APPENDIX A

ABB Combustion Engineering

Prediction of Tube Wear in the Batwing Stay Cylinder Region for
Palo Verde Steam Generator 22 Operating Cycle 7

A-PVNGS-9416-1165 Rev 0

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PREDICTION OF TUBE WEAR IN THE BATWING STAY CYLINDER REGION FOR PALO VERDE STEAM GENERATOR 22 OPERATING CYCLE 7

A-PVNGS-9416-1165, REV. 0

NON-PROPRIETARY VERSION

Quality Class 3 (Non - Safety-Related)

PURPOSE: To predict the tube wear at the batwings in the central cavity region for Unit 22 Cycle 7.

This Design Analysis is complete. Management authorizes the use of its results.

PREPARED BY R. E. Johnson DATE: Signed 4/30/97

VERIFICATION STATUS: NOT APPLICABLE

The information contained in this document is not design related and verification is not required.

APPROVED BY: D. P. Siska DATE Signed 4/30/97

ABB COMBUSTION ENGINEERING
CHATTANOOGA, TENNESSEE

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1.0 EXECUTIVE SUMMARY

This report contains tube wear predictions for tubes in the batwing central cavity wear region of the Unit 22 steam generator at Palo Verde. The wear predictions are made for the end of the current cycle of operation, Cycle 7, and consider the thermal hydraulic conditions existing in the cavity subsequent to the modification of the generator by installation of the 45 flow holes in the downcomer shroud. This modification results in a predicted increase in the fluid velocity in the central stay cavity which is expected to cause an increase in the wear rates on the tubes in the region. A significant increase in wear rates was observed in Unit 32 Cycle 6 after a similar modification to that generator which resulted in a smaller increase in the fluid velocity.

The wear predictions in this report are made using the wear progression analysis developed when the batwing wear problem was first observed in 1985. The results of the wear progression analysis, reported in CEN-328 (Reference 1), are updated to reflect the batwing wear experience at Palo Verde since the units began operation and to consider the increased flow loadings on the batwings and tubes as a result of the installation of flow holes in the downcomer shroud.

The results of this analysis indicate that the highest average expected wear depth on an unplugged tube is 60% through wall after Cycle 7. Some tubes are predicted to have average expected depths greater than 60%; however, the wear in these tubes would have previously exceeded the plugging limit and they would not be in service during Cycle 7. It should be noted that these wear predictions are not maximum expected values. Rather, they represent the average values for tubes that experience significant wear. Therefore, some tubes can be expected to exceed the predictions.

2.0 INTRODUCTION

2.1 Background

In December of 1984 Eddy Current Inspections at SONGS 2 indicated steam generator tube wear at the interface between the diagonal tube supports (batwings) and the tubes just below the 90° bends. The wear appeared to be confined to the tubes immediately adjacent to the central cavity and to tubes one or two rows beyond. A small number of tubes deeper into the bundle also exhibited wear. At the time it was determined that several other CE designed plants had a similar support design which might be susceptible to this type of wear mechanism. The six steam generators at Palo Verde which were not yet in operation were included in this group. Subsequent inspections of other operating plants in the affected group showed results consistent with those at SONGS 2.

Combustion Engineering immediately began an investigation of the cause of the wear and developed a comprehensive analytical and testing program to support that investigation. At the same time another program was initiated to develop hardware changes which might be installed to mitigate or arrest the wear. During 1985 results from the analysis and testing program indicated that the wear was be self limiting. That is, as the wear progressed further into the tube bundle, the wear rate at each successive tube would decrease as more tubes wore and that the number of affected tubes which could wear to a depth requiring plugging would be acceptable. Further, the wear rates would decrease to the point that the wear could be easily monitored and the affected tubes removed from service.

A plant specific wear progression analysis for each affected plant was performed to estimate the number of tubes which were at risk of wearing to 40% through wall or greater during the 40 year design life and preventive plugging of these tubes was recommended. Tubes immediately adjacent to the stay cavity were also staked to eliminate any possibility of severance and to provide protection for tubes deeper into the bundle. The tubes subject to unacceptably high wear rates during the first cycles of operation were also identified and required to be preventively plugged.

Rather than to preventively plug all tubes predicted to wear to 40%, the plant owners chose to monitor these tubes and to plug as necessary. Subsequent experience with this population of tubes has confirmed that the predictions of the wear progression analysis are generally correct.

The wear progression analysis for the Palo Verde units demonstrated that the expected wear rates were much lower than any of the operating plants which had experienced this wear mechanism. Even during the first cycle of operation when wear rates are greatest, the maximum wear was predicted to be below the plugging limit. On this basis, APS elected to operate the units without preventive plugging or staking and to monitor the condition of the affected tubes at each outage. Subsequent experience at Palo Verde has shown the predictions of the wear progression analysis to be conservative.

In 1995 and 1996 several of the steam generators at Palo Verde were modified to mitigate another tube degradation mechanism. One feature of the planned modification included the installation of 45 flow holes on the hot side of the downcomer shroud. A consequence of this modification was to increase the fluid velocities in the central stay cavity.

As part of an eddy current inspection during a planned outage, Unit 32, after operating for one cycle in a partially modified configuration with 26 flow holes, was observed to have sustained a significant increase in tube wear rates at the batwing. Consequently APS is concerned for operation of Unit 22 through its current operating cycle (Cycle 7) and that an early shutdown of this unit may be warranted. This concern exists because Unit 22 has 45 flow holes and is predicted to have higher flow velocities in the central stay cavity than existed in Unit 32. Note that although the increased wear rates observed with 26 flow holes are considered acceptable for continued operation, a question remains that wear rates may be unacceptable in Unit 22 due to its condition with 45 holes.

As part of the effort to assess the severity of the increased wear rates in Unit 22 Cycle 7, APS requested that the original wear progression analysis for Palo Verde be updated to predict the wear expected in this unit during Cycle 7.

2.2 Objectives

The objective of this report is to update the original wear progression analysis for Palo Verde to predict the expected wear rates for Unit 22 Cycle 7. The update will include consideration of the historical wear rates at Palo Verde which have proven to be somewhat less than the original analysis predicted. It will also address the effects of the increased flow loadings resulting from the modified condition of Unit 22.

2.3 Expected Results

The following results will be obtained:

(a) The wear coefficient for Archard's wear equation based on the Unit 22 operating history and measured tube wear in the batwing wear region through Cycle 6.
(b) The wear coefficient for Archard's wear equation based on the Unit 32 operating history and measured tube wear in the batwing wear region during Cycle 6.
(c) The predicted wear by tube line and row number in Unit 22 at the end of Cycle 7 for the cases of no batwing wear and of batwing wear equal to 1.5 times tube wear.
(d) To bound the tube wear rates on unplugged tubes in the first row adjacent to the stay cavity the tube wear will be predicted assuming no prior wear at the start of Cycle 7.
(e) To bound the tube wear rates on tubes beyond the first row the tube wear will be estimated including the wear in Cycles 1 through 6 in the wear progression analysis.

3.0 ANALYTICAL TECHNIQUE

The wear predictions made in this report are based on extrapolations of the original wear progression analysis for the Palo Verde steam generators in CEN-328 (Reference 1). In the following sections a brief summary of the original wear progression analysis is provided and then the basis for the extrapolation of the results to Unit 22 Cycle 7 is described.

3.1 Wear Progression Analysis Methodology

The wear mechanism responsible for the tube wear at the batwing was identified through a flow test program which demonstrated that the batwings were statically deflected by the flow in the central stay cavity causing them to remain in continuous contact with the tubes immediately adjacent to the cavity. Further testing showed that the tubes were excited by turbulent buffeting and vibrated while in contact with the batwings. This behavior gives rise to an adhesive wear mechanism which can be described by Archard's wear equation:

$$dV = (K \cdot 10^{-12}) \cdot F \cdot L \cdot dt$$

where dV is the differential wear volume occurring during time dt with contact force F and sliding distance per unit of time L. K is the specific wear coefficient; it depends on the interfacing materials as well as the surrounding environment. The factor of 10^{-12} is introduced for convenience.

Archard's equation provides a way of calculating the volume removed as a function of the contact force, F, the sliding distance, L, and time, t. Based on the observed wear scars at SONGS the relationship between wear volume and wear depth on a tube was established. Thus, the wear depth could be determined as a function of F, L and t.

The contact force F was determined to be proportional to the dynamic pressure in the central stay cavity as the flow exerted a lateral load on the batwing strip and forced it into contact with the tubes. On any particular tube the contact force was found to vary with time through its dependence on prior wear at each batwing-tube intersection. That is, wear at any contact point causes the distribution of forces between the batwing and all adjacent tubes to change. At contact points with high wear rates the contact force is reduced, lowering the wear rate at that point but simultaneously inducing an increase in the contact forces and wear rates at other contact points.

CEN-328 also established the relationship between the sliding distance L and the fluid flow in the stay cavity region. It was determined that the sliding distance resulted from tube vibrations caused by turbulent buffeting. The spectral forcing function (G_{FT}) causing this vibration was defined from flow test data as follows:

$$G_{FT} = C^2 \cdot \left(\frac{\rho v^2}{f_t}\right)^2 \cdot As \cdot Ac$$

where C is an empicially determined constant, f_t is the dominant frequency of the turbulence, As is the surface area of the tube and $Ac = \pi D^2$ is the coherence area (D is tube diameter). The frequency f_t is dependent on flow velocity also,

$$f_t = N_s \cdot v/D$$

where N_s is the Strouhal number. The spectrum width was found to be the frequency range from 0 to $1.5f_t$.

