UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

ENCLOSURE 1

SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

RESPONSE TO BULLETIN 88-11

(PRESSURIZER SURGE LINE THERMAL STRATIFICATION)

BABCOCK & WILCOX OWNERS GROUP

1.0 INTRODUCTION

By reports BAW-2127, "Final Submittal for Nuclear Regulatory Commission Bulletin 88-11, 'Pressurizer Surge Line Thermal Stratification,'" and 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," the Babcock & Wilcox Owners Group (BWOG) demonstrated the integrity of the pressurized surge line (PSL) in view of the occurrence of thermal stratification during 40-year service life as described in NRC Bulletin 88-11. The reports responded generically to the NRC concern for the following six lowered loop plants:

50-313	Arkansas Nuclear One, Unit 1
50-302	Crystal River, Unit 3
50-269/270/287	Oconee, Units 1, 2, and 3
50-289	Three Mile Island, Unit 1

2.0 EVALUATION

NRC Bulletin 88-11 required all licensees for PWR Operating Plants to take the following actions to demonstrate that the integrity of PSLs is maintained for the 40-year design life of these piping systems.

1.a Perform a visual inspection walkdown (ASME Section XI, VT-3) at the first available cold shutdown which exceeds 7 days.

1.b Perform a plant-specific or generic-bounding analysis to demonstrate that the surge line meets applicable design codes and other Final Safety Analysis Report (FSAR) and regulatory commitments for the design life of the plant. The analysis is requested within 4 months for plants in operation over 10 years and within 1 year for plants in operation less than 10 years. If the analysis does not demonstrate compliance with these requirements, submit a justification for continued operation (JCO) and implement actions 1.c and 1.d below.

1.c Obtain data on thermal stratification, thermal striping, and line deflections either by plant-specific monitoring or through collective efforts among plants with a similar surge line design. If through collective efforts, demonstrate similarity in geometry and operation.

1.d Perform detailed stress and fatigue analyses of the surge line to ensure compliance with applicable code requirements incorporating any observations from 1.a. The analysis should be based on the applicable plant-specific or referenced data and should be completed within 2 years. If the detailed analysis is unable to show compliance, submit a Justification for Continued Operation (JCO) and description of corrective actions for effecting long-term resolution.

Although not required by the Bulletin, licensees were encouraged to work collectively to address the technical concerns associated with this issue, as well as to share the PSL data and operational experience. The BWOG implemented a series of programs to address the issue of surge line stratification in B&W plants.

In a July 24, 1991, letter (J. Shea, NRC, to J. Taylor, B&W), the staff provided its safety evaluation of BAW-2127 and concluded that the BWOG methodology used to analyze and evaluate the stress and fatigue effects due to thermal stratification and thermal striping was generally acceptable, with the exception of how secondary and peak stresses in the surge line elbows were calculated. In order to resolve this issue, BWOG reevaluated the surge line elbows using elastic-plastic analysis methods and criteria given in ASME Code, Section III, Subsection NB-3228.4 as documented in B&W report BAW-2127, Supplement 2.

The B&W reevaluation was based on the alternate ASME Code criteria of Section III, Subsection NB-3228.4, "Shakedown Analysis," which allows certain stress limits to be exceeded at a specific location provided a plastic analysis demonstrates that shakedown occurs and that the deformations which occur prior to shakedown do not exceed specified limits. Using an ABAQUS finite element model of the surge line piping which was identical to the original ANSYS model, except for the use of elastic-plastic pipe elbow elements, in conjunction with bounding load histories, the B&W analysis showed all of the stress points corresponding to the stratification peaks to be acceptable. In addition, the shakedown analysis showed that the maximum accumulated local strain that occurred due to the application of the bounding load cycles was 1.07%.

