MAY 1992

THE B&W OWNERS GROUP

MATERIALS COMMITTEE

BAW-2127
SUPPLEMENT 2

PRESSURIZER SURGE LINE THERMAL STRATIFICATION FOR THE B&W 177-FA NUCLEAR PLANTS

SUMMARY REPORT

FATIGUE STRESS ANALYSIS
OF THE SURGE LINE ELBOWS

B&W NUCLEAR
SERVICE COMPANY

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FATIGUE STRESS ANALYSIS

OF THE SURGE LINE ELBOWS

Prepared for

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EXECUTIVE SUMMARY

Purpose:

The purpose of this supplement is to report on the re-evaluation of the pressurizer surge line elbows fatigue usage in order to close out the Nuclear Regulatory Commission Safety Evaluation Report (SER) open item on BAW-2127 (Reference 13).

Background:

On December 20, 1988, the Nuclear Regulatory Commission issued NRC Bulletin 88-11. The bulletin addressed technical concerns associated with thermal stratification in the pressurizer surge line and required utilities to establish and implement a program to ensure the structural integrity of the surge line. The B&W Owners Group has developed a comprehensive program to address the requirements of the bulletin. This program and its results were summarized in BAW-2127, Final Submittal for Nuclear Regulatory Commission Bulletin 88-11 "Pressurizer Surge Line Thermal Stratification", for the B&W-designed lowered loop plants. In September 1991, Supplement 1, Plant-Specific Analysis in Response to Nuclear Regulatory Commission Bulletin 88-11 "Pressurizer Surge Line Thermal Stratification" Davis-Besse Nuclear Power Station Unit 1, presented the results for the B&W-designed raised loop plant.

The Nuclear Regulatory Commission Safety Evaluation Report (Reference 13) on BAW-2127 found the methodology used to analyze and evaluate the stress and fatigue effects due to thermal stratification and thermal striping acceptable with one exception. The NRC staff and its consultant disagreed with the B&W interpretation of the secondary stress index (C_2) for elbows, thus, leaving the fatigue usage of the elbows as an open item to be resolved.

Summary:

A re-evaluation of the surge line elbows was performed using the Code table stress indices for elbows. The surge line was reevaluated to include shakedown, as described in NB-3228.4 of the ASME Code, and strain based fatigue of the surge line elbows.

Detailed finite element analyses were performed on the limiting portions (the elbows) of the surge line piping, as well as on the entire surge line to demonstrate shakedown. Shakedown was demonstrated to occur within 3 to 4 cycles and resulted in a maximum accumulated local strain of 1.07% compared to the 5.0% of ASME Code Cases N-47-28 and N-196-1.

The fatigue usage for all surge line elbows was demonstrated to be less than 0.6 over the 40 year design life of the B&W 177 fuel assembly plants. Thus, at all surge line locations the 40-year cumulative fatigue usage factor remains less than the Code allowable fatigue usage factor of 1.0.

Conclusion:

Having previously demonstrated the fatigue usage of the nozzles and piping to be acceptable, excluding the elbows, and having demonstrated the acceptability of the elbows in this supplement, the B&WOG response to NRC Bulletin 88-11 is complete.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

This document is a supplement to B&WOG Topical Report BAW-2127, Final Submittal for Nuclear Regulatory Commission Bulletin 88-11 "Pressurizer Surge Line Thermal Stratification" (Reference 1). The analyses described in this supplement confirm that all surge line elbows satisfy applicable ASME Code stress allowables for the operating B&W lowered and raised loop plants, considering the effects of thermal stratification and thermal striping.

This introduction briefly reiterates the background for the thermal stratification, striping and cycling issues, and provides a summary of the pressurizer surge line fatigue analysis results and conclusions contained within Reference 1 which address the technical issues described in NRC Bulletin 88-11 (Reference 2). The remaining sections of this supplement are as follows:

- Section 2 discusses the shakedown analysis performed, and provides a brief justification for the use of the ABAQUS finite element code,
- Section 3 discusses the fatigue analysis performed,
- Section 4 provides summary results of the shakedown and fatigue evaluation of the surge line elbows, as well as the conclusion regarding the integrity of the entire pressurizer surge line, and
- Section 5 lists all references.

1.1 Background

The surge line in B&W 177 fuel assembly (177-FA) plants is approximately 50 feet of piping which connects the pressurizer lower head and the reactor coolant hot leg piping. During plant operation, the reactor coolant system (RCS) is pressurized with a steam bubble in the pressurizer. Thus, the pressurizer contains saturated fluid while the remainder of the RCS is subcooled with temperatures cooler than the pressurizer fluid. During normal plant operation, this temperature difference is less than 50°F. However, during plant heatup and cooldown conditions, the temperature difference can be much higher. The surge line is the fluid flow path through which the pressurizer accommodates changes in RCS liquid volume. When the reactor coolant pumps are operating, there is normally a small outflow from the pressurizer due to continuous pressurizer spray flow through the spray bypass line. During plant heatup and cooldown conditions the surge line accommodates a significant number of fluid exchanges between the pressurizer and RCS.

Due to differences in density, the fluid temperature can vary in the horizontal surge line piping sections from top to bottom with the warmer fluid located above the more dense (cooler) fluid. This phenomenon, known as thermal stratification, is most pronounced during outsurges from the pressurizer. During an insurge or outsurge under stratified conditions, thermal striping may occur at the fluid layer interface. Thermal striping is a rapid oscillation of the thermal boundary interface caused by interfacial waves and turbulence effects. The original plant design fatigue analyses did not account for thermal stratification cycles in the pressurizer surge line, which causes additional bending moments in the piping, nor did the analyses account for thermal striping which affects the fatigue usage at the inner surface of the pipe.

To assure pressurizer surge line integrity for the 40-year design life of pressurized water reactors (PWRs), the Nuclear Regulatory Commission issued NRC Bulletin Number 88-11, Pressurizer Surge Line Thermal Stratification (December 20, 1988). This bulletin requires certain actions of licensees of all operating pressurized water reactors. The applicable actions are paraphrased below:

1a. At the first available cold shutdown after receipt of the bulletin, and which exceeds seven days, conduct a visual inspection of the pressurizer surge line.

1b. Within four months of receipt of the bulletin, licensees of plants in operation over ten years are requested to demonstrate that the pressurizer surge line meets the applicable design codes and other FSAR and regulatory commitments for the licensed life of the plant, considering thermal stratification and thermal striping in the fatigue and stress evaluations; or provide the staff with a justification for continued operation while a detailed analysis of the surge line is performed that implements items 1c and 1d below.

1c. If necessary, obtain plant specific surge line thermal and displacement data. Data can be obtained through collective efforts if sufficient similarities in geometry and operation can be demonstrated.

1d. Update the fatigue and stress analyses to ensure compliance with the applicable Code and Regulatory requirements within two years of receipt of the Bulletin or submit a justification for continued operation and a description of the proposed corrective actions for effecting long-term resolution.

A portion of the B&W Owners Group program was presented to the Nuclear Regulatory Commission Staff on September 29, 1988 and April 7, 1989. An interim evaluation, BAW-2085, dated May 1989, provided the staff with a justification for near term operation for all of the operating B&W 177-FA plants (Reference 3). The NRC concluded that sufficient information had been provided to justify near term operation for B&W plants until the final report could be completed (References 4 and 15).

