STEAM GENERATOR DEPOSIT CONTROL PROGRAM ASSESSMENT AT COMANCHE PEAK

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ABSTRACT

Comanche Peak has employed a variety of methods to assess the effectiveness of the deposit control program. These include typical methods such as an extensive visual inspection program and detailed corrosion product analysis and trending. In addition, a recently pioneered technique, Low Frequency Eddy Current Profile analysis (LFEC) has been utilized. LFEC provides a visual mapping of the magnetite deposit profile of the steam generator. Analysis of the LFEC results not only provides general area deposition rates, but can also provide local deposition patterns, which is indicative of steam generator performance. Other techniques utilized include trending of steam pressure, steam generator hideout-return, and Flow Assisted Corrosion (FAC) results. The sum of this information provides a comprehensive assessment of the deposit control program effectiveness and the condition of the steam generator. It also provides important diagnostic and predictive information relative to steam generator life management and mitigative strategies, such as special cleaning procedures. This paper discusses the techniques employed by Comanche Peak Chemistry to monitor the effectiveness of the deposit control program and describes how this information is used in strategic planning.

DEPOSIT CONTROL PROGRAM DEVELOPMENT

Corrosion product transport is minimized in order to control fouling and corrosion in nuclear steam generators. The Chemistry program at Comanche Peak Station is designed to minimize corrosion release, corrosion product transport and solids deposition during operation and non-steady conditions. Key to the strategy is the control of soluble iron transport, which has been implicated in the densification of tube deposits, or loss of porosity. The strategy was developed considering the overall plant design and the integration of chemistry objectives to the common goal of protecting plant components, particularly the steam generators. The integration of chemistry objectives to a common goal is an important aspect of the program design at Comanche Peak, as some objectives when pursued without regard to others, can actually result in an undesirable condition. One such example is the reduction of condensate oxygen to the point where iron transport increased to an unacceptable level (1).

The Chemistry objectives were carefully evaluated to determine the appropriate priority of each objective to provide the common goal of total secondary system protection. This was accomplished through the integration of the objectives considering the potential trade-off of specific objectives in regard to total system protection. The prevention of steam generator fouling was chosen as the highest priority objective as this condition has the greatest impact on steam generator conditions and corrosion, and is comprised of the following sub-objectives:

- Maintain crevices in open condition to prevent concentration of impurities
- Prevent build up of sludge and tube scale
- Minimize soluble iron transport in order to maintain scale/sludge in porous condition
- Minimize Flow Assisted Corrosion (FAC)
- Maximize the stability of balance of plant (BOP) oxide inventories

Critical to the deposit control strategy at Comanche Peak is the use of Dimethylamine (DMA) chemistry to augment Morpholine. This results in a mixed amine optimization that provides a Condensate system pH of >9.8 at 25^{O} C. The amine mix provides for complete balance of plant (BOP) protection, including mitigation of FAC, while also providing corrosion product transport control to the steam generators. High concentration DMA soaks during outages are also employed as a measure to control steam generator deposits. DMA soaks have been shown to remove silica-based deposits, affect the removal of magnetite scale, and are effective at copper and lead removal (2)(3). DMA is also important to the soluble iron goal as it has been proven to reduce soluble iron transport (4). Table 1 illustrates the history of the amine optimization process at Comanche Peak Unit 1.

Period	Chemistry	Conc.	Iron Transport
Cycle 1&2	Morpholine	4-6 ppm	~8-10 ppb
Cycle 3	Optimize Morpholine	8-10 ppm	~ 2.5 ppb
Cycle 3 (end)	ADD DMA	200-400 ppb	~1.5 ppb
Cycle 4	Optimize DMA	400-600 ppb	~0.8-1.0 ppb
	Optimize Morpholine	20 ppm	
Cycles 5-8	Optimize DMA	1 ppm	~ 0.55 ppb for C5 and less for Cycles 5 - 8
	Optimize Morpholine	35 ppm	

Table 1: Unit 1 Amine History

Integral to the priority of deposit control is the proper control of electrochemical potential (ECP) conditions. This is accomplished by a minimum feedwater Oxygen goal of 1 ppb as measured by local sampling and the control of Hydrazine in the concentration range of 25-35 ppb. For more details of the chemistry strategy, see paper SFEN n° 154, "Strategic Elements of Steam Cycle Chemistry Control Practices at TXU's Comanche Peak Steam Electric Station," presented at this conference (5).

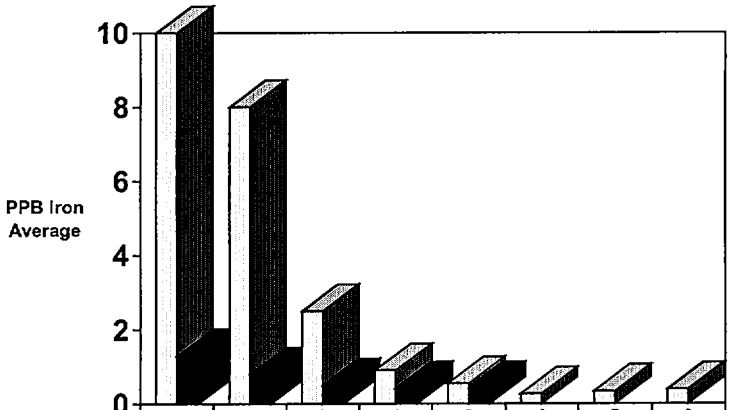
PROGRAM ASSESSMENT INDICATORS

All available parameters were evaluated to provide a comprehensive assessment of the program effectiveness. The parameters chosen to assess the program are as follows:

