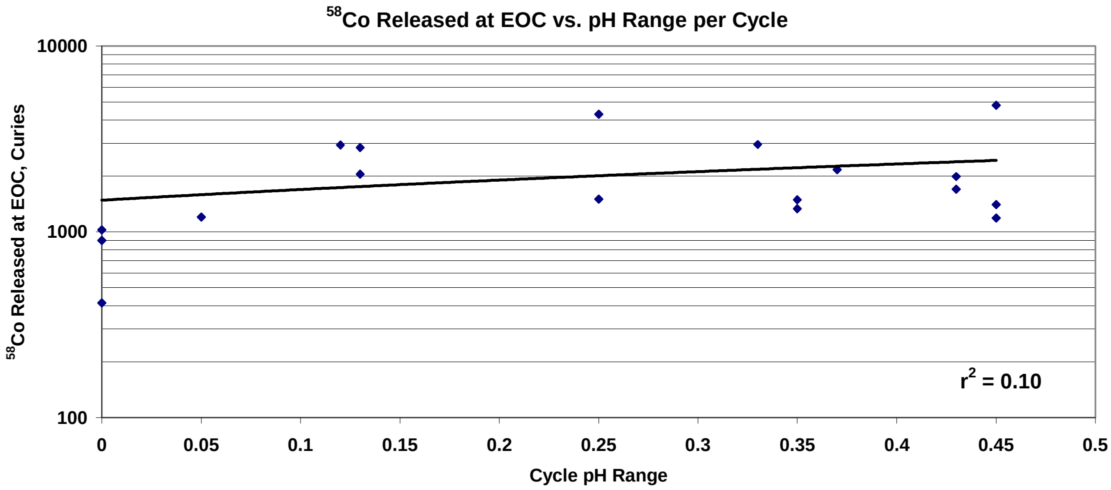
Figure 3-6
Correlations of Shutdown Activity Releases and Cycle Length

Table 3-7
Average Coolant pH for Plant Operating Cycles

Plant	Cycle	Chemistry	pH_{Tave}	pH_{300}	$\Delta\ pH_{Tave}$
Callaway	8	Modified	7.10	7.01	0.45
Callaway	9	Mod. Coordinated	6.98	6.91	**
Callaway	10	Coord. Increasing	6.96	6.86	**
Comanche Peak 1	5	Modified	7.15	7.05	0.35
Comanche Peak 1	6	Modified	7.11	7.01	0.25
Comanche Peak 1	7	Inc. BOL pH	7.13	7.03	0.12
Comanche Peak 2	3	Modified	7.16	7.06	0.33
Comanche Peak 2	4	Inc. BOL pH	7.12	7.02	0.13
Seabrook	4	Modified	7.17	7.08	0.37
Seabrook	5	Modified	7.11	7.00	0.45
Seabrook	6	Inc. BOL pH	7.09	6.99	0.13
South Texas 1	6	Modified	7.16	7.06	0.43
South Texas 1	7	Modified	7.17	7.07	0.43
South Texas 1	8	Inc. BOL pH	7.05	6.96	0.0
South Texas 1	9	Inc. BOL pH	7.15	7.06	0.0
South Texas 2	5	Modified	7.21	7.11	0.35
South Texas 2	6	Modified	7.11	7.01	0.45
South Texas 2	7	Inc. BOL pH	7.15	7.06	0.0
Watts Bar 1	1	Modified	7.25	7.18	0.25
Watts Bar 1	2	Inc. BOL pH	7.17	7.07	0.05

**Not included in evaluation since not representative of increased pH BOL operation.





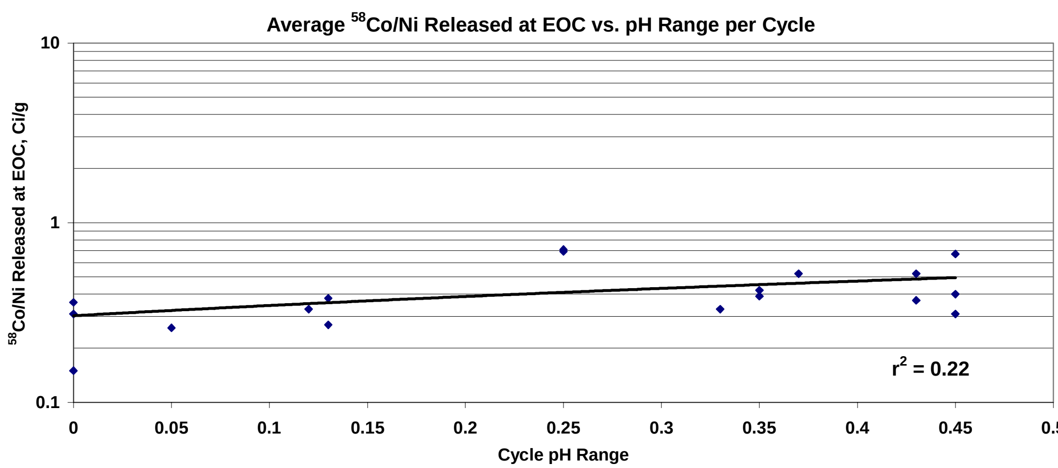


Figure 3-7
Correlations of ^{58}Co Activity Concentrations and Shutdown Release Data with pH Range

The correlation coefficient for the coolant ^{58}Co concentration is 0.41, which is considered to indicate some statistical relationship between the average concentration and the range in pH over a cycle. The correlation indicates that as the coolant pH control range is decreased (i.e., approaches a constant pH), the ^{58}Co concentration decreases.

