PALO VERDE NUCLEAR GENERATING STATION
UNIT 2 OPERATIONAL ASSESSMENT

BATWING SUPPORT INDUCED WEAR DEGRADATION OF STEAM GENERATOR TUBING DURING CYCLE 7

MAY 1997

ARIZONA PUBLIC SERVICE
STEAM GENERATOR PROJECTS

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EXECUTIVE SUMMARY

An evaluation of the significance of increased tube wear rates on the structural integrity of Alloy 600 steam generator tubing at Palo Verde Nuclear Generation Station Unit 2 was performed by APS. A change in the kinetics of this degradation mechanism was brought about by modifications performed by APS and ABB-Combustion Engineering, in an effort to improve the thermal hydraulic condition in the upper region of the PVNGS steam generators. The intent of this improvement was the reduction in the number of tubes impacted by an aggressive corrosion mechanism.

A probabilistic run time model developed by APS and APTECH was employed for the assessment. The processes of defect initiation, wear rate and eddy current inspection were modeled in a Monte Carlo simulation. Benchmarking of the simulation model was performed by comparing predictions of the severity of eddy current indications for Unit 3 against actual observations from U3R6. With model stability demonstrated, end-of-cycle (EOC) conditions were projected for Unit 2 Cycle 7. Using a well defined beginning-of-cycle (BOC) condition, projections were made based on an anticipated increase in wear growth rates. Model results strongly support 16.5 effective full power months (EFPM) of operation in Unit 2. In terms of Regulatory Guide 1.121 structural margins, the probability of a structural limit exceedance after 16.5 EFPM is estimated to be 7×10^{-4}. A deterministic assessment of wear progression was also performed by ABB-CE using proven wear analysis techniques. The analysis was performed as an independent assessment. The ABB-CE analysis provided good correlation in terms of projected EOC conditions. Therefore, in terms of the significance of this wear mechanism, full cycle operation in Unit 2 is strongly supported.

Section 1
INTRODUCTION

During the U3R6 eddy current inspection program, a region-specific increase in the number and severity of tube wear indications was observed in steam generator (SG) 3-2. This affected tube population has been historically characterized as the Batwing Stay Cylinder Region (BWSC). The "batwing supports" are diagonal spacer strips designed to limit out-of-plane movement of the bend region in Combustion Engineering (CE) steam generators (See Figure 1-1). The tubesheet in the PVNGS steam generators is supported by a forged stay cylinder. Its location prevented the installation of tubes, thereby forming a central cavity within the tube bundle. The presence of a central cavity results in a number of batwings which have unsupported spans before penetration into the tube bundle (See Figure 1-2).

Diagonal support induced wear, in tubes adjacent to the tube bundle central cavity, has been a well documented tube damage mechanism in the CE 3410 Mwt steam generators (References 1, 2 and 3). Analysis and operating experience has demonstrated that the System80 steam generators at PVNGS have been affected to a much reduced extent, due to lower vertical flow in the central cavity region. However, based on the potential for rapid wear, PVNGS has employed, since the start of commercial operation, an administrative plugging criteria of 20% through-wall for tubes in the affected region. Designated tubes are also staked when removed from service to reduce the possibility of tube severance.

During U3R5, APS implemented several steam generator modifications designed to improve thermal hydraulics, and reduce the progression of ARC

Region Outside Diameter Stress Corrosion Cracking (ODSCC) (Reference 4). One of these modifications involved the cutting of holes in the downcomer shroud to reduce recirculating loop flow resistance. The engineering evaluation of this modification determined that no local adverse flow induced vibration (FIV) conditions resulted from the modification. A consequential increase in central cavity vertical flow rates and potential impact on wear rate in the BWSC region was not specifically identified in the engineering evaluation for the steam generator modifications.

As reported in Reference 5, only a partial shroud modification was completed in Unit 3 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. The details of this Unit 3 Cycle 7 plugging pattern are described in Appendix B. APS and ABB-CE concluded that no operability issues with regard to this wear mechanism exist for Unit 3 Cycle 7.

Based on the Unit 3 observations, transportability issues to the Unit 1 and 2 steam generators were also assessed by APS. Steam generator modifications were implemented in Unit 2 during U2R6 and Unit 1 during U1R6. Once again, due to production issues, no shroud holes were cut in SGs 1-1, 1-2 and 2-1. However, the full complement of 45 holes were cut in SG 2-2. Consequently, APS has elected to conduct a supplementary run time assessment for Unit 2. The results and conclusions of Reference 4, are not impacted by this condition with respect to ARC Region ODSCC. Since the central cavity flow conditions are higher for a 45 hole configuration versus the 26 holes in SG 3-2, the condition observed in Unit 3 is not considered bounding with respect to wear rate. Therefore, an analysis to consider the impact of higher wear rates was undertaken by APS with support from APTECH and ABB-CE.

For the operational assessment, APS utilized an analysis process which has provided good and conservative correlation between predicted and actual end-of-cycle (EOC) conditions for corrosion mechanisms. This calculational framework has been presented on several occasions by APS to the USNRC. The analytical model, used previously for axial and circumferential SCC, is a mechanistic simulation of operating and inspection processes used at PVNGS. Based on the success of this process, the same approach was applied in the assessment of the batwing induced tube wear. A probabilistic run time model was developed by APS/APTECH to make projections of EOC conditions regarding the number of wear indications and their severity. The projected EOC condition forms the input for the structural integrity evaluation. The run time model is based on the physical processes of a tube fretting wear mechanism. The measured condition of the steam generator tubing at the start of Cycle 7, and measurement uncertainty during eddy current inspections is explicitly treated. Since the mechanism is well understood with respect to the number of tubes, a re-evaluation of Unit 2 EOC 6 eddy current data was conducted to best describe the beginning-of-cycle (BOC) 7 condition. The Monte Carlo simulation model was run on a single cycle basis, and was benchmarked by performing a supplemental Unit 3 simulation, and comparing projected EOC severity of the wear indications versus the actual observations for Unit 3 Cycle 6.

In addition, ABB-CE conducted an independent wear progression analysis. The analysis is a deterministic wear progression assessment based on historical plant data and extensive laboratory testing. The ABB-CE analysis (Appendix A) provides an independent check as to the reasonableness of the probabilistic model.

The following sections describe the general approach of the simulation model, and the analysis input parameters of the probabilistic analysis. Attention is given to the development of the wear rate estimates. The simulation results are then presented.