- Corrosion product trending and Flow Assisted Corrosion monitoring results
- Non-steady state corrosion product transport trending
- Sludge lancing solids trending and analysis
- Hideout-Return (HOR) results
- Steam Pressure trending
- Venturi Vs Leading Edge Flow Meter trends
- NDE indications (distorted signals)
- Pulled tube analysis
- Visual Inspection
- Low Frequency Eddy Current (LFEC) Profiling

CORROSION PRODUCT TRANSPORT TRENDING

The results of the chemistry strategy to minimize corrosion product transport and to maintain a stable protective oxide on plant metallurgy can be observed in Figures 1 and 2. Operational steady state total iron transport after optimization of amines have been consistently <1 ppb and near 0.5 ppb to a low of 0.3 ppb for an average during the cycle (Figure 1). This demonstrates good corrosion product transport control. Additionally, soluble iron transport is typically below or near detection levels.



	1	2	3	4	5	6	7	8
□ Unit 1	10	8	2.5	0.9	0.55	0.27	0.34	0.4
■ Unit 2	1.3	0.81	0.495	0.41	0.42			

Figure 1: Operational Iron Transport History

Comanche Peak practices non-steady state sampling to more completely assess the steam generator loading and to evaluate the effectiveness of the chemistry program objective to maintain a stable protective oxide layer (Figure 2). This is accomplished by analyzing sample filters that were in service during a plant trip to capture iron transport during such a system transient. To capture transport during a startup, a sampling filter is placed in service as soon as the forward feed to the steam generator is started. These procedures are performed to insure capture of the full inventory of corrosion products being transported to the steam generators. The values indicate very good control of corrosion product transport during these conditions and represent a small fraction of total inventory transported during a cycle (<2%). Additionally, the values reveal good startup oxidant control. The higher startup values of cycles 7-9 are believed to be the result of a change in shutdown and operational startup practice. The non-steady state condition trend is a strong confirmation of oxide stability. This is accomplished during a startup without intensive lay-up measures during the outage. The systems can be simply drained and left open to air dry. This provides an outage schedule benefit as shutdown maintenance can proceed without the inconvenience of coordination of extensive lay-up activities. Also, the units have no need to plan schedule holds for iron cleanup during startup. For example, iron loading on the precoat condensate polishers is not sufficient to require replacement during startup and often remain in extended service.

In addition, the flow assisted corrosion monitoring results trended since early operation indicate essentially no loss of material is being observed as the pipe wall thickness values are within margins of error for the measurement period.

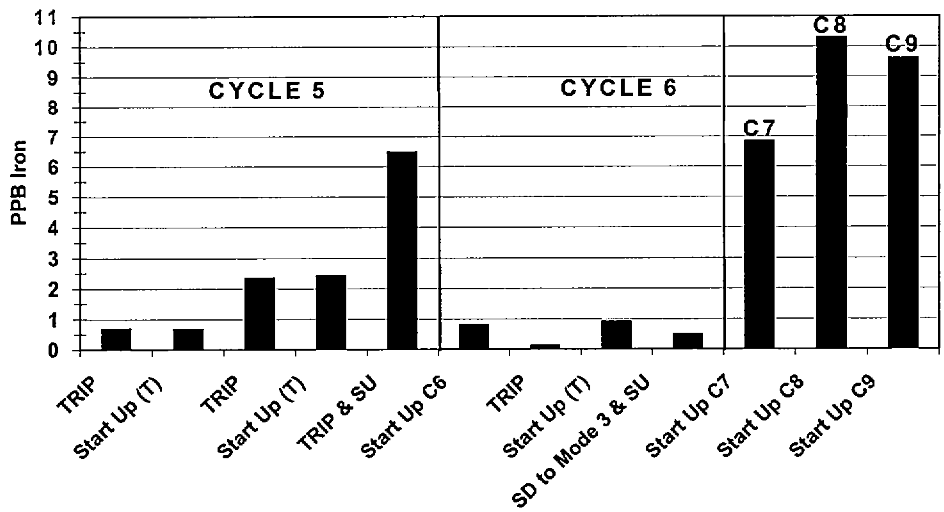


Figure 2: Unit 1 Non-Steady State Iron Transport

STEAM GENERATOR HIDEOUT-RETURN RESULTS

Hideout return (HOR) results at Comanche Peak continue to be a good indicator of the clean conditions of the steam generator and good chemistry control. There has been no measurable (less than detectable) rapid/prompt sodium return for 8 cycles of operation at Comanche Peak Unit 1. The return of retrograde materials upon cooldown is very limited, as the return of calcium, silica and sulfate was less than 10 ppb. The HOR results indicate open crevices with general clean steam generator conditions, and particularly that the tube deposits are not densified but porous. Figure 3 illustrates the maximum values of HOR for selected species at 1RFO8.