The tube displacement from the ith mode of vibration resulting from the above spectrum is given by the following equation:

$$x_i^2 = \int_0^{1.5f_t} G_{FT} \cdot H_i(f)^2 \cdot df$$

where $H_i(f)$ is the transfer function from load to displacement at the batwing for ith mode. The total sliding distance from all modes is

$$L^2 = \Sigma\,(f_i \cdot x_i)^2$$

where f_i is the frequency of the ith mode and the summation includes all modes with frequencies in the range from 0 to f_t.

The wear progression analysis incorporated the above relationships into a finite element model to predict the wear on tubes as a function of their location in the bundle, the flow paramenters in the central stay cavity and operating time. The finite element model of the batwing and the adjacent tubes on either side was used to calculate the contact forces between the batwing and each tube. The contact force and sliding distance for each tube were employed in Archard's equation and the volume depth relationship to calculate the wear depth for each tube for a small time increment. Then the geometry of the finite element model was adjusted to account for the wear and the new distribution of contact forces was calculated. Creep strain was used to simulate the wear depths in the finite element model. This process was repeated until the desired operating time was reached.

The specific wear coefficient was obtained by normalizing the predictions from the wear progression analysis to the measured wear at the operating plants. In each unit the wear volume for each tube with a wear indication was calculated and the total wear volume was determined. The K value for that unit was then adjusted so that the wear progression analysis results gave the same total wear volume for those tubes. Since all measured wear data was for plants with carbon steel batwings and Palo Verde had ferritic stainless batwings, the wear coefficient for the Palo Verde units was adjusted based on laboratory wear tests. In these tests wear coefficients were determined with carbon steel and ferritic stainless batwings on Inconel tubes in prototypical situations. The wear coefficient for ferritic stainless was found to be as much as 40% greater than for carbon steel. Therefore, the wear coefficient for the Palo Verde wear progression analysis was taken to be 40% greater than the value obtained from the operating plants.

3.2 Extrapolation to Unit 22 Cycle 7 Conditions

From the discussion in the previous section it is apparent that the contact force F and sliding distance at any particular tube are dependent on the fluid velocity and density in the central stay cavity. At each tube the contact force and sliding distance are related to the flow parameters by the following equations:

$$\frac{F}{F_o} = \frac{\rho \cdot v^2}{\rho_o \cdot v_o^{\,2}} \quad \text{and} \quad \frac{L}{L_o} = \frac{\rho \cdot v^{3/2}}{\rho_o \cdot v_o^{\,3/2}}$$

where ρ and v are the density and fluid velocity in the central stay cavity and the subscript 'o' refers to the reference values of ρ and v used in the wear progression calculations in CEN-328. F_o and L_o are the contact force and sliding distance for a particular tube in the original analysis and F and L are the corresponding values with the changed flow fields.

The above equation for the sliding distance is valid as long as the number of modes participating in the response of the tube to turbulent buffeting is not affected by the change in the flow parameters. For the increased flows at Palo Verde the conclusion that additional modes do not participate is valid for the tubes in the immediate vicinity of the stay cylinder cavity (say tubes in rows 30-44). These tubes are subject to the highest wear rates and, consequently, are the ones at risk of unacceptably high wear rates in one cycle. These are also the tubes which showed high wear in Unit 32 Cycle 6. The calculation of sliding distances for these tube rows in CEN-328 indicates that predicted velocity increases will not cause additional modes to participate in the response.

For a short term wear progression analysis (for 1 or 2 cycles) the tubes discussed above will have the highest contact forces and, as a result, will dominate the progression of the wear. Consequently, short term projections can be made with reasonable accuracy using the simple relationship given above. However, for longer term projections the wear may progress to tubes which would not follow this relationship. In this case the actual tube displacements need to be calculated including the additional modes..

With the above relationships established, the cumulative wear volume with different values of K, ρ and v can be related to the original Palo Verde calculations by the following equation:

$$V(t) = \int_0^t K_o \cdot F_o \cdot L_o \cdot \frac{K}{K_o} \cdot \left(\frac{\rho}{\rho_o}\right)^2 \cdot \left(\frac{v}{v_o}\right)^{7/2} dt$$

where K_o is the wear coefficient used in the reference analysis. Defining a time scale factor

$$k = \frac{K}{K_o} \cdot \left(\frac{\rho}{\rho_o}\right)^2 \cdot \left(\frac{v}{v_o}\right)^{7/2}$$

the wear volume V(t) for any set of flow parameters which satisfies the aforementioned restrictions is given by

$$V(t) = \int_0^{k\cdot t} K_o \cdot F_o \cdot L_o \cdot dt = V_o(k \cdot t)$$

where

$$V_o(t) = \int_0^{t} K_o \cdot F_o \cdot L_o \cdot dt$$

is the wear volume calculated in the original wear progression analysis for Palo Verde. Of course, the wear depth is uniquely defined from the wear volume by the volume-depth relationship.

Thus, with a simple adjustment of the time scale the reference wear progression calculations can be used to predict wear for values of the specific wear coefficient and flow field parameters which differ from the reference values.

If there are several different values of the flow parameters during the operating life of a plant resulting in time scale factors of k_1, k_2, k_3,... from times 0 to t_1, t_1 to t_2, t_2 to t_3, and so forth, it can be shown that the cumulative wear volume is given by

$$V(t) = V_o(t_e)$$

where t_e is the effective wear time based on the operating history, defined as

$$t_e = k_1 t_1 + k_2(t_2 - t_1) + k_3(t_3 - t_2) + \ldots$$

3.3 Calculation of the Specific Wear Coefficient

The specific wear coefficient K is calculated by correlating the tube wear predictions from the wear progression analysis with the actual measured wear in the operating plants. Let the measured wear at each wear site be designated as wm_i where i defines the specific line and row number where the wear occurs. Further let t_i be the operating time in EFPD when wm_i was recorded. The tube wear volume for each wm_i is determined from the volume-to-depth relationship as follows:

$$Vm_i = Vol(wm_i)$$

where Vol(w) is the function defining the volume-to-depth relationship. Note that the actual function Vol(w) depends on the assumed batwing-to-tube wear ratio.

Based on the reference wear coefficient K_o, the predicted wear depths at each measured wear site can determined from the wear progression analysis as

$$wc_i = wc(i, t_i)$$

where the function wc(i,t) describes the wear depth predicted by the wear progresson analysis at the tube line and row number corresponding to the ith wear site at the time t_i. The tube wear volume based on the calculated wear depths is then

$$Vc_i = Vol(wc_i) = Vol[wc_i(i, t_i)]$$

As previously shown the predicted wear depth for any value K of the wear coefficient can be determined from the reference wear progression analysis by using a time scale factor k. For simplicity it will be assumed that the actual and reference flow parameters are identical so that

$$k = K/K_o$$

Then the tube wear volume at each site based on the calculated depths is

$$Vc_i = Vol[wc_i(i,kt_i)]$$

The value of k and hence of the actual wear coefficient K is determined by requiring that the total tube wear volumes based on the measured and calculated wear depths be equal:

$$\Sigma\, Vm_i = \Sigma\, Vc_i$$

The value of k is adjusted by trial and error until this equation is satisfied. The actual wear coefficient is the easily calculated as

$$K = k \cdot K_o$$

The above procedure can be generalized to account for differences in the actual and reference flow fields. The resulting equation for the actual wear coefficient is

$$K = k \cdot K_o \cdot \left(\frac{\rho_o}{\rho}\right)^2 \cdot \left(\frac{v_o}{v}\right)^{7/2}$$

where ρ_o and v_o are the density and velocity used in the reference wear progression calculation and ρ and v are the actual values in the operating plant.

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4.0 SELECTION OF DESIGN INPUTS

The design inputs to this calculation consist of the operational history of the average flow parameters in central stay cavity for Unit 22 and Unit 32 at Palo Verde and the history of tube wear in the central stay region of these two plants. The flow parameters were calculated in Reference 2 using the ATHOS 3 computer code with homogeneous flow. The values of the fluid density, velocity and dynamic pressure in the central stay cavity used in this calculation are summarized in the table below:

Unit No.	Operating Condition	ATHOS Parameters in Central Cavity			Operating Time (EFPD)
		Axial Velocity (ft/sec)	Density (lbm/ft^3)	Dynamic Pressure (lb/ft^2)	
22	As Designed				2387
22	45 Shroud Holes, 1308 plugged tubes, 1949 MW/SG				500*
32	As Designed				2078
32	26 Shroud Holes, 173 plugged tubes, 1949 MW/SG				445

*Estimated

The measured wear at both units was provided by APS in Reference 3. The files provided in Reference 3 are included in Attachment 1 for information. The values used in the calculation of the specific wear coefficients are shown in Appendix B. Since there was very little wear in Unit 32 prior to Cycle 6 the wear coefficient for that unit was based on the wear measured during Cycle 6 only.