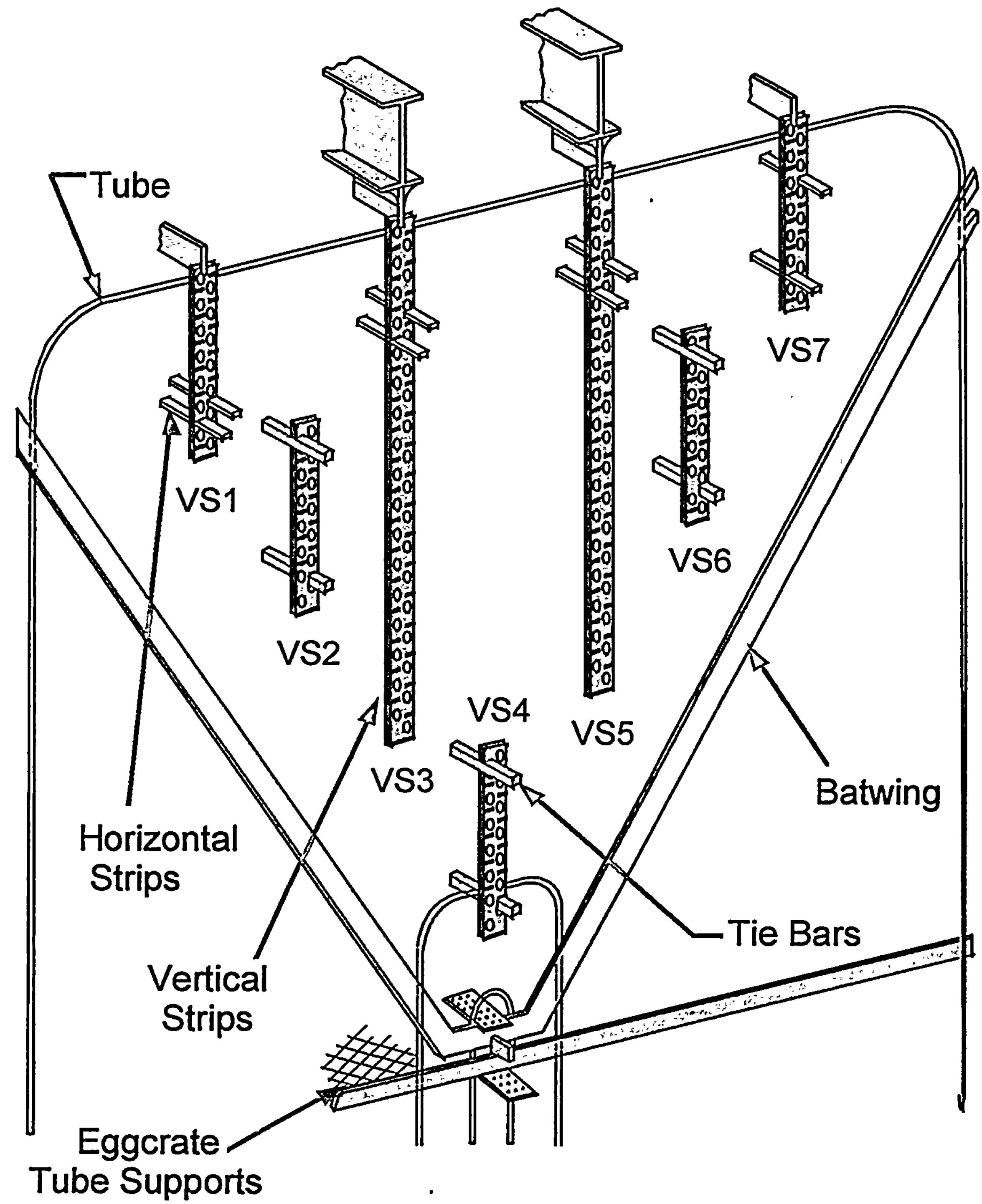

Figure 1-1 Bend Region Support Structures

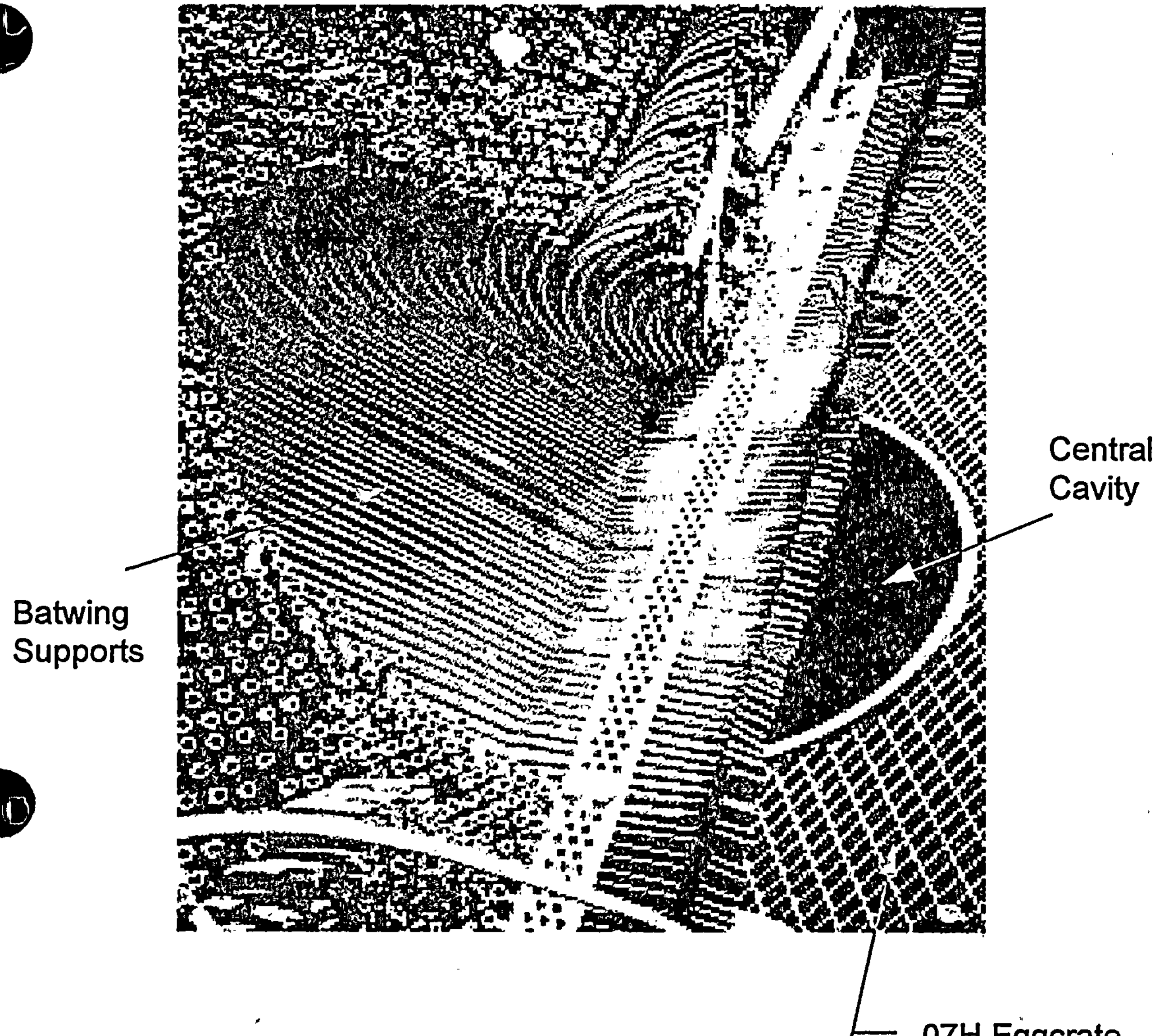

Figure 1-2 Steam Generator Central Cavity Region (Scrapped Steam Generator)

Section 2

BURST PRESSURE CONSIDERATIONS

This section presents a discussion of the burst pressure requirements and calculational methodology used in the determination of structural integrity margins for PVNGS steam generator tubing containing batwing wear scars.

2.1 BURST PRESSURE REQUIREMENTS

According to Regulatory Guide 1.121, the EOC structural integrity for a degraded tube must be greater than three (3) times the normal operating differential pressure or 1.43 times emergency and faulted (accident) condition differential pressures, whichever is greater. For PVNGS Unit 2, the limiting requirement is the 3ΔP pressure of 3810 psi. From a safety perspective, the main concern is the potential for tube burst at normal operation or under the limiting condition of a postulated main steam line break. In this context, a degraded tube burst strength of 2400 psi or greater eliminates concerns relative to tube burst under accident conditions during the proposed operating cycle.

2.2 BURST PRESSURE CALCULATIONS

As observed in Figure 2-1, the degradation of interest consist of long tapered wear scars caused by contact of the tubes by the batwing supports. In Reference 1, it was found that these wear scars have taper angles ranging from 1 to 2 degrees. Corresponding lengths of these wear scars are in the vicinity of 1 to 2 inches. The circumferential extent is relatively

small. For a wear depth of just under 100% through wall, the maximum circumferential extent of the wear mark is 54°. The circumferential extent of the deep portion (say 75% TW) of this wear mark is 28°. The end result can be characterized as a shallow, tapered flat spot about 1-2 inches long and about 0.18 inches wide.

For burst pressure calculations, the wear scars can be treated as partial depth axial cracks. The lack of sidewall support caused by the width of the wear mark compared to a crack is essentially offset by the lack of a strain concentrating notch at the maximum depth location in contrast to a crack. The actual depth versus length profile of the wear scar is important, as it is for axial cracks. Only the deep portion of the profile controls the burst pressure. A computer program was used by APTECH to sample depth profiles over various contiguous lengths to find the minimum burst pressure. For axial cracks, this methodology has been referred to in APS submittals as the "structural minimum method" and uses the Framatome burst equation for partial depth axial cracks. This method was applied in this assessment to locally thinned areas of steam generator tubing.

This burst pressure calculation methodology for locally thinned regions was benchmarked versus burst test data in NUREG/CR-0718 for elliptical wastage specimens. These specimens had long, narrow thinned areas produced by very large diameter milling cutters. The depth versus length profiles are thus partial arcs of large circles. Circumferential extents, essentially wrap angles, spanned the range of interest relative to wear scars. Measured versus calculated burst pressures are plotted in Figure 2-2. The burst pressure calculations are in excellent agreement with the test data. Calculated burst pressures are slightly conservative relative to the bulk of the test measurements.

Using the benchmarked approach described above, burst pressures were calculated for long, tapered wear scars with various maximum depths. Lower tolerance mechanical properties were used to produce the burst pressures calculated for 1° and 2° wear scars shown in Figure 2-3. As indicated, shallower wear angles are limiting with respect to burst pressure. For 1° wear scars, the 3Δ P burst pressure is met for maximum depths up to 75% TW even assuming lower bound mechanical properties. At typical mechanical property levels, the steam line break pressure of 2400 psi is met. Only very long, deep scars with lower bound tensile properties appear to offer a threat of tube burst under postulated accident conditions.

In 1985, Combustion Engineering (Reference 6) conducted burst and leak tests of tubes with simulated batwing wear. The burst tests were conducted for 50 and 75 percent through-wall samples at various wear angles. Due to a limited number of tests (6), and no data on tubing material properties, this data was compared qualitatively with the above burst correlation. Additional tests were recently performed by ABB-CE. The measured data from the 1997 test program was also compared to the calculated values. Some discrepancies were noted. In the 1997 test program, depth versus length profiles were not directly measured but inferred from OD measurements. In the vicinity of the projected EOC wear depths (≈75% TW), the measured burst strengths from the 1985 and 1997 (preliminary) testing when compared to the calculated burst values based on nominal dimensions agreed to within 4%. Hence, in terms of the conclusions relative to 3ΔP burst pressure requirements, the burst pressure calculations and all burst measurements are in good agreement.

However, for very deep (>90%) simulated wear scars, the measured burst pressures from the 1997 test program are substantially less than the calculated values. This is believed to be due to a lack of good characterization of actual maximum depths, and depth profiles in the critical deep areas. A difference in the maximum depth of 0.002 inches influences the burst pressure by about 500 psi. In the range of steam line break burst pressures, this difference constitutes a 20% swing in measured and calculated burst pressure. Despite this sensitivity, at maximum depths greater than 90% TW, the calculated burst pressures are within the assumed error band of possible dimensional variations. Since the 1997 burst test program is ongoing, several additional actions, such as, specimen sectioning, dimensional checks and test specimen preparation changes are under review by APS and ABB-CE. However, as indicated in Section 4 and Appendix A, the projected EOC conditions for Unit 2, SG 2-2, are in the range of through-wall depths where there is good agreement between the calculated and measured burst strength.