The final report for the lowered loop plants was completed and submitted to the NRC in December 1990 (Reference 1). Supplement 1 to this report, describing the plant-specific analysis and providing a basis for a Justification for Continued

Operation (JCO) for the raised loop Davis-Besse Unit 1 plant, was submitted to the NRC in September 1991 (Reference 7). This report used the same methodology applied in Reference 1. Questions from the NRC, regarding these methods and the applied analysis, were answered by Reference 11.

The NRC SER, based on the lowered loop plant final report (Reference 1), contained an open item regarding the analytical technique used to demonstrate acceptable integrity of the surge line elbows. A similar open item was included in the NRC acceptance of the JCO for Davis-Besse Unit 1 (Reference 12). As a result, the B&WOG performed a shakedown analysis of the surge line and a strain based fatigue analysis of all surge line elbows. The preliminary results were presented to the NRC at a meeting with the B&W Owners Group Thermal Stratification Working Group on January 15, 1992. This second supplement to BAW-2127 summarizes the results from these analyses to demonstrate the integrity of the surge line elbows in order to resolve the NRC open item.

Only those B&W Owners Group program aspects directly contributing to the surge line shakedown and elbow fatigue are considered herein. All other program aspects and general methodologies, including the thermal loading conditions (thermal stratification peaks and valleys, thermal striping, fluid flow conditions), remain unchanged from the original BAW-2127 and BAW-2127 Supplement 1 (References 1 and 7). The Reference 11 response (Responses to Nuclear Regulatory Commission Questions), regarding earthquake combinations, remains unchanged as a result of this supplement.

1.2 Conclusion

The limits on thermal stress ratchet (NB-3222.5), progressive distortion (NB-3227.3), local membrane stress (NB-3221.2), primary plus secondary stress intensity (NB-3222.3) and expansion stress intensity (NB-3222.3) need not be satisfied at a specific location if a shakedown analysis satisfying the requirements of NB-3228.4 is performed. Such an analysis has shown that shakedown of the surge line is achieved within a few cycles and the maximum accumulated local strain is well below ASME Code Case allowables (References 9 and 10). The response to an ASME-Code Inquiry (Attachment A and Reference 14)

has confirmed that the thermal expansion stress criterion of NB-3222.3 does not need to be satisfied since shakedown has been demonstrated in accordance with NB-3228.4(b).

All operating lowered loop plants have been shown to have acceptable cumulative fatigue usage for the full 40 year licensed plant life. Similarly, the elbow fatigue usage factors for Davis-Besse Unit 1, the only operating raised loop plant, are within the allowable limit of 1.0 for the licensed 40 year plant lifetime based on the design transients defined in BAW-2127, Supplement 1 (Reference 7). In all cases, the structural analysis of the surge line has accounted for the thermal conditions (thermal stratification, thermal striping, and thermal cycling) which are expected to occur during the 40 year life of the plant.

Table 1-1 gives an overview of the highest Total Cumulative Usage Factors in the Surge Line of the seven B&W 177-FA nuclear plants. These factors are based on 240 heatup and cooldown cycles over the 40 year design life for all the plants except for the three Oconee Units which are based on 360 heatup/cooldown cycles over the 40 year design life.

The Nuclear Regulatory Commission has approved operation of Davis-Besse Unit 1 through the 9th operating cycle based upon a Justification for Continued Operation submitted in September, 1991 (Reference 12). An updated cumulative fatigue usage factor for Davis-Besse Unit 1, considering the modifications to be completed prior to restart from the 9th refueling outage, will be provided at a later date.

TABLE 1-1. Overview of the Highest Total Cumulative Usage Factors in the Surge Line of the Seven B&W 177-FA Nuclear Plants.

	<---------- As Previously Reported		------------->	<--- Revised -->
Nuclear Plants.	Pressurizer Surge Nozzle	Surge Line to Hot Leg Nozzle	Surge Line Non-Elbow Locations	Surge Line Elbows
Oconee Unit 1	0.40	0.59	0.48	0.49
Oconee Unit 2	0.41	0.59	0.48	0.50
TMI Unit 1	0.33	0.62	0.38	0.40
C.R. Unit 3	0.32	0.62	0.37	0.40
ANO Unit 1	0.32	0.62	0.38	0.40
Oconee Unit 3	0.41	0.59	0.47	0.48
Davis-Besse Unit 1	0.93 (Note 1)	0.76 (Note 1)	0.62 (Note 1)	0.59 (Note 2)

Notes relative to Davis-Besse Unit 1 surge line:

Note 1: All of these usage factors assumed certain modifications including the surge line support whip restraints and thermal insulation during the 7th refueling outage. Additional analyses have been performed to show that the cumulative usage factors up to the 9th refueling outage (without completion of modifications) are well within the allowable limit of 1.0.

Note 2: The usage factors for the elbows are for a 40 year plant life, and consider the committed modifications including the spring support and pipe whip restraints during the 9th refueling outage to assure unrestricted motion of the surge line.

General Davis-Besse Note:

The NRC Staff concluded (Reference 12) that continued operation of Davis-Besse Unit 1 is acceptable through the 9th refueling outage pending final resolution of the pressurizer surge line stratification items which should be completed by the end of the 8th refueling outage, if possible.

2. SHAKEDOWN ANALYSIS

2.1 Generalities

The shakedown analysis has been performed to satisfy the ASME Code (Reference 6) via use of NB-3228.4, which replaces the requirements of NB-3653.6(a) and/or NB-3222.3 Thermal Expansion Stress Intensity. The response to an ASME Code Inquiry (Reference 14) has confirmed that the thermal expansion stress criterion of NB-3222.3 does not need to be satisfied if shakedown can be demonstrated in accordance with NB-3228.4(b).

NB 3213.34 of the ASME Code, Reference 6, defines shakedown as follows:

> "Shakedown of a structure occurs if, after a few cycles of load application, ratcheting ceases. The subsequent structural response is elastic, or elastic-plastic, and progressive incremental inelastic deformation is absent. Elastic shakedown is the case in which the subsequent response is elastic."

2.2 Shakedown Options

Shakedown of the surge line has been demonstrated using two methods. The most sophisticated method is the elastic-plastic analysis of the entire surge line piping system. The second method utilized the Bree-Diagram for the surge line location which experiences the largest strain.

Since the Bree-Diagram only appears in the high-temperature Code Case N-47-28 (Reference 9), both the Bree-Diagram and the more sophisticated elastic-plastic analysis were used. In this elastic-plastic analysis, the surge line was analyzed as a system (surge line modeled from the pressurizer to the hot leg) with elastic-plastic properties for all elbows. This model was loaded with the

most severe cyclic loads until shakedown was reached. The elastic-plastic shakedown analysis is described in Sub-sections 2.3 through 2.6.

The Bree-Diagram method was also used for the most severe elbow and cyclic loads (see Sub-sections 2.4 and 2.5).

2.3 Verification of Shakedown by Elastic-Plastic Analysis

2.3.1 Input Stress-Strain Curves

Stress-strain curves (for austenitic stainless steel material) were developed for 150°F, 300°F, and 450°F and employed kinematic hardening for the "loading/unloading" behavior. These were the temperatures corresponding to the thermal conditions of the surge line for the most severe cyclic loads (Reference 1) to be applied in the elastic-plastic shakedown analysis. These stress-strain curves have been developed using the general equations:

stress $\sigma = E * \epsilon$ in the purely elastic domain, and

stress $\sigma = K * \epsilon^n$ in the elastic-plastic domain,

where ϵ is the total strain value,

and the exponent n is approximately equal to 0.3 for stainless steels.