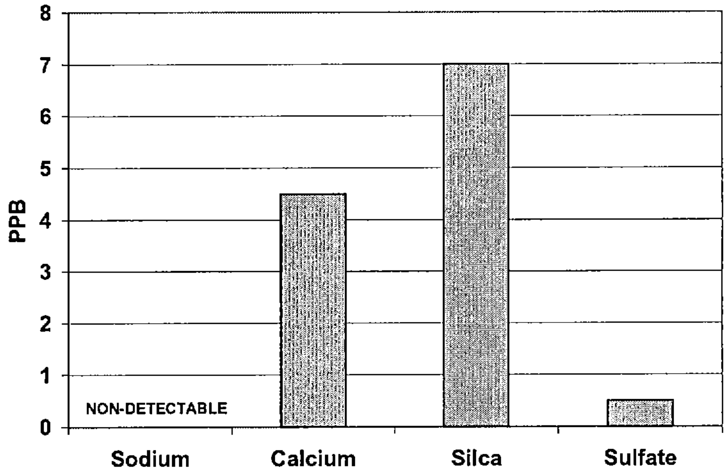


FIGURE 3: IRFO8 Hideout Return Maximum Values

SLUDGE-LANCING RESULTS

The solids removed from sludge lancing have been minimal for the life of Comanche Peak (Table 2). This is a confirmation of the low corrosion product transport and oxide stability, notwithstanding the preheat design. Sludge lancing is performed routinely not only to remove the transported material during the cycle, but also to mitigate collar formation at the top-of-tubesheet (TTS). The chemical cleaning at 1RFO5 aggressively pursued collar removal. The collars were partially dissolved, but not completely removed by the chemical cleaning. The practices of routine sludge lancing and DMA soaks have successfully removed the remainder of the collars. The initial formation of collars on Unit 2 has been arrested without chemical cleaning.

RFO	SG 1	SG 2	SG 3	SG 4	Total
1	8	5	4	9	26
2	2.5	3	4	1	10.5
3	N/A	N/A	N/A	N/A	N/A
4	5	5	7	5	22
5(1)	N/A	<1	<1	N/A	2
6	N/A	N/A	N/A	N/A	N/A
7	5.5	5	5	4	19.5
8	3	2.5	2.5	2	10
Total	24	21.5	23.5	21	90

Table 2: Unit 1 sludge removal results (lbs.)

(1) Chemical Cleaning was performed at RFO5 and removed approximately 4000 lbs. of material from the SG's.

SLUDGE ANALYSIS TRENDING

Trending of sludge analysis results has been accomplished since cycle 1. Comanche Peak performed a pre-operational hot functional test with a copper condenser. As a result, early cycle deposit analysis contained traces of lead and copper, which have decreased over time in the deposits. This confirms, in addition to transport analysis, that there is relatively low (less than detectable) transport of lead and copper. Additionally, it has been established that these metals are selectively removed by DMA soaks.

The most recent results from cycle 8 reveal that the primary constituent in the deposits is magnetite. Analysis of deposit samples ranged from 96 wt% to 99 wt% magnetite. XRD analysis reveals the iron state in sludge is essentially 100% magnetite, confirming reducing conditions in the steam generators. Leachable anionic contaminants such as chloride and sulfate were near detection limits. Corrosive species such as lead and copper were low or below detection limits. There were no indicators of oxidizing conditions, such as reducible oxides. The primary component of the solids removed was a powdery magnetite, with a very minor constituent of particles of unknown origin. None of these were identified as tube scale, consistent with the visual program inspections. The cycle 8 results are typical of the recent cycle results and exhibit low transport of iron, copper, and lead, and confirm reducing conditions in the steam generator.

STEAM PRESSURE TRENDING

The steam pressure is trended for indications of fouling as a result of solids accumulation on heat transfer surfaces. The steam pressure is normalized to the operating primary system average temperature value and to 100% power. The steam pressure has historically been trended since Cycle 2 and the operating steam pressure for Unit 1 has remained relatively consistent, essentially above 980 psia. The administrative limit for investigative actions is 970 psia, based on the historical steam trends. There has been no major trend of decreasing pressure that would indicate fouling conditions. Figure 4 illustrates typical results from cycle 7 to the present. The trends indicate the steam generators are in a clean condition. In fact, a slightly lower-than-design operational steam pressure is realized due to the clean conditions of the tubing, which limits effective heat transfer surface contributed by magnetite deposits.

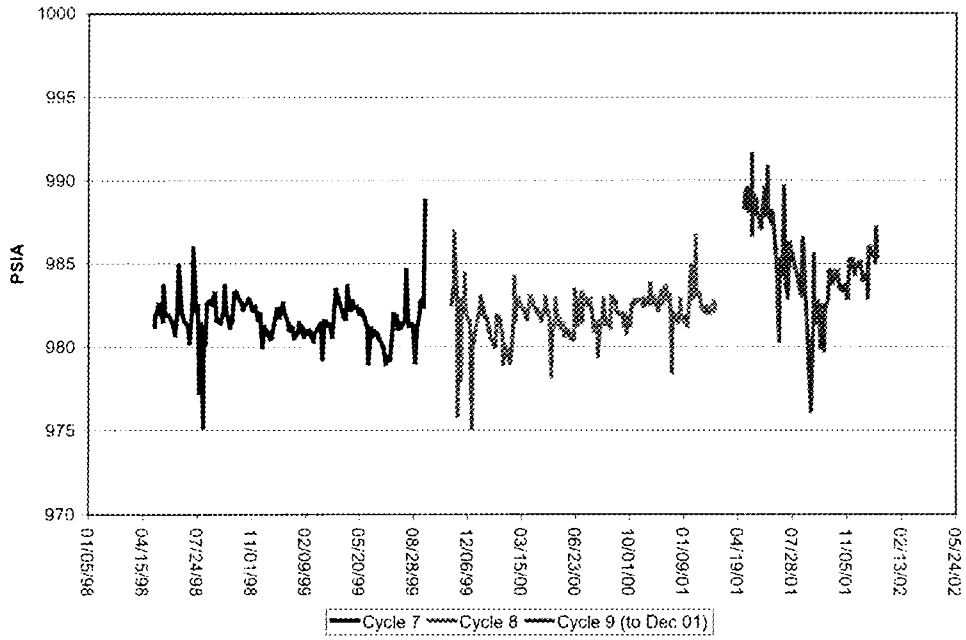


Figure 4: Unit 1 Steam Pressure Trends

LEFM AND VENTURI TRENDING

The Leading Edge Flow Meter (LEFM) was implemented at Comanche Peak as the feedwater flow measurement due to industry problems with venturi measurements, as a result of venturi fouling. The difference of the two measurements can by utilized as a fouling indicator since the LEFM is not affected by fouling. The measurement flow difference is calculated as follows:

$$\text{Flow Difference (\%)} = [(b - c)/b] \times 100$$

Where:
b = Venturi FFW Flow (lbs./hr)
c = LEFM FFW Flow (lbs./hr)

The LEFM flow is subtracted from the Venturi flow since the Venturi flow should be slightly higher (fouling produces a higher than actual flow) than the LEFM flow due to some minute fouling assumed to be present.

The measurement difference has been trended since the LEFM began operation in Cycle 2. The typical trends results from cycle 8 and cycle 9 show that the measurement difference has not trended higher but remained essentially steady, indicating that the venturi is not fouling (Figure 5). Therefore the secondary system can be considered to be in a non-fouling condition.

Figure 5: Unit 1 LEFM - Venturi Measurement
FFW Flow Difference for Cycle 8 to and Cycle 9 to Dec. 01

NDE TRENDING

Tube support plate distorted signals were growing in number and intensity in Unit 1 prior to chemical cleaning, reaching a maximum in steam generator 4 of 205 signals. The distorted signals can be indications of fouling at tube-to-tube support plate intersections. This was confirmed by the disappearance of a large number of distorted signal locations and the decrease in intensity of other distorted signal locations after chemical cleaning, indicating the effectiveness of the cleaning process performed. Subsequent to chemical cleaning, the distorted signals did not increase in number or intensity during cycles 6 or 7, but actually decreased from 75 to 66, respectively. This not only confirms low fouling conditions, but also indicates a cleaning or de-fouling property of the chemical treatments.

The distorted signals increased at 1RFO8 due to change in inspection criteria that utilized correlation to pulled tube analysis, but is below the original number prior to chemical cleaning. Future comparisons will be trended from the new baseline as a result of the criteria change.

TUBE PULL EXAMINATION

Four tubes were pulled at 1RFO7 to investigate the cracking mechanism. Results from the analysis (6) failed to identify a chemistry mechanism. Indicators of pH conditions revealed slightly acidic to neutral conditions. The absence of highly alkaline conditions was confirmed by failing to identify potassium or sodium silicates and nickel rich oxides. Also, the high metal oxide to hydroxide bonding ratio and limited carbonate bonding revealed the absence of highly alkaline conditions. No nickel sulfides were found to indicate acid sulfate attack. A slight chromium enrichment was found to suggest a slightly acidic to neutral environment. Indications of electrochemical potential (ECP) revealed reducing conditions as the iron state was identified as magnetite (no hematite identified), the valence states of other metals (Cr, Ni, and Cu) were in the reduced state, and the tube crack face oxide thickness measurements were among the lowest of a nine plant database. Corrosive species such as lead or reduced sulfur were found to be at low levels. This information confirms the absence of oxidizing conditions in the steam generators and verifies the plant strategy of oxygen and hydrazine control.

VISUAL INSPECTION PROGRAM

Comanche Peak has developed an extensive visual inspection program of the steam generators and available secondary system components to monitor the fouling condition of steam generators and measure the effectiveness of the chemistry and FAC program. Secondary components include condenser, moisture separator/reheater, main steam cross under piping, and any other available systems that are opened for maintenance.

After inspection of the entire bundle of all four steam generators at 1RFO4, routine inspections include the TTS of all four steam generators and the upper bundle of one of the steam generators on a rotating basis. At least one pre-sludge lance inspection is included in order to more accurately monitor the chemistry program by providing an "as found" condition of the steam generator. The pre-sludge lance inspection also provides an assessment of the sludge lancing process by providing a before and after condition.

The secondary system components have been found to exhibit a stable oxide condition, with all components inspected being free of solids accumulation. The lower temperature parts of the system, such as the condenser, exhibit a dark rouge colored mixed oxide that is very adherent and stable. The higher temperature portions of the system, such as feedwater, moisture separator/reheater, and heater drains, exhibit a magnetite appearing deposit that is also tightly adherent and stable.

Visual inspections of the steam generators indicate that the TTS is generally clean and free of accumulated or hardened sludge pile, even prior to sludge lancing. The majority of the TTS crevices are clean and open. The visual inspection program aided in the identification of tube collars and was an important factor in the decision to proactively chemically clean the Unit 1 steam generators after 5 cycles of operation. Subsequent inspections confirmed the partial removal of the collars by the chemical cleaning and the complete removal of the collars by the DMA soaks performed at each outage, the use of DMA during operation, and high pressure sludge lancing.

In general, the results of the inspections reveal that the steam generator tubes are generally very clean with only a slight accumulation of magnetite, which is easily rubbed off by the inspection probe. The Alloy 600 patina is visible through the porous magnetite layer. The majority of the limited accumulation is occurring (as expected) at the upper bundle and U-bend region where it is more difficult to see the oxide patina through the material than the lower bundle area. The accumulated material appears to be porous and self-limiting in depth. This is evidenced by the visual trends over several cycles, the fact that exfoliated areas are visible, and that the deposit is easily rubbed off of most areas by the inspection probe.