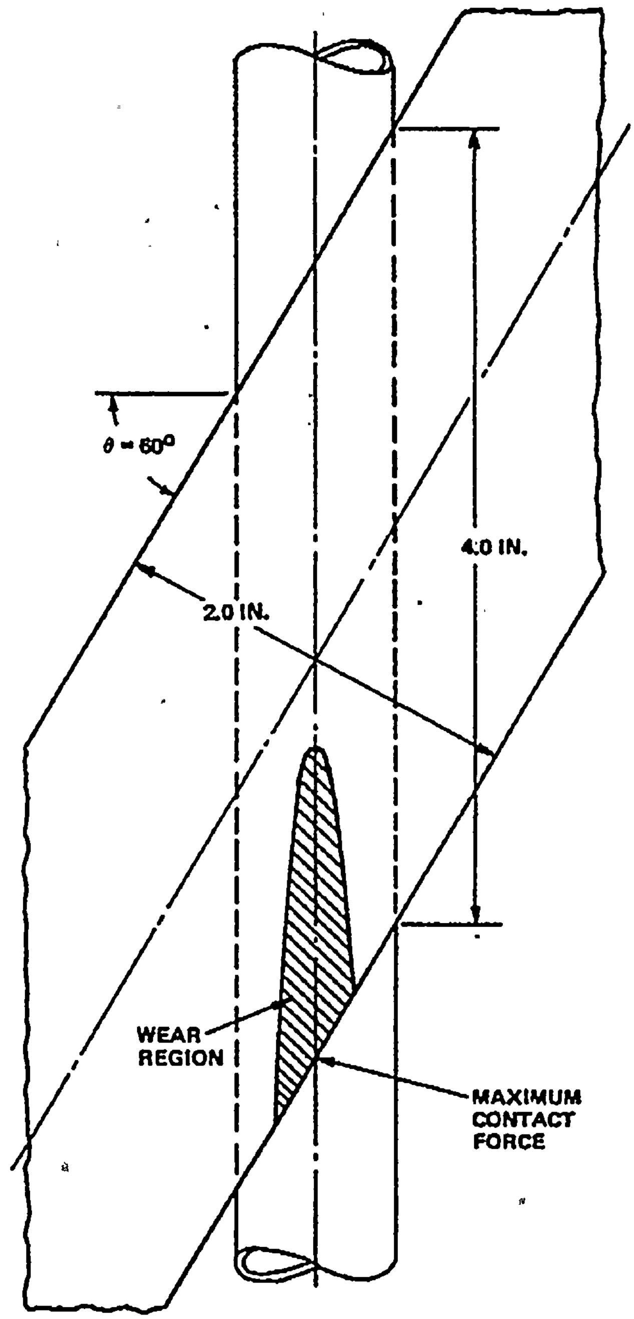

Figure 2-1 Batwing Wear Scar Geometry

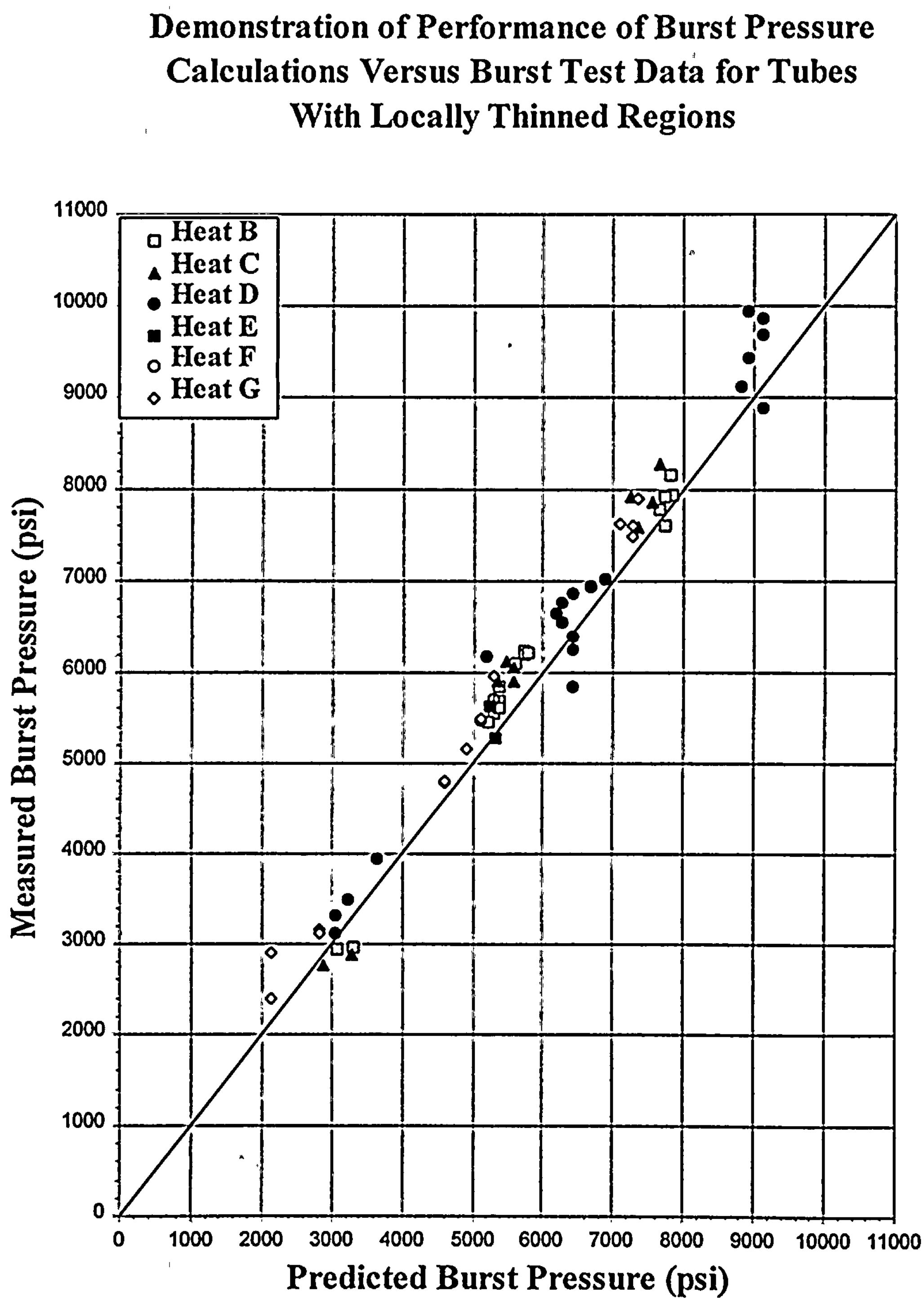

Figure 2-2 Measured versus Predicted Burst Pressure

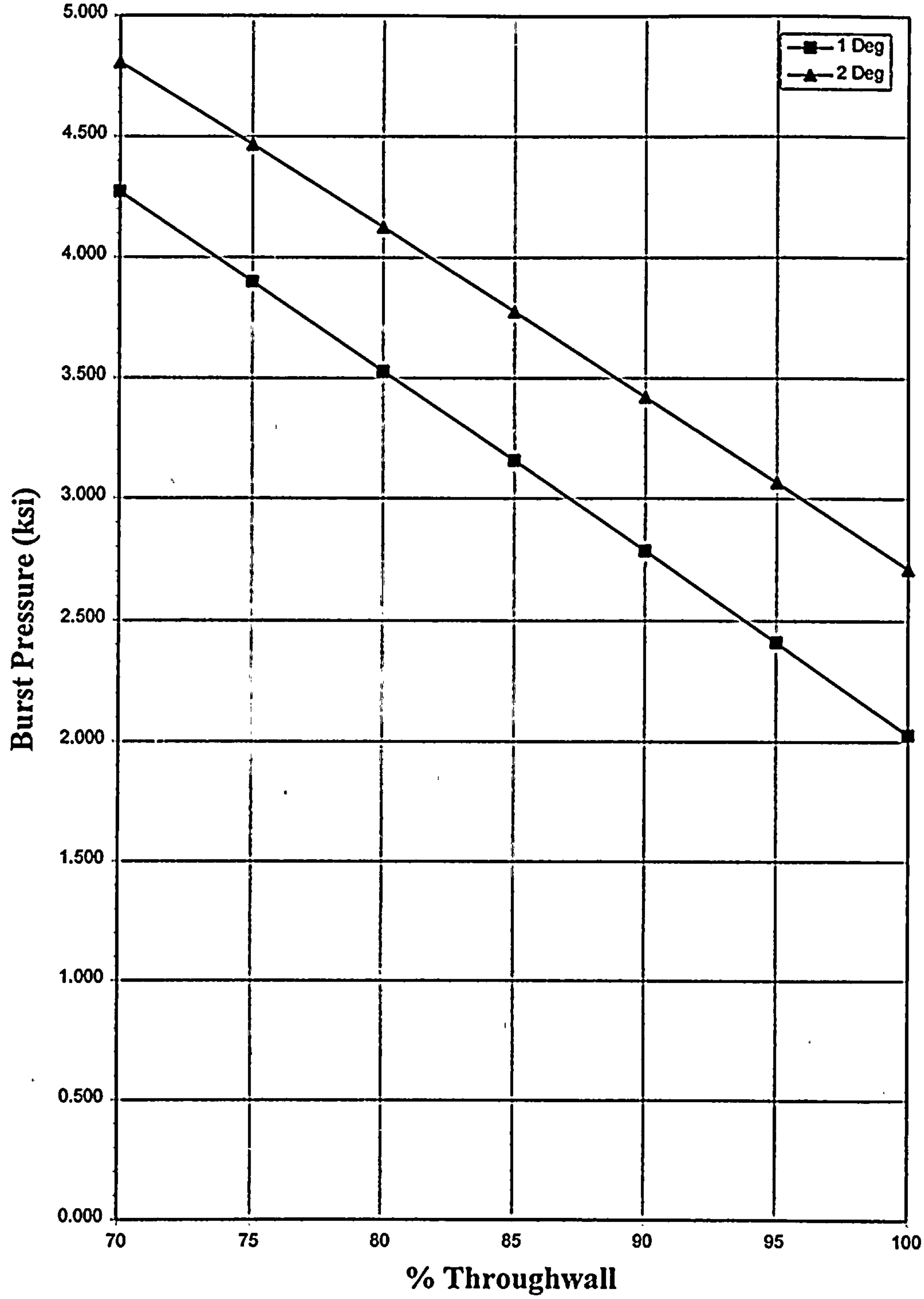

Figure 2-3 Flaw Size versus Burst Pressure

Section 3
ANALYSIS INPUT PARAMETERS

The following paragraphs describe the input parameters to the probabilistic structural evaluation model for Unit 2 Cycle 7. These parameters include beginning of cycle tubing condition, the development of the wear growth rate distribution and the distribution of Unit 2 tube strength properties.

3.1 BEGINNING OF CYCLE (BOC) CONDITION

The affected tube population for the BWSC mechanism is limited and well defined. It has been shown that the wear mechanism is caused by the central cavity flow field acting on a region of long unsupported batwing spans. The operating experience at CE 3410 Mwt plants and the PVNGS steam generators, has been well documented, and is consistent with the expectations presented in Reference 1 with respect to tube location and wear progression. Based on this experience, the affected tube pattern for a single cycle assessment was provided by ABB-CE in Reference 7, and is depicted in Figure 3-1. Utilizing this information, APS developed a steam generator specific definition of the BOC condition for the number and location of affected tubes, tubes plugged, and current ECT measured condition of the active steam generator tubing.

Based on additional review of the technical literature and actual operating experience, APS also found that the at-risk tube population can be further defined as three (3) different susceptibility patterns. This position is based on analysis and NDE results which indicate that tube wear rates diminish as unsupported batwing span is lowered. Additionally, studies and plant

experience has found that the interacting forces between the batwing supports and the tubes attenuate rapidly with distance into the bundle. As a result, a final susceptibility pattern for this analysis was developed (See Figure 3-2). It is also noted that, at the start of Cycle 7, a number of tubes within the affected region have already been plugged and removed from service. These tubes, shown in Figure 3-3, are no longer active and were excluded from the Cycle 7 assessment.

With knowledge of the affected tubes, the APS Level III ECT analyst performed a re-evaluation of the ECT data from U2R6. A 100% bobbin coil exam of the BWSC region was performed. This ECT evaluation reduces analyst uncertainty and permits a normalized indication of the BOC condition of the steam generator tubing. Despite a demonstrated improvement in reducing measurement uncertainty with this approach (see Table 3-1), a standard industry measurement uncertainty value from EPRI Appendix H was used in this analysis. The BOC condition of the Unit 2 SG 2-2 steam generator is provided in Table 3-2. Based on this treatment of the BOC condition, and the input assumption that *all* active tubes in the affected population are degrading according to the wear rate distribution, no POD scale factor was applied to define the BOC population basis.

3.2 WEAR GROWTH RATES

The defect growth rate probability distribution is the dominant stochastic variable in a run time analysis. Since no actual data exist for the current Unit 2 configuration, a review of the PVNGS and industry observed data was conducted. Considerable information regarding the behavior and progression of batwing support wear is available. This information was utilized in a conservative matter in an effort to describe an appropriate wear

rate distribution for Unit 2 Cycle 7. Information regarding the development of the probability distribution is provided as follows.

3.2.1 THEORETICAL WEAR CONSIDERATIONS

ABB-CE has developed a considerable database of laboratory test data, field observation, and wear progression analysis results for tube-tube support wear in CE steam generators. Based on this library of work, it has been found that the volume of removed tube wall due to mechanical fretting can best be represented by Archard's equation for wear.

Archard Wear Equation: $V = 10^{-12} K F_N L$

Where

V = Wear Volume (in^3)

K = Wear Coefficient (material dependent) (in^2/lb)

F_N = Normal Force (lb)

L = Total Slipping Distance (in)

In Appendix A and Reference 1, ABB-CE established, that for a common support design, wear rates would vary as a function of the flow field properties. The installation of 26 shroud holes in SG 3-2 during U3R5 resulted in an increase in fluid velocity and dynamic pressure in the central cavity region. The modification caused a consequential increase in wear rates during Cycle 6. With the installation of 45 holes in SG 2-2, further increases in wear rates are credible. Using the Archard wear equation, a scaling factor for wear rate increases can be assessed based on the calculated change in flow field properties.