However, NB-3228.4 did not provide relief from the thermal expansion stress limit of $3S_m$ given in NB-3653.6 (Equation 12) and NB-3222.3, and B&W was not able to demonstrate that the limit could be met. Because it appeared that demonstrating shakedown would satisfy the intent of this stress limit, an ASME Code inquiry to confirm this interpretation was submitted. The ASME Code Committee response confirmed that the expansion stress criterion of NB-3222.3 need not be satisfied if shakedown is demonstrated in accordance with NB-3228.4(b).

3.0 CONCLUSION

BNL has reviewed the BWOG reports BAW-2127, "Final Submittal for Nuclear Regulatory Commission Bulletin 88-11, 'Pressurizer Surge Line Thermal Stratification,'" and 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," as documented in the attached Technical Evaluation Report (TER) A-3869(66). The staff has reviewed the TER and concurs with BNL that the methodology used to analyze the effects of thermal stratification and striping in the PSL is acceptable, and concludes that the B&W analyses adequately demonstrates the structural integrity of the lowered loop plant surge lines for the 40-year design life of the plant, while considering the effects of thermal stratification. Accordingly, we conclude that the results of the BWOG analysis may be used as the basis for BWOG licensees to update their plant-specific Code stress reports to demonstrate compliance with applicable Code requirements as requested in Bulletin 88-11.

However, due to the fact that an elastic-plastic analysis was necessary in performing the PSL evaluation, the staff concurs with BNL's recommendation that enhanced inservice inspections of the surge line be performed to provide additional confidence in structural integrity. The staff recommends that licensees perform volumetric examination of critical elbow components as part of future ASME Section XI inservice examinations. Examinations of elbow bodies, as well as elbow welds, should be performed to ensure that the most highly-stressed areas have not sustained damage.

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Attachment: Technical Evaluation Report

TECHNICAL EVALUATION REPORT

EVALUATION OF THE BABCOCK AND WILCOX OWNERS GROUP PRESSURIZER SURGE LINE THERMAL STRATIFICATION PROGRAM TO ADDRESS NRC BULLETIN 88-11

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EXECUTIVE SUMMARY

This report presents a summary of the Brookhaven National Laboratory (BNL) technical review and evaluation of the Babcock and Wilcox Owners Group (B&WOG) program to reevaluate the integrity of the pressurizer surge line considering the effects of thermal stratification. NRC Bulletin 88-11 identified the potential for thermal stratification in surge lines and requested all PWR licensees to establish and implement a program to verify the structural integrity of these lines. The NRC Bulletin requested a number of specific actions including conducting visual inspections of the surge lines and supports for indications of structural damage or distress, performing bounding analyses to justify continued operation, establishing monitoring programs to obtain plant specific data on stratification, and updating stress and fatigue analyses to ensure compliance with applicable ASME Code requirements. Licensees were encouraged to work collectively to address the technical concerns associated with this issue.

In response to the Bulletin, the B&WOG established a program to address the concerns for all B&W plants. Based on similarities in plant design and operation, B&WOG demonstrated that a generic evaluation could be performed for the following six B&W lowered loop plants:

Arkansas Nuclear One Unit 1
Crystal River Unit 3
Oconee Units 1, 2, 3
Three Mile Island Unit 1

Davis-Besse Unit 1, the only B&W raised loop plant required a plant-specific evaluation. The B&WOG program consisted of several tasks including the collection and reduction of temperature and displacement data from a representative lowered loop plant, the assessment of operating practices and procedures, the collection and review of historical plant data, the development of revised design basis thermal transients with consideration to thermal stratification and striping, and the structural and fatigue analysis and evaluation of the surge line piping and nozzles. The visual inspections of the surge lines required by Bulletin 88-11 were performed by each licensee.

The methodology and results of the B&WOG program were published in B&W report BAW-2127 dated December 1990. The report concluded that all ASME Code stress and fatigue limits were met for the lowered loop plant surge lines for the remainder of their forty year design lives. BNL reviewed the report and raised several questions and concerns. BNL then participated in an NRC staff audit in February 1991 to discuss the concerns and review the program in depth. The BNL findings were incorporated in an NRC Safety Evaluation Report (SER) issued in July 1991. The reevaluation methodology was found to be acceptable with one exception. BNL disagreed with the B&W interpretation of stress indices used to calculate stresses in elbows. This left the Code qualification of the elbows as an open item.