Unit 2 can be considered the best overall indicator of the treatment program because the steam generator condition represents 5 cycles of operation without chemical cleaning, with most of the history including optimized chemistry. Unit 1 has operated for 3 complete cycles since chemical cleaning. Figure 6 reveals the condition of the TTS of Unit 2 after 5 cycles at 2RFO5. As stated earlier, there is no soft or hardened sludge accumulation and the machining marks on the tubesheet surface can be clearly seen.

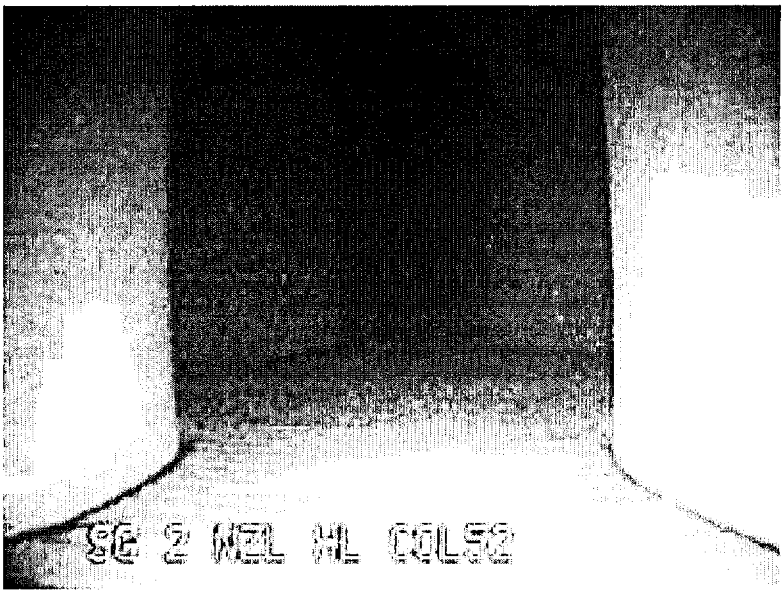


Figure 6: Unit 2 SG 2 TTS - 5 Cycles of Operation

Figure 7 reveals the top of the bundle U-bend area of Unit 2 after 4 cycles of operation at 2RFO4 (the upper bundles of the steam generators were not inspected at 2RFO5). The A600 patina is clearly visible, indicating the absence of significant deposits.

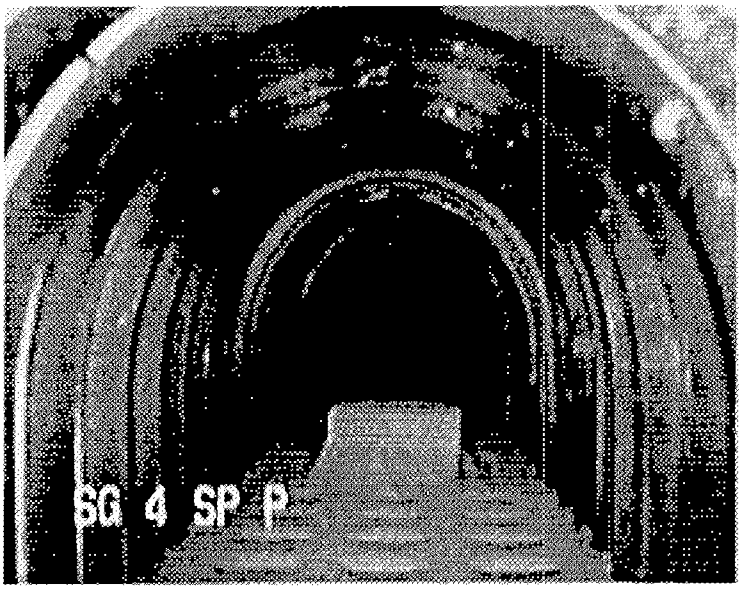


Figure 7: Unit 2 After 4 Cycles of Operation

The visual inspections of Unit 1 indicate a similar clean condition. Figure 8 illustrates the "as found" pre-sludge lancing condition, which is the best indication of tubesheet conditions after the operating cycle. This picture reveals very little difference between the pre-lance and the post lance (Figure 9) condition. This is considered to be a strong indication of the effectiveness of the chemical treatment program.