The $^{58}Co/Ni$ correlation (correlation coefficient of 0.22) indicates that the specific activity decreases with a more constant pH. This suggests a shorter residence time of nickel on core surfaces, at least for the latter months of the cycle. The amount of ^{58}Co released at the EOL is not highly correlated (coefficient of 0.10) with pH range but is consistent with the expectation that a more constant pH operation should result in reduced amounts of activity generated over the cycle and released during shutdowns.

3.4 Comparison of Plant Data to Theoretical Projections

An assessment of the potential effects of changing from a modified coolant chemistry to a constant pH operation was made using the CORA computer model of crud generation and transport in PWR systems [6]. The code is used to assess the effects of design and operational changes (including operational chemistry) on activity deposits in nuclear plants. The calculated activities per unit area on primary system surfaces are then translated into relative radiation field information and compared to actual plant experience. The information can then be used in cost-benefit evaluations associated with the implementation of plant ALARA measures and in establishing occupational radiation exposure (ORE) projections and goals.

3.4.1 Description of the CORA Model

The basic CORA model consists of a set of individual nodes which represent homogeneous sources and sinks of corrosion products in a reactor system. The associated nodal diagram is presented in Figure 3-8. Differential equations are developed for each of the nodes based on the general balance equation,

Net Rate of Accumulation = Rate of Input – Rate of Loss

or in mathematical form,

$$dn_i /dt = \alpha_{ji} \cdot n_j - \alpha_{ij} \cdot n_i$$

where,

n_i = atoms of a nuclide in node i

n_j = atoms of a nuclide in node j

α_{ji} = transfer coefficient for the transfer process from node j to node i

α_{ij} = transfer coefficient for the transfer process from node i to node j

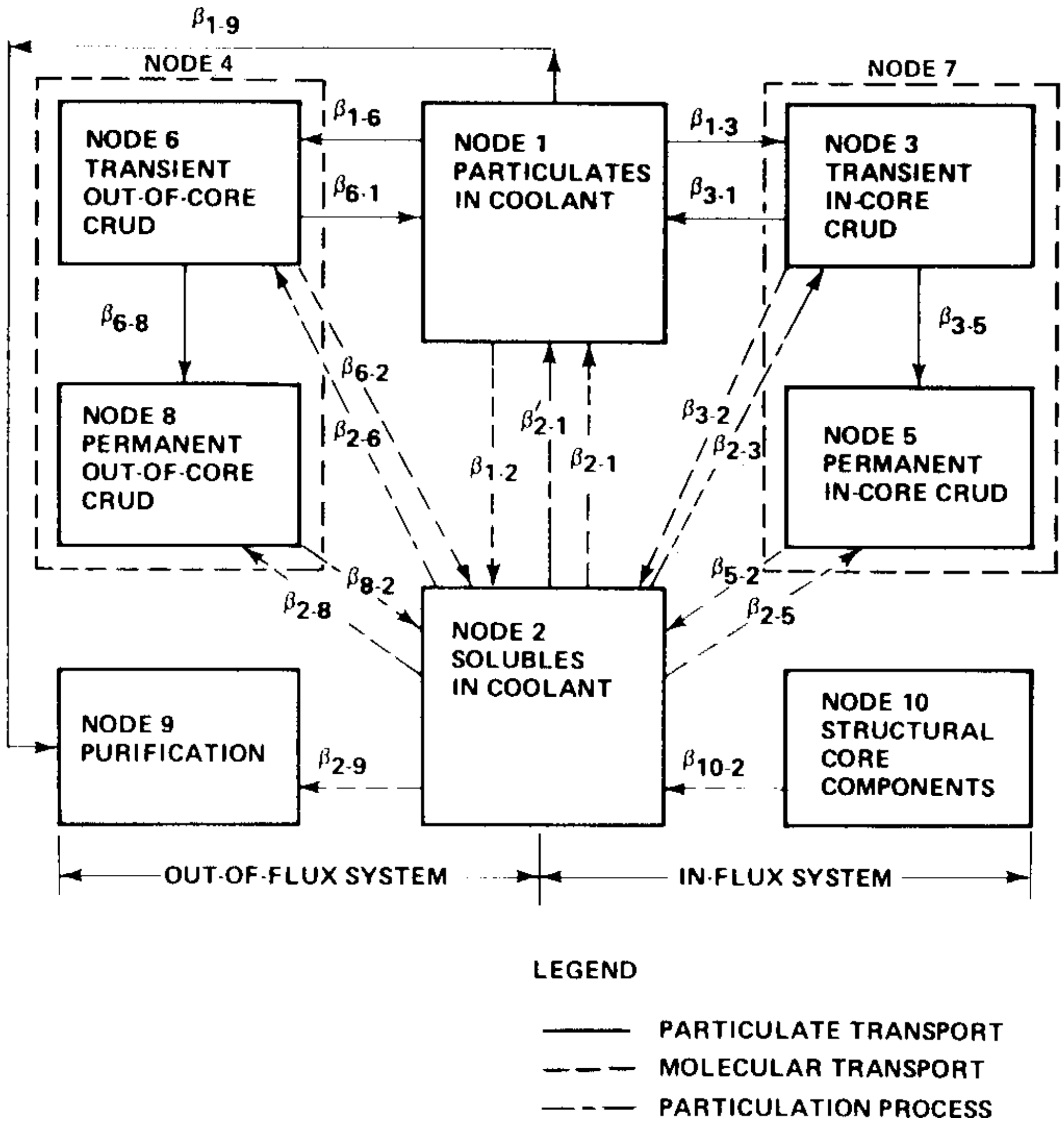


Figure 3-8
CORA Nodal Diagram

The nodal equations are then solved simultaneously to give deposit activities and masses as a function of time.