5.0 RESULTS AND DISCUSSION

The results of this calculation are presented in two parts. First the calculated wear coefficients based on the measured wear in Units 22 and 32 are presented. Then the predicted wear for Unit 22 Cycle 7 based on the more conservative estimates for the wear coefficients is provided. Both sets of results include the two bounding cases for the batwing to tube wear ratio, R=0 and R=1.5.

5.1 Calculated Wear Coefficients

Specific wear coefficients were calculated for Palo Verde Unit 32 with the Cycle 6 wear data and for Palo Verde Unit 22 with the wear data from Cycles 1 thru 6. Wear coefficients were calculated for the cases of no batwing wear (batwing to tube wear ratio R=0) and of maximum expected batwing wear (R=1.5). The wear data used was obtained from APS in Reference 3 and included in Attachment 1. The measured depths were converted to volumes with the volume-to-depth relationship for .042" wall tube. The calculations and the volume-depth relationships are provided in Appendix B. For conservatism only indications with depths of 10% or greater were included in the calculations. The results are shown below:

Wear Data	R	k	ρ (lb/ft^3)	v (ft/sec)	K (in^2/lb)
Unit 22, Cycles 1-6	0	0.274			27.4
Unit 22, Cycles 1-6	1.5	0.56			56
Unit 32, Cycle 6	0	0.771			29.2
Unit 32, Cycle 6	1.5	1.814			68.7

R = Batwing-to-Tube wear ratio
k = Time scale factor based on indications ^{3} 10%
ρ = average density in central cavity
v = average velocity in central cavity
K = calculated wear coefficient for Archard's equation
$= k \cdot K_o \cdot (r_o/r)^2 \cdot (v_o/v)^{3.5}$
where K_o = 100 = reference wear coefficient
ρ_o = = reference density
v_o = = reference velocity

Based on these results the wear coefficents predicted from the Unit 32 Cycle 6 data were used for the wear progression for Unit 22 Cycle 7.

5.2 Tube Wear Predictions for Unit 22 Cycle 7

The results of the wear progression analysis for Unit 22 Cycle 7 are shown in Appendix A. Predictions are made for the tube wear by line and row number for the two limiting cases of the batwing to tube wear ratio, R. For each case of the batwing wear ratio, two predictions are made. The first assumes that wear occurs at each tube during Cycles 1 thru 6 and in Cycle 7; this prediction can be applied to tubes showing wear during the previous cycles. In most cases these tubes have been plugged so this prediction is most useful for the unplugged tubes deeper into the tube bundle. The second prediction assumes no wear occurred during

the previous cycles and can be used for tubes which had no indications at the end of Cycle 6. This prediction provides conservative wear estimates for these tubes.

The wear progression analysis was run for three different batwing spans since the contact forces depend on the unsupported length of the batwing. Spans to tube rows 38, 35 and 31 were run. For each batwing span the predicted tube wear is reported on the A and B tubes according to the convention used in CEN-328. The A1 tube is the shortest tube adjacent to the batwing; so for the span to tube row 38, the A1 tube is at row 38. The A2 tube is the tube immediately behind A1 or row 40 in this example, and A3 is row 42 and so on. The B tubes are on the opposite side of the batwing; in the example B1 is row 39, B2 is row 41 and so on.. The results for the three spans were interpolated and extrapolated to other spans to make wear predictions on all tubes in the affected region.

In Appendix A Tables A-1 through A-8 present the results for the case of R=0 with the estimated wear coefficient of K=29.2. Table A-1 shows the operating history and the effective time parameter for this case. Tables A-2 through A-4 give the wear predictions for the three batwing spans at several times, the last two times being the end of Cycles 6 and 7. Table A-5 shows the results from Tables A-2, -3 and -4 at the end of Cycle 7 expanded to other batwing spans and Table A-6 maps the predicted wear at the end of Cycle 7 on to each tube in the affected region by line and row number. Tables A-7 and A-8 are equivalent to Tables A-5 and A-6 except that it is assumed that there was no wear prior to Cycle 7.

Tables A-9 through A-16 present the results for the case of R=1.5 with the estimated wear coefficient of K=68.7.

A comparison of the results for the two cases of batwing wear ratio shows that the case with R=1.5 and K=68.7 shown in Tables A-9 through A-16 gives more conservative predictions for the depth of wear. From Table A-14 it is seen that a number of first row tubes are predicted to wear to depths of 60% or greater by the end of Cycle 7. However, in all cases these tubes would have had wear well in excess of 20% by the end of Cycle 6 and would have been plugged. Considering only those tubes which might not have been plugged prior to the start of Cycle 7, the maximum predicted wear depth according to Table A-14 is something less than 50%.

Table A-16 indicates that for tubes having no wear prior to Cycle 7 the maximum expected wear depth at the end of the cycle is 56%. The volumetric wear rate for this tube can be determined from Figure B-1 as .003 in^3. If a tube started the cycle at just below the 20% plugging limit, it would have had a wear volume of about .0003 in^3 according to Figure B-1. Conservatively assuming it experiences the maximum volumetric wear rate for tubes without prior wear duirng Cycle 7, the wear volume at the end of Cycle 7 would be about .0033 in^3. Then from Figure B-1 the predicted maximum depth would be about 60%.

It should be noted that these wear predictions are not maximum expected values. Rather, they represent the average values for tubes that experience significant wear. Therefore, some tubes can be expected to exceed the predictions. The wear progression analysis does not address the extent to which the actual wear may exceed the average values.

6.0 SUMMARY AND CONCLUSIONS

The specific wear coefficients for Palo Verde based on the wear observed in Units 22 and 32 are 29.2 in^2/lb for the case of no batwing wear (R=0) and 68.7 in^2/lb for the case of maximum batwing wear (R=1.5). These values result from the wear depths measured in Unit 32 during Cycle 6. The corresponding values based on data from Unit 22 Cycles 1 through 6 are 27.4 and 56.0 in^2/lb, respectively.

With the wear coefficients from Unit 32 Cycle 6 and the operating conditions for Unit 22, the maximum depth of wear on an unplugged tube is predicted to be about 60% at the end of Cycle 7 in Unit 22. The most conservative tube wear predictions result from the case of maximum batwing wear (R=1.5). When wear during prior cycles is included in the wear predictions, a number of tubes are predicted to have wear depths exceeding 60% by the end of Cycle 7. However, in all cases these tubes would have been plugged before the start of Cycle 7, since the wear during prior cycles is predicted to exceed the 20% plugging limit used by APS. When no wear is assumed for the prior cycles, the maximum predicted wear at the end of Cycle 7 is 56%. Based on this wear rate, a tube just below the plugging limit at the start of Cycle 7 would wear to a depth of 60% by the end of the cycle.

7.0 REFERENCES

1. CEN-328, Remedy for Steam Generator Tube and Diagonal Strip Wear, March, 1986, Combustion Engineering, Inc., Windsor, Connecticut

2. CSE-97-129, "Steam Generator Secondary System Flow Characteristics for Evaluation of Stay Cylinder Batwing Wear", April, 1997.

3. E-Mail from K. Sweeney (APS) to D. Siska (ABB CENO), April 15,1997.

APPENDIX A

RESULTS OF WEAR PROGRESSION ANALYSIS

TABLE A-1 - UNIT 22 OPERATING HISTORY

TIME(EFPD)	0	840	1686	2044	2387	2887
DENSITY(LB/FT³)						
VELOCITY(FT/SEC)						
EFF. TIME (EFPD)						

TABLE A-2 - BATWING SPAN TO TUBE ROW 38
WITH WEAR COEFFICIENT K = 29.2 AND BATWING WEAR RATIO R = 0.

TIME	A1	A2	A3	A4	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
840	30	11	0	0	0	2	7	8	7	4	2	0	0	0
1686	39	19	0	0	0	4	11	13	11	9	5	2	0	0
2044	42	21	0	0	0	4	12	14	13	10	6	4	0	0
2387	44	23	0	0	0	4	13	15	15	12	8	5	0	0
2887	60	32	0	0	0	6	17	21	21	19	14	10	3	0

TABLE A-3 - BATWING SPAN TO TUBE ROW 35
WITH WEAR COEFFICIENT K = 29.2 AND BATWING WEAR RATIO R = 0.

TIME	A1	A2	A3	A4	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
840	22	4	0	0	0	0	4	6	5	4	2	0	0	0
1686	31	10	0	0	0	1	7	9	9	7	5	2	0	0
2044	33	13	0	0	0	1	8	11	10	8	6	3	0	0
2387	35	15	0	0	0	1	9	12	11	10	7	4	1	0
2887	44	23	0	0	0	1	12	16	17	16	13	9	6	1

TABLE A-4 - BATWING SPAN TO TUBE ROW 31
WITH WEAR COEFFICIENT K = 29.2 AND BATWING WEAR RATIO R = 0.

TIME	A1	A2	A3	A4	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
840	11	0	0	0	0	0	0	2	3	2	1	0	0	0
1686	19	1	0	0	0	0	1	4	5	5	3	2	0	0
2044	21	3	0	0	0	0	1	5	6	5	4	2	0	0
2387	23	4	0	0	0	0	2	5	7	6	5	3	1	0
2887	32	11	0	0	0	0	3	8	10	10	9	7	4	1

TABLE A-5 - SUMMARY OF WEAR PROGRESSION RESULTS FOR UNIT 22 AT 2887 EFPD
WITH WEAR COEFFICIENT K = 29.2 AND BATWING WEAR RATIO R = 0.