B&WOG subsequently proposed another approach to qualify the elbows. BNL participated in followup NRC staff meetings to discuss the proposed alternate analysis methods. The issue was resolved when B&WOG performed an elastic-plastic analysis which demonstrated that the surge line elbows meet the alternate requirements of ASME Code Section III Subsection NB-3228.4. The surge line was shown to shake down after a few cycles of severe thermal stratification loads with an acceptable amount of accumulated local strain and a maximum elbow cumulative fatigue usage factor of less than 1.0. The revised methodology and results were documented in B&W report BAW-2127 Supplement 2. Based on the additional information presented in the final report, BNL concluded that the B&WOG program adequately demonstrated that the lowered loop plant surge lines and nozzles will meet ASME Code stress and fatigue requirements for their forty year design lives with consideration of the thermal stratification and thermal striping phenomena. To provide additional confidence, BNL also recommended that licensees perform volumetric inspections of critical surge line elbows as part of future ASME Code Section XI in-service inspections.

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1.0 INTRODUCTION

This technical evaluation report (TER) presents a summary of the Brookhaven National Laboratory (BNL) evaluation of the Babcock and Wilcox Owners Group (B&WOG) program to confirm the integrity of the pressurizer surge line in view of the occurrence of thermal stratification as described in NRC Bulletin 88-11 (Ref. 1).

The existence of the thermal stratification phenomenon in pressurizer surge lines in U.S. plants was first identified at the Trojan plant when unexpected pipe movements were observed. Licensee investigations determined that the movements were caused by thermal stratification in the line. The stratification was found to be most severe during heatup and cooldown when large temperature differences existed between the pressurizer and the hot leg. As hot water flowed over a layer of cooler water, the upper part of the pipe was heated to a higher temperature than the lower part. The differential thermal expansion of the pipe metal resulted in significant pipe deflections. This phenomenon was not considered in the original piping design. The NRC staff's concern was that the additional bending moments and loads introduced by this condition may invalidate the analyses supporting the integrity of the surge line.

NRC Bulletin 88-11 requested all PWR licensees to take a series of actions to verify the integrity of their surge lines. These actions included conducting visual inspections for indications of structural damage or distress, performing bounding analyses to justify continued operation, establishing monitoring programs to obtain plant specific data on stratification, and updating stress and fatigue analyses to ensure compliance with applicable Code requirements. Subsequent to the issuance of the bulletin, the B&W Owners Group developed a program to address the requirements of the bulletin for B&W plants. The results of the program were published in B&WOG report BAW-2127 in December 1990 (Ref. 2). The NRC staff and BNL performed a preliminary review of the report and prepared a request for additional information (RAI) needed to complete the review. Meetings with B&W were subsequently held to discuss the RAI responses and to review the program in greater detail. Based on the additional information, BNL found the overall program acceptable with the exception of the methodology used to perform the ASME Code evaluation of the surge line elbows. After further discussion with the NRC staff and BNL, B&W revised their methodology and reevaluated the elbows. The revised methods and results were documented in B&WOG report BAW-2127 Supplement 2 which was issued in May 1992 (Ref. 3). The BNL evaluation of this program is presented in this TER.

2.0 NRC BULLETIN 88-11 REQUIREMENTS

NRC Bulletin No. 88-11 requested all PWR licensees to establish and implement a program to confirm pressurizer surge line integrity in view of the occurrence of thermal stratification and inform the staff of the actions taken to resolve this issue. Licensees of operating PWR's were requested to take the following actions:

Action 1.a - Perform a visual inspection walkdown (ASME Section XI, VT-3) at the first available cold shutdown which exceeds seven days.

