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SUBJECT: Provides data from Units 2 steam generator tube rupture investigation.Note that info in preliminary form & been marked as such.Summary list also encl.

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102-02544-TRB/JRP
June 22, 1993

U. S. Nuclear Regulatory Commission
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Dear Sirs:

Subject: Palo Verde Nuclear Generating Station (PVNGS)
Unit 2
Docket No. STN 50-529
Preliminary Steam Generator Information
File: 93-056-026

The purpose of this letter is to provide you data from the PVNGS Unit 2 Steam Generator tube rupture investigation. Please note that this information is in preliminary form and has been marked as such. A summary list is also enclosed for your information.

Should you have any questions, please contact J. R. Provasoli at (602) 393-5730.

Sincerely,

Thomas R. Bradish, Manager
Nuclear Regulatory Affairs

TRB/JRP/ap

Enclosure

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SUMMARY LIST
JUNE 22, 1993
DRAFT A

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VI. TROUBLESHOOTING ACTION PLAN

A. EXPANDED SCOPE OF ECT

Initial Outage Plan

The fourth refueling outage for Palo Verde - Unit 2 began on March 14, 1993 due to a steam generator tube rupture. The original outage schedule was to begin on March 20, 1993. The initial examination plan for both steam generators was a 100% full length bobbin examination with approximately 10% of the tubes to be tested using MRPC for the 01H and TSH intersections. The tubes were to be examined full length with the exception of some row 1, 2, and row 3 tubes which were examined through the U-bend from both the hot and cold legs.

After the manways were removed, the secondary side of the steam generator 22 was filled until the leaking tube could be identified. Visual examination confirmed that row 117 column 144 was the leaking tube. Eddy current probes and a Welch Allyn video probe was used to characterize the tube leak. It was determined that the leaking tube had an approximate 8 inch long midspan axial indication located 34 inches above the 08H support. A 2-inch long fishmouth rupture was found in this tube starting one inch above the start of the 8 inch axial indication.

The eddy current testing began on 4-11-93. Initial results identified a number of tubes with indications of axial cracking. The majority of the indications were located in the upper area of the hot leg side in SG 22. As a result of this initial testing, the scope of the testing in both generators was expanded. The scope was then systematically expanded as additional flaws were detected.

VI. TROUBLESHOOTING ACTION PLAN (CONT.)

A. EXPANDED SCOPE OF ECT (cont.)

Unit 2, Steam Generator 1:

First Expansion

During the third refueling outage, (U2R3) a mid-span axial indication was found three inches above the 09H support in row 117 column 54. Since the axial indication in U2R3 and the ruptured tube were on the same row, the first examination was performed on rows 116 through 118 in each steam generator. Bobbin and MRPC examinations performed on these rows found a greater amount of wear indications in the 08H and 09H supports than expected. The next axial indications were found in rows 104 and 105. As a result, approximately 150 tubes were tested surrounding these tubes and a symmetrical spot on the other side of the generator.

Second Expansion

The second eddy current expansion consisted of testing all bobbin indications via MRPC to distinguish between wear and axial indications. On tubes with indications located from the TEH to the 09H, MRPC was performed on the 01H and TSH support locations. This was in order to satisfy the random approximate of 10% MRPC of the 01H and tubesheet.

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VI. TROUBLESHOOTING ACTION PLAN (CONT.)

A. EXPANDED SCOPE OF ECT (cont.)

Unit 2, Steam Generator 1: (cont.)

Third Expansion

The purpose of the third expansion was to try and bound the SAI (single axial indication) band found in SG21 and SG22, using MRPC. After plotting the axial indications, it appeared that they followed an "arc" that started around row 100 column 25 and continued to row 100 column 165. The arc was three to ten tubes in from the periphery of the tube bundle.

Fourth Expansion

The fourth expansion was a checkerboard expansion to MRPC examination of the upper supports. This was done in an attempt to locate any axial indications outside the arc not found by the bobbin examination in SG21. This expansion consisted of approximately 124 tubes.

Fifth Expansion

The fifth expansion was to bound axial indications found on the edge of the arc expansion (third expansion) and to see if the arc continued below row 100.

Sixth Expansion

The sixth expansion consisted of testing tubes around the periphery from BW1 to VS3. This was done to test within the arc region in the horizontal sections of the tubing.

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VI. TROUBLESHOOTING ACTION PLAN (CONT.)

A. EXPANDED SCOPE OF ECT (cont.)

Unit 2, Steam Generator 1: (cont.)

Seventh Expansion

The seventh expansion was to make the arc of interest larger to match the thermo-hydraulic modeling performed using the ATHOS modeling program. The arc was expanded to include row 90.

Eighth Expansion

The eighth expansion extended the arc to match the refined modeling done in expansion seven. This increased the arc to an area of interest including row 70.

Ninth Expansion

The ninth expansion consisted of testing groups of tubes that were outside the arc, from the BW1 support down to the 01H support.

Tenth Expansion

The tenth expansion tested tubes within the arc from the BW1 to VS3 support using the flexible MRPC probe. The testing was performed in the arc in four separate blocks scattered around the area of interest.

VI. TROUBLESHOOTING ACTION PLAN (CONT.)

A. EXPANDED SCOPE OF ECT (cont.)

Unit 2, Steam Generator 1: (cont.)

Eleventh Expansion

The eleventh expansion tested tubes full length within the arc from the 07H down to the 01H support. This was done in order to check for indications in the lower sections of tubing below the arc.

Twelfth Expansion

The twelfth expansion tested tubes in groups outside the arc. Testing of these tubes varied from part length to full length examination. The purpose of this expansion was to outline the amount and type of indications outside the area of interest.

Unit 2, Steam Generator 2:

First Expansion

Due to the tube pulling activities, the eddy current examination was stopped in steam generator 22. Eddy current testing continued in steam generator 21, however. The expansion groups were consolidated when the tube pulls were completed. The first expansion consisted of the original arc and rows 116, 117, and 118.

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VI. TROUBLESHOOTING ACTION PLAN (CONT.)

A. EXPANDED SCOPE OF ECT (cont.)

Unit 2, Steam Generator 2: (cont.)

Second Expansion

The second expansion was to test via MRPC all indications found by the eddy current bobbin probe.