In References 1 and 2, it was proven that the contact force between the batwing and the tube is proportional to the dynamic pressure in the central cavity region, such that:

$$F_N \propto \rho(v^2)$$

where ρ is the fluid density and v is the fluid velocity

In Appendix A, a similar relationship between sliding distance L and the fluid flow properties was also developed. Assuming that the change in fluid flow does not increase the bandwidth of the spectral forcing function, and therefore no additional vibration modes are introduced, the sliding distance will change in proportion to the square root of the spectral forcing function, such that:

$$L \propto \rho(v^{3/2})$$

The assumption that no additional modes of vibration outside the original spectrum range occur is based on the confined range of at-risk tubes. The original calculations in Reference 1 indicate that for the affected tube pattern, a 100% increase in the fluid velocity will not cause additional modes to participate in the response. Additionally, there was no indication in SG 3-2 that the expected tube wear pattern changed in response to the increased fluid velocity. Consequently, for the affected tube/tube support population, and the range of fluid flow fields associated with; the original design, 26 hole and 45 hole configurations, the predicted increase in tube wall volume removal can be assessed via the following relationship:

From the Archard equation: $V \propto F\,L$

Therefore: $V \; \alpha \; \rho^2 \, (v^{7/2})$

This relationship permits the development of a scaling factor from ATHOS calculated changes in the central cavity flow field. This scaling factor can be applied to the wear rate distribution for either the original design operating conditions, or the modified operating conditions experienced in Unit 3 during Cycle 6. By applying the appropriate scale factor, a SG 2-2 specific wear rate distribution for Unit 2 Cycle 7 can then be utilized in the run time simulation. Table 3-3 provides the calculated average flow field values from the ATHOS thermal hydraulic code. Based on the values listed in Table 3-3, a scale factor of 1.77 was applied to the Unit 3 Cycle 6 wear rate distribution (Figure 3-4).

3.2.2 WEAR FACTORS

As stated previously, the average wear progression in the affected population of tubes is not only impacted by the flow field forcing function, but also the unsupported batwing geometry. Engineering study and field observation indicate that wear rates attenuate when unsupported spans are lower, or as the support penetrates further into the bundle. References 1 and 3 found that the affected tubes could be grouped into sub-populations. Wear progression for these groups can be shown to differ by a column oriented wear factor. As shown in Figure 3-2, the BWSC population has been subgrouped from highest to lowest wear factor as red (R), blue (B) and yellow (Y). A boxplot of normalized Unit 3 Cycle 6 volumetric growth rate data shown in Figure 3-5 depicts this relationship. Benchmarking, as

described in Section 4, of the simulation model against actual U3R6 ECT shows good agreement for each subgroup.

3.2.3 VOLUME - DEPTH RELATIONSHIP

Since Archard's wear equation is expressed in terms of wear volume instead of wear depth, it is necessary to have a volume-to-depth relationship for the batwing wear scar geometry. Figure 2-1 depicted a typical wear scar contour and the longitudinal cross section of the wear volume. This wear scar configuration illustrates the importance of defining the range of angular penetration in order to calculate wear volume. In Reference 1, ABB-CE considered several different wear models, and compared the predicted relationship between depth and angle to observed ECT from the 3410 Mwt plants.

The first model assumed nominal support-to-tube clearances (0.013 inch) and rigid batwing motion. The wear scenario assumed that wear was shared equally between the tube and the batwing, and that the wear was evenly distributed between the top and bottom contact points.

The second wear model assumed a prying action of the rotating batwing occurs between tube columns. Such a prying action could double the initial nominal clearance thereby increasing the angle of penetration. The second model assumes no wear of the batwing support.

The ECT data from the 3410 Mwt CE plants indicates that a best estimate wear model for BWSC wear is a hybrid of the two models, indicating that some wear on the support is probable. Since the first model produces shallower wear angles, it is more conservative with respect to burst

pressure. However, the second model produces conservative values with respect to through-wall penetration per cycle. Consequently, the volume-to-depth relationship that assumes no wear of the batwing support, was utilized in wear rate calculation. The correlation is depicted in Figure 3-6.

The ABB-CE evaluation provided in Appendix A was performed for both scenarios. As indicated in Section 2, shallow wear angles, that bound both wear scenarios, were used in the development of the burst correlation.

3.3 TUBING MECHANICAL PROPERTIES

The actual yield strength and ultimate tensile strength properties were available for the Palo Verde Unit 2 steam generator tubing. Room temperature test results were adjusted to account for the variation of flow strength with temperature. A normal distribution was fitted to this data, and this provided the tube strength input to the probabilistic calculations. Figure 3-7 depicts the probability distribution used for the SG 2-2 tubing in the simulation.

Wear Angle	Actual %TW	Bobbin%
0.5 degrees	7	4
	19	19
	29	29
	41	35
	48	44
	55	47
1.5 degrees	5	6
	17	19
	29	27
	43	36
	48	43
	55	47
2.5 degrees	7	6
	17	19
	31	26
	43	36
	48	42
	52	46

Table 3-1 PVNGS Bobbin Measurement of Batwing Wear Standard

Table 3-2 Unit 2 SG 2-2 BWSC Status

Number	Row	Column	Cycle 1-6 SG 22 Status	EOC 6 ECT Re-evaluation
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%
9	35	86	Plugged 21% U2R4	
10	37	86		16%
11	36	87		0
12	38	87		18%
13	37	88	Plugged 29% U2R3	
14	39	88		9%
15	41	88		0
16	38	89		15%
17	40	89		0
18	42	89		0
19	37	90	Plugged 55% U2R2	
20	39	90	Plugged 22% U2R4	
21	41	90	-	6%
22	38	91	Plugged 43% U2R2	
23	40	91		9%
24	42	91		0
25	39	92		0
26	41	92		0
27	43	92		0
28	38	93		0
29	40	93		0
30	42	93		0
31	39	94	Plugged 32% U2R2	
32	41	94	Plugged SAI U2R4	
33	43	94		9%
34	40	95		16%
35	42	95		6%
36	39	96	Plugged 30% U2R4	

Number	Row	Column	Cycle 1-6 SG 22 Status	EOC 6 ECT Re-evaluation
37	41	96		0
38	43	96		0
39	38	97		13%
40	40	97	Plugged 18% U2R4	
41	42	97	Plugged SCI U2R6	
42	39	98	Plugged 41% U2R4	
43	41	98	Plugged 30% U2R2	
44	43	98		18%
45	38	99	Plugged 19% U2R5	
46	40	99		0%
47	42	99		0
48	37	100	Plugged 25% U2R1	
49	39	100	Plugged 33% U2R3	
50	41	100		0
51	38	101	Plugged 28% U2M5	
52	40	101		11%
53	42	101		0
54	37	102	Plugged 20% U2R6	
55	39	102		12%
56	41	102		5%
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%
64	35	106		0
65	32	107	Plugged 22% U2R1	
66	31	108	Plugged 32% U2R5	
67	30	109		14%
68	29	110		8%

Notes:

1. The data has been color coded to match the susceptibility pattern depicted in Figure 3-2

Steam Generator (Operating Conditions)	ATHOS T-H Parameters 257 inches above the Tubesheet Homogeneous Flow Model		
	Axial Velocity (Ft/Sec)	Density (Lbm/Ft^3)	Dynamic Pressure (Lbf/Ft^2)
CE 3410 Mwt 100% Power [1,2]	15.3	12.78	46.5
PVNGS Original Design [3]	7.96	14.42	46.5
PVNGS SG 32 w/o Mods - 173 plugged tubes 989 psia, 1908 Mwt/SG	7.74	14.59	13.59
PVNGS SG 32 [4] With FR/SP/26 Holes 173 plugs, 1949 Mwt/SG	11.01	13.28	25.02
PVNGS SG 22 [4] With FR/SP and 45 Shroud Holes 1308 Plugs, 1949 Mwt/SG	13.66	12.12	35.15

Table 3-3 ATHOS Secondary Side Flow Analysis Results Central Cavity Region

Notes:

1. Report CENC 1681 Rev 1, February 27, 1985
2. Based on 6x6x26 (R,θ,Z) ATHOS Model
3. Based on (18x12x35) (R,θ,Z) ATHOS Model Averages at IY=1 and IY=2
4. 2% Power Uprate and FW Temperature Reduction