Action 1.b - Perform a plant specific or generic bounding analysis to demonstrate that the surge line meets applicable design codes and other FSAR and regulatory commitments for the design life of the plant. The analysis is requested within four months for plants in operation over ten years and within one year for plants in operation less than ten years. If the analysis does not demonstrate compliance with these requirements, submit a justification for continued operation (JCO) and implement actions 1.c and 1.d below.

Action 1.c - Obtain data on thermal stratification, thermal striping, and line deflections either by plant specific monitoring or through collective efforts among plants with a similar surge line design. If through collective efforts, demonstrate similarity in geometry and operation.

Action 1.d - Perform detailed stress and fatigue analyses of the surge line to ensure compliance with applicable code requirements incorporating any observations from 1.a. The analysis should be based on the applicable plant specific or referenced data and should be completed within two years. If the detailed analysis is unable to show compliance, submit a JCO and a description of corrective actions for effecting long term resolution.

Although not required by the Bulletin, licensees were encouraged to work collectively to address the technical concerns associated with this issue, as well as to share pressurizer surge line data and operational experience. In response, the Babcock and Wilcox Owners Group (B&WOG) developed and implemented a program to address the technical issues of surge line stratification in B&W plants. A summary of this program is presented in the next section of this TER.

3.0 SUMMARY OF B&WOG PROGRAM

The B&W Owners Group Materials Committee developed a comprehensive program to address all technical concerns identified in NRC Bulletin 88-11. Based on similarities in design and operation, B&WOG was able to perform a generic evaluation for all lowered loop plants. They include the following six plants:

Arkansas Nuclear One Unit 1
Crystal River Unit 3
Oconee Units 1,2,3
Three Mile Island Unit 1

The B&WOG determined that Davis-Besse Unit 1, which is the only B&W raised loop plant, differed significantly and required a plant-specific evaluation. The Davis-Besse analysis was beyond the scope of the BNL review and is not addressed in this TER.

The B&WOG program was divided into two basic parts. The first part investigated the thermal hydraulic phenomena occurring in the surge lines. The goal of the first part of the program was the development of revised design basis thermal transients which appropriately account for the effects of thermal stratification and thermal striping. This effort included the instrumentation and monitoring of the Oconee Unit 1 surge line to determine circumferential temperature profiles and displacements of the line under stratified flow conditions. It also involved the assessment of operating practices and procedures, and the collection and review of historical plant data from all lowered loop B&W plants. Upper limits on surge line differential temperatures were established based on 10CFR50 Appendix G pressure/temperature limits. Analytical correlations were developed to predict thermal stratification and thermal striping based on surge line flow rates and differential temperatures. These correlations were based on Oconee measured data and on thermal striping experimental data. Based on the measured data, historical data and upper limits, B&W established generic conservative magnitudes and numbers of thermal stratification cycles for past and future operation. The end result of this part of the program was a revised set of design basis transients that were used as input to the surge line stress and fatigue analysis.

The second part of the program addressed the structural analyses needed to assess the integrity of the surge line and nozzles for the balance of the design life of each plant. This required the development of a structural mathematical model of the surge line. A structural loading analysis was performed by applying the revised design basis transients to this model. This generated the internal forces and moments for the stress and fatigue analysis of the surge line and nozzles. The line was then evaluated in accordance with the 1986 Edition of the ASME Code NB-3600. Based on this evaluation, B&WOG concluded that the surge line satisfied all Code stress and fatigue limits. However, upon review of the analysis, BNL questioned the analytical methodology used to determine stresses in the elbows. B&W had redefined the secondary stress index and the peak stress index based on an elastic-plastic finite element analysis. BNL disagreed with the B&W interpretation of secondary stress versus peak stress in an elbow and suggested that the elbows be reevaluated using the stress indices given in NB-3600. However, when the Code indices were applied, the surge line elbows did not satisfy the Code limits for expansion stress or fatigue usage. As a result, B&W performed another analysis based on the alternate ASME Code criteria given in NB-3228.4. Using an elastic-plastic model of the surge line, B&W demonstrated that shakedown will occur after a few cycles of the most severe thermal stratification loading with an acceptably small amount of accumulated strain. The fatigue evaluation based on this analysis demonstrated that the usage factor for the bounding plant is below the Code allowable. Thus the revised analysis showed that all Code requirements are satisfied for the forty year design life of each lowered loop plant.