Third Expansion

The third expansion was to increase the original arc to match the seventh expansion in steam generator 21.

Fourth Expansion

The fourth expansion was done in order to have the arc in steam generator 22 match the thermo-hydraulic modeling performed using the ATHOS computer modeling program. This expansion went down to row 70.

Fifth Expansion

The fifth expansion tested tubes in groups outside the arc, from part length to full length examination. The purpose of this expansion was to outline the amount and type of indications outside the area of interest.

VI. TROUBLESHOOTING ACTION PLAN (CONT.)

A. EXPANDED SCOPE OF ECT (cont.)

STEAM GENERATOR 21

	# TUBES
1ST MRPC EXPANSION (R116, 117, 118)	600
2ND MRPC EXPANSION (INDICATIONS)	500
3RD MRPC EXPANSION (ARC)	922
4TH MRPC EXPANSION (CHECKERBOARD)	124
5TH MRPC EXPANSION (ARC EXPANSION)	816
6TH MRPC EXPANSION	116
7TH MRPC EXPANSION	752
8TH MRPC EXPANSION	625
9TH MRPC EXPANSION	225
10TH MRPC EXPANSION	161
11TH MRPC EXPANSION	114
12TH MRPC EXPANSION	1552
	6507

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VI. TROUBLESHOOTING ACTION PLAN (CONT.)

A. EXPANDED SCOPE OF ECT (cont.)

STEAM GENERATOR 22

	# TUBES
1ST MRPC EXPANSION (R116, 117, 118)	1259
2ND MRPC EXPANSION (INDICATIONS)	1135
3RD MRPC EXPANSION (ARC)	1118
4TH MRPC EXPANSION	1151
5TH MRPC EXPANSION	1279
	5942

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VI. TROUBLESHOOTING ACTION PLAN (CONT.)

B. ORIENTATION TESTING

During the outage, all tubes were inspected using the bobbin coil method of ECT, in addition, selected tubes were examined by motorized rotating pancake coil (MRPC). MRPC was used to characterize tube indications. In addition to detecting tube flaws, the MRPC also recorded indications at the low frequency (20KHz). Those indications have been characterized as deposits on the tubes' outside diameter. The MRPC inspection also detected several tubes with axial flaws and deposit indications located between and at supports. The information obtained by identifying the orientation of flaws/deposits to adjacent tubes or the tube bundle could be used in determining and evaluating the damage mechanism.

Test Description

In order to determine the orientation of a tube's flaws and/or deposits, a special inspection technique consisting of a magnetic indexing referencing (MIR) probe was used. The reference angle of the flaw/deposit is found by inserting the MIR probe into a tube adjacent to a target tube. The target tube is then inspected by the MRPC.

The magnetic field generated by the high energy magnets located in the MIR provides a reference in the MRPC signal. In order to avoid distorting the flaw/deposit, the MIR probe is positioned below the area of interest in the target tube. The MRPC probe is then positioned above the area of interest and withdrawn past both the flaw/deposit and MIR probe as the data is being recorded. By knowing the relative position of the tube with the MIR probe and the target tube, which was inspected by MRPC. the orientation of the flaw/deposit can be identified.

C. VIDEO ANALYSIS

Following the removal of the tube pull candidates, a secondary side video inspection was performed of the surrounding tubes. A video record was made by moving a remove camera through the full length of the channel created by the pulled tube. In order to assure areas of special interest received a detailed inspection, a check list was prepared as shown on table VI.C.a. The objectives of this inspection was to evaluate potential tube OD conditions such as flaws and deposits, as well as any abnormal tube bundle physical configurations

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VI. TROUBLESHOOTING ACTION PLAN (CONT.)

C. VIDEO ANALYSIS (cont.)

The following video tapes were recorded:

22-13 & 29-24 (5/29/93)

116-41 (5-7-93)

116-41 (5-17-93)

103-156 (5-15-93)

105-156 (5-13-93)

117-40 (5-8-93)

117-144 (5-19-93)

127-140 (5-13-93)

(11)

VI. TROUBLESHOOTING ACTION PLAN (CONT.)

D. TUBE PULLING

Background:

Tube pulls previously had been scheduled, independently of this plan, in order to investigate the cause of axial cracking at the 01H support (flow distribution plate). Shortly before the unit's fourth refueling outage was scheduled to start, a tube rupture occurred between the 08H and 09H support of tube 117-144 (SG 22). Subsequent eddy current inspection identified axial indications at other mid-span and support locations in the upper bundle. In order to determine the root cause of the tube rupture as well as the axial flaws, the originally planned tube pull program (i.e., 01H) was expanded to include tube sections from the upper tube bundle.

VI. TROUBLESHOOTING ACTION PLAN (CONT.)

D. TUBE PULLING (cont.)

Selection Process:

- Tube Sample Categories

Tubes selected for removal and laboratory examination fell into four category:

1. Tubes with Flaws at 01H
2. Tubes with Mid-span Flaws
3. Tubes with Flaws at upper bundle supports
4. "Clean" Tube

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VI. TROUBLESHOOTING ACTION PLAN (CONT.)

D. TUBE PULLING (cont.)

Selection Process: (cont.)

- Tubes Selected

Starting with the list of all tubes with axial indications, each tube was evaluated to determine which tube(s) would provide the most information within the identified categories. The steam generator inspection process included a 100% bobbin examination, with selected tubes inspected by MRPC. There were tubes where the bobbin inspection did not record an indication but with the MRPC an axial defect was identified. To evaluate that discrepancy, two tubes were selected which met that condition.

Also, tubes were evaluated based on their position relative to other tubes with axial indications, including axial deposits. (Refer to section VI.B. Orientation Testing for relative location of pulled tubes to adjacent tubes with indications at similar elevations). In addition, tubes were chosen to represent different regions of the tube bundle. As a contingency, extra tubes were selected as backup candidates.

Table VI.D.a. lists the primary and secondary tube pull candidates and the basis for selection. A brief summary of the basis for selection is provided below. Figure VI.D.a. shows the areas of the tube sheet where tube sections were removed.

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VI. TROUBLESHOOTING ACTION PLAN (CONT.)