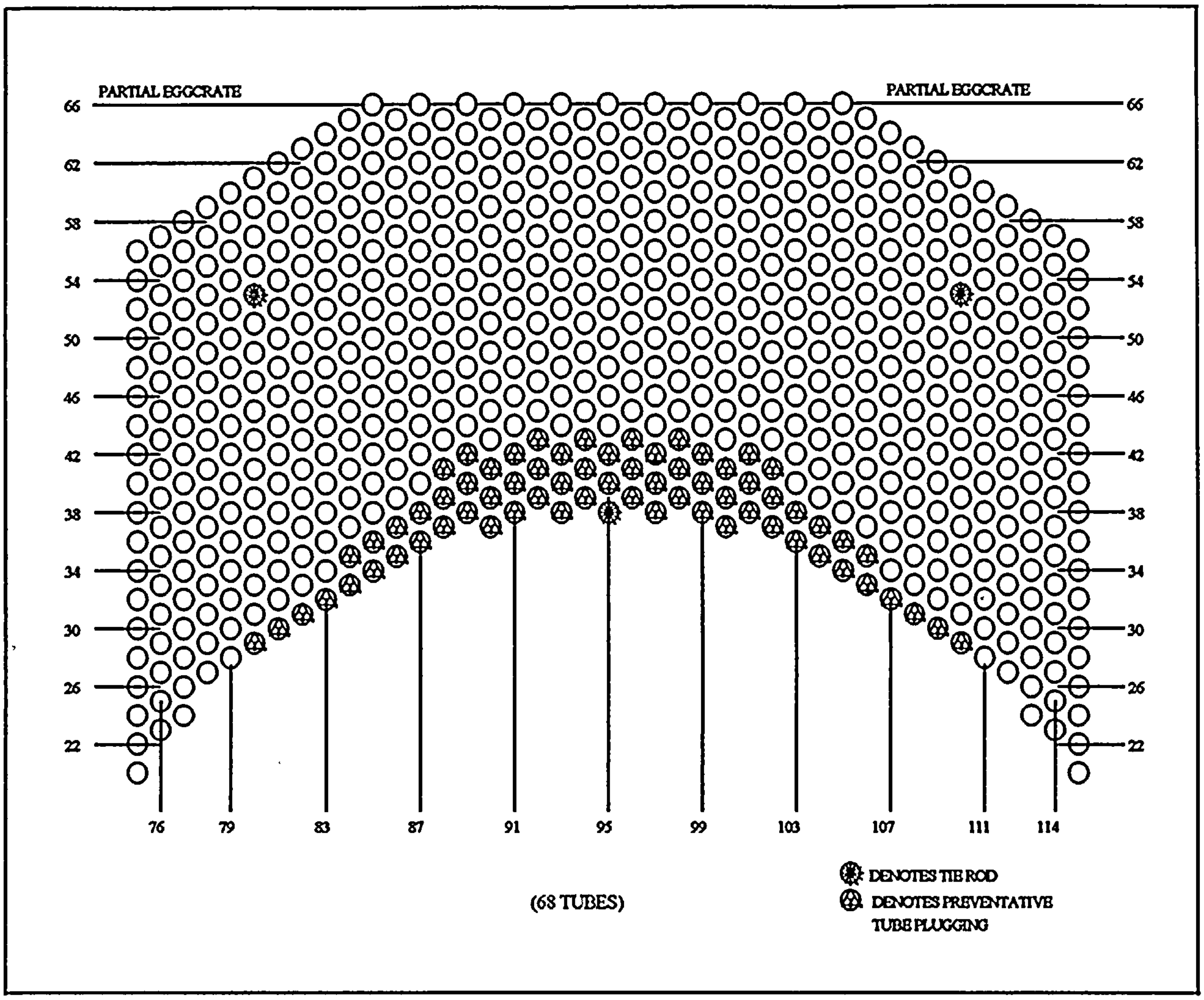

Figure 3-1 BWSC Single Cycle Tube Pattern

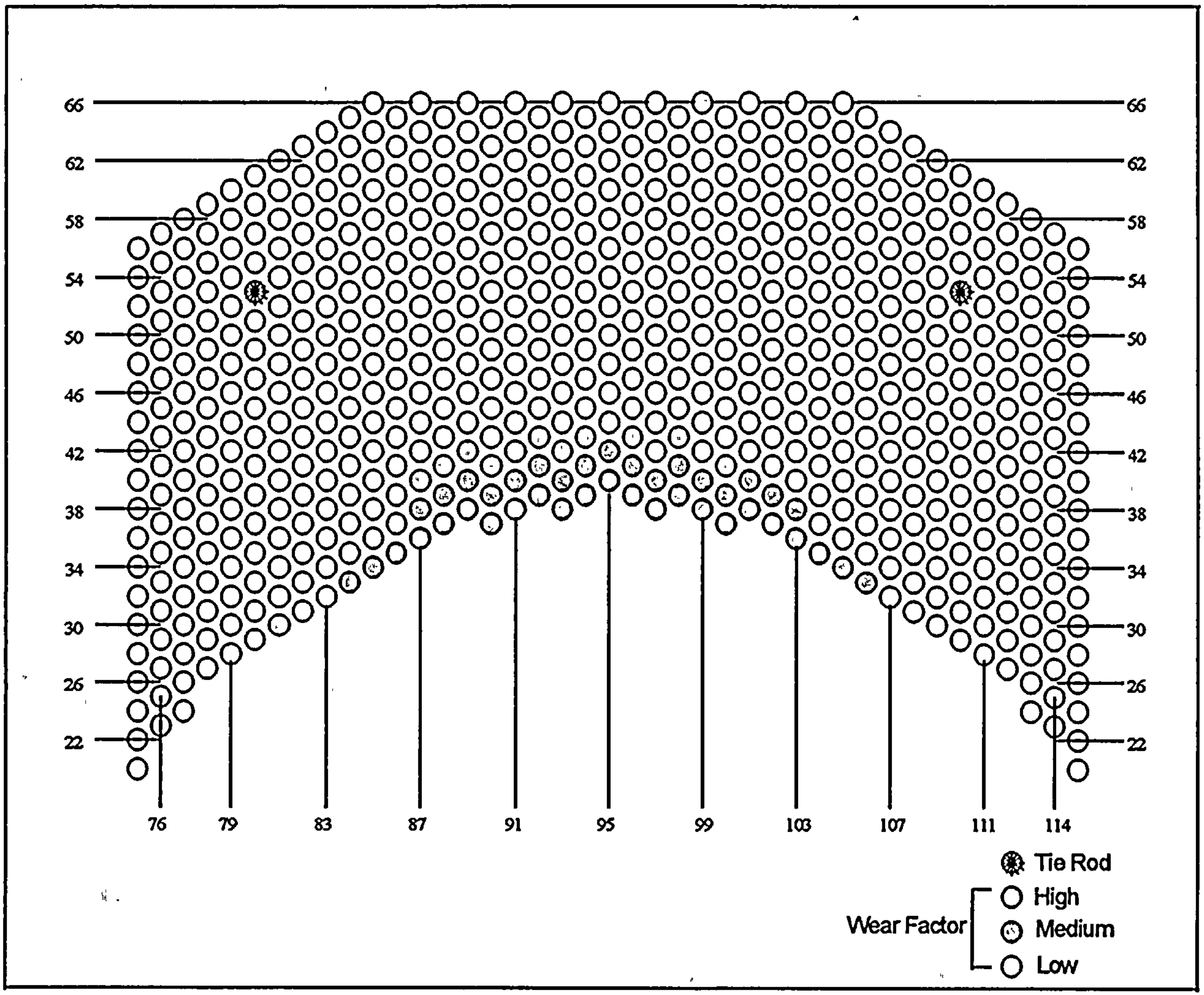

Figure 3-2 BWSC Wear Susceptibility Pattern

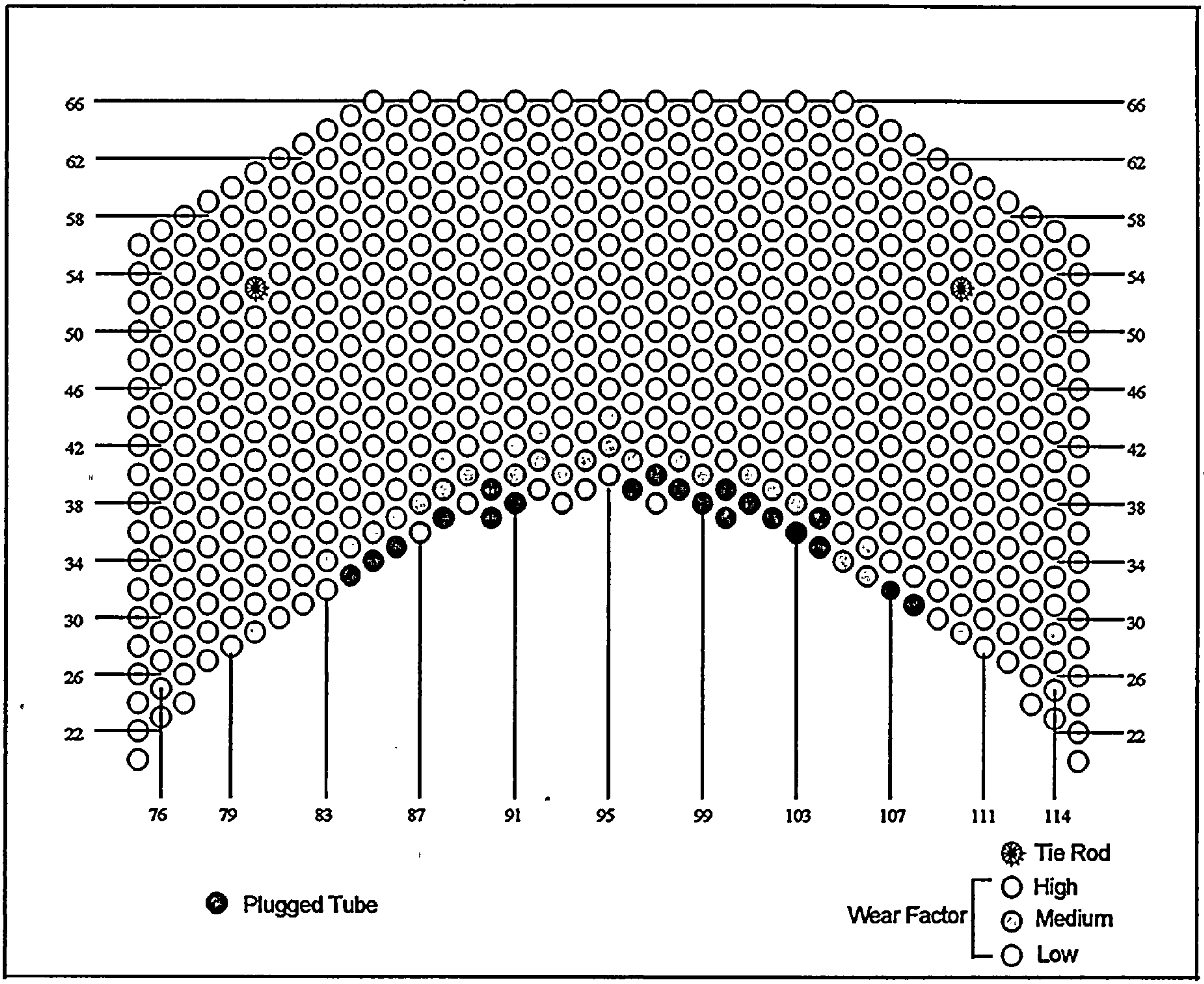

Figure 3-3 SG 2-2 Active Tubes at BOC 7

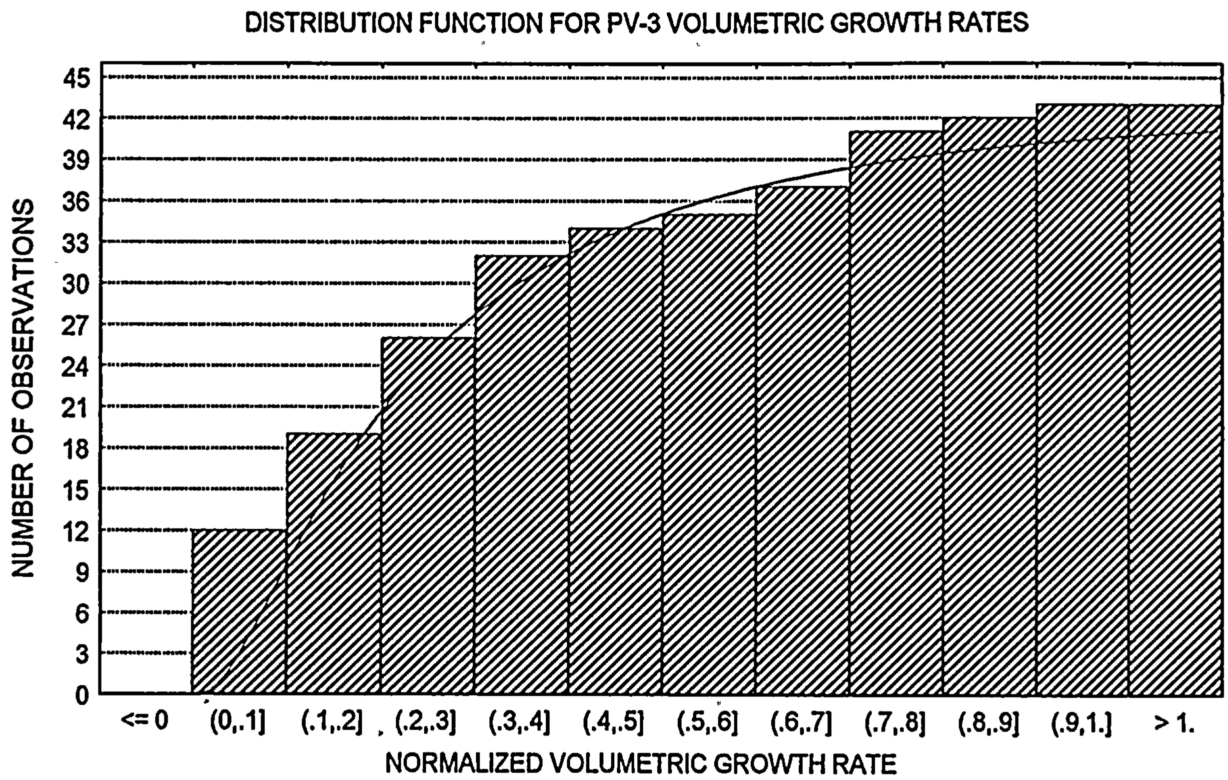

Figure 3-4 Normalized Wear Rate Distribution Unit 3 Cycle 6

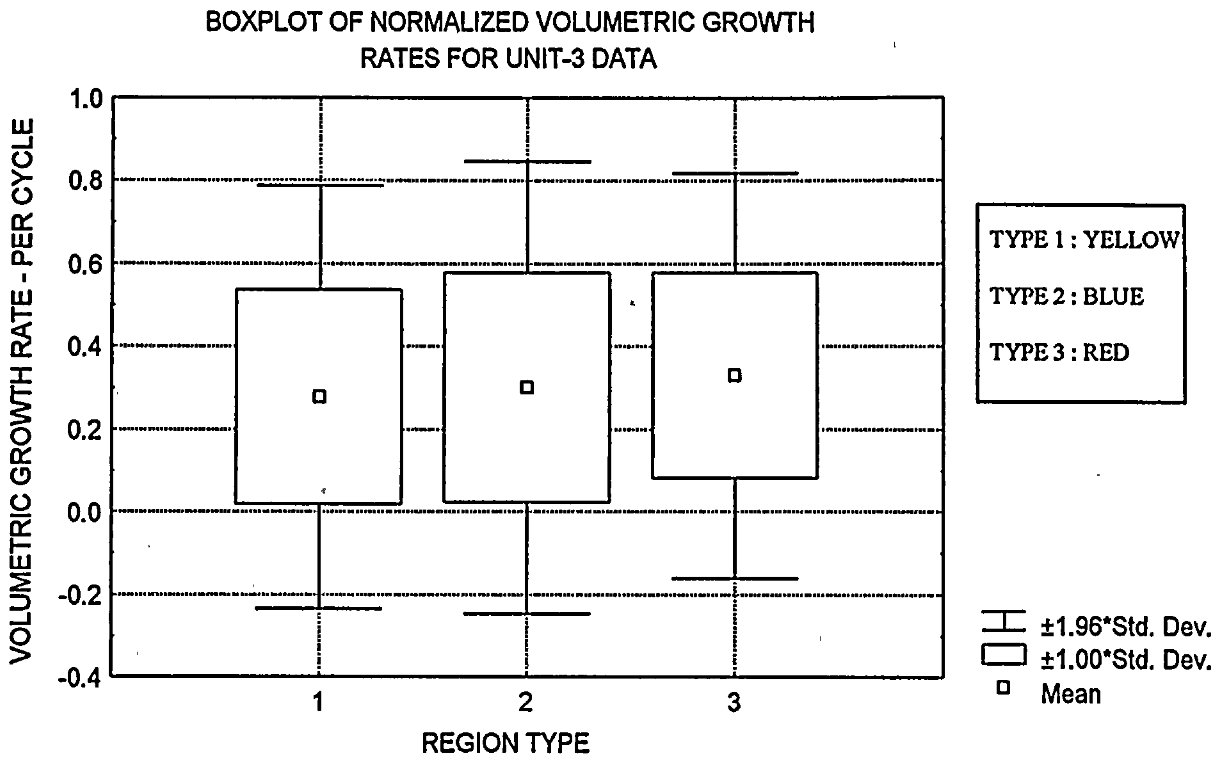

Figure 3-5 Normalized Wear Factor Unit 3 Cycle 6

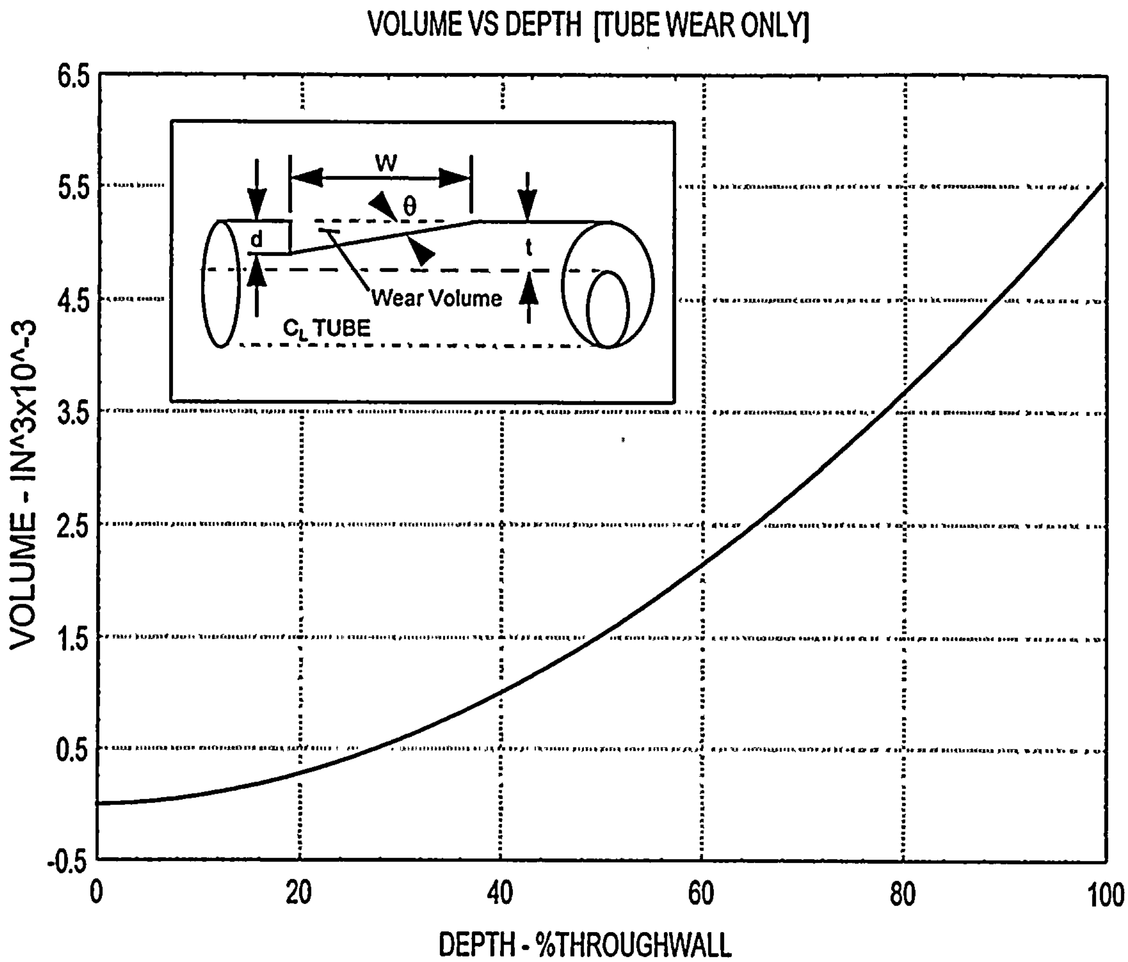

Figure 3-6 Wear Volume to Wear Depth Relationship

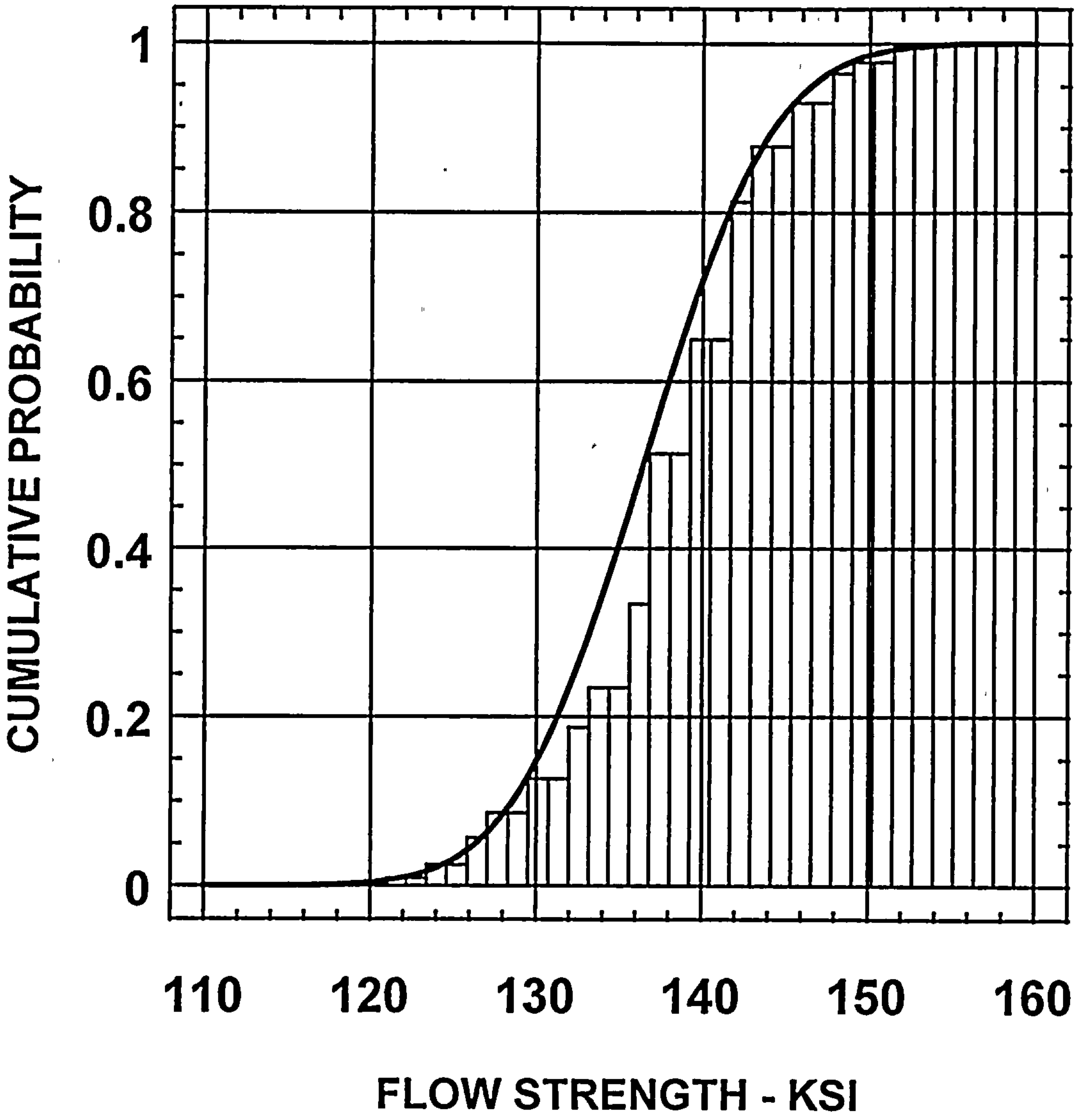

Figure 3-7 Tube Flow Stress Distribution for Unit 2

Section 4
PROBABILISTIC MODEL

The probabilistic run time model for the evaluation of the PVNGS Unit 2 batwing wear phenomenon models the evolution of wear depth for a limited number of at-risk tubes as described in Section 3. The simulation is performed as a single cycle evaluation in which the BOC state is established, and wear propagation is modeled to establish an EOC state for the entire population of at-risk tubes. The burst pressure for each tube in the susceptibility pattern is then computed using the burst pressure function described in Section 2. The evaluation conservatively assumes that all tubes in the population will experience a growth in wear depth during the operating cycle.

The analysis divides the affected population into three groups based on different general wear rates as described in Section 3.2.2. The presence of plugged tubes is accommodated in the analysis by censoring the resulting EOC depth burst pressure computations for the population.

The computations are performed using a well established Monte Carlo simulation technique to account for uncertainties in BOC defect sizing and wear rates. The results of the simulation are specifically oriented toward a "worst tube" evaluation in which the extreme value distribution for minimum EOC burst pressure is the primary figure of merit. The program flow is shown in Figure 4-1 which describes the basic structure of the wear simulation.