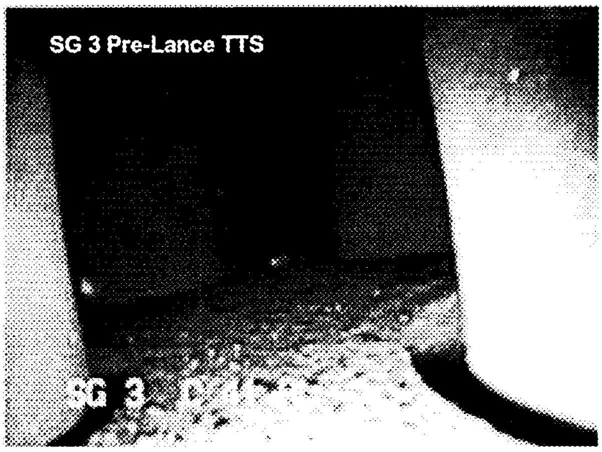


Figure 8: Pre-Lance Condition 1RFO8

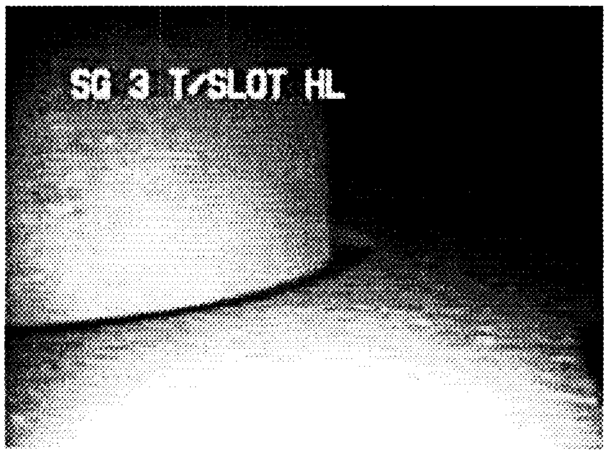


Figure 9: General TTS Condition 1RFO8

Figures 10 and 11 illustrate the deposit assessment of the upper bundle region. Figure 10 displays the condition at tube support plate "N." The supports are clean and generally free of deposits. The tube-to-support plate crevices are free of material and are clean and open. The metal surface of the steam generator tubes are clearly visible through the very light deposit. Figure 11 displays the condition of the underside of the top tube support plate, "P," and the condition of the U-bend region of the steam generator tubes. The underside of "P" support plate is free of accumulated material and the tube-to-support plate crevices are free of material and with open and clean crevices. The metal surfaces of the tubes are slightly obscured by the light deposit and the angle of the reflection of light. It has been found that the angle of light is very critical to the view of the metal surface. The metal surface can be clearly visible from one angle, while from another angle on the same tube location, the metal surface can be obscured due to the effects of the reflected light from the magnetite crystals. The U-bend region of the tube bundle is judged to be relatively clean and free of major deposit accumulation. The visual inspection results are a confirmation of low corrosion product transport, including soluble iron, and minimal deposition of deposits.

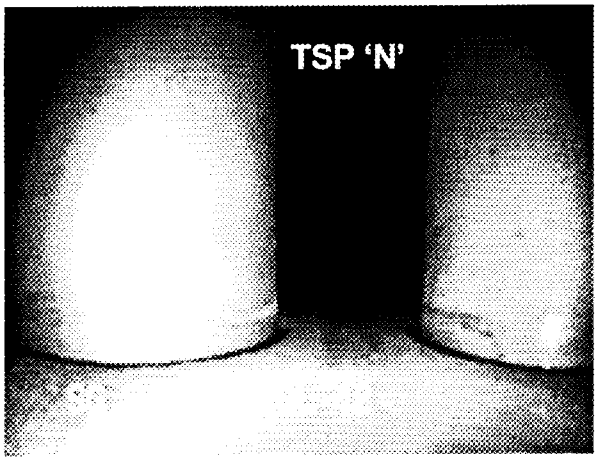


Figure 10: 1RFO8 TSP N

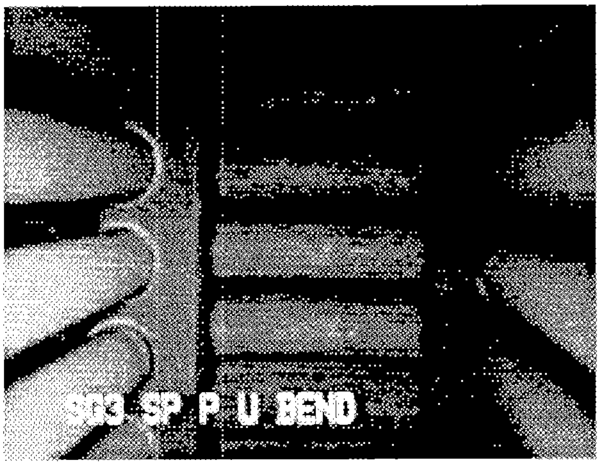


Figure 11: 1RFO8 U-Bend

LFEC SCALE PROFILING TECHNOLOGY

The relatively new technology of low frequency eddy current technology (LEFC) utilizes the low frequency of the Eddy Current Testing (ECT) response to characterize magnetite on the steam generator tubes. The data can be used to provide an estimate of the steam generator magnetite inventory and visualization of the deposit distribution within the tube bundle.

LFEC was used to verify the steam generator magnetite loading for the chemical cleaning of Unit 1 at 1RFO5. Iron transport mass balance predicted approximately 850 lbs. of magnetite per steam generator, of which 82% was transported in the first two operating cycles. The LFEC method predicted approximately 900 lbs. of magnetite per steam generator. The chemical cleaning process actually removed 1012 lbs. of magnetite per steam generator. This demonstrates excellent agreement between both estimation techniques at this level of loading. The present loading of the Comanche Peak steam generators is below the level at which the LFEC, at the present state of technology, can reliably predict the magnetite loading and therefore cannot be used to compare to the iron transport method. Efforts are currently in progress to improve the detection limit for the magnetite loading estimate.

Visualization software, used in the analysis of the ECT data, can provide a three-dimensional representation of the deposit profile. This can provide more specific information as to the distribution of the magnetite in the steam generator bundle. LFEC displays the deposit profile or actual distribution as opposed to an average distribution, or total inventory, as calculated from mass balance. This concept is very useful in determining local deposition rates for planning of specific objectives, such as an upper bundle cleaning. The profile can also be used to assess steam generator performance. This is because heavier deposits in the upper bundle region would be indicative of a higher steam quality. Visualization of the bundle profile is especially useful in assessment of the entire bundle in cases where there is limited access due to circumstances such as tube pitch or lack of access ports.