D. TUBE PULLING (CONT.)

1. Tubes with Flaws at 01H: (22-13 & 29-24)

In the 1993 inspection, three tubes were identified with axial indications at the 01H. One tube exhibited significant growth from the 1991 inspection results. In addition to that tube, a second tube, one which contained an axial indication (recorded by MRPC) which the bobbin reported as a distorted support indication (DSI), was selected.

2. Tubes with Mid-span Flaws

2.1 Rupture Tube and Large Through Wall Flaw (117-144 & 105-156)

The tube rupture occurred mid-span below the 09H. In addition to the ruptured tube, a second tube with a mid-span flaw comparable to the rupture, was selected.

2.2 Axial Flaw detected by MRPC but not Bobbin (103-156 & 117-40)

Two tubes were selected which contained mid-span axial indications detected by MRPC but not by bobbin coil eddy current inspection. Both indications werer recorded /between the 08H and 09H.

3. Tubes with Flaws at Supports (07H, 08H, & 09H) (127-140)

In addition to the recorded axial indications at mid-span, some axial indications were found at upper bundle supports. One tube which contained arc axial indication at both the 07H and 08H was selected for removal to evaluate this type of degradation.

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VI. TROUBLESHOOTING ACTION PLAN (CONT.)

D. TUBE PULLING (CONT.)

4. "Clean" Tube (116-41)

In order to evaluate the detectability limits of eddy current, one tube, which had no indications identified between the 08H and 09H support, was selected. An additional criteria for this tube was that it would be located next to tube(s) with recorded axial flaws.

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VI. TROUBLESHOOTING ACTION PLAN (CONT.)

E. ANALYSIS

In addition to troubleshooting data, several reviews and analyses were performed to support/refute the probable failure modes. The analyses also helped the team more fully understand conditions in the steam generator (thermo-hydraulics, vibration etc.).

1. Contact Forces

Contact Force and Lateral Deflection Analysis - An analysis was initiated to evaluate the hypothetical possibility of a lock-up of a tube within the bundle. The analysis would be developed from design characteristics of the generator tube and tube support structures. A three dimensional finite element model of the tube bundle would be used, with many tubes lumped together for model simplification. The analysis would include the effect of dead weight and thermal loading for several load cases.

Basis of Studies Performed

Detailed three dimensional finite element studies of the Palo Verde steam generator tube bundle were initiated in order to gain an understanding of the causes of tube defect indications found in the upper bundle regions. Besides evaluating normal operating design geometry, thermal and flow conditions, additional load uses were considered for hypothetical boundary conditions which might result from the presence of a corrosive environment. The load cases are summarized below:

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VI. TROUBLESHOOTING ACTION PLAN (CONT.)

E. ANALYSIS (cont.)

1. Contact Forces (cont.)

Case A: Design Geometry, Thermal Growth and Flow Loads

Under normal operating conditions, tube-to-tube support contact forces do occur due to differential thermal expansion. However, a 3-D analysis of this effect was not performed during the design phase. Since the tube wear indications were occurring in localized regions, a 3-D model evaluation was deemed appropriate.

Case B: Dead Weight Plug Thermal Loading

This condition was evaluated in order to provide a comparison of thermal loads with normal dead weight.

Case C: Elastic I-Beam/Vertical Support Lock-up (Zero Vertical Gap) with Thermal Growth Loading

During normal operating conditions (gap = .31"), the I-beams and vertical supports do not come into contact. However, if a zero gap condition were to exist from to corrosion or manufacturing non-conformance, additional tube/support contact forces would develop because of differential thermal expansion. It was decided to investigate this "hypothetical" condition to see if it would help explain reports of tube "bowing."

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VI. TROUBLESHOOTING ACTION PLAN (CONT.)

E. ANALYSIS (cont.)

1. Contact Forces (cont.)

Case D: Tube/Batwing Lock-up

This "hypothetical" condition was also evaluated to see if sufficient reaction forces could develop at tube/batwing intersections which might cause some tubes to bow or defect into adjacent tubes.

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VI. TROUBLESHOOTING ACTION PLAN (CONT.)

E. ANALYSIS (cont.)

2. Crack Growth

Failure modes which could produce axially oriented mid-span cracks were investigated. Based on the orientation and location of the crack and the morphology of the rupture observed in the video probe inspection, outside diameter stress corrosion cracking (ODSCC) and fatigue were identified as the most probable failure modes.

Once metallurgical examinations determined ODSCC to be the failure mode, a review of potential crack growth rates, as published in the industry literature, was performed to determine if ODSCC could produce crack growth rates consistent with that indicated to have occurred in the ruptured tube (R117/C144). Since R117/C144 did not have any detectable indication during the last inspection, a reasonable approximation of the crack growth rate could be determined by assuming crack depths just below the level of detection at the last inspection. A more conservative approach is to assume essentially zero crack depth at the last inspection and base crack growth rate calculations on the current bobbin depth divided by the total cycle length of 15 months. The following analyses were performed to determine the maximum operating time until a re-inspection of the steam generators must be performed to ensure the safety margins are maintained specified in Regulatory Guide 1.121.

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VI. TROUBLESHOOTING ACTION PLAN (CONT.)

E. ANALYSIS (cont.)

2. Crack Growth (cont.)

Crack Growth Analysis Action Plan

a. Develop Critical Flaw Size Diagram

A critical flaw size diagram would be developed for axial cracks to assist in defining the maximum allowable crack size at the end of the operating cycle to meet Reg. Guide 1.121 required margins.

b. Develop Crack Growth Rates

Reasonable crack growth rate predictions based on the most probable root cause outside diameter stress corrosion cracking (ODSCC) would be developed in order to qualitatively assess the predicted crack growth rate.

c. Determine Initial Flaw Size

The initial flaw size based on the assumed ECT detectability threshold would be determined and used in the crack growth analysis.

d. Determine Length of Operating Cycle

The operating time prior to exceeding Reg Guide 1.121 limits would then be determined based on the assumed initial flaw size and crack growth rates.

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VI. TROUBLESHOOTING ACTION PLAN (CONT.)

E. ANALYSIS (cont.)

3. Thermodynamic Model for Quality/Velocity Distribution

In order to evaluate the environmental conditions within the tube bundle a thermodynamic model was used. The thermodynamic model has become well established for use on ABB/CE steam generators. The model analyzes the thermodynamic conditions throughout the tube bundle and evaluates the environmental conditions within the bundle. The model would be used at PVNGS to develop velocity, quality and chemical concentrations. The results would be used to correlate areas of degradation in the steam generators with area of severe environment.