As shown in Figure 3-8, the nodes are divided into in-flux (core) and out-of-flux (out-of-core) regions with coolant nodes that are common to both regions and serve as the transfer medium between core and out-of-core surfaces. The transfer mechanisms are based on a combination of theoretical and empirical relationships defining the various particulate and molecular transport phenomena. The associated coefficients are based on pertinent plant parameters including coolant chemistry conditions (boron, lithium, and hydrogen concentrations) and temperature, power level, flow rates, material compositions, etc., as well as measured materials wear and corrosion properties.

3.4.2 Modeling of Operating Chemistry Regimes

The CORA model for the evaluation of operating chemistry regimes was based on parameters associated with a typical 4-loop Westinghouse plant operating for ten 18-month cycles. The coolant chemistry condition was varied in the model in order to quantify the impact of different chemistry regimes on surface activity concentrations and dose rates as a function of operating time. The following operating scenarios were evaluated:

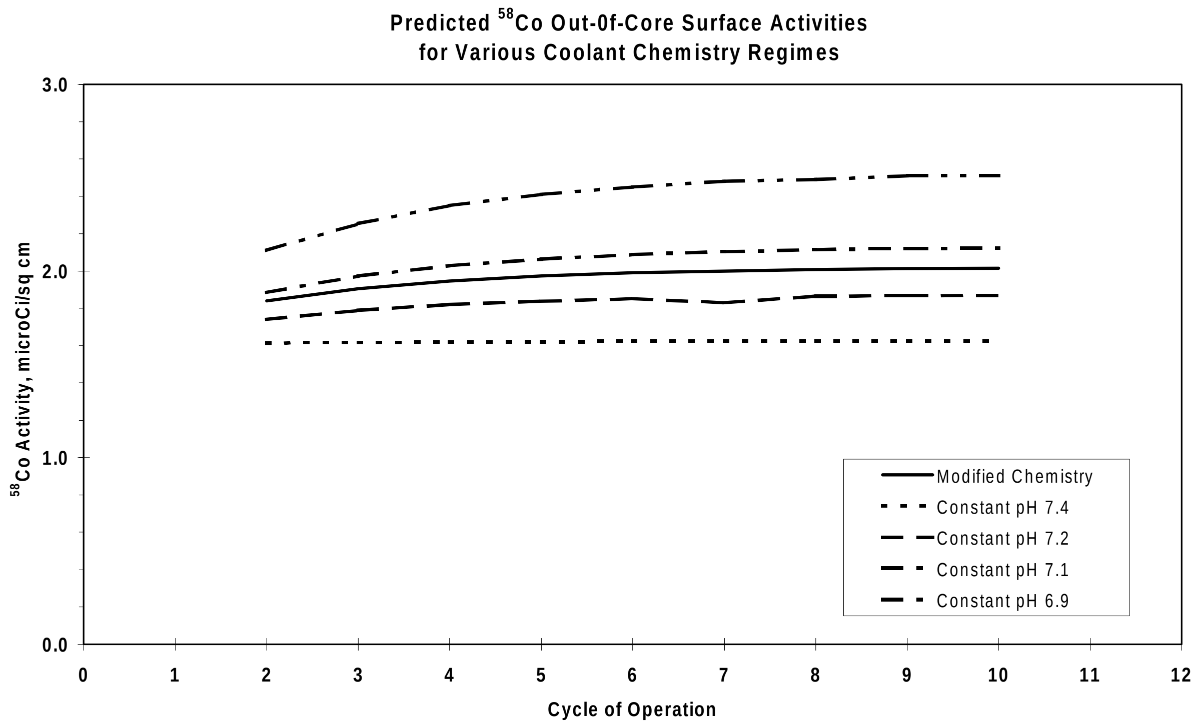
- Continuous Operation for Ten Cycles with Modified Chemistry (Base Case)
- Continuous Operation for Ten Cycles with Constant pH (pH of 6.9, 7.1, 7.2, and 7.4)
- Conversion from Modified Chemistry to Constant pH after Five Cycles of Operation

The projected effect of coolant chemistry regimes on the major corrosion product nuclides, i.e. ^{58}Co and ^{60}Co, is illustrated in Figure 3-9. The activity levels on out-of-core surfaces are plotted as a function of operating time based on operation with modified chemistry in which the pH_{Tave} varies from 6.9 to 7.4, and for operation with constant pH_{Tave} conditions throughout the cycle(s). The constant pH values considered in the analyses are 6.9, 7.1, 7.2, and 7.4. The figure indicates that, relative to operation with modified chemistry, operation with 6.9 results in ^{58}Co and ^{60}Co activities that are about 25% and 50% higher, respectively. Operation with constant pH 7.4 is indicated to be the better operating chemistry regime with ^{58}Co and ^{60}Co activities that are about 20% and 30% lower than those associated with modified chemistry.