BW	TUBE LOCATION													
SPAN	A1	A2	A3	A4	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
40	67	36	0	0	0	8	19	23	21	20	14	10	2	0
39	64	34	0	0	0	7	18	22	22	20	14	10	2	0
38	60	32	0	0	0	6	17	21	21	19	14	10	3	0
37	55	29	0	0	0	4	15	19	20	18	14	10	4	0
36	49	26	0	0	0	3	14	18	18	17	13	9	5	1
35	44	23	0	0	0	1	12	16	17	16	13	9	6	1
34	41	20	0	0	0	1	10	14	15	15	12	9	6	1
33	38	17	0	0	0	1	8	12	14	13	11	8	5	1
32	35	14	0	0	0	0	5	10	12	12	10	8	5	1
31	32	11	0	0	0	0	3	8	10	10	9	7	4	1
30	29	8	0	0	0	0	1	6	8	9	8	7	4	1
29	26	5	0	0	0	0	0	4	7	7	7	6	3	1

TABLE A-6 - PREDICTED WEAR IN UNIT 22 BY LINE AND ROW NUMBERS AFTER 2887 EFPD
WITH WEAR COEFFICIENT K = 29.2 AND BATWING WEAR RATIO R = 0.

	LINE NUMBERS															
ROW NO.	95 95	94 96	93 97	92 98	91 99	90 100	89 101	88 102	87 103	86 104	85 105	84 106	83 107	82 108	81 109	80 110
44	18		18		19		19		19		17		13		9	
43		17		17		17		18		18		15		12		8
42	36		7		15		15		16		16		14		10	
41		34		34		6		14		14		14		12		9
40	67		32		32		32		12		12		12		10	
39		64		64		29		29		10		10		10		8
38			60		60		60		26		8		8		8	
37						55		55		23		5		6		7
36									49		20		3		4	
35										44		17		1		7
34											41		14		0	
33												38		11		4
32													35		8	
31														32		5
30															29	
29																26

TABLE A-7 - SUMMARY OF WEAR PROGRESSION RESULTS FOR UNIT 22 AT 2887 EFPD*
WITH WEAR COEFFICIENT K = 29.2 AND BATWING WEAR RATIO R = 0.

BW	TUBE LOCATION													
SPAN	A1	A2	A3	A4	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
40	48	27	0	0	0	5	15	17	14	12	8	6	0	0
39	46	25	0	0	0	5	14	16	15	11	8	5	0	0
38	44	23	0	0	0	4	13	15	14	11	8	5	0	0
37	41	20	0	0	0	3	12	14	13	10	8	4	0	0
36	38	17	0	0	0	2	10	12	12	10	7	4	1	0
35	35	14	0	0	0	1	9	11	11	9	7	3	1	0
34	32	12	0	0	0	1	7	10	10	8	7	3	1	0
33	29	9	0	0	0	1	6	8	9	8	6	3	1	0
32	26	7	0	0	0	0	4	7	7	7	6	3	1	0
31	23	4	0	0	0	0	2	5	6	6	5	3	1	0
30	20	2	0	0	0	0	0	4	5	5	5	3	1	0
29	17	0	0	0	0	0	0	2	4	5	4	3	1	0

TABLE A-8 - PREDICTED WEAR IN UNIT 22 BY LINE AND ROW NUMBERS AFTER 2887 EFPD*
WITH WEAR COEFFICIENT K = 29.2 AND BATWING WEAR RATIO R = 0.

	LINE NUMBERS															
ROW NO.	95 95	94 96	93 97	92 98	91 99	90 100	89 101	88 102	87 103	86 104	85 105	84 106	83 107	82 108	81 109	80 110
44	14		14		14		14		14		11		8		5	
43		13		13		13		13		12		10		7		5
42	27		5		12		12		12		11		9		6	
41		25		25		4		10		10		10		7		5
40	48		23		23		23		9		9		8		6	
39		46		46		20		20		7		7		7		5
38			44		44		44		17		6		6		5	
37						41		41		14		4		4		5
36									38		12		2		2	
35										35		9		0		4
34											32		7		0	
33												29		4		2
32													26		2	
31														23		0
30															20	
29																17

*ASSUMING NO WEAR IN CYCLES 1 THRU 6 (2387 EFPD)

TABLE A-9 - UNIT 22 OPERATING HISTORY

TIME(EFPD)	0	840	1686	2044	2387	2887
DENSITY(LB/FT³)						
VELOCITY(FT/SEC)						
EFF. TIME (EFPD)						

TABLE A-10 - BATWING SPAN TO TUBE ROW 38
WITH WEAR COEFFICIENT K = 68.7 AND BATWING WEAR RATIO R = 1.5

TIME	A1	A2	A3	A4	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
840	29	12	0	0	0	6	11	13	13	11	9	7	4	1
1686	43	23	5	0	0	6	11	14	15	15	13	11	8	4
2044	47	26	8	0	0	6	11	15	16	15	14	12	9	5
2387	51	29	10	0	0	6	11	15	16	16	15	13	9	6
2887	68	44	23	5	0	6	11	15	17	18	18	16	13	9

TABLE A-11 - BATWING SPAN TO TUBE ROW 35
WITH WEAR COEFFICIENT K = 68.7 AND BATWING WEAR RATIO R = 1.5

TIME	A1	A2	A3	A4	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
840	19	5	0	0	0	4	8	10	11	10	8	6	5	2
1686	30	14	0	0	0	4	9	12	13	13	12	10	8	5
2044	33	16	1	0	0	4	9	13	14	14	13	11	9	6
2387	36	19	3	0	0	4	9	13	15	15	14	12	10	7
2887	51	32	14	0	0	4	9	13	16	17	17	15	14	11

TABLE A-12 - BATWING SPAN TO TUBE ROW 31
WITH WEAR COEFFICIENT K = 68.7 AND BATWING WEAR RATIO R = 1.5

TIME	A1	A2	A3	A4	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
840	9	1	0	0	0	0	4	6	7	6	6	5	3	2
1686	16	4	0	0	0	1	6	8	9	10	9	8	7	5
2044	18	6	0	0	0	1	6	9	10	11	10	9	8	6
2387	20	7	0	0	0	1	6	9	11	11	11	10	9	7
2887	31	16	3	0	0	1	6	10	13	14	14	14	12	11

TABLE A-13 - SUMMARY OF WEAR PROGRESSION RESULTS FOR UNIT 22 AT 2887 EFPD
WITH WEAR COEFFICIENT K = 68.7 AND BATWING WEAR RATIO R = 1.5

BW	TUBE LOCATION													
SPAN	A1	A2	A3	A4	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
40	76	49	27	7	0	7	12	16	17	18	18	16	13	0
39	72	47	25	6	0	6	11	15	17	18	18	16	13	0
38	68	44	23	5	0	6	11	15	17	18	18	16	13	9
37	62	40	20	3	0	5	10	14	17	18	18	16	13	10
36	57	36	17	2	0	5	10	14	16	17	17	15	14	10
35	51	32	14	0	0	4	9	13	16	17	17	15	14	11
34	46	28	11	0	0	3	8	12	15	16	16	15	14	11
33	41	24	9	0	0	3	8	12	15	16	16	15	13	11
32	36	20	6	0	0	2	7	11	14	15	15	14	13	11
31	31	16	3	0	0	1	6	10	13	14	14	14	12	11
30	26	12	0	0	0	0	5	9	12	13	13	14	12	11
29	21	8	0	0	0	0	5	9	12	13	13	14	11	11

TABLE A-14 - PREDICTED WEAR IN UNIT 22 BY LINE AND ROW NUMBERS AFTER 2887 EFPD
WITH WEAR COEFFICIENT K = 68.7 AND BATWING WEAR RATIO R = 1.5

	LINE NUMBERS															
ROW NO.	95 95	94 96	93 97	92 98	91 99	90 100	89 101	88 102	87 103	86 104	85 105	84 106	83 107	82 108	81 109	80 110
44	27		11		14		14		16		16		16		14	
43		25		25		11		14		15		15		15		13
42	49		23		23		23		13		15		15		14	
41		47		47		20		20		12		14		14		14
40	76		44		44		44		17		12		13		13	
39		72		72		40		40		14		11		12		13
38			68		68		68		36		11		10		12	
37						62		62		32		9		9		13
36									57		28		6		9	
35										51		24		5		12
34											46		20		5	
33												41		16		9
32													36		12	
31														31		8
30															26	
29																21

TABLE A-15 - SUMMARY OF WEAR PROGRESSION RESULTS FOR UNIT 22 AT 2887 EFPD*
WITH WEAR COEFFICIENT K = 68.7 AND BATWING WEAR RATIO R = 1.5