These stress-strain curves are based on the following values from the ASME Code (Reference 6): the modulus of elasticity, E, the yield stress, Sy (at 0.2% offset), and the ultimate tensile stress, Su.

2.3.2 Input Loads

The most severe thermal stratification ranges for the shakedown analysis have been defined in the previous fatigue evaluation of the surge line based on the operating design transient information (Reference 1). These transients were developed to conservatively reflect past operation. The most severe stress loading range, as identified in BAW-2127 (Reference 1) fatigue evaluation, was between the highly stressed Peak, PV4 of HU1A1 heatup (top to bottom temperature difference of 393°F while the pressure is 578 psi.). and nominally stressed Valley, PV402 of CD1B1 cooldown (top to bottom temperature difference of 12°F while the pressure is 379 psi.). This severe hypothetical stress load range was specified for 13 design cycles. These 13 cycles envelope the number of

occurrences for all lowered loop plants. Therefore, the shakedown analysis applied this load cycle 13 times, using the following cyclic loading map:

PV No.4 / PV No.402 / PV No.4 / PV No.402 / PV No.4 / PV No.402, etc...

The concurrent thermal expansion, thermal stratification, internal pressure, and deadweight were simultaneously loaded on the surge line for each Peak or Valley condition. The model included the anchor motions resulting from the thermal expansion of the pressurizer and RCS hot leg.

2.3.3 Use of ABAQUS Finite Element Code

The ABAQUS finite element code was utilized in constructing a model of the surge line to perform the shakedown analysis. ABAQUS (Reference 8), developed by Hibbitt, Karlsson and Sorensen, Inc., is specifically designed for advanced structural analysis. These applications include nonlinear effects which dominate the overall program design. ABAQUS development started early in 1978. Electric Power Research Institute developmental funding has resulted in the implementation of capabilities that are generally useful in structural integrity evaluations of nuclear components.

Piping system design relies heavily on the use of elbows. This allows extra flexibility in the line to accommodate thermal loading. Therefore, the elbows themselves are the critical design components. It is essential to accurately predict their response in order to structurally qualify a pipeline. In the plastic regime, piping elbows achieve their flexibility through a shell-type behavior, responding to bending loads with significant ovalization of the pipe cross-section. In contrast, the straight pipe cross-section does not deform to any significant extent until Brazier buckling occurs.

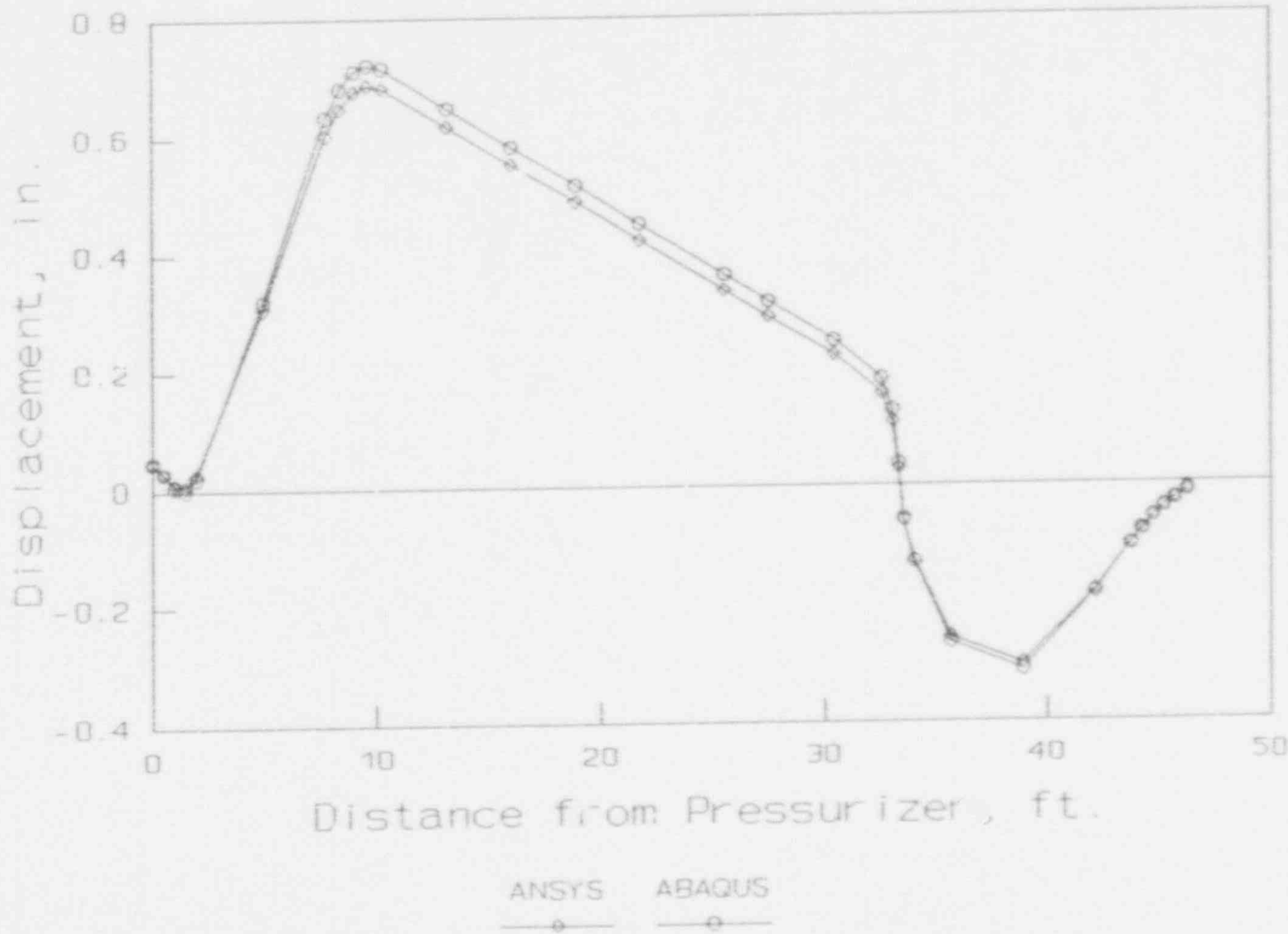
The elbow elements of ABAQUS are intended for piping applications wherein nonlinear effe[illegible] associated with ovalization and warping must be included. The elbow elements use a combination of polynomial interpolation along the axis of the pipe and Fourier interpolation around the circumference of the pipe. The elements contain nine integration points through the thickness and twenty-four

around the cross-section. The elbow elements of ABAQUS have been experimentally verified and lend themselves well to the shakedown analysis summarized in this document.

The ABAQUS shakedown model has been verified by comparison with the ANSYS mathematical model of the surge line (Reference 1), which was bench-marked to actual surge line displacements measured during the Oconee Unit 1, February, 1989 heat-up. To demonstrate that the ABAQUS model yielded comparable displacements, this verification was performed using two purely elastic computer analyses: the 100% power thermal expansion load case and the most severe thermal stratification condition, Peak PV4 of HU1A1 heat-up. For both load cases, the surge line displacements using ABAQUS agreed with the ones using ANSYS. Figures 2-1 through 2-3 show the results of the comparison between the displacements for the Peak PV4 load case.