Operation with pH 7.1 or 7.2 results in radiocobalt activity levels that are similar to that projected for modified chemistry with slightly higher values for pH 7.1 and slightly lower values for pH 7.2. Thus the model predictions indicate that the out-of-core activities for the increased BOL pH regime with pH values of 7.1-7.2 should be nearly the same as those associated with modified chemistry operation.

3.4.3 Comparison to Plant Measurements

Plant dose rate measurements were collected at key locations including the steam generator channel heads, outside the steam generator tube bundles, and outside the RCS piping at the end of each cycle. The measurements are discussed in Section 3.2 and summarized in Table 3-4. The "Ratio of Dose Rates" from this tabulation are included in Table 3-8, where the "ratio" is defined as the dose rate at the end of the cycle which employed increased BOL pH divided by the dose rate at the end of the previous cycle that operated with modified chemistry. The table also includes comments regarding the pH levels during the operating cycle and other potential influencing factors associated with the data as discussed in previous sections.



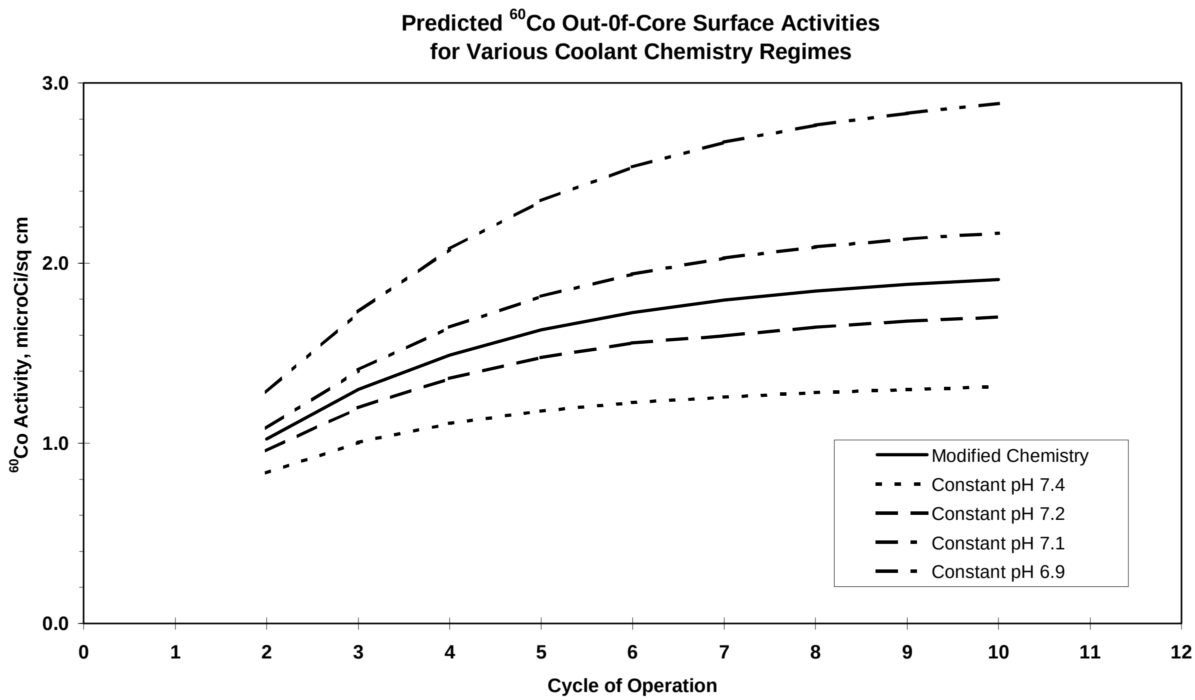


Figure 3-9
Out-Of-Core Surface Activities for Various Coolant Chemistry Regimes

Table 3-8
Ratio of Measured Dose Rates

Plant	Cycle	*Ratio of Dose Rates*			Remarks
		C5	S1 and S2	2 and 10	
Comanche Peak 1	7	0.54	0.96	0.78	1/3 of cycle @ pH 7.1 2/3 of cycle @ pH 7.2
Comanche Peak 2	4	0.94	0.57	0.74	1/3 of cycle @ pH 7.1 2/3 of cycle @ pH 7.2 AOA observed in cycle 3
Seabrook	6	0.60	0.83	0.72	2/3 of cycle @ pH 7.05 1/3 of cycle @ pH 7.15 AOA observed in cycles 5 and 6
South Texas 1	8	0.96	1.01	0.99	Constant pH @ 7.05
	9	0.93	0.93	–	Constant pH @ 7.15
South Texas 2	7	0.82	0.82	0.82	Constant pH @ 7.15

Although the CORA model provides deposit activity concentrations rather than dose rates at locations in the primary system, the results can be converted to relative values that are approximations of such dose rates. The calculated values of surface activity on out-of-core surfaces for the major activated corrosion product isotopes (i.e. ^{58}Co and ^{60}Co) are weighted by their respective energy per disintegration values in order to determine an "effective" source strength as a function of time. The CORA results, converted in this manner, are shown in Figure 3-10 as a function of operating cycle, along with measured values.