4.1 BOC WEAR DEPTHS

The basic state of the affected population (68 tubes) is BOC input to the simulation. For each of the 68 tubes, which retain their identities during the evaluation, three values are specified:

- TYPE (high, medium, low growth rate)
- BOC SIZE (NDE)
- REPAIR STATE (plugged/not plugged)

This information provides the bases for determining actual BOC size, selection of growth rates, and output censoring. This information remains constant throughout a specific simulation.

The correction of BOC depths to account for NDE measurement error is repeated for each trial in the simulation. The error is assumed to be additive and normally distributed with a standard deviation of 5% through-wall.

4.2 EOC WEAR DEPTHS

The EOC depths for the affected population are computed by adding a randomized growth component to the BOC depths (with uncertainties).

A normalized growth rate sampling distribution expressed in terms of volumetric growth (See Figure 3-4) is used for this purpose. The distribution is adjusted by a wear rate scale factor to account for changes in wear due to an increase in central cavity flow rates. The TYPE identifier for each tube is used to de-normalize the sampled growth rate to obtain an appropriate value for that tube. A volume/depth relationship established for tube wear only, as described in Section 3.2.3 and Figure 3-6, is used to establish the depth growth for a specific tube.

4.3 BURST PRESSURE COMPUTATIONS

The burst pressure for each of the 68 tubes is then computed using the burst pressure versus wear depth relationships shown in Figure 2-3. As can be seen, the burst pressure is a function of both depth and wear angle. For a given tube the wear angle is assumed to be a uniformly distributed random variable with a minimum value of one degree and a maximum value of two degrees. Linearity is assumed between burst pressure and wear angle within this region.

4.4 OUTPUT

The computations for a given trial are processed to obtain the minimum burst pressure and/or the maximum wear depth. At this point, a censoring based on plugging information takes place. Only active tubes are considered in the establishment of minimum burst pressure values. In the case of Palo Verde Unit 2, this is important since a large number of high growth rate population tubes are, in fact, plugged.

The repetition of 1000 trials of the type described, is used to establish extreme value distributions such as those shown in Figure 4-2 and 4-3.

4.6 BENCHMARK COMPUTATIONS

The tube wear simulation was benchmarked against the Palo Verde Unit 3 data obtained at U3R6. The simulation was modified to permit

benchmarking on a "wear group" basis. The results are shown in Figure 4-4 for the "blue" group and Figure 4-5 for the higher growth rate "red" group. Agreement with observed data is good in that observed maxima were well within the predicted uncertainty band of the simulation.

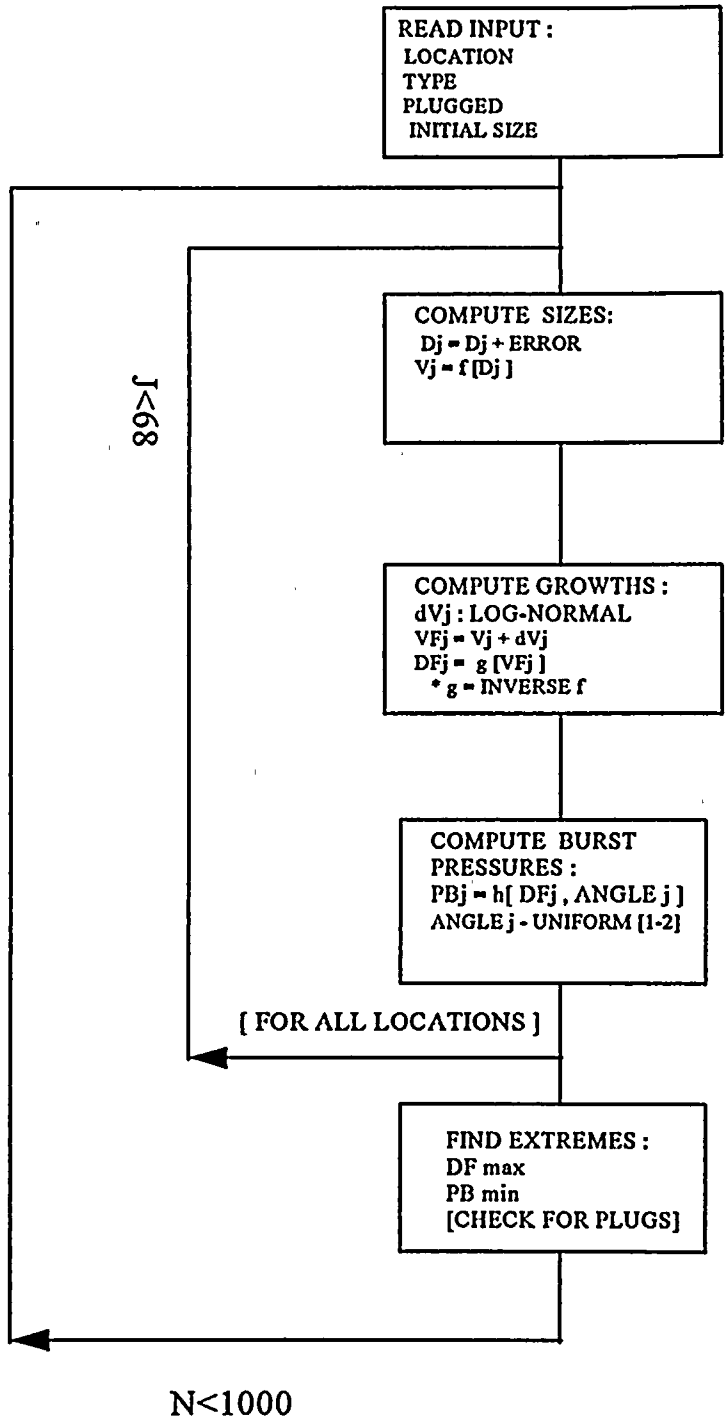

Figure 4-1 Flow Chart of Wear Simulation Process

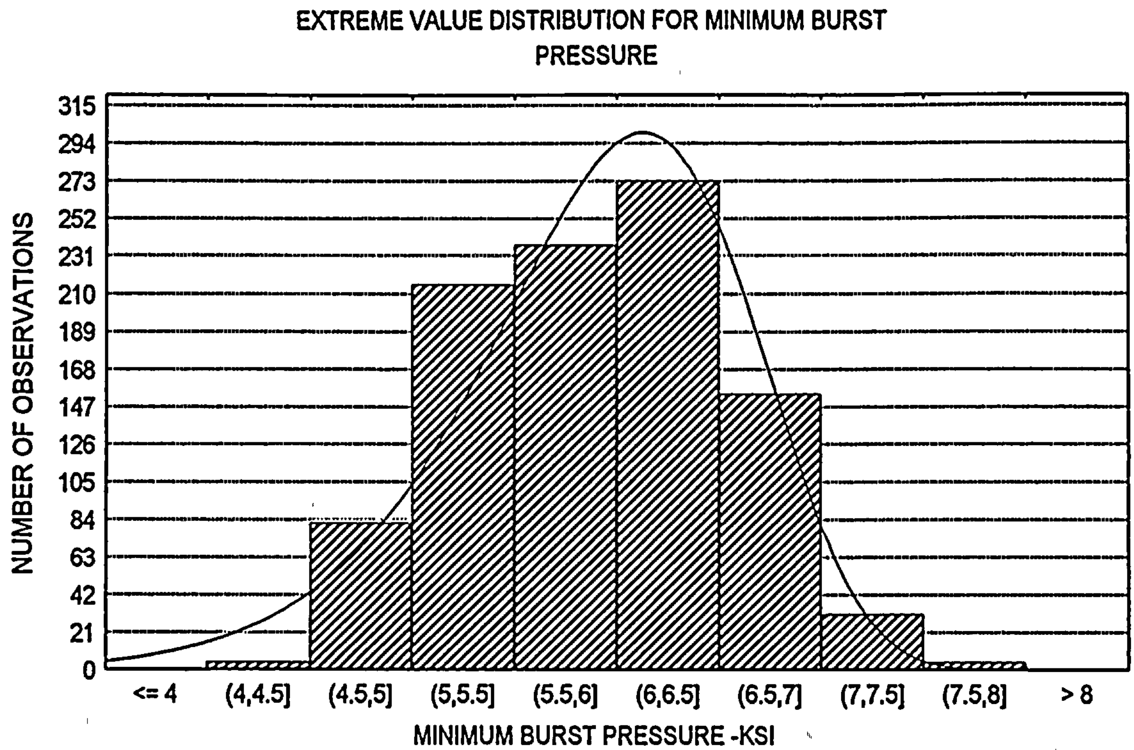

Figure 4-2 Extreme Value Distribution of Minimum Burst Pressure Unit 2 Cycle 7 BWSC Wear Prediction

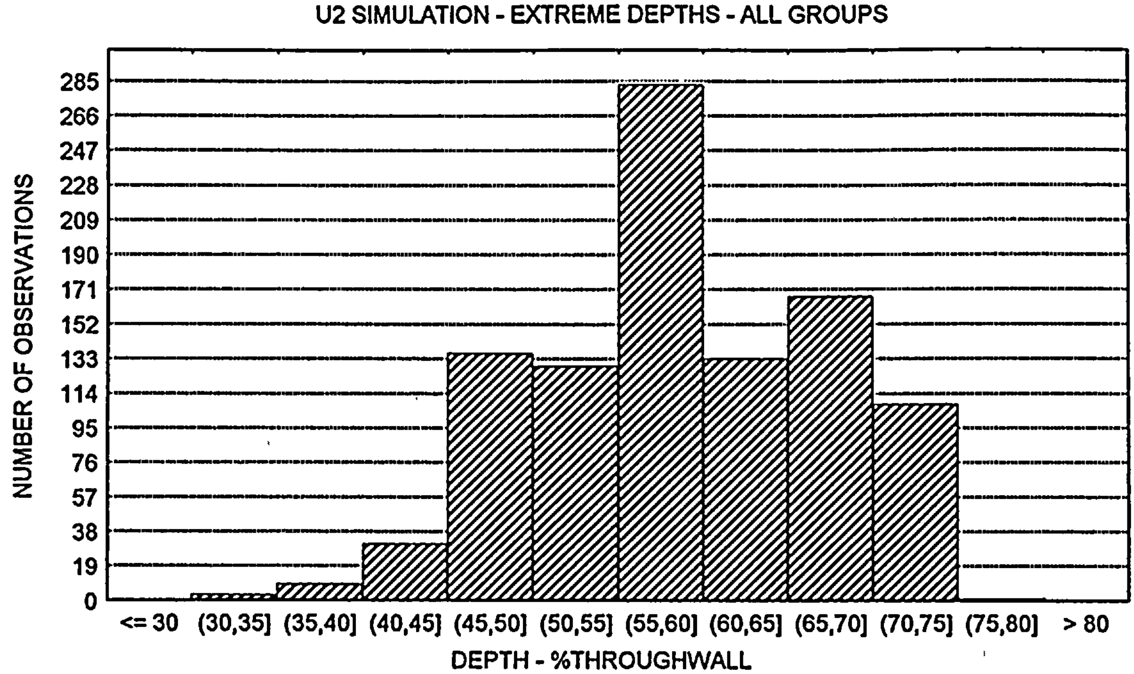

Figure 4-3 Extreme Value Distribution of Maximum Depth Unit 2 Cycle 7 BWSC Wear Prediction