FIGURE 2-1

PV# 4 X-Displacement



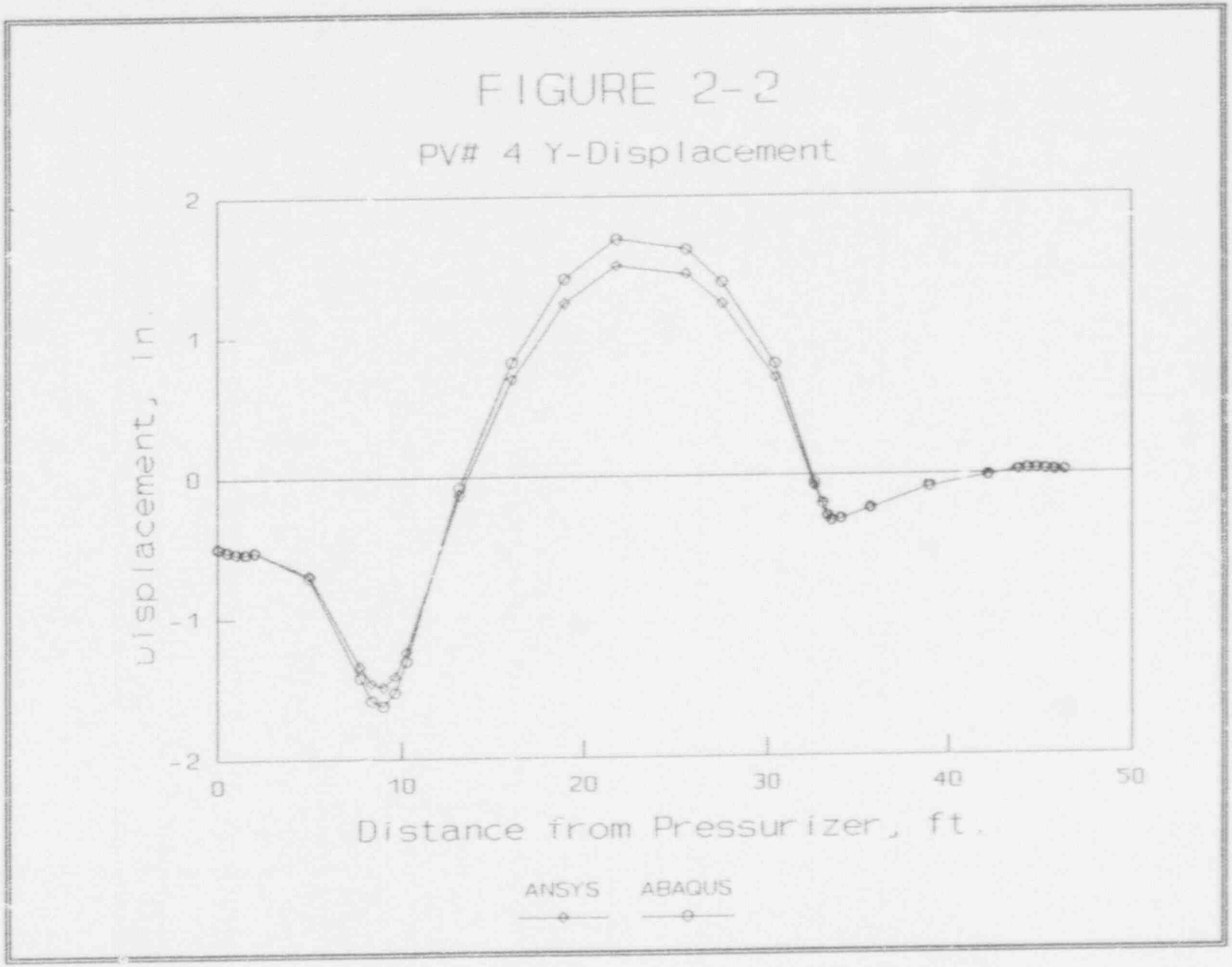
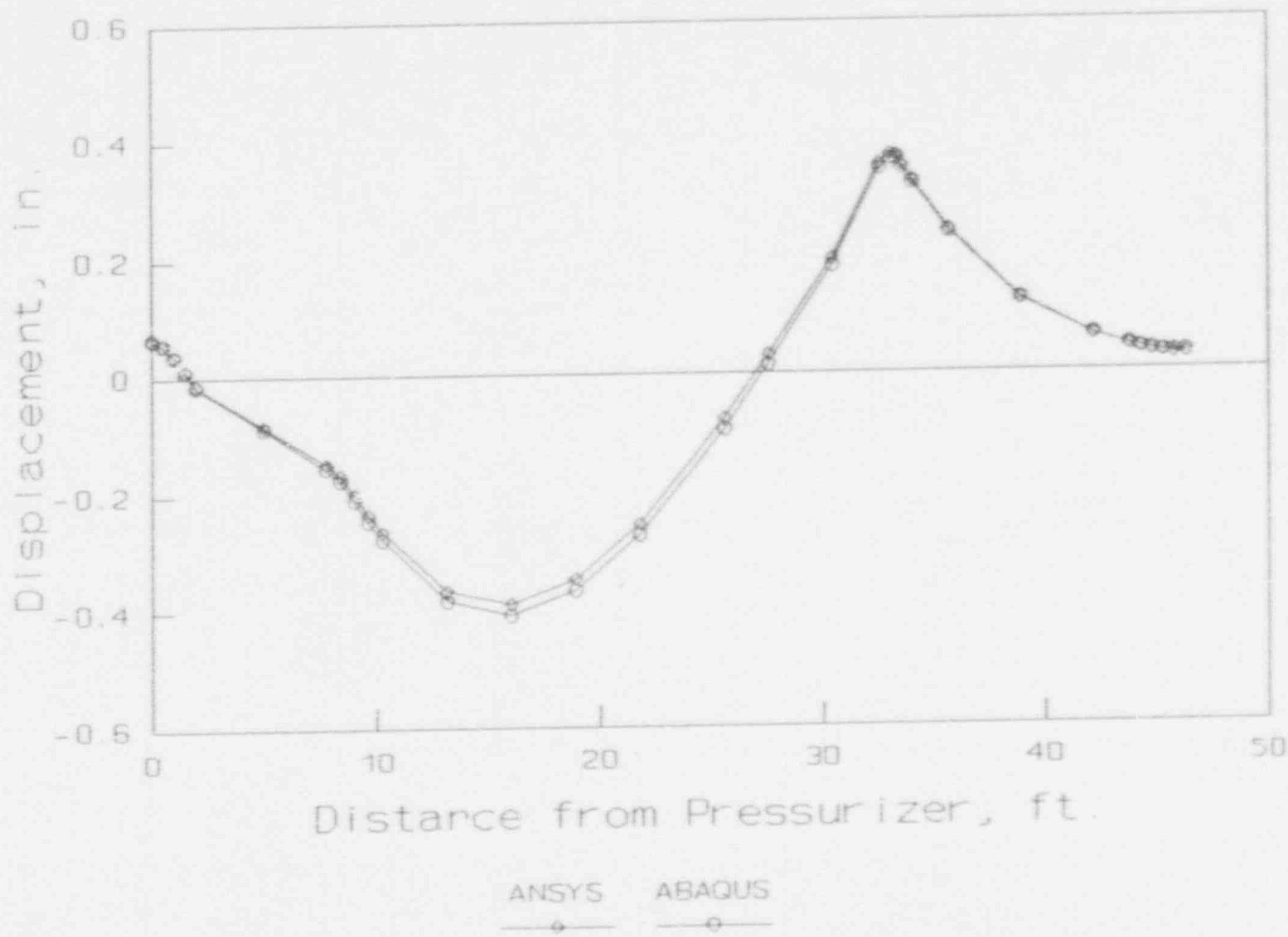