Analysis of two phase flow induced vibration was performed to evaluate the possibility that high stress was present in the Unit 2 steam generators. The analysis was based on mathematical models used for modeling steam generators thermalhydraulic behavior.

In particular, the stability ratio for a tube in tube row 117 was to be evaluated for a number of specific models for tube/tube support interactions. The analysis was performed by two independent groups to ensure the results could be uniformly accepted.

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[illegible]

VI. TROUBLESHOOTING ACTION PLAN (CONT.)

E. ANALYSIS (cont.)

3. Thermodynamic Model for Quality/Velocity Distribution (cont.)

a. Athos II Code Description

ATHOS (Analysis of the Thermal-Hydraulic Of Steam Generators) is a three-dimensional, two-phase, steady state and transient code for thermal-hydraulic analysis of recirculating U-tube steam generators. The code was developed for the Electric Power Research Institute (EPRI) by CHAM of North America. ATHOS was further modified by Combustion Engineering (CE) to incorporate modeling of plugged, sleeved, removed and pulled tubes. The CE version of the code also includes capability to model sludge deposits on the tubesheet. A more detailed description of the mathematical and physical models, finite difference equations, the code structure and solution procedure is presented in Reference 1.

VI. TROUBLESHOOTING ACTION PLAN (CONT.)

E. ANALYSIS (cont.)

3. Thermodynamic Model for Quality/Velocity Distribution (cont.)

a. Athos II Code Description (cont.)

The ATHOS code has been checked and verified by Combustion Engineering and others (References 2,3,4,5,6,7). The check-out studies included comparing the ATHOS geometry pre-processor computed values of the steam generator geometric parameters against hand calculations; checks on the mass, momentum, and energy balances, and consistency and plausibility of steady-state and transient solutions for a number of different cases. For code verification measured data from several small-scale experiments, model steam generators, and full scale steam generators were compared with ATHOS results. In one case, an analytical solution was available for comparison with ATHOS calculations. In general, the agreement between the ATHOS results and available experimental data was good. In addition, consistent trends were found in all parametric studies. More details of ATHOS verification may be found in References 2 through 7.

VI. TROUBLESHOOTING ACTION PLAN (CONT.)

E. ANALYSIS (cont.)

3. Thermodynamic Model for Quality/Velocity Distribution (cont.)

b. S.G. Level Oscillation

A review of SG 22 operating data revealed that the steam generator had a history of feedwater flow and the downcomer water level oscillations. the downcomer water level data indicated that the level had fluctuated approximately ± 5 percent of Narrow Range (NR) with a period of one and half minutes. During the Eddy Current and video inspections of the SG 22, deposit indications on the outer tube surface have been discovered. The linear deposit indications are located in the upper tube bundle, mostly between tube supports 07H and 09H. Following the discovery of the tube damage and deposits, thermal hydraulic analyses were performed to understand the root cause of the observed phenomena and to investigate a possible link between feedwater flow oscillations and tube degradations. The analyses were performed using the ATHOS II code.

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VI. TROUBLESHOOTING ACTION PLAN (CONT.)

E. ANALYSIS (cont.)

3. Thermodynamic Model for Quality/Velocity Distribution (cont.)

b. S.G. Level Oscillation (cont.)

ATHOS Analysis

The ATHOS model of the Palo Verde Unit 2 steam generator includes specifications for the geometric details, transport correlations, and operating conditions. Details of the geometric specifications are input to the ATHOS Geometry Pre-Processor (ATHOSGPP) program. The necessary geometric data calculated by ATHOSGPP which includes the finite difference grid, steam generator shell and shroud details, and all the geometric parameters utilized by the ATHOS code are written on a tape. The finite difference grid selected for the model is 14 x 10 x 27 in the circumferential (0), radial (R) and axial (Z) directions, respectively. The arrangement of the finite difference grid in the R-Z and R-0 plane is shown in Table 1 and Figure 1. The steam generator operating conditions utilized for the analysis are included in Table 2 for the four steady state cases investigated.

For Case 1 and 2 the downcomer level was set at the normal operating level (NWL) which is 449.72 inches above the top of the tubesheet. Homogeneous two-phase flow was modeled for Case 1 and algebraic slip was modeled for Case 2. Cases 3 and 4 represent homogeneous flow models with downcomer levels NWL + Narrow Range, 457.25 inches and 442.19 inches, respectively.

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VI. TROUBLESHOOTING ACTION PLAN (CONT.)

E. ANALYSIS (cont.)

4. Effect of Level Oscillation

A study and analysis on the effects of Feedwater flow oscillations, of 5% peak-to-peak, on the steam generator (SG) and the subsequent SG level oscillations will be investigated. From the data collected to date, it appears that SG #2 has a large peak-to-peak level oscillation than the other SG's in the other units, and Unit 2 SG #1.

Two potential adverse effects from flow oscillation that can contribute to initiation and propagation of axial cracks are:

(1) Inducing alternating boiling, and consequently ridge deposits, in the high void fraction zone. The ridge deposits are crevices that can concentrate damaging chemicals.

(2) Enhancing FIV mechanisms (either unsteady momentum or fluideliastic instability) due to flow regime changes.

The objective of this study and analysis is to show the effects and/or correlation (if any) to the ruptured tube. The relationship between this phenomenon and the ruptured tube may be a contributing factor in the root cause analysis of the tube rupture. The results of the study and analysis may explain the uniqueness of this phenomenon to unit 2 only.

VI. TROUBLESHOOTING ACTION PLAN (CONT.)

E. ANALYSIS (cont.)

~~4. Effect of Level Oscillation~~

~~See next page~~

5. ECT Methodology Review

The primary method used to identify and define SG tube degradation was eddy current testing. Concerns regarding the validity of our ECT methodology and detectability were identified (i.e., the possibility that the apparent increase in degradation indicated by 1993 ECT results, was a function of problems with ECT methodology).

As a result, the ECT methodology would be reviewed and attention would be focused on ECT signal/noise ratio, standards, limits of detectability, and sensitivity.