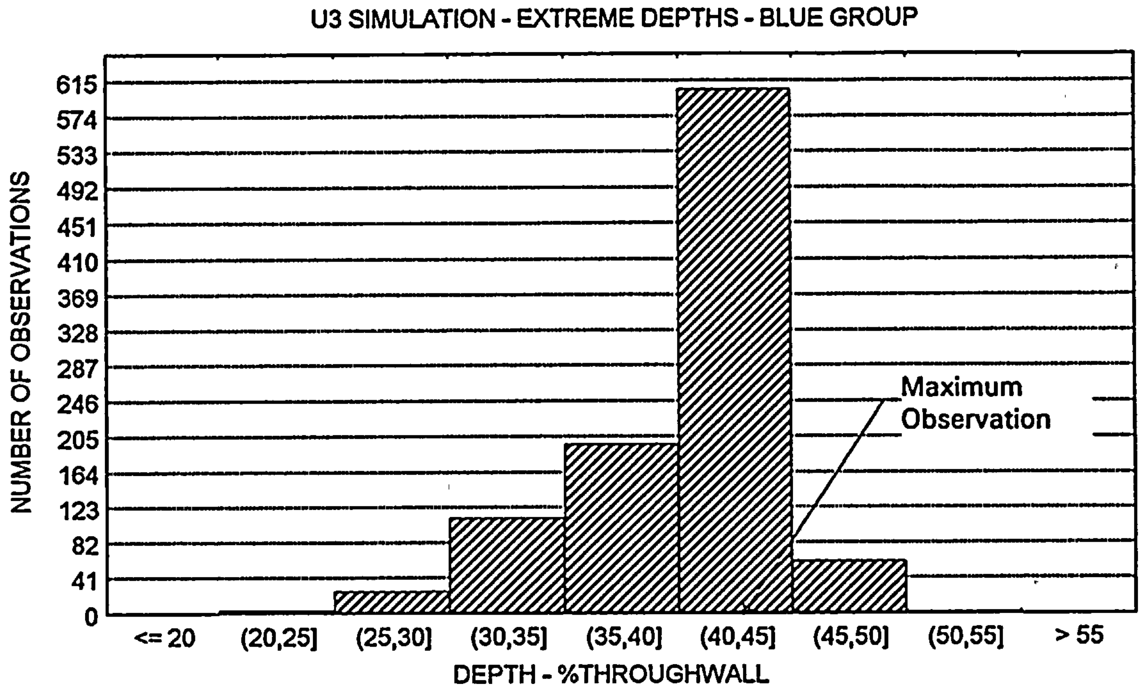

Figure 4-4 Benchmark Simulation U3R6 - Blue Group

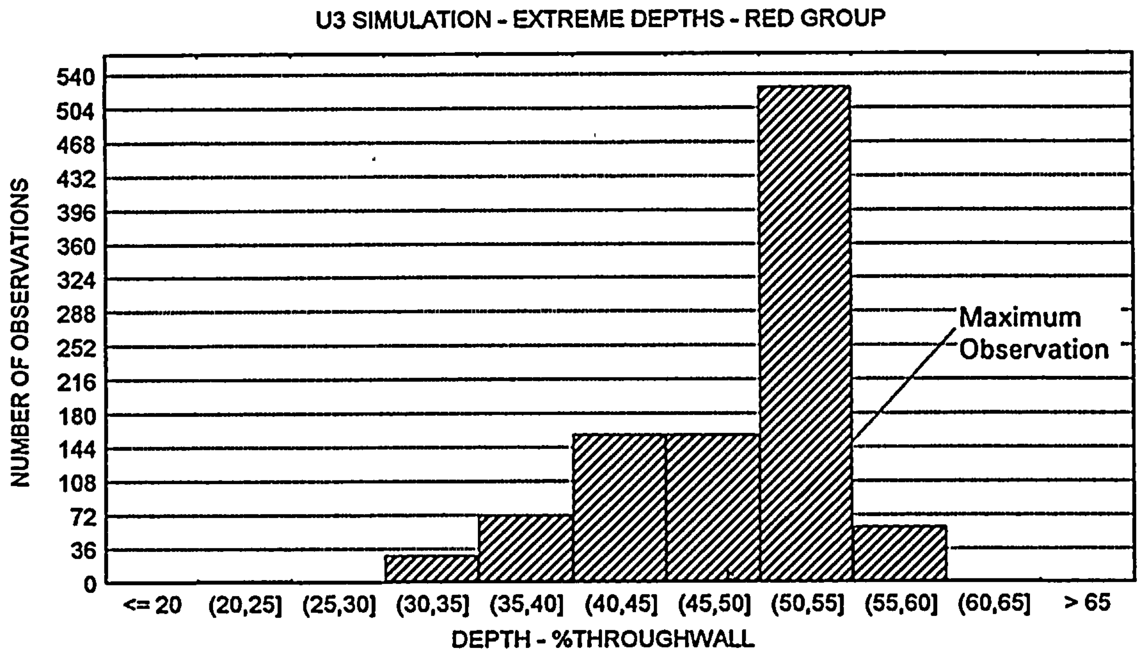

Figure 4-5 Benchmark Simulation U3R6 - Red Group

Section 5
STRUCTURAL MARGIN EVALUATION

The parameters of interest in a probabilistic structural margin evaluation are the conditional probability of tube burst given a postulated main steam line break at end of cycle and the likelihood of multiple RG 1.121 structural limit exceedances. The expected leak rate under accident conditions is another important consideration. Both structural margin and leak rate evaluations with respect to possible increased batwing wear are presented in the following paragraphs.

Relative to structural integrity, a reasonable figure of merit for conditional probability of an MSLB tube burst is provided by a historical value of 0.050. A value less than 0.01 provides a good benchmark of structural integrity. In terms of meeting Regulatory Guide 1.121 structural margins, a reasonable probabilistic criteria is a goal of at least 90% probability that one or fewer tubes will be expected to violate structural limits at end of cycle.

The PVNGS Unit 2 analysis, simulated Cycle 7 as a 16.5 EFPM run with a 45 shroud hole modification and 102% of original design rated power. The results of the Monte Carlo simulation showed no occurrence of tube burst at MSLB conditions in 1000 trials. The simulation under a 3ΔP loading had the same outcome, thus the conditional probability of tube burst in each case was less than
10^{-3}. These null results, therefore give a best estimate burst probability of 7×10^{-4} for both MSLB and RG 1.121 conditions. The corresponding upper 95% confidence estimate is 3×10^{-3} for both conditions.

As shown in Figure 4-3, the extreme value distribution for the maximum projected through-wall indication is provided. This is important for leakage considerations, since a through-wall defect is required for leakage to occur. As can be seen, the possibility of a 100% through-wall defect due to batwing wear and subsequent leakage is very remote.

As in past APS submittals, an independent verification process is employed by APS for all run time evaluations. For the batwing wear assessment, ABB-CE was contracted to perform an independent wear progression analysis. The analysis is a deterministic wear progression assessment based on historical plant data and extensive laboratory testing. The ABB-CE analysis (Appendix A) provides an independent check as to the reasonableness of the probabilistic model. By applying on a tube basis the worst case BOC condition to a worst case wear rate, the limiting EOC condition can be assessed. For tube R40C95, the BOC condition with 5% ECT error is 23% through-wall. The wear rate from Table A-16 of Appendix A shows the wear rate for R40C95 to be 56% for Cycle 7. The EOC calculation is then performed on a volume basis using Figure B-1 of Appendix A. The EOC 7 maximum defect depth is calculated to be 62% through-wall. The ABB-CE assessment is therefore, in good agreement with the probabilistic analysis as it predicts a low risk of a defect exceeding RG 1.121 allowables.

Section 6

SUMMARY AND CONCLUSIONS

An evaluation was performed of the significance of BWSC wear degradation on the structural and leakage integrity of steam generator tubes at Palo Verde Unit 2. The assessment was required due to a change in the kinetics of this degradation mechanism brought about by modifications performed by APS and ABB-Combustion Engineering, in an effort to improve the thermal hydraulic condition in the upper region of the PVNGS steam generators. The intent of this improvement was the reduction in the number of tubes impacted by an aggressive corrosion mechanism

A probabilistic run time model developed by APS and APTECH was employed for the assessment. The processes of defect initiation, wear rate and eddy current inspection were modeled in a Monte Carlo simulation. Benchmarking of the simulation model was performed by comparing predictions of the severity of eddy current indications for Unit 3 against actual observations from U3R6. With model stability demonstrated, end-of-cycle (EOC) conditions were projected for Unit 2 Cycle 7. Using a well defined beginning-of-cycle (BOC) condition, projections were made based on an anticipated increase in wear growth rates. Model results strongly support 16.5 effective full power months (EFPM) of operation in Unit 2. In terms of Regulatory Guide 1.121 structural margins, the probability of a structural limit exceedance after 16.5 EFPM is estimated to be 7×10^{-4}.

A deterministic assessment of wear progression was also performed by ABB-CE using proven wear analysis techniques. The analysis was performed as an independent assessment. The ABB-CE analysis provided good correlation in terms of projected EOC conditions and risk of exceeding the structural margins defined by RG 1.121.

As indicated in Reference 4, APS has employed a defense-in-depth philosophy with respect to steam generator degradation management and preventing challenges to nuclear safety. In addition to performing state-of-the-art tube integrity analysis, additional preventative measures such as comprehensive ECT and conservative plugging criteria have been applied to the BWSC tube population. The PVNGS Steam Generator Degradation Management Program also employs strict administrative controls on primary-to-secondary leakage and RCS activity levels, enhanced radiological monitoring, emergency procedures improvements and continued operator training for steam generator tube leakage and tube rupture events. Based on these actions, and in terms of the significance of this BWSC wear mechanism, full Cycle 7 operation in Unit 2 is strongly supported.

REFERENCES

1. *Remedy for Steam Generator Tube and Diagonal Strip Wear*, Combustion Engineering Report CEN-328, March 1986

2. *Evaluation of Steam Generator Tube and Diagonal Spacer Strip Interaction and Wear*, Combustion Engineering Report CEN-299, March 1985

3. M. L. Badlani et. al., *Evaluation of Tube Wear in the San Onofre Units 2 and 3 Steam Generators*, O'Donnell and Associates, March 28, 1985

4. K. M. Sweeney, *Unit 2 Cycle 7 Steam Generator Evaluation*, Arizona Public Service Report, December 30, 1996

5. K. M. Sweeney, *Unit 3 Cycle 6 Steam Generator Evaluation*, Arizona Public Service Report, June 26, 1996

6. D.E. Hart, W. J Heilker, *Leak Rate and Burst Tests of Steam Generator Tubes with a Simulated Wear Condition from Batwings*, Combustion Engineering Report CENC 1699, July 1985

7. Letter - J. Compas (ABB-CE) to W. Ide (APS), *ABB CENO Recommendations for Preventative Plugging on the Palo Verde Unit 3 Steam Generators to Address Potential Batwing Wear*, March 20, 1997

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

9. EPRI Report NP-3928, *Evaluation of Eddy-Current Procedure for Measuring Wear Scars in Preheat Steam Generators*, April 1985

10. EPRI Report NP-6341, *PWR Steam Generator Tube Fretting and Fatigue Wear*, April 1989