FIGURE 2-2
PV# 4 Y-Displacement
2
1
0
-1
-2
Displacement, in.
0
10
20
30
40
50
Distance from Pressurizer, ft.
ANSYS
ABAQUS

FIGURE 2-3

PV# 4 Z-Displacement



2.3.4 Shakedown Analysis Results

Shakedown has been demonstrated for the most severe ranges of thermal stratification conditions (Peaks and Valleys) based on the following results evaluated at the location of maximum plastic strain (within each elbow):

a.) Stress-strain Hysteresis and Stability Check

b.) Maximum Accumulated Local Strain developed through Shakedown

c.) Strain Range per complete cycle (used in Fatigue Analysis)

A.) Stress-strain Hysteresis Results

The stress-strain hysteresis was stable after 3 to 4 cycles of loading and unloading.

B.) Maximum Accumulated Local Strain Results

The maximum accumulated local strain was the maximum peak strain developed during the shakedown analysis. The resulting maximum accumulated local strain occurred at the peak stratification, PV4, and was 1.07% for the most critical elbow (Figure 3-1, Elbow B at the bottom of the riser).

Code cases N-47-28, approved July 27,1988, Appendix T (Reference 9), and N-196-1, approved January 21, 1982, Condition No. 2 (Reference 10) provide a maximum allowable accumulated local strain of 5.0%. These Code cases define the applicability of this maximum allowable accumulated local strain to any plastically analyzed location at which the calculated local strain is the result of cyclic operations. The maximum accumulated local strain anywhere in the shakedown model of the surge line was 1.07% (1.07% << 5.0%). Therefore, the maximum accumulated local strain from the shakedown analysis is acceptable.

C.) Strain Range Per Complete Cycle Results

Shakedown occurred within three to four load cycles. After shakedown, the resulting strain range at the most critical elbow (Elbow B at the bottom of the riser) was 0.759%.

2.4 Verification of Shakedown by Use of the Bree Diagram (lowered-loop plants)

Shakedown has been demonstrated for the most severe cyclic loads which lead to distortion. The most severe cyclic loads have been defined in the previous fatigue evaluation of the surge line (Reference 1). In the most severe heat-up to be analyzed (associated with early plant life operation), the primary stress effects due to internal pressure become significant only at the end of this heat-up. At that time, the most severe thermal stratification peak stresses (which occur at the beginning of the heat-up) have been established and have shaken down. A Bree Diagram has been built for the surge line location undergoing the largest strain. On this Bree Diagram, the most severe thermal stratification cyclic loads (analyzed in the elastic-plastic shakedown analysis) have been shown to be the controlling conditions for shakedown when compared to other conditions during the same heatup transient. Also, on the same Bree Diagram, all of the stress points corresponding to the thermal stratification Peaks have been shown to be acceptable. This again demonstrates that shakedown has occurred in the surge line.

2.5 Verification of Shakedown for Davis-Besse Unit 1 Surge Line

A separate analysis to demonstrate shakedown of the Davis-Besse (raised loop plant) pressurizer surge line was not performed. The following is justification that the shakedown analysis results for the lowered loop plants provides bounding results for the Davis-Besse raised loop plant.

The lowered and raised loop surge lines have the same pipe size (10 inch, schedule 140) and the same material, with similar length and flexibility. Based on BAW-2127 and BAW-2127 Supplement No. 1 (References 1 and 7), the most severe thermal bending stress range (equation 12) for the Davis-Besse surge line was less than that of the lowered loop plants. The ratio of elbow in-plane to out-of-plane moment was also lower for Davis-Besse. Therefore, the plastic strain results in the Davis-Besse surge line elbows would be lower than the results from the analyzed lowered loop plant. This has been illustrated on a Bree diagram, where the corresponding thermal stratification peaks for the most severe Davis-Besse surge line heatup transient were lower than those analyzed in the elastic-plastic shakedown analysis of the lowered loop plant surge lines. Thus, the

lowered loop plants provide a conservative demonstration of the shakedown for the Davis-Besse surge line.

3. FATIGUE ANALYSIS

3.1 Generalities

The total cumulative fatigue usage calculated in References 1 and 7 consisted of the sum of:

1) Main Fatigue Usage (Shakedown and Post-Shakedown Fatigue)

and

2) Additional Fatigue Usage (Items 3, 4, and 5 of Sub-section 3.2).

Only the main fatigue usage for cycles with Equation 10 Stress Range Intensity greater than the Code 3*Sm limit was recalculated for this analysis. All other fatigue usage values remained unchanged from References 1 and 7. For Equation 10 Stress Ranges exceeding 3*Sm, fatigue was recalculated using the cyclic strain range as a function of the moment and pressure terms along with a strain based penalty factor applied to the additional peak stresses of that cycle.

3.2 Factors Contributing to Fatigue

The total cumulative usage factor is equal to the sum of the following fatigue contributions:

1.) Shakedown Fatigue (see Sub-section 3.3).

2.) Post-Shakedown Fatigue (see Sub-section 3.4) of:

   a.) Stratified Ranges Failing Equation 10, thus Recalculated

   b.) Stratified Ranges Passing Equation 10, thus No Recalculation

   c.) Non-Stratified Ranges Passing Equation 10, thus No Recalculation

3.) Fatigue Usage for the non-stratified High Velocity Fluid Flow conditions.

4.) Thermal Striping Fatigue by itself.

5.) Fatigue Usage for the remaining Operating Basis Earthquake Ranges.

Only those contributions designated by Items 1. and 2a. (listed above) were recalculated. All other fatigue contributions meet Code Equation 10 and correspond to the original BAW-2127 and BAW-2127 Supplement 1 (Reference 1 and Reference 7).

3.3 Shakedown Fatigue

For the most severe thermal stratification ranges (PV No.4 - PV No.402) analyzed in the ABAQUS shakedown analysis, the total elastic-plastic strain range occurring between the maximum Peak (PV4) and the minimum Valley (PV402) was retained. The purely elastic strain range for the thermal stratification cycle PV4-PV402 was also calculated in an elastic structural analysis of the surge line mathematical model, and the corresponding Kpp penalty factor (elastic-plastic strain divided by the purely elastic strain) was calculated. Using the total elastic-plastic strain range (for PV4-PV402) and the corresponding Kpp penalty factor, the alternating stress, S_{alt}, was calculated using the equation below.

$$S_{alt} = \frac{1}{2} * \left(E_{70F} * strain\ range + \frac{E_{70F}}{E_{average}} * K_{pp} * additional\ peak\ stress \right)$$

where Kpp was the plastic penalty factor, and the additional peak stress was the combination of the peak stresses due to fluid flow (through-wall thermal gradients), thermal striping, and the non-linearity of the temperature profile (combination as performed in Reference 1).