VI. TROUBLESHOOTING ACTION PLAN (CONT.)

E. ANALYSIS (cont.)

6. Secondary Side Inspection

A secondary side inspection of the upper tube bundle in steam generator 22 was performed. The purpose of the inspection was to: 1) look for indications of the tube bundle or individual tubes being restrained from thermally expanding and 2) compare the over-all condition of the upper bundle with the condition observed during a similar inspection 2 operating cycles previous (U2R2). The two individuals performing the inspection, one from APS and one from ABB/CE, had participated in the previous inspection of the same steam generator. This allowed a direct comparison between the two inspections to be made. The inspection consisted of the following steps:

- Observed gap between top of VS3 and 5 crescent plate and bottom of I-beam.
- Used feeler gauge to verify clearance between the crescent plates and structural angles.
- Observed number of local vertical support strip deformations for comparison with previous outage.
- Observed proximity of batwing wrapper bar to shroud. Look for evidence of contact.
- Performed general observation of condition of upper bundle. Look for distortions, changes from previous inspections.
- Observed condition of separator can splitter vanes (as was done in Unit 1)

VI. TROUBLESHOOTING ACTION PLAN (CONT.)

E. ANALYSIS (cont.)

6. Secondary Side Inspection (cont.)

- Viewed area on can deck near "J" tube discharge for any deposits or debris.

7. Chemistry Review & Evaluation

Investigation and research of pertinent chemistry data and parameters has been concluded. The following information outlines whether the data reviewed indicates a causal link with the SGTR.

- Feedwater Flow Rate

  A review of the feedwater flow data for Unit 2 Cycle 4 was conducted. The data indicated the average mass flow to each generator was about 8,750 Klb/Hr. The mass flow to S/G 1 was approximately 100 Klb/Hr higher than the mass flow to S/G 2. This is a difference of 1.15%.

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VI. TROUBLESHOOTING ACTION PLAN (CONT.)

E. ANALYSIS (cont.)

7. Chemistry Review & Evaluation (cont.)

- Blowdown Flow Rate

In the past, the steam generator blowdown flow rates for Units 1, 2 and 3 have varied, as a result of chemistry data and blowdown philosophy. Unit 2 has typically had longer periods of abnormal rates of blowdown than Units 1 and 3. The typical blowdown regime has been 2 hours of abnormal blowdown each night, and twice a week high rate blowdown for two minutes per hot leg and cold leg. In 1992 Unit 1 and 3 began the twice a week two minute high rate blowdown for hot leg and cold leg followed by a two hour abnormal blowdown. Other changes in the blowdown flow rate varied dependent upon transient chemistry conditions.

Blowdown effectiveness had been evaluated through a number studies. The 1986 lithium injection test and the EPRI sponsored ATHOS model both suggested a significant contribution from the feedwater to the blowdown. A review of the plant downcomer vs. hot leg data along with the EPRI tracer injection test supported the above findings. The ABB tube bundle chemistry model considered these observations and predicted that the blowdown water contained 80-90% feedwater.

Blowdown flow tests conducted in Unit 2 during the EPRI tracer injection study (August 1992) showed the normal S/G blowdown flow rate to be nearly equivalent between S/G 1 and S/G 2. However, the abnormal S/G blowdown flow rate was a factor of 2 higher for S/G 2 than S/G 1.

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VI. TROUBLESHOOTING ACTION PLAN (CONT.)

E. ANALYSIS (cont.)

7. Chemistry Review & Evaluation (cont.)

- Hideout Return Studies

Hideout return data is considered the most accurate indicator of the chemistry present within steam generator crevices during operation, and as such, can provide insight into potential damage mechanisms. A review of data, obtained during shutdowns in the three Palo Verde units, was conducted to determine whether there was a difference in the hideout return characteristics of the six steam generators. A total of 53 shutdown data sets covering January 1987 through March 1993 were reviewed. Data for shutdowns that occurred prior to January 1991 were reviewed by site chemistry for peak concentrations observed during the shutdown. More recent shutdown data was reviewed with cumulative grams returned quantified. In addition, samples were taken from the flow distribution plate (hot leg).

A summary of peak concentration data (prior to 1991) is presented in Figure V.A.2.a.i The data included are:

- The average chloride, sulfate and sodium peak concentrations observed during the shutdown,
- The calculated ratios of sodium divided by chloride plus sulfate (cation/anion balance),
- The calculated molar ratios of sodium divided by chloride, and
- The ratio of each units' SG 1 to SG 2 for each impurity (SG 1 divided SG 2)

[illegible]

VI. TROUBLESHOOTING ACTION PLAN (CONT.)

E. ANALYSIS (cont.)

7. Chemistry Review & Evaluation (cont.)

- Hideout Return Studies (cont.)

Hideout return data (1991 - 1993) obtained in accordance with 74DP-9ZZ06, Hideout Return, is much more extensive and provides for quantification of grams returned for 12 species and an estimation of crevice pH (MULTEQ) and is also summarized as Figure V.A.2.a.i. Included in the table is:

- The average grams returned during the shutdown from each generator, and
- The MULTEQ predicted crevice pH during operation as determined from sodium, chloride, sulfate, calcium, magnesium, silica, potassium, etc.

- Sulfate Source

An assessment of sulfate in the secondary cycle was conducted due to the implications of sulfate causing intergranular stress corrosion cracking (IGSCC).

- <u>Unit 2 Steam Generator Can Deck Resin Contamination Action Plan</u>

The initial step was to determine the quantity of resin remaining within the steam generator. Depending upon the amount of resin remaining, it would be necessary to determine whether there were any cation resin functionality groups remaining. The cation resin functional groups are sulfonic bearing which may decompose to sulfuric acid when exposed to steam generator temperatures. If this had already taken place, the remaining cation resin will be inert. Any inert resin present will not cause a problem from a chemical point of view. Anion resin will not pose a problem either.

VI. TROUBLESHOOTING ACTION PLAN (CONT.)

E. ANALYSIS (cont.)

7. Chemistry Review & Evaluation (cont.)

- Unit 2 Steam Generator Can Deck Resin Contamination Action Plan (cont.)

The following test was designed as a go/no go test and could be performed remotely without analytical equipment. To determine if any functional groups are remaining on the cation resin:

1. Prepare a saturated sodium chloride solution. Fill a 250 ml (approx.) clear container with the saturated salt solution.