BW	TUBE LOCATION													
SPAN	A1	A2	A3	A4	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
40	56	34	13	0	0	7	12	16	16	16	14	13	9	0
39	53	31	12	0	0	6	11	15	16	16	14	13	9	0
38	50	29	10	0	0	6	11	15	16	16	14	13	9	6
37	45	25	8	0	0	5	10	14	16	16	14	13	9	6
36	41	22	5	0	0	5	10	14	15	15	14	12	10	7
35	36	18	3	0	0	4	9	13	15	15	14	12	10	7
34	32	15	2	0	0	3	8	12	14	14	13	12	10	7
33	28	13	2	0	0	3	8	11	13	13	13	11	9	7
32	24	10	1	0	0	2	7	10	12	12	12	11	9	7
31	20	7	0	0	0	1	6	9	11	11	11	10	8	7
30	16	4	0	0	0	0	5	8	10	10	10	10	8	7
29	12	2	0	0	0	0	5	7	9	9	10	9	7	7

TABLE A-16 - PREDICTED WEAR IN UNIT 22 BY LINE AND ROW NUMBERS AFTER 2887 EFPD*
WITH WEAR COEFFICIENT K = 68.7 AND BATWING WEAR RATIO R = 1.5

	LINE NUMBERS															
ROW NO.	95 95	94 96	93 97	92 98	91 99	90 100	89 101	88 102	87 103	86 104	85 105	84 106	83 107	82 108	81 109	80 110
44	13		11		14		14		15		15		13		11	
43		12		12		11		14		14		14		12		10
42	34		10		10		10		13		13		13		11	
41		31		31		8		10		12		12		12		10
40	56		29		29		29		9		11		11		11	
39		53		53		25		25		8		10		10		10
38			50		50		50		22		8		9		9	
37						45		45		18		7		8		9
36									41		15		6		7	
35										36		13		5		9
34											32		10		5	
33												28		7		7
32													24		4	
31														20		2
30															16	
29																12

*ASSUMING NO WEAR IN CYCLES 1 THRU 6 (2387 EFPD)

APPENDIX B

CALCULATION OF WEAR COEFFICIENTS

Figure B-1

Volume vs. Depth Relationship

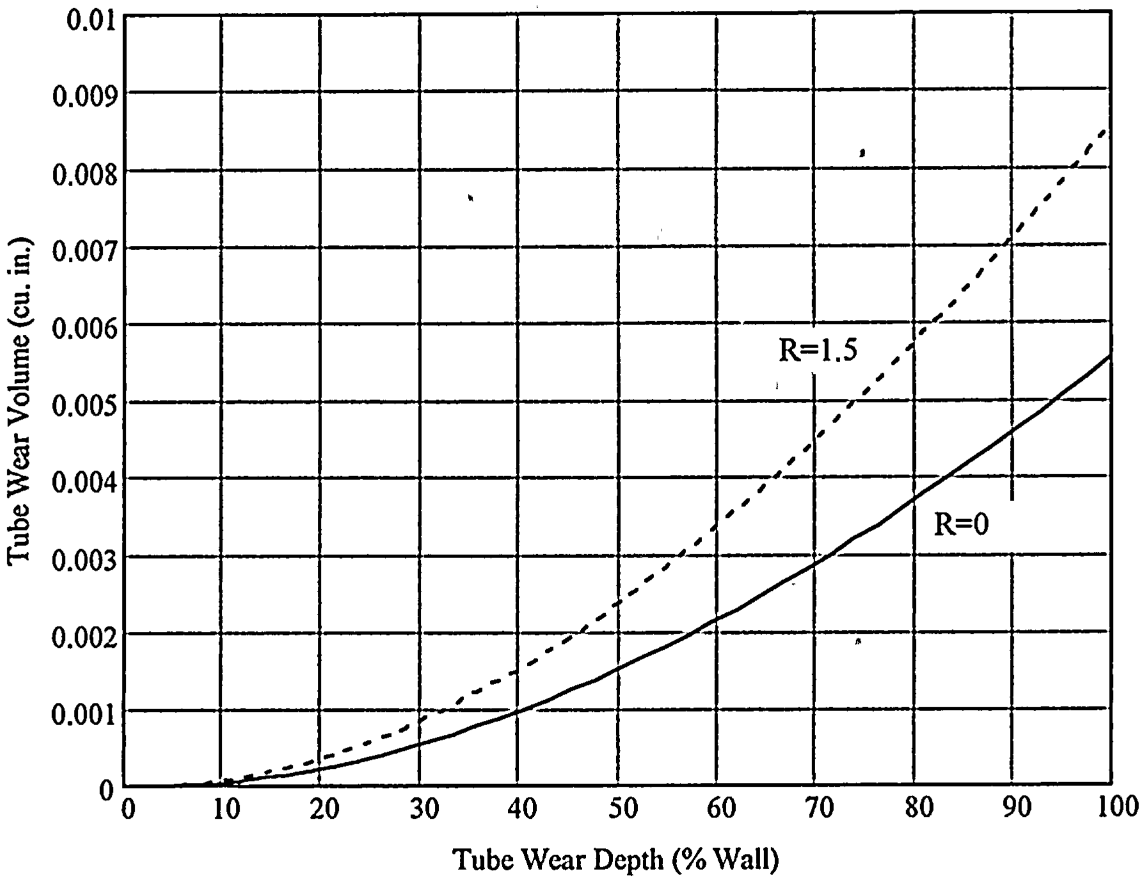

TABLE B-1 - CALCULATED WEAR COEFFICIENT FOR UNIT 22 CYCLES 1 THRU 6
WITH A BATWING TO TUBE WEAR RATIO, R = 0

Row	Line	Depth (%)	Time (EFPD)	Wear Equation	Outage	Actual Volume	Calculated Results with Wear Coefficient					
							K=24.1		K=27.4		K=43.1	
							Depth	Volum	Depth	Volum	Depth	Volume
33	84	37	840	5	U2R2	840	19.2	211	20.8	250	26.6	425
34	85	44	840	5	U2R2	1189	19.2	211	20.8	250	26.6	425
35	86	21	1686	5	U2R4	257	28.1	478	29.8	538	35.4	770
37	88	29	1686	1	U2R4	509	36.5	817	38.1	890	44.7	1224
37	90	55	840	1	U2R2	1837	27.7	463	29.4	523	35	753
39	90	22	1686	2	U2R4	284	16.5	153	18.1	186	23.7	333
38	91	43	840	1	U2R2	1136	27.7	463	29.4	523	35	753
39	94	32	840	1	U2R2	625	27.7	463	29.4	523	35	753
39	96	30	1686	1	U2R4	547	36.5	817	38.1	890	44.7	1224
39	98	41	1686	1	U2R4	1033	36.5	817	38.1	890	44.7	1224
41	98	30	840	2	U2R2	547	8.7	35	10	49	15.1	125
37	100	25	447	1	U2R1	373	19.4	215	21	257	27.1	442
39	100	33	1273	2	U2R3	666	13.1	92	14.7	117	20.2	236
38	101	28	1793	1	U2M5	473	37.3	852	38.9	928	45.8	1284
37	102	20	2387	1	U2R6	231	41	1033	42.9	1132	51.7	1632
36	103	33	840	5	U2R2	666	19.2	211	20.8	250	26.6	425
35	104	30	447	5	U2R1	547	12.2	78	13.5	97	18.6	197
37	104	20	2387	6	U2R6	231	12.3	78	13.8	102	19.2	212
32	107	22	447	8	U2R1	284	5.7	11	6.4	16	9.5	43
31	108	32	2044	8	U2R5	625	19.1	210	20.6	247	26.3	414
38	97	13	2387	1	U2R6	89	41	1033	42.9	1132	51.7	1632
36	85	14	2387	6	U2R6	105	12.3	78	13.8	102	19.2	212
37	86	16	2387	6	U2R6	142	12.3	78	13.8	102	19.2	212
38	87	18	2387	6	U2R6	184	12.3	78	13.8	102	19.2	212
38	89	15	2387	1	U2R6	123	41	1033	42.9	1132	51.7	1632
40	95	16	2387	1	U2R6	142	41	1033	42.9	1132	51.7	1632
40	97	18	1686	2	U2R4	184	16.5	153	18.1	186	23.7	333
43	98	18	2387	4	U2R6	184	11.7	71	12.5	82	15.3	129
38	99	19	2044	1	U2R5	207	38.9	930	40.6	1014	48.3	1428
40	101	11	2387	2	U2R6	61	20.8	252	22.4	295	28	475
39	102	12	2387	2	U2R6	74	20.8	252	22.4	295	28	475
30	109	14	2387	8	U2R6	105	21	256	22.6	299	28.2	481
39	88	9	2387	2	U2R6	38	20.8	252	22.4	295	28	475
41	90	6	2387	3	U2R6	13	4	4	4.3	5	5.2	9
40	91	9	2387	2	U2R6	38	20.8	252	22.4	295	28	475
43	94	9	2387	4	U2R6	38	11.7	71	12.5	82	15.3	129
42	95	6	2387	2	U2R6	13	20.8	252	22.4	295	28	475
41	102	5	2387	7	U2R6	8	7.8	27	8.3	32	10.4	53
33	106	8	2387	5	U2R6	28	32.5	647	34.1	713	39.9	977
29	110	8	2387	8	U2R6	28	21	256	22.6	299	28.2	481

Sum of all Indications	14704	14716	16547	24821
Sum of Indications ≥ 10%	14500	12955	14531	21747
Sum of Indications ≥ 20%	12900	7708	8658	12894