The shakedown fatigue from the resulting alternating stress was performed to retain consistency between the shakedown analysis and the fatigue analysis, even though the ASME Code only requires the post-shakedown strain ranges to be considered [NB-3228.4(c)]. The shakedown fatigue was also included in response to NRC comments during the January 15, 1992 meeting with the B&W Owners Group Thermal Stratification Working Group.

3.4 Post-Shakedown Fatigue

In the Post-Shakedown Fatigue, the calculation of the alternating stress S_{alt} results from the same formula given in Sub-section 3.3:

$$S_{alt} = \frac{1}{2} * \left(E_{70F} * strain\ range + \frac{E_{70F}}{E_{average}} * K_{pp} * additional\ peak\ stress \right)$$

The values for the strain range and the plastic penalty factor, Kpp (elastic-plastic strain divided by the purely elastic strain), were calculated through a detailed finite element ABAQUS elbow model. The additional peak stress was the combination of the peak stresses due to fluid flow (through-wall thermal gradients), thermal striping, and the non-linearity of the temperature profile (combination as performed in Reference 1).

For the thermal stratification ranges which meet Equation 10 Stress Range Intensity of the ASME-Code (within the 3*Sm allowable), the alternating stress values and the usage factors are calculated using the simplified equations of the ASME-Code.

3.5 Input Stress-Strain Curve for Post-Shakedown Fatigue.

For each thermal stratification cycle, the temperature of interest is the mean value of the temperature during the cycle [see NB-3222.5 and NB-3228.4(c)]. This mean value has been found to be 300°F or less, depending on the location of the elbow analyzed. Therefore, the applicable stress-strain curve will be taken at 300°F in the finite element elastic-plastic analysis of the surge line elbow.

The input stress-strain data for the finite element elastic-plastic analysis of the elbow (Post-shakedown) are defined as follows: linear purely elastic regime up to 1.5 * Sm (modulus of elasticity E from the ASME Code), and linear stress-strain relationship in the elastic-plastic regime intersecting the nonstrain-hardened stress-strain curves at the 1.0 % total strain location. This second

slope is conservatively low in that no strain-hardening is included for the stress at 1.0 % total strain.

Note that in the fatigue analysis, the moment ranges applied after shakedown on each one of the surge line elbows were calculated "purely elastically" in the structural analysis of the surge line. Reduction of the moments due to plasticity in the elbows is not taken into account.

3.6 Strain Correlations for Post-Shakedown Fatigue

The ABAQUS surge line elbow finite-element model has been loaded by combinations of bending moments and internal pressure values (the internal pressure values considered are 0 psi., 600 psi., 1500 psi. and 2250 psi.).

From the different load cases, the highest strain value anywhere in the elbow was employed. An analysis has been performed to compare (for the same internal pressure values) the highest strain range due to a combined "in-plane opening moment / in-plane closing moment" load case with the highest strain range due to "out-of-plane moment" in the elbow mid-section. From this analysis it has been found that the "out-of-plane moment" load case leads to a lower value for the highest strain range in the elbow. Therefore, using the "in-plane opening moment / in-plane closing moment" load case, correlation tables were built for the calculation of the highest strain range anywhere in the elbow as a function of the elastically calculated moment range and of the internal pressure in the elbow. Similarly, correlation tables were built for the plastic penalty factor Kpp to be applied on the additional peak stresses.

For each thermal stratification cycle, the strain range and the plastic penalty factor, Kpp, are calculated through a conservative linear interpolation between values in the correlation tables mentioned above. Knowing this strain range and the corresponding Kpp value, the alternating stress is calculated using the formula given earlier in Sub-section 3.4.

3.7 Elbow Fatigue Analysis Results

For the surge line elbows of the lowered loop plants, the highest 40-year total cumulative usage factor occurred in elbow B of Figure 3-1 (vertical elbow at the bottom of the surge line riser). It was equal to 0.50 for Oconee Unit 2, 0.49 for Oconee Unit 1, 0.48 for Oconee Unit 3, and 0.40 for TMI Unit 1, Crystal River Unit 3 and Arkansas Nuclear One Unit 1.

For the surge line elbows of Davis-Besse Unit 1, the shakedown fatigue was based on the maximum strain range calculated in the surge line elbows of the lowered loop plants. The strain range of the most highly stressed elbow in the lowered loop plants was conservatively applied to each elbow of the Davis-Besse Unit 1 plant. The remaining fatigue (post-shakedown) for Davis-Besse utilized Davis-Besse loads and the elastic-plastic finite element elbow results. This resulted in a maximum total cumulative usage factor of 0.59. The maximum total cumulative usage factor for Davis-Besse Unit 1 occurred in the vertical elbow at the bottom of the pressurizer, elbow A.

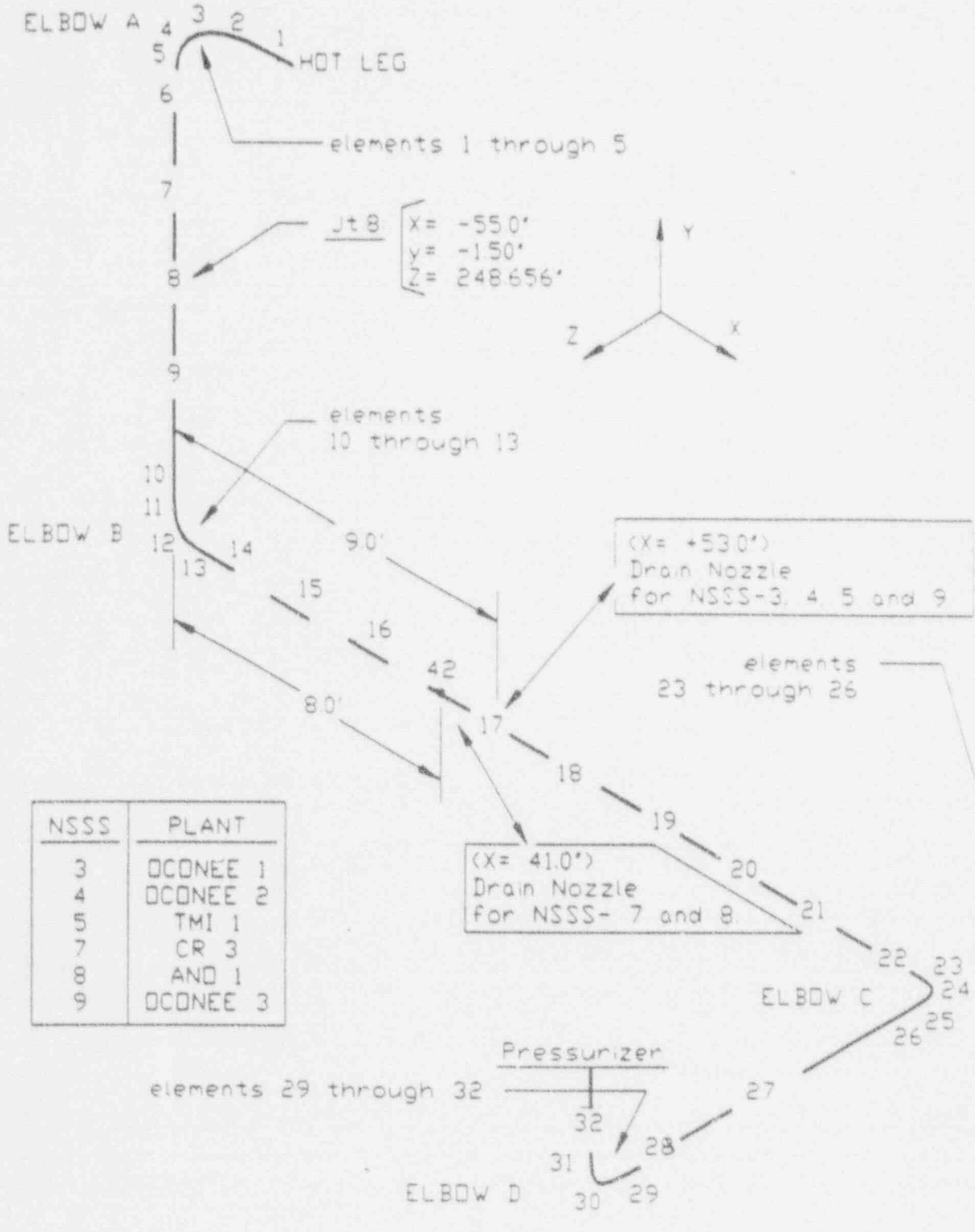
Table 3-1 on the following page gives the resulting Total Cumulative Usage Factors for all elbows (see Figure 3-1 and Figure 3-2) and highlights the maximum values for each plant.