The projected dose rates following conversion to increased BOL pH after an extended period of operation (5 cycles) with modified chemistry are noted to be similar to those associated with modified chemistry, i.e., ± 2% after the first cycle of conversion, depending on the value of constant pH (7.1 or 7.2) that is maintained. The potential benefits predicted by the theoretical model are noted to be much more significant if a constant pH of 7.4 were maintained, with associated reductions of 6% after one cycle, 12% after two cycles, and approximately 25% after 5 cycles of operation.

Note that only the measurements from Comanche Peak Unit 1 and the South Texas plants are compared to projections in Figure 3-10. From previous discussions, higher dose rate reduction factors appear to be associated with the occurrence of AOA during the previous cycle. Since the CORA model does not currently include boiling duty as parameter in the derivation of the transfer coefficients, data from plants where AOA was observed were not included in the comparison to the projected (relative) dose rates.

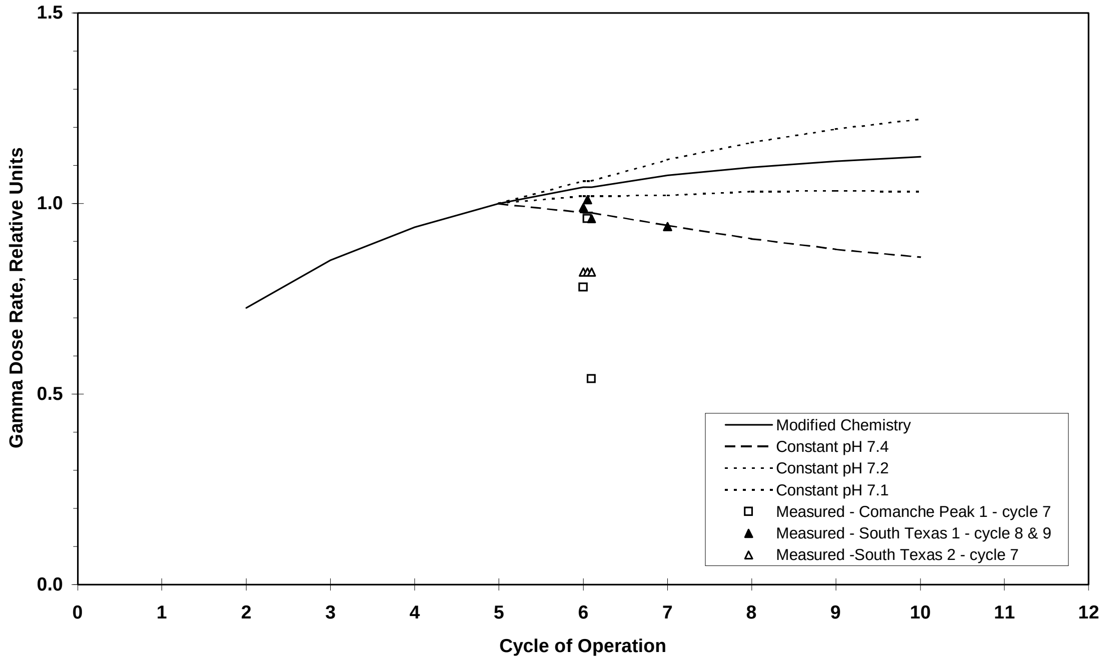


Figure 3-10
Projected and Measured Dose Rates Following Conversion of Coolant Chemistry

As noted in Figure 3-10, the observed changes in radiation fields levels following the conversion to the increased BOL chemistry tend to be greater than predicted. Although the measured data is scattered, the sets of data for any particular plant tend to be reasonably consistent, with the exception of the Comanche Peak values. All of the South Texas Unit 1 measurements and one of the Comanche Peak Unit 1 data points are noted to be reasonably consistent with CORA predictions. Further, the measurements tend to be more consistent with the projections for a constant pH of 7.4 rather than that projected for pH 7.2. It is concluded that the projected impact of the alternative chemistry on plant dose rates is not necessarily confirmed by the measurements and that more data from additional cycles is needed to establish an increased confidence level in the model predictions.

3.5 Summary of Data Evaluations

The data indicate positive benefits of operation with a constant coolant pH. The average coolant radiocobalt and ^{54}Mn activity concentrations range from 20% to 32% less with increased BOL pH chemistry as compared to that with modified chemistry. The ^{58}Co reduction is less in the plants that operated with the most constant pH during the cycle. Higher reduction factors were found to be related to the occurrence of AOA during the cycle. It was also found that the second cycle of operation with increased BOL pH at South Texas 1 has lower activity levels than that observed during the first cycle, indicating a continuing beneficial effect.

The average radiocobalt and ^{54}Mn concentrations were inversely related to coolant pH in the range of 6.9 to 7.2 when pH is maintained relatively constant during operation. This relationship was based on data from Callaway cycles 9 and 10, where the coolant pH was decreased from a higher to a lower constant value, and data from four cycles at the South Texas and Watts Bar plants, where the pH was essentially constant for the complete cycle.

After a cycle of operation with increased BOL pH, radiation fields were either unchanged or exhibited decreases of as much as 28% from values at the end of cycles operated with modified pH coolant chemistry. Further, the dose rates at South Texas 1 after the second cycle of increased BOL pH operation decreased by another 5%. The largest dose rate reduction was observed in the two plants (Comanche Peak 2 and Seabrook) that had experienced AOA in the cycle prior to implementation of the increased BOL pH operation. Thus, the larger reduction factors were observed following cycles that were believed to have typical core crud activity inventories as evidenced by AOA indications.