Figures 12 and 13 illustrate the volumetric representation of the present condition of Unit 1 steam generator 4 at 1RFO8. These images represent the condition of 3 cycles of operation after chemical cleaning. In the three-dimensional or volumetric representation, a color code is used to communicate the relative deposition distribution throughout the bundle. The color code is relative to the lightest deposit found by the ECT signal and is assigned the relative scale of 0 to 50 corresponding to the colors indicated. In this representation, blue is the lightest deposit determined and the colors transition to red to indicate the multiples of the lightest deposit at the highest value of the scale. The representation can be visually displayed in different ways in order to gain insights into the different areas within the tube bundle. Figure 12 is a three-dimensional, full volume representation and Figure 13 is a cross-sectional view of the bundle at selected locations, as examples of different visualizations. As can be seen, blue is found to be the predominant color throughout the bundle, which indicates the deposit profile of the Unit 1 steam generators is very light and relatively consistent throughout the bundle. Visual inspection and magnetite loading calculations from iron transport analysis confirm this finding.

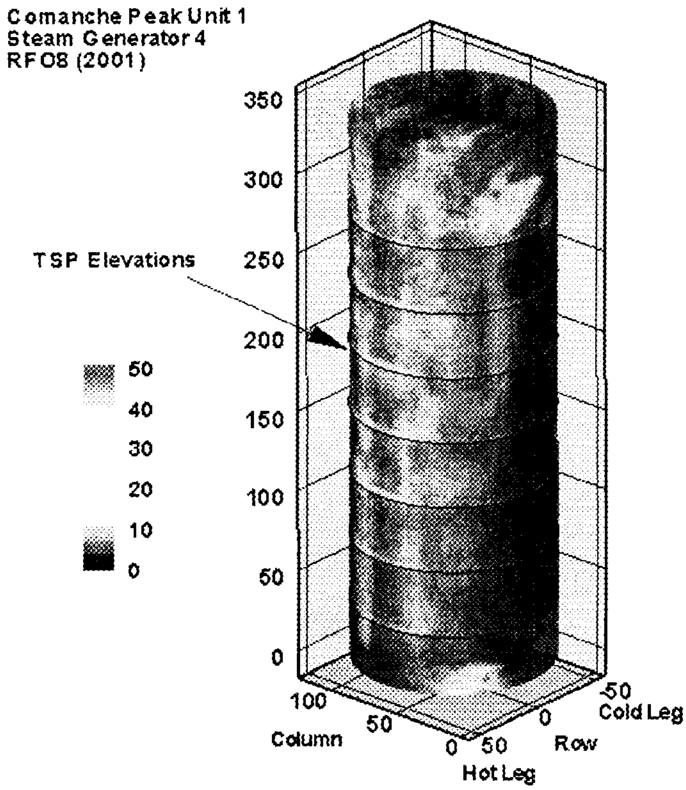


Figure 12: Hot Leg Side view of Steam Generator 4

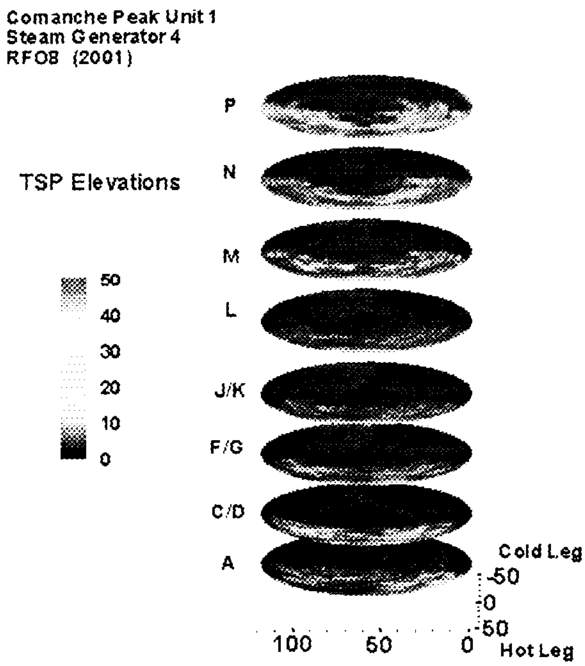


Figure 13: Cross Sectional View of the TSP Regions for Steam Generator 4

Even though the deposit inventory cannot be accurately estimated at this point, a relative comparison of cycle to cycle can be accomplished. Figure 14 is a relative comparison of the steam generator inventory of 1RFO7 in 1999 to 1RFO8 in 2001. A zero change from the 1RFO7 deposit profile is characterized by the color green. The predominant green color of the profile indicates no accumulation of magnetite from cycle 7 to cycle 8. However, some minor accumulation difference is observed at the TTS region on the hot leg side of steam generator 4 and at the U-bend region, which also exhibits some loss of magnetite on the cold leg side. Figure 15 is a comparison of a single tube ECT signal from cycle 7 to cycle 8, which also confirms the full bundle comparison, as the signal traces are nearly identical.