Elbow Fatigue Analysis:

TABLE 3-1. TOTAL CUMULATIVE USAGE FACTORS FOR THE SURGE LINE ELBOWS

Elbows ===>	Elbow A	Elbow B	Elbow C	Elbow D	Elbow E
Oconee Unit 1 (4 elbows)	0.13	0.49	0.34	0.38	does not apply.
Oconee Unit 2 (4 elbows)	0.13	0.50	0.35	0.39	does not apply.
TMI Unit 1 (4 elbows)	0.10	0.40	0.29	0.33	does not apply.
Cr. River Unit 3 (4 elbows)	0.10	0.40	0.29	0.33	does not apply.
ANO Unit 1 (4 elbows)	0.10	0.40	0.29	0.33	does not apply.
Oconee Unit 3 (4 elbows)	0.13	0.48	0.33	0.38	does not apply.
Davis-Besse Unit 1 (5 elbows)	0.59	0.57	0.44	0.15	0.30

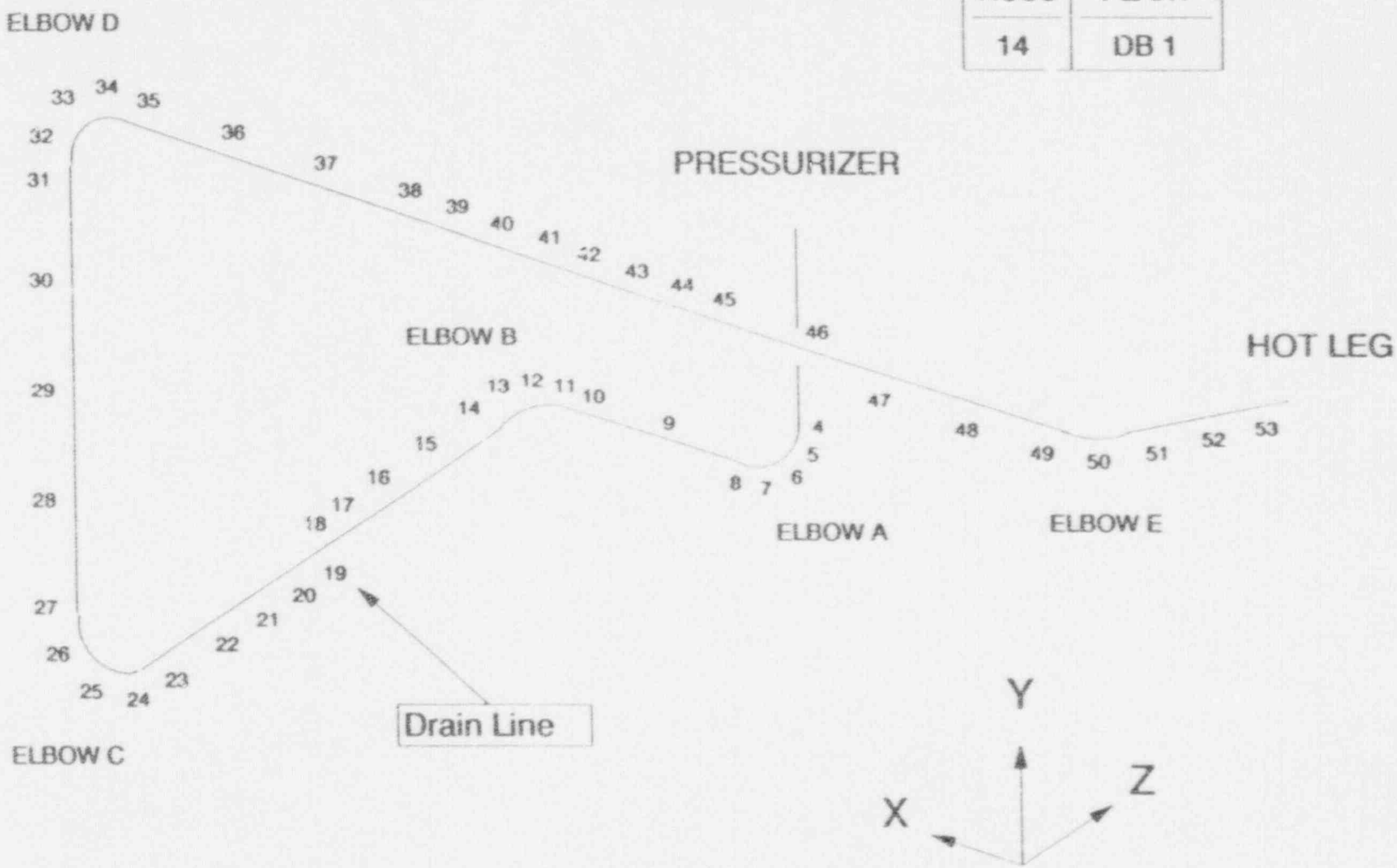
Figure 3-1 Surge Line Mathematical Model



NSSS	PLANT
3	OCONEE 1
4	OCONEE 2
5	TMI 1
7	CR 3
8	ANO 1
9	OCONEE 3

Figure 3-2 Surge Line Mathematical Model

NSSS	PLANT
14	DB 1



4. SUMMARY OF RESULTS

Surge Line Shakedown Analysis:

Surge line shakedown occurred within the first three to four thermal stratification cycles. The maximum peak strain anywhere in the elbow, and at any time during the shakedown, occurred in elbow B for the lowered loop plants (vertical elbow at the bottom of the surge line riser). It was equal to 1.07%, to be compared with the maximum allowable peak strain of 5.0%. Therefore, the shakedown analysis has satisfied the Primary Plus Secondary and the Thermal Expansion Stress Intensity requirements of the ASME Code (References 6 and 14).