Theoretical evaluations (using the CORA computer model) of the impact of pH on radiocobalt activities in out-of-core surface deposits indicate that operation with a constant pH_{Tave} of 7.4 results in activities that are about 20-30% lower than those associated with modified chemistry control. The model predicts that the out-of-core activities for the increased BOL pH regime with pH values of 7.1-7.2 should be nearly the same as those associated with modified chemistry operation. However, the observed reductions in radiation fields following the conversion to the increased BOL pH chemistry tend to be greater than those predicted by the model. The (albeit limited) data is generally more consistent with predictions for constant pH 7.4 rather than that associated with pH 7.1-7.2.

A positive correlation was indicated for the relationship between steam generator dose rates and an indicator of fuel boiling duty (lead channel mass evaporation rate). This is consistent with plant observations of an increasing trend in coolant activities and subsequent shutdown radiation fields with the incidence of AOA. This suggests that higher radiation fields in plants with AOA are a function of a parameter related to fuel boiling duty, but it does not imply that a plant radiation fields are a simple function of fuel boiling duty. Corrosion product transport is extremely complex and is a function of many other influencing parameters.

The amounts of ^{58}Co released during shutdown evolutions in the cycle with increased BOL pH control are consistently less than those released during the prior cycle with modified pH operation. Although the amounts of ^{60}Co and nickel released were generally less at the end of the cycle with increased BOL pH chemistry, there were instances in which this was not the case. In the two plants with the most constant pH operation for the cycles of interest, namely South Texas 1 and 2, the reduced release amounts were consistently lower for both ^{58}Co and ^{60}Co, as well as nickel.

Relatively weak correlations were determined for operational pH with, a) coolant ^{58}Co activity during the cycle, b) the amount of ^{58}Co activity released at the EOL, and c) specific activity of ^{58}Co per gram of nickel released at the EOL. Correlations for ^{60}Co and nickel were not statistically significant. The relationships found for ^{58}Co indicate that operating with a constant coolant pH tends to result in lower ^{58}Co coolant concentrations and a lower $^{58}Co/Ni$ specific activity of the material released at the EOL.

3.6 References

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6. The CORA-II Model of PWR Corrosion Product Transport, Interim Report, EPRI NP-4246, September 1985.

4
CONCLUSIONS

A number of domestic PWRs have recently changed from operation with a "modified" coolant pH (i.e., 6.9 increasing to 7.4 over the fuel cycle) program of coolant chemistry to a more coordinated (constant) pH with elevated BOL pH levels of 7.1-7.2. The potential benefits from a crud transport point-of-view include a reduction in plant radiation fields and a reduced risk of axial offset anomaly (AOA).

Plants that have recently converted to increased BOL pH coolant chemistry programs were evaluated to determine the impact of the change in coolant chemistry on plant dose rates. Operational coolant chemistry and radiochemistry data during power operation, boiling duty information, and shutdown activity release and dose rate data were analyzed. The evaluations indicated that decreases were noted in the following key parameters:

- coolant activity concentrations during plant operation,
- activity releases during shutdown,
- ^{58}Co specific activity of crud released during shutdown, and
- plant shutdown radiation fields

In addition some positive correlations were developed between coolant activities and operational pH (inverse proportionality), shutdown releases and range in pH during operation, and shutdown dose rates and fuel boiling duty.

Observations and conclusions of the evaluation are summarized below:

- The activity concentration trends during each cycle for ^{58}Co, ^{60}Co, and ^{51}Cr generally follow a traditional U shape or "bathtub curve" relationship. The ^{54}Mn activity concentration trend is somewhat different from that of the other nuclides in that it tends to continuously decrease during the cycle.
- The ^{58}Co and ^{54}Mn coolant activity trends, as well as EOL dose rates in plant cycles with AOA, appear to differ from traditional trends that are observed over cycles where AOA is not observed. However, the coolant activity trends of ^{60}Co and ^{51}Cr do not appear to be significantly different. Since the parent elements of these nuclides are different, this pattern could indicate that nickel and iron deposition on the core is influenced by fuel boiling duty to a much greater extent than cobalt and chromium.
- The dose rates at all locations in five plants that changed to the increased BOL pH operation decreased after the cycle of the change. The average radiation fields remained essentially unchanged in one plant and decreased by as much as 28% in other plants. Further, the dose

rates at South Texas 1 after the second cycle of increased BOL pH operation decreased by another 5%.