TABLE B-2 - CALCULATED WEAR COEFFICIENT FOR UNIT 22 CYCLES 1 THRU 6
WITH A BATWING TO TUBE WEAR RATIO, R = 1.5

Row	Line	Depth (%)	Time (EFPD)	Wear Equation	Outage	Actual Volume	Calculated Results with Wear Coefficient					
							K=50.6		K=56.0		K=85.6	
							Depth	Volum	Depth	Volum	Depth	Volume
33	84	37	840	5	U2R2	1313	14.9	190	16	223	21.7	429
34	85	44	840	5	U2R2	1849	14.9	190	16	223	21.7	429
35	86	21	1686	5	U2R4	401	24.3	545	25.9	625	33.6	1082
37	88	29	1686	1	U2R4	792	36.7	1294	38.8	1441	47.7	2165
37	90	55	840	1	U2R2	2865	24	532	25.7	610	33.4	1072
39	90	22	1686	2	U2R4	443	17.8	280	19.4	338	26.9	676
38	91	43	840	1	U2R2	1768	24	532	25.7	610	33.4	1072
39	94	32	840	1	U2R2	981	24	532	25.7	610	33.4	1072
39	96	30	1686	1	U2R4	854	36.7	1294	38.8	1441	47.7	2165
39	98	41	1686	1	U2R4	1610	36.7	1294	38.8	1441	47.7	2165
41	98	30	840	2	U2R2	854	8.3	49	9.4	67	15.2	199
37	100	25	447	1	U2R1	579	15.2	199	16.4	235	22.3	456
39	100	33	1273	2	U2R3	1045	13.6	156	15.1	196	21.8	434
38	101	28	1793	1	U2M5	734	38	1383	40	1536	49.1	2293
37	102	20	2387	1	U2R6	361	43.9	1840	46.1	2019	55.8	2942
36	103	33	840	5	U2R2	1045	14.9	190	16	223	21.7	429
35	104	30	447	5	U2R1	854	9	59	9.8	72	13.7	159
37	104	20	2387	6	U2R6	361	14.2	171	15.6	212	22.5	465
32	107	22	447	8	U2R1	443	4	9	4.4	11	6.6	27
31	108	32	2044	8	U2R5	981	14.5	179	15.6	210	20.8	394
38	97	13	2387	1	U2R6	141	43.9	1840	46.1	2019	55.8	2942
36	85	14	2387	6	U2R6	166	14.2	171	15.6	212	22.5	465
37	86	16	2387	6	U2R6	223	14.2	171	15.6	212	22.5	465
38	87	18	2387	6	U2R6	287	14.2	171	15.6	212	22.5	465
38	89	15	2387	1	U2R6	194	43.9	1840	46.1	2019	55.8	2942
40	95	16	2387	1	U2R6	223	43.9	1840	46.1	2019	55.8	2942
40	97	18	1686	2	U2R4	287	17.8	280	19.4	338	26.9	676
43	98	18	2387	4	U2R6	287	10.9	95	10.9	95	10.9	95
38	99	19	2044	1	U2R5	323	40.6	1581	42.7	1747	52.1	2586
40	101	11	2387	2	U2R6	96	23.6	514	25.5	602	34	1113
39	102	12	2387	2	U2R6	118	23.6	514	25.5	602	34	1113
30	109	14	2387	8	U2R6	166	16.2	228	17.3	265	23.1	491
39	88	9	2387	2	U2R6	59	23.6	514	25.5	602	34	1113
41	90	6	2387	3	U2R6	22	5.6	18	5.6	18	5.6	18
40	91	9	2387	2	U2R6	59	23.6	514	25.5	602	34	1113
43	94	9	2387	4	U2R6	59	10.9	95	10.9	95	10.9	95
42	95	6	2387	2	U2R6	22	23.6	514	25.5	602	34	1113
41	102	5	2387	7	U2R6	14	9.2	62	9.2	62	9.2	62
33	106	8	2387	5	U2R6	44	30.3	870	32.1	989	40.5	1569
29	110	8	2387	8	U2R6	44	16.2	228	17.3	265	23.1	491

	Actual Volume	K=50.6 Volum	K=56.0 Volum	K=85.6 Volume
Sum of all Indications	22967	22978	25920	41994
Sum of Indications ≥ 10%	22644	20163	22685	36420
Sum of Indications ≥ 20%	20133	10918	12343	20125

TABLE B-3 - CALCULATED WEAR COEFFICIENT FOR UNIT 32 CYCLE 6
WITH A BATWING TO TUBE WEAR RATIO, R = 0

Row	Line	Depth (%)	Time (EFPD)	Equation	Actual Volume	Calculated Results for Wear Coefficient					
						K=72.9		K=77.1		K=102.3	
						Depth	Volume	Depth	Volume	Depth	Volume
31	82	26	445	8	405	14.3	111	15	123	18.2	188
34	85	33	445	5	666	25.2	379	25.9	403	29.6	531
36	87	42	445	5	1084	25.2	379	25.9	403	29.6	531
37	88	25	445	1	373	33.7	696	34.4	726	37.9	881
38	89	33	445	1	666	33.7	696	34.4	726	37.9	881
37	90	47	445	1	1354	33.7	696	34.4	726	37.9	881
38	93	27	445	1	439	33.7	696	34.4	726	37.9	881
39	96	42	445	1	1084	33.7	696	34.4	726	37.9	881
38	99	34	445	1	708	33.7	696	34.4	726	37.9	881
39	100	37	445	2	840	13.8	102	14.5	114	17.9	182
38	101	29	445	1	509	33.7	696	34.4	726	37.9	881
37	102	35	445	1	751	33.7	696	34.4	726	37.9	881
36	103	22	445	5	284	25.2	379	25.9	403	29.6	531
35	104	43	445	5	1136	25.2	379	25.9	403	29.6	531
34	104	39	445	5	934	25.2	379	25.9	403	29.6	531
30	109	31	445	8	585	14.3	111	15	123	18.2	188
34	85	20	445	5	231	25.2	379	25.9	403	29.6	531
34	85	24	445	5	342	25.2	379	25.9	403	29.6	531
36	103	27	445	1	439	33.7	696	34.4	726	37.9	881
36	103	29	445	1	509	33.7	696	34.4	726	37.9	881
34	105	22	445	5	284	25.2	379	25.9	403	29.6	531
29	80	17	445	8	162	14.3	111	15	123	18.2	188
34	85	13	445	5	89	25.2	379	25.9	403	29.6	531
36	85	14	445	6	105	6.2	15	6.7	18	9.6	44
37	88	11	445	1	61	33.7	696	34.4	726	37.9	881
40	93	11	445	2	61	13.8	102	14.5	114	17.9	182
40	97	14	445	2	105	13.8	102	14.5	114	17.9	182
39	98	14	445	1	105	33.7	696	34.4	726	37.9	881
41	98	12	445	2	74	13.8	102	14.5	114	17.9	182
38	99	11	445	1	61	33.7	696	34.4	726	37.9	881
38	101	18	445	1	184	33.7	696	34.4	726	37.9	881
35	104	11	445	5	61	25.2	379	25.9	403	29.6	531
37	104	17	445	6	162	6.2	15	6.7	18	9.6	44
36	105	17	445	6	162	6.2	15	6.7	18	9.6	44
33	106	18	445	8	184	14.3	111	15	123	18.2	188
31	108	15	445	8	123	14.3	111	15	123	18.2	188
31	82	9	445	8	38	14.3	111	15	123	18.2	188
41	98	9	445	2	38	13.8	102	14.5	114	17.9	182
37	102	9	445	1	38	33.7	696	34.4	726	37.9	881

Sum of All Indications	15436	15451	16282	20695
Sum of Indications ≥ 10%	15322	14542	15319	19444
Sum of Indications ≥ 20%	13623	10316	10844	13616