Fatigue Usage:

The fatigue usage for all surge line elbows was demonstrated to be less than 0.6 over the 40 year design life of the B&W 177 fuel assembly plants. Thus, the cumulative fatigue usage factor remains less than the Code allowable fatigue usage factor of 1.0 at all surge line locations. The results from the elbow fatigue analysis are presented on the following page, Table 4-1.

Conclusion:

Having previously demonstrated the fatigue usage of the nozzles and piping to be acceptable, excluding the elbows, and having demonstrated the acceptability of the elbows in this supplement, the B&WOG response to NRC Bulletin 88-11 has been completed. The highest Total Cumulative Usage Factors for all surge line locations are given in Table 1-1 of Section 1.

TABLE 4-1. TOTAL CUMULATIVE USAGE FACTORS FOR THE SURGE LINE ELBOWS					
Elbows ===>	Elbow A	Elbow B	Elbow C	Elbow D	Elbow E
Oconee Unit 1 (4 elbows)	0.13	0.49	0.34	0.38	does not apply.
Oconee Unit 2 (4 elbows)	0.13	0.50	0.35	0.39	does not apply.
TMI Unit 1 (4 elbows)	0.10	0.40	0.29	0.33	does not apply.
Cr. River Unit 3 (4 elbows)	0.10	0.40	0.29	0.33	does not apply.
ANO Unit 1 (4 elbows)	0.10	0.40	0.29	0.33	does not apply.
Oconee Unit 3 (4 elbows)	0.13	0.48	0.33	0.38	does not apply.
Davis-Besse Unit 1 (5 elbows)	0.59	0.57	0.44	0.15	0.30

The elbows are shown on Figure 3-1 and Figure 3-2.

5. References

1. BAW-2127, Final Submittal for Nuclear Regulatory Commission Bulletin 88-11 "Pressurizer Surge Line Thermal Stratification", December 1990.

2. NRC Bulletin 88-11, "Pressurizer Surge Line Thermal Stratification", December 20, 1988.

3. BAW-2085, Submittal in Response to NRC Bulletin 88-11, "Pressurizer Surge Line Thermal Stratification", May 1989.

4. NRC Letter dated May 18, 1990, J.T. Larkins to M.A. Haghi, "Evaluation of Babcock and Wilcox Owners Group Bounding Analysis Regarding NRC Bulletin 88-11".

5. "ANSYS" Computer Code, Versions 4.1c and 4.3. Engineering Analysis System, User's Manual Volumes I and II, Swanson Analysis Systems, Inc.

6. "ASME Boiler and Pressure Vessel Code", Section III, 1986 Edition with no Addenda.

7. BAW-2127, Supplement 1, Plant-Specific Analysis in Response to Nuclear Regulatory Commission Bulletin 88-11 "Pressurizer Surge Line Thermal Stratification" Davis-Besse Nuclear Power Station Unit 1, September 1991, B&W Owners Group letter number OG-970.

8. "ABAQUS" Computer Code, Version 4.8.5, Hibbitt, Karlsson & Sorensen Inc., Pawtucket, RI, User's Manual Volume I, 1989.

9. ASME Code Case N-47-28, "Class 1 Components in Elevated Temperature Service", approved July 27, 1988, Appendix T, Paragraph T-1310, "Limits for Inelastic Strains".

10. ASME Code Case N-196-1, "Exemption from the Shakedown Requirements When Plastic Analysis is Performed", approved January 21, 1982, Condition Number 2.

11. Responses to Nuclear Regulatory Commission Questions on B&W Owners Group Report BAW-2127, Final Submittal for Nuclear Regulatory Commission Bulletin 88-11 "Pressurizer Surge Line Thermal Stratification", October 1991, B&W Owners Group letter number OG-961.

12. NRC Letter dated November 6, 1991, Jon B. Hopkins, Sr., to Donald C. Shelton, Docket No. 50-346, Subject: "Pressurizer Surge Line Thermal Stratification, NRC Bulletin 88-11 (TAC NO. 72128)".

13. NRC Letter dated July 24, 1991, Joseph W. Shea to James A. Taylor, Subject: "NRC Bulletin 88-11, Pressurizer Surge Line Thermal Stratification, Safety Evaluation Report".

14. Response to a Code Inquiry relative to Section III, Division 1, NB-3228.4, File NI92-6, March 26, 1992. This Code Inquiry and Response is provided herein as Attachment A.

15. NRC Letter dated August 7, 1990, M. D. Lynch, Sr. to D. C. Shelton, Toledo Edison Company, "NRC Bulletin 88-11, Pressurizer Surge Line Thermal Stratification - Evaluation of Babcock and Wilcox Owners Group Bounding Analysis" (TAC No. M72128).

6. DOCUMENT SIGNATURES

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ATTACHMENT A

Section III, Division 1,

NB-3228.4 Code Inquiry and Response

DONALD F. LANDERS, President

TELEDYNE ENGINEERING SERVICES
130 SECOND AVENUE
WALTHAM, MASSACHUSETTS 02254-9195
(617) 890-3350 TWX (710) 324-7500

December 30, 1991
7569-2

Secretary
ASME Boiler and Pressure Vessel Committee
345 East 47th Street
New York, NY 10017

Subject: Technical Inquiry - ASME BPVC Section III

Gentlemen:

The writer respectfully requests that the attached Technical Inquiry be considered by Section III.

Very truly yours,

Donald F. Landers

DFL/tmo

Attachment

SCOPE

Additional guidance is requested regarding paragraph NB-3228.4, Shakedown Analysis (19 Edition with Addendum).

BACKGROUND

The structural integrity of a pressurizer surge line undergoing thermal loading (including expansion bending moments and forces) as a result of flow stratification has been demonstrated by performing a Shakedown Analysis in accordance with NB-3228.4 conservatively using kinematic hardening. Shakedown occurred in a few cycles and a cumulative usage factor of < 1.0 over the design life was calculated. The deformations prior to shakedown are well within specified limits. Subparagraph (b) of NB-3228.4 recognizes that the following limits have been satisfied by the Shakedown Analysis:

NB-3221.2 - Local Membrane Stress Intensity
NB-3222.2 - Primary Plus Secondary Stress Intensity
NB-3222.5 - Thermal Stress Ratchet
NB-3227.3 - Progressive Distortion of Nonintegral Connections

However, satisfaction of NB-3222.3 Expansion Stress Intensity is not specifically exempted even though in satisfying NB-3222.2 for piping, loadings categorized as expansion must be included.

INQUIRY

In demonstrating Shakedown in accordance with NB-3228.4(b) are the expansion stress criterion of NB-3222.3 satisfied?

RESPONSES

Yes, as long as the range of strain calculated on a plastic [illegible]sis includes the effect of all cyclic loads which lead to distortion.

Codes and Standards

The American Society of Mechanical Engineers
345 East 47th Street
New York, NY 10017

March 26, 1992

Donald F. Landers
President
Teledyne Engineering Services
130 Second Ave.
Waltham, MA 02254

Subject: Section III, Division 1, NB-3228.4
File #: NI92-6
Reference: Your letter dated December 30, 1991

Dear Mr. Landers:

Our understanding of the questions in your inquiry, and our reply, is as follows:

Question: In demonstrating shakedown in accordance with NB-3228.4(b), does the expansion stress criterion of NB-3222.3 need to be satisfied?

Reply: No.

Very truly yours,

Christian Sanna
Assistant Secretary, Boiler & Pressure Vessel Committee
(212) 605-4705