- The projected surface activities of the out-of-core crud deposits as determined from the CORA computer model of corrosion product generation and transport for operation with constant pH_{Tave} of 7.1-7.2 are not significantly different than those projected for operation with modified chemistry. The observed reductions in plant radiation fields were found to be more than those predicted by the model. However, the data base available for use in the comparison (two plants with one cycle of operation and one plant with two cycles of operation with the alternative chemistry) is limited and additional data is desirable in order to confirm the impact of increased BOL pH chemistry on plant radiation fields.
- Higher dose rate reduction factors were associated with the occurrence of AOA during the cycle and/or abnormal coolant pH conditions during the previous cycle(s) of operation. Thus, reduction of radiation fields at plants with more typical dose rate trends may only be a few percent.
- The average coolant radiocobalt and ^{54}Mn activity concentrations in the plants that changed to the increased BOL pH operation also decreased by 20% to 32% after changing to the alternative chemistry. The second cycle of operation with increased BOL pH at South Texas 1 had lower activity levels than those observed during the first cycle, indicating a continuing beneficial effect.
- It was determined that a positive correlation exists between steam generator dose rates and an indicator of fuel boiling duty (lead channel mass evaporation rate). This is consistent with plant observations of an increasing trend in coolant activities and subsequent shutdown radiation fields with AOA and suggests that radiation fields increase with fuel boiling duty. However, there was essentially no correlation with RCS piping dose rates and the results do not imply that plant radiation fields are a simple function of fuel boiling duty.
- The ^{58}Co releases during shutdown evolutions at the end of cycles with increased BOL pH operation are consistently less than those released during the prior cycle with modified pH operation. In the majority of the shutdowns that were reviewed, the amounts of ^{60}Co and nickel released were also less during the cycle with increased pH operation.
- The effect of pH variability (or range of pH values) over the fuel cycle was weakly correlated with ^{58}Co relative to the average coolant activity during the cycle, the amount of activity released at the EOL, and the specific activity of ^{58}Co per gram of nickel released at the EOL. Similar correlations for ^{60}Co and nickel were not statistically significant. The relationships found for ^{58}Co indicates that operating with a constant coolant pH tends to result in lower ^{58}Co coolant concentrations and a lower $^{58}Co/Ni$ specific activity of the material released at the EOL.
- The coolant average radiocobalt and ^{54}Mn concentrations were inversely related to the pH_{Tave} values in the range of 6.9 to 7.2 in those cycles or portions of a cycle wherein the pH was relatively constant.

A
APPENDIX A – DATA TABLES AND FIGURES

This Appendix includes a summary table of the radiation field data used in this report, and data obtained since the issuance of the last radiation field report (Section 2 - Ref. 6) with the exception of the Callaway plant. For Callaway, the data was re-calculated since slightly different locations were used for comparison.

Table A-1
Summary of Plant Radiation Fields at SRMP Locations

PLANT	CYCLE	S/D DATE	POWER	EFPY	AVERAGE DOSE RATE Pts 2+10 (R/hr)	Pts S1+S2* mR/hr	Pt C5** mR/hr
Callaway	-1	03/30/85	**1192**	0.30			59
	-1	11/05/85		0.91			75
	1	02/28/86		1.06	6.8		103
	+1	05/18/86		1.13			90
	+1	06/21/86		1.20			100
	+1	04/02/87		1.86	5.3		175
	2	09/10/87		2.18	7.5		138
	3	03/31/89		3.42	6.5		
	4	09/21/90		4.72	6.1		
	5	03/20/92		6.02	7.0		183
	6	10/01/93		7.37	13.8		
	7	03/24/95		8.70	14.0	25	99
	8	10/12/96		10.08	21.0	40	175
	9	04/03/98		11.31	15.5	37	125
	10	10/02/99		12.68	20.1	55	205
Comanche Peak 1	1	10/03/91	**1161**	0.88	4.4	10	
	2	10/22/92		1.63	7.2	11	27
	3	10/06/93		2.34	8.5	17	26
	4	03/04/95		3.49	7.7	14	30
	5	10/05/96		4.81	8.1	14	28
	6	03/21/98		6.12	10.0	15	30
	7	09/25/99		7.50	7.8	14	16
Comanche Peak 2	1	10/07/94	**1161**	0.89	1.8	9	14
	2	02/23/96		2.06	5.3	7	20
	3	10/25/97		3.50	8.4	16	37
	4	03/20/99		4.67	6.2	9	34
Seabrook	1a	10/28/90	**1194**	0.28			17
	1b	03/30/91		0.63			38
	1(end)	07/25/91		0.90	3.1	8	29
	2	09/07/92		1.79	4.7	9	39
	3	04/09/94		2.97	3.8	8	39
	4	11/04/95		4.17	5.8	13	45
	5	05/10/97		5.58	6.4	13	54
	6	03/27/99		7.06	4.6	11	32
South Texas 1 (TGX)	1	08/05/89	**1315**	0.78	4.8		
	2	03/31/90		1.18		15	21
	3	11/22/90		1.49		17	21
	4	09/19/92		2.81		28	22
	5	03/04/95		3.78	7.1	19	20
	6	05/18/96		4.84	6.8	17	23
	7	09/13/97		6.07	7.9	18	25
	8	03/27/99		7.49	7.8	19	24
	9	03/01/00		8.31		17	23
South Texas 2	1	9/29/90	**1315**	0.90	3.9	10	20
	2	9/14/91		1.55	6.7		23
	3	2/27/93		2.64		28	28
	4	10/7/95		3.94	8.8	29	18
	5	2/8/97		5.14	7.4	26	33
	6	10/3/98		6.69	11.6	30	23
	7	10/13/99		7.63	9.5	23	19
Watts Bar 1	1	09/06/97	**1218**	1.15	2.3		27
	2	02/27/99		2.42	4.1	3	23

* Callaway - Loops B&C only
** Callaway Pt - C2 (Loops A&D only), South Texas 1 & 2, Loop B excluded

Table A-2
Steam Generator Channel Head Radiation Fields at SRMP Location 2 and 10