TABLE B-4 - CALCULATED WEAR COEFFICIENT FOR UNIT 32 CYCLE 6
WITH A BATWING TO TUBE WEAR RATIO, R = 1.5

Row	Line	Depth (%)	Time (EFPD)	Equation	Actual Volume	Calculated Results for Wear Coefficient					
						K=173.3		K=181.4		K=223.1	
						Depth	Volume	Depth	Volume	Depth	Volume
31	82	26	445	8	628	11.7	111	12.1	120	14.1	168
34	85	33	445	5	1045	22.7	474	23.4	506	26.8	669
36	87	42	445	5	1688	22.7	474	23.4	506	26.8	669
37	88	25	445	1	579	34.8	1160	35.7	1221	39.8	1518
38	89	33	445	1	1045	34.8	1160	35.7	1221	39.8	1518
37	90	47	445	1	2099	34.8	1160	35.7	1221	39.8	1518
38	93	27	445	1	679	34.8	1160	35.7	1221	39.8	1518
39	96	42	445	1	1688	34.8	1160	35.7	1221	39.8	1518
38	99	34	445	1	1110	34.8	1160	35.7	1221	39.8	1518
39	100	37	445	2	1313	16.2	230	16.9	252	20.2	370
38	101	29	445	1	792	34.8	1160	35.7	1221	39.8	1518
37	102	35	445	1	1176	34.8	1160	35.7	1221	39.8	1518
36	103	22	445	5	443	22.7	474	23.4	506	26.8	669
35	104	43	445	5	1768	22.7	474	23.4	506	26.8	669
34	104	39	445	5	1458	22.7	474	23.4	506	26.8	669
30	109	31	445	8	917	11.7	111	12.1	120	14.1	168
34	85	20	445	5	361	22.7	474	23.4	506	26.8	669
34	85	24	445	5	532	22.7	474	23.4	506	26.8	669
36	103	27	445	1	679	34.8	1160	35.7	1221	39.8	1518
36	103	29	445	1	792	34.8	1160	35.7	1221	39.8	1518
34	105	22	445	5	443	22.7	474	23.4	506	26.8	669
29	80	17	445	8	254	11.7	111	12.1	120	14.1	168
34	85	13	445	5	141	22.7	474	23.4	506	26.8	669
36	85	14	445	6	166	8.3	48	8.8	56	11.4	105
37	88	11	445	1	96	34.8	1160	35.7	1221	39.8	1518
40	93	11	445	2	96	16.2	230	16.9	252	20.2	370
40	97	14	445	2	166	16.2	230	16.9	252	20.2	370
39	98	14	445	1	166	34.8	1160	35.7	1221	39.8	1518
41	98	12	445	2	118	16.2	230	16.9	252	20.2	370
38	99	11	445	1	96	34.8	1160	35.7	1221	39.8	1518
38	101	18	445	1	287	34.8	1160	35.7	1221	39.8	1518
35	104	11	445	5	96	22.7	474	23.4	506	26.8	669
37	104	17	445	6	254	8.3	48	8.8	56	11.4	105
36	105	17	445	6	254	8.3	48	8.8	56	11.4	105
33	106	18	445	8	287	11.7	111	12.1	120	14.1	168
31	108	15	445	8	194	11.7	111	12.1	120	14.1	168
31	82	9	445	8	59	11.7	111	12.1	120	14.1	168
41	98	9	445	2	59	16.2	230	16.9	252	20.2	370
37	102	9	445	1	59	34.8	1160	35.7	1221	39.8	1518

	Actual Volume	K=173.3 Volume	K=181.4 Volume	K=223.1 Volume
Sum of All Indications	24083	24100	25523	32633
Sum of Indications ≥ 10%	23906	22599	23930	30577
Sum of Indications ≥ 20%	21235	15844	16750	21238

ATTACHMENT 1

MISCELLANEOUS REFERENCE MATERIAL

The following 4 pages provide the listing of recorded wear indications in Palo Verde Units 22 and 32. These documents were provided as attachments to Reference 3.

wing Stay Cylinder Wear Evaluation SG 22 BOC 7 Information									
Affected Tubes									
						RE BW		RE BW	
Number	Row	Column	SG 22 Status			REVIEW	LOCATION	REVIEW	LOCATION
1	29	80				0			
2	30	81				0			
3	31	82				0			
4	32	83				0			
5	33	84	Plugged 37% U2R2						
6	35	84				0			
7	34	85	Plugged 44% U2R2						
8	36	85				14%	BW2 +2"		
9	35	86	Plugged 21% U2R4						
10	37	86				16%	BW1 +2"		
11	36	87				0			
12	38	87				18%	VS4		
13	[illegible]	88	Plugged 29% U2R3						
14	39	88				9%	BW1 -2"	13%	VS4
15	41	88				0			
16	38	89				15%	BW1 +2		
17	40	89				0			
18	42	89				0			
19	[illegible]	90	Plugged 35% U2R2						
20	39	90	Plugged 22% U2R4						
21	41	90				6%	BW2 -2"		
22	38	91	Plugged 40% U2R4						
23	40	91				9%	BW2 -2"		
24	42	91				0			
25	39	92				0			
26	41	92				0			
27	43	92				0			
28	[illegible]	93				0			
29	40	93				0			
30	42	93				0			
31	[illegible]	94	Plugged 29% U2R2						
32	41	94	Plugged SAI U2R4						
33	43	94				9%	BW2 -2"		
34	40	95				16%	BW2 -2"		
35	42	95				16%	BW2 -2"		
36	[illegible]	[illegible]	Plugged 30% U2R4						
37	41	96				0			
38	43	96				0			
39	[illegible]	97				[illegible]	BW2		
40	40	97	Plugged 18% U2R4						
41	42	97	Plugged SCI U2R6						
42	39	98	Plugged 31% U2R4						
43	41	98	Pluggd 30% U2R2						
44	43	98				18%	BW1		

45	[redacted]						
46	40	99		0%			
47	42	99		0			
48	[redacted]						
49	38	100	Plugged 33% U2R3				
50	41	100		0			
51	[redacted]						
52	40	101		11%	BW2 +2"		
53	42	101		0			
54	[redacted]						
55	39	102		12%	BW2 -2"		
56	41	102		5%	BW2 +2"		
57	36	103	Plugged 33% U2R2				
58	38	103		0			
59	35	104	Plugged 30% U2R1				
60	37	104	Plugged 20% U2R6				
61	34	105		0			
62	36	105		0			
63	33	106		8%	BW1 -2"	15%	BW2 -2"
64	35	106		0			
65	32	107	Plugged 22% U2R1				
66	31	108	Plugged 32% U2R5				
67	30	109		14%	BW2		
68	29	110		8%	BW2		

Unit 3 ECT Results - Growth Rate Determination												
Number	Row	Column	SG 32 Status	U3M4	U3R4	U3R5	U3R6	Delta TW Cycle 6	Delta TW Cycle 5	U3R5 Wear Volume	U3R6 Wear Volume	Delta Vol
1	29	80				0	0	0	0	0	0	0
2	30	81				0	17	17	0	0	0.0001522	0.1522
3	31	82	Plugged 26% U3R6			0	32	32	0	0	0.0010012	1.0012
	31	82	BW2			0	9	9	0	0	0.00004	[redacted]
4	32	83				0	0	0	0	0	0	0
5	33	84	Plugged 24% U3R4		24			plugged	0	n/a	n/a	n/a
6	35	84				0	0	0	0	0	0	0
7	34	85	Plugged 33% U3R6			6	33	27	6	0	0.0010578	1.0578
	34	85	BW2			0	20	20	0	0	0.000322	[redacted]
	34	85	BW2			5	24	19	5	0	0.0005484	
	34	85	BW1			0	13	13	0	0	0.0001	
8	36	85				0	14	14	0	0	0.00012	0.12
9	35	86	Plugged 21% U3R4		21			plugged	0	n/a	n/a	n/a
10	37	86				0	0	0	0	0	0	0
11	36	87	Plugged 42% U3R6			7	42	35	7	0	0.0015672	1.5672
	36	87	BW2			0	14	14	0	0	0.00012	[redacted]
12	38	87				0	0	0	0	0	0	0
13	[redacted]									0	0.000605	[redacted]
									0	0	0.000067	
14	39	88				0	0	0	0	0	0	0
15	41	88				0	0	0	0	0	0	0
16	[redacted]									0.000085	0.0010578	[redacted]
17	40	89				0	0	0	0	0	0	0
18	42	89				0	0	0	0	0	0	0
19	[redacted]									0.0002654	0.0018502	[redacted]
20	39	90				0	0	0	0	0	0	0
21	41	90				0	0	0	0	0	0	0
22	[redacted]									0	0	[redacted]
23	40	91				0	0	0	0	0	0	0
24	42	91				0	0	0	0	0	0	0
25	[redacted]									0	0	[redacted]
26	41	92				0	0	0	0	0	0	0
27	43	92				0	0	0	0	0	0	0
28	[redacted]									0	0.0007182	[redacted]
29	40	93				0	11	11	0	0	0.000067	0.067
30	42	93				0	0	0	0	0	0	0
31	[redacted]									0	0	[redacted]
32	41	94				0	0	0	0	0	0	0
33	43	94				0	0	0	0	0	0	0
34	[redacted]									0	0	[redacted]
35	42	95				0	0	0	0	0	0	0
36	[redacted]									0.0002088	0.0015672	[redacted]
37	41	96				0	0	0	0	0	0	0
38	43	96				0	0	0	0	0	0	0

39	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	[illegible]	0	0		
40	40	97				0	14	14	0	0	0.00012	0.12	
	42	97				0	0	0	0	0	0	0	
41	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	0.00012		
42	41	98				0	9	9	0	0	0.00004		
	41	98	BW1			0	12	12	0	0	0.000085	0.085	
43	43	98				0	0	0	0	0	0	0	
44	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	0.0011144		
45	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	0	0.000067		
	40	99				0	0	0	0	0	0	0	
46	42	99				0	0	0	0	0	0	0	
47	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	0		
48	39	100	Plugged 37% U3R6		14	14	37	23	0	0.00012	0.0012842	[illegible]	
49	41	100				0	0	0	0	0	0	0	
50	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	0.0008314		
51	[illegible]	101	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	8	0	0	0.0002088		
	40	101				0	0	0	0	0	0	0	
52	42	101				0	0	0	0	0	0	0	
53	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	0.001171		
54	37	102	BW2			0	9	9	0	0	0.00004		
	39	102				0	0	0	0	0	0	0	
55	41	102				0	0	0	0	0	0	0	
56	36	103	Plugged 22% U3R6	9	11	14	20	8	3	0.00012	0.000322		
57	38	103	BW2			2	27	25	2	0	0.0007182		
	36	103	BW2			0	29	29	0	0	0.0008314	0.8314	
	36	103	BW1			8	22	13	9	0.00004	0.0004352		
	38	103				0	0	0	0	0	0	0	
58	35	104	Plugged 43% U3R6			0	43	43	0	0	0.0016238	1.6238	
59	35	104	BW2			0	11	11	0	0	0.000067		
	37	104				0	17	17	0	0	0.0001522	0.1522	
60	34	105	Plugged 39% U3R6		18	11	13	2	0	0.000067	0.0001		
61	34	105	BW1			11	39	28	11	0.000067	0.0013974	1.3304	
	34	105	BW2		10	13	22	9	3	0.0001	0.0004352		
	36	105				0	17	17	0	0	0.0001522	0.1522	
62	33	106				0	18	18	0	0	0.0002088	0.2088	
63	35	106				0	0	0	0	0	0	0	
64	32	107				0	0	0	0	0	0	0	
65	31	108				10	15	5	10	0.0000488	0.000139	0.0902	
66	30	109	Plugged 31% U3R6		19	19	27	8	0	0.0002654	0.0007182	0.4528	
67	30	109	BW2			9	10	1	9	0.00004	0.0000488		
	29	110				0	0	0	0	0	0	0	
68									101				
								771	101				
							43	17.9	6.7	15			