2. Add several grams of the resin to be tested to the clear flask and agitate.

3. Observe whether any resin falls to the bottom of the flask.

If any cation resin with intact functional groups are remaining, these resin beads will drop to the bottom of the flask due to their density being higher than either inert resin, anion resin, or cation resin with no functional groups remaining. If none of the resin sinks, the resin would pose no chemical problem. If some of the resin sinks, it may mean either:

1. Functional cation groups are present, or

2. The resin may be fouled with iron, etc. which would make it more dense.

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[illegible]

VI. TROUBLESHOOTING ACTION PLAN (CONT.)

E. ANALYSIS (cont.)

7. Chemistry Review & Evaluation (cont.)

- Unit 2 Steam Generator Can Deck Resin Contamination Action Plan (cont.)

  Therefore, if the above go/no go tests results in sinking resin, it would be necessary to rule out the possibility of fouled resin. This could be done by to removing the iron fouling by acid dissolution or ultrasonic cleaning, rinsing, and then repeating the salt test.

- EPRI Tracer Test

A hideout evaluation test was performed at Unit 2 from 8/18 to 8/22/92.

VI. TROUBLESHOOTING ACTION PLAN (CONT.)

E. ANALYSIS (cont.)

7. Chemistry Review & Evaluation (cont.)

- EPRI Tracer Test (cont.)

  The test had a two fold purpose:

  1) Measure the impurity accumulation (i.e. hideout) in the crevice regions of the steam generator and

  2) Measure the abnormal and normal blowdown flow rates from each steam generator.

- Sampling Methodology

  Prior to 1993, the hot leg sample point was used to monitor and control steam generator chemistry. The downcomer sample is currently used due to information gathered from various sources. These sources include a lithium tracer study conducted by APS and CE, an EPRI sponsored tracer injection test performed by NWT Corporation (EPRI S401-1 topical report, March 1993), a blowdown flow model developed by CE (CRDRC Report 4039/1, January 1993) and comparisons of Site Chemistry's steam generator blowdown sample database.

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VI. TROUBLESHOOTING ACTION PLAN (CONT.)

E. ANALYSIS (cont.)

7. Chemistry Review & Evaluation (cont.)

- Condenser Leaks

  A "Condenser Tube Leak Assessment" was conducted by Systems Engineering. The assessment separated tube leak rates into two categories, before and after lathing was installed in the condensers to stabilize the tubing.

- Operational Secondary Chemistry History

  A review of steam generator operating chemistry has been completed for all three units. This review also considered changes to operational conditions and parameters.

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VI. TROUBLESHOOTING ACTION PLAN (CONT.)

E. ANALYSIS (cont.)

8. Deposit Formation

Deposits create opportunities for tube degradation. The deposits act as the equivalent of a crevice due to the stagnation that occurs under the deposit. Secondly, the deposit provides a "host" location for the concentration of chemicals and contaminants which differs from the bulk chemistry. Lastly, the deposits may contribute to higher tube wall temperatures. Actions to be taken included:

- Conducting ECT to identify deposits (PDPs)
- Conducting video inspection of deposits through pulled tube location
- Conducting laboratory examination of deposits
- Performing visual and micrographic characterization of the deposits
- Conducting chemical analysis of the deposits:

  At BWNS (Lynchburg, VA):

  1) 8 sample locations

     crevice and free-span, 117-40, 08H

     crevice and free-span, 117-40, 05H

     crevice and free-span, 117-40, 01H

     crevice and free-span, 22-13, 01H

  100g of sample to be sent to Alliance laboratory for XRD (X-ray defraction) and semi-quantitative spectroscopy.

VI. TROUBLESHOOTING ACTION PLAN (CONT.)

E. ANALYSIS (cont.)

8. Deposit Formation (cont.)

2) Balance of sample

   a) Acid digestion and deposit characterization of 05H sample, one upper bundle free-span, and one lower bundle crevice sample.

   b) Leachate test, then ICP (inductively coupled plasma) on residue and solute, 01H and 08H samples.

VI. TROUBLESHOOTING ACTION PLAN (CONT.)

E. ANALYSIS (cont.)

9. Other

a. Tube Metallurgical Analysis

The scope of the metallurgical examinations intended for steam generator tube failure analysis were developed by APS Nuclear Engineering and the Inservice Inspection group and utilized the guidance provided in Electric Power Research Institute (EPRI) report NP-6743-L, Appendix C. The purpose of the examinations were intended to determine a) tube degradation mechanisms; b) correlations of laboratory eddy current data with field data; and c) tube integrity testing via laboratory burst testing of defective, pulled tubing. The tube examinations were conducted at two different lab facilities, ABB-CE in Windsor, CT and B&W in Lynchburg, VA. Once the Palo Verde tube sections were received by the laboratories, the investigation process required ongoing daily planning sessions between APS Metallurgists and vendor project managers, and, when required, consultation with the APS Root Cause Failure Team to determine if more specific tube information was required to support the total scope of investigations. Therefore, communication among all parties was an integral key to the examination process.

A detailed description and purpose of each tube examination method is described below. Specific tube section examination results are described in the following section.

VI. TROUBLESHOOTING ACTION PLAN (CONT.)

E. ANALYSIS (cont.)

9. Other (cont.)

a. Tube Metallurgical Analysis (cont.)

- **Receipt Inspections:** Radioactive tube sections were received by the laboratories and documented by the Health Physics technician. Tube sections were measured for length and checked for orientation and section markings.
- **Visual Inspections:** Tube sections were visually examined with a low power stereomicroscope to identify and characterize any tube degradation on the tube. Tube deposit visual characteristics were also determined, and any apparent damage from the tube pulling process was noted. The tube sections were photographed in the as-received condition. Areas of interest were also photographed for review and record purposes. Those areas could be selected for further investigation in addition to planned areas of interest.
- **Eddy Current Testing (ECT):** Tube sections were selected for ECT testing using both the bobbin coil and the motorized rotating pancake coil (MRPC) to precisely verify and locate tube defects for investigation. Qualified ECT personnel performed the inspections and analyzed the data. The ECT data was then used to both identify defect areas and to correlate to field ECT findings.

VI. TROUBLESHOOTING ACTION PLAN (CONT.)

E. ANALYSIS (cont.)

9. Other (cont.)

a. Tube Metallurgical Analysis (cont.)