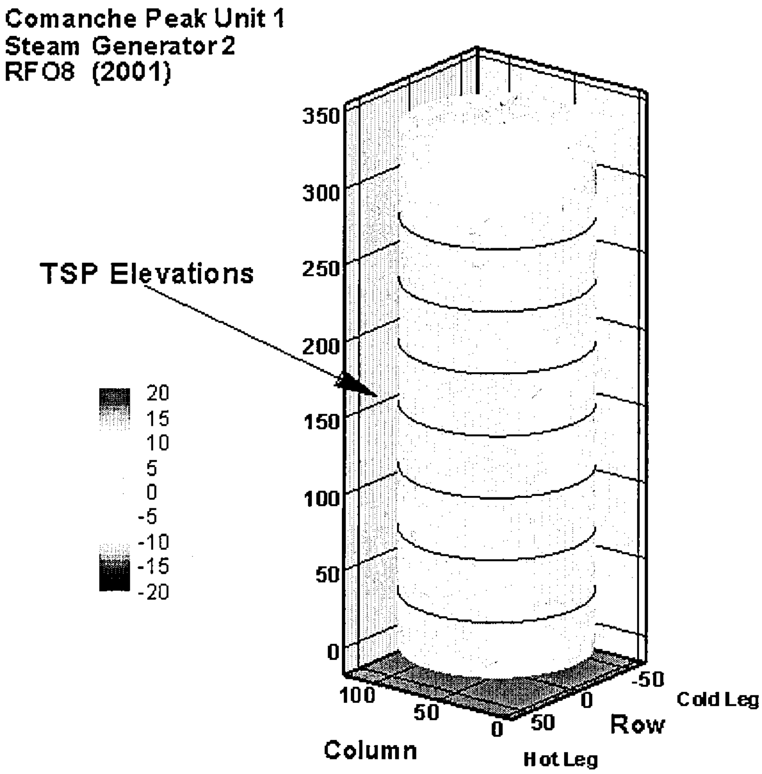


Figure 14: **Visualization Showing the Difference Between 1999 and 2001 Scale Profiling Results (Hot Leg View)**

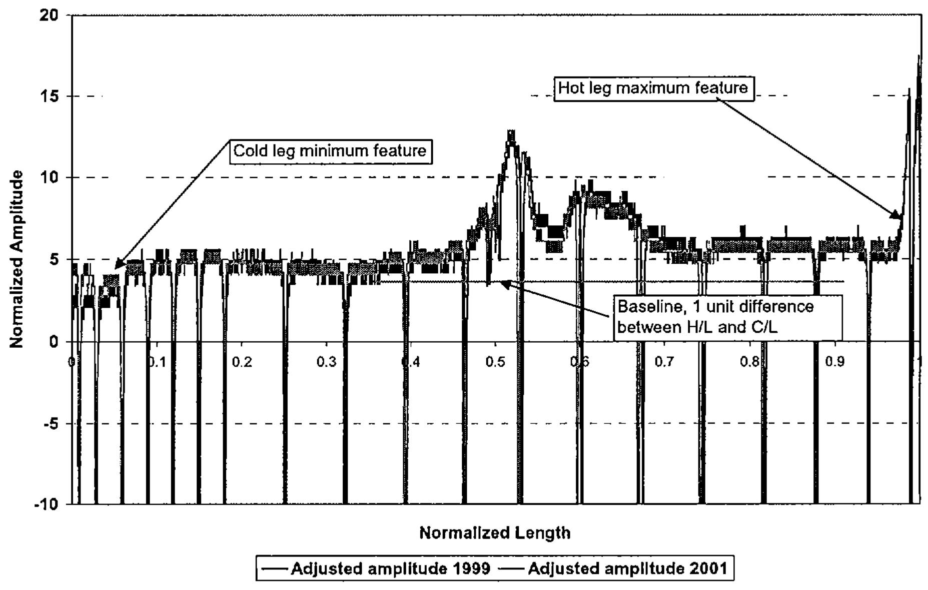


Figure 15: **Single tube ECT signal comparison**

The LFEC deposit profiles can also be used to direct visual inspections for a more accurate and efficient assessment, which supports outage objectives such as schedule considerations and reduction of radiation exposure. The visual inspection program, which visually documents all deposits, and the LFEC profile of magnetite deposits work synergistically to provide a more complete assessment of the steam generator condition and deposit control effectiveness. This information can be useful in the life management of the steam generators as follows:

- Aids in determining the need for chemical cleaning
- Assists in planning targeted objectives such as upper bundle cleaning
- Aids in evaluation of degradation mechanisms
- Useful in life predictions and/or component performance
- Improvements to sludge lancing process
- Indicate any deposition trends due to chemistry program changes
- Aids in assessment of performance of chemical or mechanical cleaning operations by providing a before and after comparison

Additionally, with improved detection limits, LFEC can provide a local deposit profile (instead of an overall average) that can be used to determine local deposition rates on Comanche Peak steam generators.

CONCLUSIONS

There is a large benefit of the multifaceted approach to assess the condition of the steam generators and the balance-of-plant components. The results of the condition monitoring parameters all provide consistent indications of the following:

- The balance of plant components are passivated with a stable, mixed oxide that resists transient conditions and is not experiencing FAC (i.e. corrosion release is minimal)
- The steam generators are very clean and free of fouling conditions
- Corrosion product transport, including soluble iron, is minimal and deposition of transported material is minimal
- Tube pull results did not indicate a chemistry component, but revealed slightly acidic to neutral pH conditions, reducing conditions in the steam generator, low concentrations of corrosive species

These results provide a strong confirmation of the Chemistry program at Comanche Peak. The deposit control program at Comanche Peak is judged to be effective in controlling corrosion product transport and deposition.

Even though its full potential has not yet been realized, LFEC technology has provided valuable insight into the steam generator condition and strategic planning. In addition, value has been realized to direct and limit resources to provide efficient performance of steam generator activities, supporting outage goals and objectives.

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