Plant	Cycle	Date	EFPY	Days Since Shutdown	Gamma Dose Rate, R/hr								
					Location 2				Location 10				Average 2 and 10
					S/G A	S/G B	S/G C	S/G D	S/G A	S/G B	S/G C	S/G D	
Comanche Peak 1	5	10/5/96	4.81	12	8.8	6.5	8.5	9	8	6.5	7.5	10	8.1
	6	3/21/98	6.12	7	8	8.9	12	8.2	10.5	7.8	13	11.6	10
	7	9/25/99	7.5	5	7	7.3	7	9.2	7.6	8.5	8	7.5	7.8
Comanche Peak 2	3	10/25/97	3.5	10	7	8.3	7.4	9.2	7.5	8.6	8.2	11.2	8.4
	4	3/20/99	4.67	13	6.7	5	6	6.8	6.2	6	6	6.5	6.2
Seabrook	5	5/10/97	5.58	19		5.6	5.4			7.1	7.3		6.4
	6	3/27/97	7.06	15	4			4.6	5.1			4.7	4.6
South Texas 1	6	5/18/96	4.84	3	6.6	6	5.7	9	5	7.7	5.7	9	6.8
	7	9/13/97	6.07	3	8	8	8		6	10	6	9	7.9
	8	3/27/99	7.49		8	9	5	10	4	11	7	8	7.8
South Texas 2	5	2/8/97	5.14	3	7	8	7	9	5	8	8	7	7.4
	6	10/3/98	6.69	3	10	12	10	14	12	10	12	13	11.6
	7	10/13/99	7.63		8.5	10.5	9	10.5	6.5	8.5	10	12.5	9.5
Watts Bar	1	9/6/97	1.15	12	2.1	2.1	2.6	2.1	2.5	2.1	2.8	2.3	2.3
	2	2/27/99	2.42	14	2.7	4.5	2.9	3.3	3.7	4.5	5.4	5.6	4.1

Table A-3
Steam Generator Tubing Radiation Fields at SRMP Locations S1 and S2

					Gamma Dose Rate, mR/hr								
					Location S1				Location S2				Average S1 and S2
Plant	Cycle	Date	EFPY	Days Since Shutdown	S/G A	S/G B	S/G C	S/G D	S/G A	S/G B	S/G C	S/G D	
Comanche Peak 1	5	10/5/96	4.81	1	12	12	10	20	12	8	9	25	13.5
	6	3/21/98	6.12	1	16	16	10	24	14	12	10		14.6
			6.12	27	15	15	12	20	15	10	12	25	15.5
	7	9/25/99	7.5	26	10	13	13	16	15	12	12	24	14.4
Comanche Peak 2	3	10/25/97	3.5	1	15	10	10	16		10	10	40	15.9
	4	3/20/99	4.67	9	6	6	8	8	15	6	8	15	9.0
Seabrook	5	5/10/97	5.58	6	8	8	20	10	15	14	15	14	13.0
	6	3/27/97	7.06	7	10	12	12	10	9	9	15	9	10.8
South Texas 1	6	5/18/96	4.84	2	20	27	20	16	9	24	7	10	16.6
	7	9/13/97	6.07	6	20	30	10	20	3	50	3	10	18.3
	8	3/27/99	7.49	3	15	35	20	20	10	35	5	8	18.5
	9	3/1/00	8.31		10	30	15	25	7	35	5	10	17.1
South Texas 2	5	2/8/97	5.14	9	60	30	10	30	15	50	2	8	25.6
	6	10/3/98	6.69	7	40	40	20	40	12	75	2	12	30.1
	7	10/13/99	7.63	3	32	60	14	32	12		8	14	24.6
Watts Bar	2	2/27/99	2.42	1	4	2	4	3	2	5	5	2	3.4

Table A-4
RCS Piping Radiation Fields at SRMP Location C5

Plant	Cycle	Date	EFPY	Days Since Shutdown	Gamma Dose Rate, mR/hr				
					Loop A	Loop B	Loop C	Loop D	Average
Comanche Peak 1	5	10/5/96	4.81	1	60	30	40	10	35
			4.81	8	12	31	10	32	21
	6	3/21/98	6.12	1	18	60	16	50	36
			6.12	28	18	35	12	30	24
	7	9/25/99	7.5	26	8	27	10	20	16
Comanche Peak 2	3	10/25/97	3.5	1	25	40	22	50	34
			3.5	8	25	50	20	60	39
	4	3/20/99	4.67	1	32	45	30	60	42
			4.67	9	20	30	18	40	27
Seabrook	5	5/10/97	5.58	6	120	100	100	200	130
			5.58	39	75	45	55	40	54
	6	3/27/97	7.06	5	45	27	35	22	32
South Texas 1*	6	5/18/96	4.84	2	24	23	20	24	23
	7	9/13/97	6.07	6	25	30	20	30	25
	8	3/27/99	7.49	3	25	30	22	25	24
	9	3/1/00	8.31		20	50	25	25	23
South Texas 2*	5	2/8/97	5.14	9	20	30	40	40	33
	6	10/3/98	6.69	7	25	25	25	20	23
	7	10/13/99	7.63	3	15	60	22	20	19
Watts Bar	1	9/6/97	1.15	1	30	24	22	30	26
	2	2/27/99	2.42	1	26	22	23	22	23

*Loop B excluded

Target:
Nuclear Power

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