APPENDIX B

Preventative Plugging Program Unit 3 Cycle 7

UNIT 3 CYCLE 7 ASSESSMENT

As reported in this report, only a partial shroud modification was completed in Unit 3 in U3R5 due to production issues. Of the originally intended 45 hole modification, 26 holes were cut in SG 3-2 and no holes were cut in SG 3-1 during U3R5. During U3R6 inspections, the observed increase in BWSC wear was found in SG 3-2 only. None of the indications found in SG 3-2 exceeded the structural integrity margins defined in Regulatory Guide 1.121. During U3R6, the full 45 hole modification was completed in both steam generators concurrent with the ECT inspections. Since wear rates may be expected to increase even further with the complete modification in place, APS elected to conduct a conservative preventative plugging program in SG 3-1 and SG 3-2. All tubes in the affected tube pattern were removed from service. Frontline or periphery tubes with > than 20% wear were plugged and staked. The plugging program conducted in Unit 3 and depicted in Figures B-1 and B-2, eliminates any operability issues for Unit 3 Cycle 7.

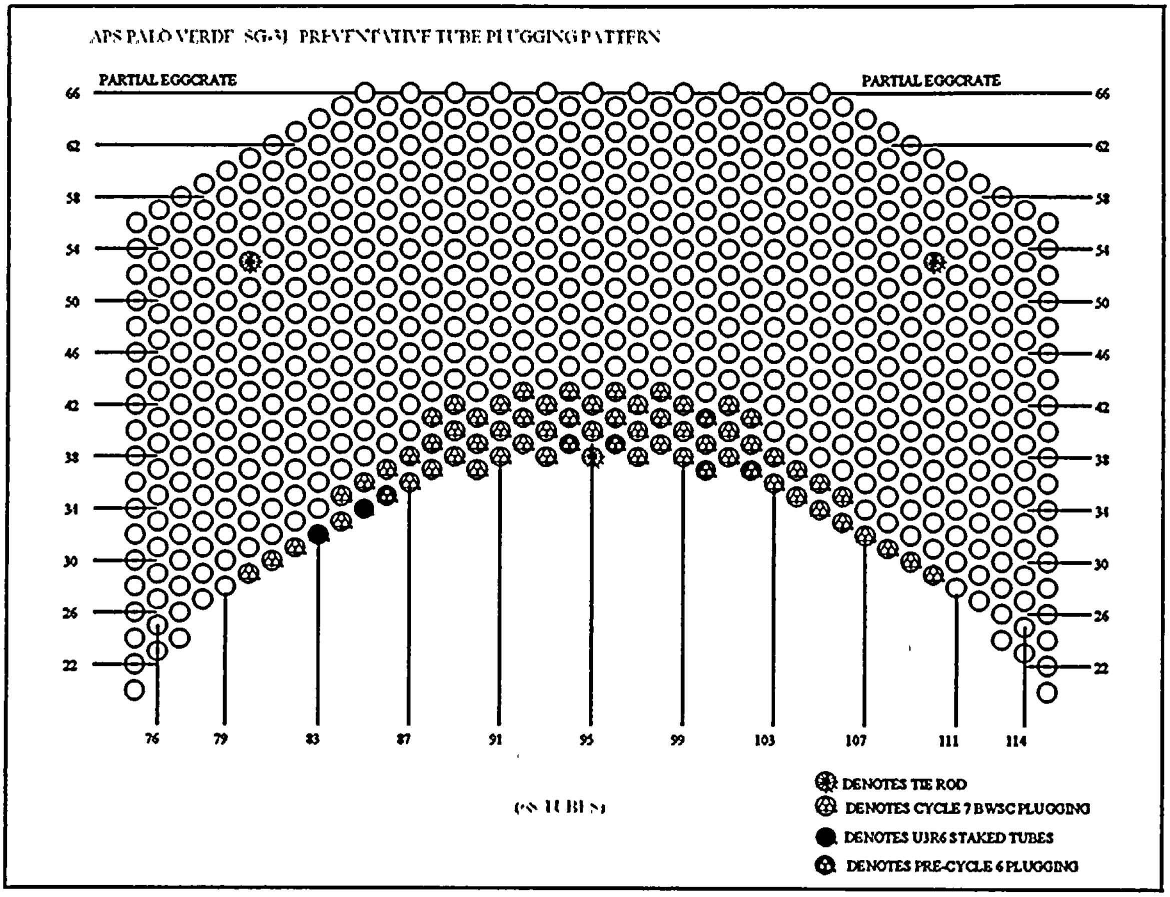

Figure B-1 Unit 3 Cycle 7 SG 3-1 BWSC Plugging Pattern

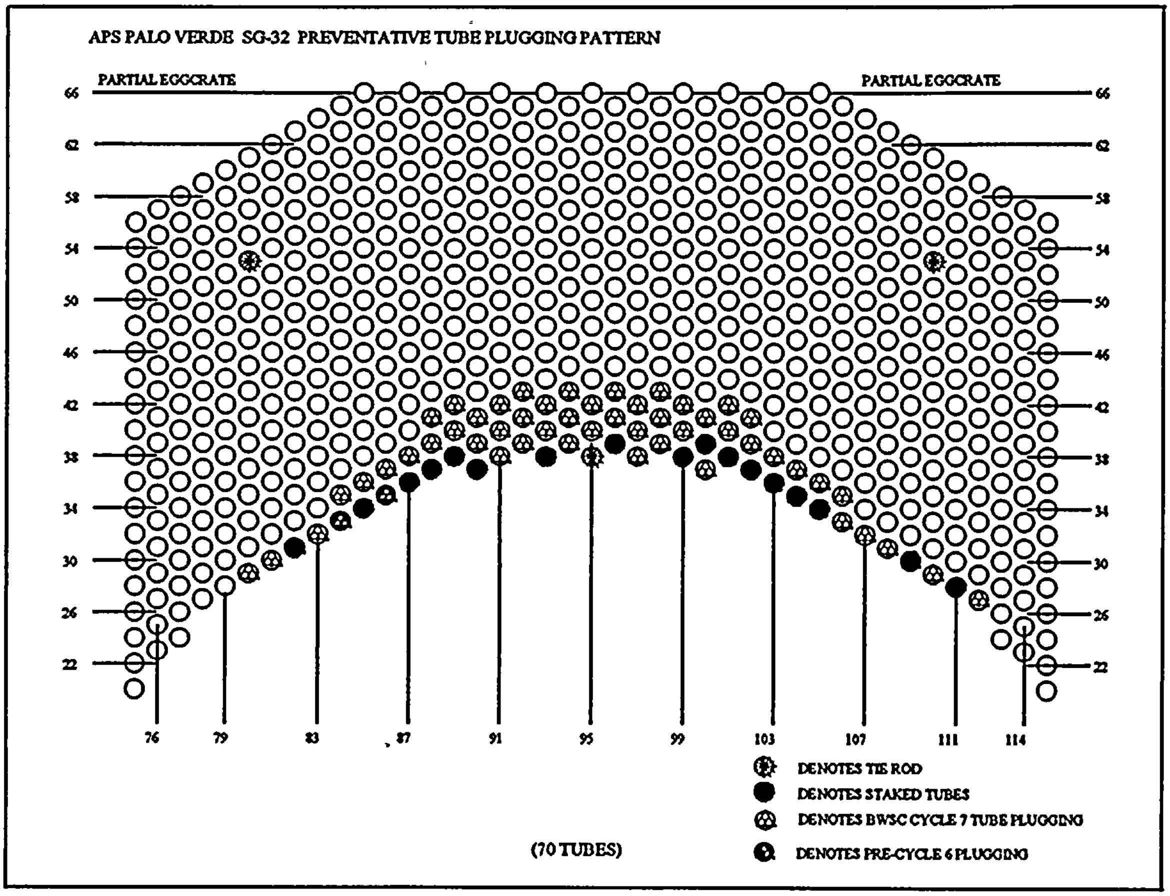

Figure B-2 Unit 3 Cycle 7 SG 3-2 BWSC Plugging Pattern