- **Radiography:** This was performed on tube sections with defect areas of interest. The primary purpose was to verify the defect location and dimensional characteristics. Radiography was not sensitive to corrosion forms of degradation such as intergranular attack (IGA) or intergranular stress corrosion cracking (IGSCC).
- **Dimensional Measurements:** These measurements were performed to determine diametrical and tube wall thickness variations, and to characterize any tube bend or bow. This information was needed to verify tube wall thickness specifications and to locate any bowing which could have contributed to degradation processes.

VI. TROUBLESHOOTING ACTION PLAN (CONT.)

E. ANALYSIS (cont.)

9. Other (cont.)

a. Tube Metallurgical Analysis (cont.)

- **Deposit Removal and Analysis:** Selected areas of tube deposit formations were identified and removed from the tube by mechanical scraping for future chemical analysis. Deposit locations and physical characteristics were noted. Deposits were then submitted for chemical analysis to identify the chemical composition and any chemical contaminants which could have contributed to a postulated corrosion degradation mechanism. The extent of deposit chemical analysis included the following:

  - X-Ray Fluorescence/Diffraction - performed to determine elemental composition and crystalline phases of deposit chemistry.
  - Mossbauer Spectroscopy - performed to determine the oxidation state of the iron in the deposits. This was necessary to positively identify the presence of magnetite, which was expected to be the prime deposit compound.
  - Leachant Analysis - included Ion Chromatography, Inductively Coupled Plasma and Flame Emission Spectroscopy to identify inorganic anions (i.e., Cl, SO_4^{2-}), metallic cations (Mg, Cu, Cr, K, Ca, Pb, Al, Sn, etc.), total sulfate and organic acids. This information was important in order to determine the crevice chemistry on the tube surface and understand the potential chemical corrodents.

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VI. TROUBLESHOOTING ACTION PLAN (CONT.)

E. ANALYSIS (cont.)

9. Other (cont.)

a. Tube Metallurgical Analysis (cont.)

- **Burst Testing:** This was performed on selected tube sections which had been identified as having tube defects, such as axial crack indications. Wear scar areas might not have been burst tested, but were subjected to characterization using the test methods described below. Burst testing was intended to pressurize the tube and measure the pressure required to burst open the defect area. Once the burst was completed, the open crack surface was examined in detail (fractography) to determine the type of cracking (i.e., intergranular cracking, fatigue cracking) and depth of attack. The surface condition of the tube burst surface was also closely examined to determine if there were any surface defects present and associated with the defect. The burst pressure was correlated with the defect depth profile and analyzed for conformance with industry standards for acceptance. This data was used in tube integrity analyses for justification for alternate tube plugging studies. The burst surface was closely examined via the following methods:

  - Low Power Stereomicroscope - the surface was examined and subsequently photographed to observe the general axial extent depth of cracking or wear. Notes were taken regarding the orientation of cracking, surface condition, and extent of secondary cracking observed that was opened as a result of the burst pressure.

VI. TROUBLESHOOTING ACTION PLAN (CONT.)

E. ANALYSIS (cont.)

9. Other (cont.)

a. Tube Metallurgical Analysis (cont.)

- Sectioning Diagram - a sectioning diagram was developed for deciding which sections were to be studied under the scanning electron microscope (SEM) and by Auger Electron Spectroscopy (AES) and X-Ray Photoelectron Spectroscopy (XPS).
- SEM - provided high magnification examination of the crack or wear surface. This allowed the mode of cracking to be determined, i.e., IGSCC or fatigue cracking. If the cracking was intergranular then it was clearly visible under the SEM, as the surface had a "rock candy"-like appearance. The examination was crucial for that aspect alone. The crack depth profile was also determined using the SEM. This information was important both for eddy current data analysis and corrosion attack characterization. The SEM also had the capability of performing qualitative chemical analysis of the defect surface and any associated deposits through the use of the Energy Dispersive Spectroscopy (EDS) equipment. EDS was based on x-ray fluorescence that resulted from bombarding the sample with an electron beam.
- AES - provided elemental analysis of thin corrosion films. This microanalytical technique was vital for identifying the chemical contaminants at the crack surface, as well as the degree of nominal material depletion, such as chromium or nickel. This information was needed to assess the nature of the crevice environment, such as whether the crevice was acidic or alkaline.
- XPS - provided elemental/compound analysis of thin corrosion films. It could add additional vital information regarding the chemical attack at the crack surface by identifying how elements were chemically combined. This information was useful in identifying corrosion products which were also indicative of the local crevice environment.

VI. TROUBLESHOOTING ACTION PLAN (CONT.)

E. ANALYSIS (cont.)

9. Other (cont.)

a. Tube Metallurgical Analysis (cont.)

- Metallography - performed on defect areas by sectioning material cross sections, polishing, etching to show contrast with grain boundaries, and viewing under light optical microscope to verify the mode of cracking. The extent of crack branching, depth of IGA, surface condition and grain size/ characterization were also determined.

• **Tube Material Characterization:** This work was specified to be performed to determine the material's property conformance to specifications. Material that was not in conformance with tube material specifications might have been more susceptible to failure by either corrosive or mechanical means.

- Dual Etch - performed to assess material grain size and carbide distribution. Those properties had been shown, both through corrosion literature and field data, to have influenced the corrosion resistant properties under specific environments.
- Modified Huey Testing - performed to determine bulk material sensitization levels in tube sections (grain boundary carbide levels). The degree of material sensitization had been shown in literature to affect the material corrosion susceptibility in various environments.
- Bulk Chemical Analysis - performed to verify nominal chemical composition of the tube material. Discrepancies noted would have also affected the material corrosion resistance and mechanical properties.
- Tensile Testing - performed to verify mechanical properties.

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VI. TROUBLESHOOTING ACTION PLAN (CONT.)

E. ANALYSIS (cont.)

9. Other (cont.)

a. Tube Metallurgical Analysis (cont.)

- Additional Testing: While most work was focused on examining tube defect areas, additional work may be performed as the investigation proceeds and further areas of interest are identified. This may include descaling of tube sections for surface characterization, liquid penetrant testing for eddy current verification, and sectioning of selected defect areas (not burst areas) for depth profiling.

In summary, steam generator tube failure analysis can be an effective method for determining tube degradation modes and providing data for corrective action evaluation. The investigation process undertaken by PVNGS, ABB/CE and BWNS was vigorous and resource intensive. Results will be carefully evaluated against plant data, past field experience and laboratory studies involving Inconel 600 tube corrosion.

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VI. TROUBLESHOOTING ACTION PLAN (CONT.)

E. ANALYSIS (cont.)

9. Other (cont.)

b. Sludge Samples

Samples were obtained from the tube sheet region, through the handholes, of SG 21 and 22 hot and cold leg region and on the flow distribution plates of SG 21 and 22. The samples were analyzed in the Unit 2 chemistry lab for lead (Pb), by inductive coupled plasma (ICP). Qualitative and quantitative analysis (including Pb) was performed by CE and B&W.

- Lead

Initial results indicated approximately 1400 ppm, from the PVNGS sample analysis. These results were questioned. The instrument vendor (Lowman Labs) was questioned as to the viability of the lead wave length (Pb-2 line 283) that Unit 2 had used. Due to the interference that a large quantity of iron gives to the Pb-2 line (220), the Pb-1 line was identified by the vendor as the appropriate line to use. At the Pb-1 line, the lead value of that sample reduced to approximately 100 ppm. Subsequent discussions determined that the Pb-1 line would be used.

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VI. TROUBLESHOOTING ACTION PLAN (CONT.)

E. ANALYSIS (cont.)

9. Other (cont.)

b. Sludge Samples (cont.)

- Lead (cont.)

  A split of SG-21 sludge has been sent to B&W, who determined that based on the Pb-1 lining, 78 ppm of lead was present. In parallel with resolving the Pb line to be used, additional samples were pulled throughout the secondary system and Unit 1. Samples were also taken from the flow distribution plate (hot leg).

The samples were digested in aqua regina (Nitric and Hydrochloric acid). PVNGS sample results were as follows:

SG 21 40 ppm Pb

SG 22 100 ppm Pb

Sludge from SG 11 (obtained during Unit 1's last outage, 1R3) was analyzed by B&W, whose results showed ~78 ppb, Pb, with the majority of the material (99+%) as magnetite.

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VI. TROUBLESHOOTING ACTION PLAN (CONT.)

E. ANALYSIS (cont.)

9. Other (cont.)

c. Chemical Source Identification Study

The scope of the study was to identify sources of lead, copper, sulfur, molybdenum (Pb, Cu, S, Mo) that exist or have existed on the wetted surfaces of the Unit 2 secondary systems. The specific systems to be examined are AF, AS, CD, CO, CT, ED, FT, FW, GS, MT, QH, SC, SG. The threshold of concern for the listed elements should consider a significant percentage of the element in a given component (e.g. 3%), an appreciable wetted surface area (e.g. several square inches), or a single event related intrusion that occurred during 1990 through the present.

The activities to be performed were:

1) A review of potential Pb, Cu, S, Mo sources

- Chemical use review board (CUP items)/Authorized Material List
- Consumables
- Secondary System Components
- Tools
- Secondary transport analysis
- Bulk chemicals

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VI. TROUBLESHOOTING ACTION PLAN (CONT.)

E. ANALYSIS (cont.)

9. Other (cont.)

c. Chemical Source Identification Study (cont.

2) A review of Site Documentation

- Engineering Evaluation Reports
- Material Nonconformance Reports
- Site Mod/Document Change Processes
- Condition Reporting Document Reviews
- Work Orders
- Temporary Modifications
- Industry document search

3) Interviews conducted with

- Demin Operators

4) A review of Radiation Protection (RP)/As Low As Reasonably Achievable (ALARA)

- Refer to previous Pb review

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VI. TROUBLESHOOTING ACTION PLAN (CONT.)

E. ANALYSIS (cont.)

9. Other (cont.)

c. Chemical Source Identification Study (cont.)

5) Identification of Plant Component Inspection

- Pump suction strainers
- Resin trap strainers
- Condensers
- Feedwater heaters (LP and HP)
- System dead legs

d. Fabrication Review

A review of CE's fabrication methods and their records relating to the fabrication of the SGs was performed. The purpose of the review was to determine if a link existed between the initial fabrication and the observed failures.

The review process included discussions with some of the personnel who were involved in the design and fabrication of the Steam Generators.

The APS Unit 2 steam generator tube rupture is postulated to be unique to Unit 2. If not unique, the tube degradation appears to manifest itself more rapidly in Unit 2. This postulation is based upon prior steam generator experience at all three units of the Palo Verde plant.

VI. TROUBLESHOOTING ACTION PLAN (CONT.)

E. ANALYSIS (cont.)

9. Other (cont.)

d. Fabrication Review (cont.)

The APS task force set out to define possible cause(s) for the seemingly advanced tube degradation in Unit 2. Among the possible causes identified was the shop fabrication, particularly as it related to the tube support assembly and the tubing operation.

Special emphasis was given to the evaluation of the tubing manufacture, the tube bending operation and the tubing insertion into the steam generators.

VI. TROUBLESHOOTING ACTION PLAN (CONT.)

E. ANALYSIS (cont.)

9. Other (cont.)

e. Wear Analysis/Review

A cursory review of the 1993 Unit 2 steam generator eddy current examination was conducted by the steam generator working group. The review revealed an increased amount of wear in the 21 and 22 steam generators. This wear was primarily located in the upper tube bundle. An in-depth review of the wear in the generators was performed to categorize the wear.

1993 wear indications of greater than 20% were studied. 1991 bobbin coil data were reanalyzed for indications that changed by greater than 10%. The results of the two inspections were then compared in juxtaposition. From this comparison a determination of the actual rate of increase of tube wear would be determined, problem areas in the generator identified, and corrective actions initiated as appropriate.

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VI. TROUBLESHOOTING ACTION PLAN (CONT.)

E. ANALYSIS (cont.)

9. Other (cont.)

f. Loose Parts Analysis

Tube wear caused by loose parts was identified as a possible failure mode. To investigate this possibility, the following was performed:

1. During performance of video inspection from inside the ruptured tube, observe for indication of a foreign object on the outside of the tube and morphology of the rupture.

2. Review low frequency channel of eddy current signal for indication of the presence of loose parts.

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