4.0 HISTORY OF REVIEW PROCESS

NRC Bulletin 88-11 was issued on December 20, 1988. The bulletin addressed technical concerns associated with thermal stratification in the pressurizer surge line and required all PWR licensees to establish and implement a program to ensure the structural integrity of the surge line. The B&W Owners Group subsequently formed a Thermal Stratification Working Group and developed a comprehensive program to address the requirements of the bulletin. A portion of the program was presented to the NRC staff on September 29, 1988 and April 7, 1989. In accordance with Bulletin Action 1.b, an interim evaluation was performed and documented in B&W report BAW-2085 dated May 1989 (Ref. 4). That report provided the staff with a justification for near term operation for all of the operating B&W plants. The NRC staff reviewed the report and concluded that sufficient information had been provided to justify near term operation for B&W plants until the final report could be completed.

The final results of the B&WOG program were documented in B&W report BAW-2127 dated December 1990 (Ref. 2). This report summarized the generic analysis and evaluation of the B&W lowered loop plants. It included the development of revised design basis transients which considered thermal stratification and striping, as well as the structural reevaluation to demonstrate that structural integrity will be maintained over the forty year design life. The report was reviewed by BNL under contract to the NRC staff. BNL generated a list of questions and additional information needed to complete the review (Ref. 5). BNL then participated in an NRC staff audit at B&W offices in February 1991 in which B&W technical personnel provided responses and additional information including detailed calculations. Following a more detailed review of the information, an audit trip report was issued which summarized the BNL findings and recommendations (Ref. 6). BNL concluded that the B&WOG program was comprehensive and addressed all of the issues described in Bulletin 88-11. The technical personnel involved in the program were well qualified and produced high quality work. However, there was one significant unresolved issue which impacted the stress evaluation. BNL disagreed with the method in which B&W calculated the secondary and peak stresses in the surge line elbows. This issue was incorporated into the NRC staff Safety Evaluation Report (Ref. 7) as an open item.

In order to resolve the SER open item, B&WOG reevaluated the surge line elbows using elastic-plastic analysis methods and demonstrated Code compliance in accordance with the alternate criteria given in ASME Code Section III Subsection NB-3228.4. The methodology was presented and discussed during meetings held at B&W offices in October 1991 and January 1992. The discussions were summarized in audit trip reports (Ref. 8 and 9). The final results were documented in B&W report BAW-2127 Supplement 2 dated May 1992 (Ref. 3). The BNL evaluation of the B&WOG program including the reevaluation is presented in this TER.

5.0 TECHNICAL EVALUATION OF B&WOG PROGRAM

The B&WOG Program for evaluation of the lowered loop plants was divided into two basic sections: thermal-hydraulics and stress analysis. The thermal-hydraulics portion developed a revised set of surge line design basis transients that account for thermal stratification and thermal striping. It involved the instrumentation and monitoring of surge line temperature and displacement data from a representative plant (Oconee Unit 1). It included an assessment of operating procedures and review of historical plant data from all B&W plants. The stress analysis portion involved the development of structural mathematical models of the surge line and associated equipment. Structural loading analysis was performed using the revised thermal-hydraulic design basis. Stress and fatigue evaluations were performed in accordance with the 1986 Edition of the ASME Code Section III requirements. The major areas of review and evaluation are summarized below.

5.1 Generic Application

B&W reviewed the factors affecting surge line thermal stratification to determine if the B&WOG plants can be evaluated generically. The assessment considered both the piping design and the plant specific operating procedures. The findings are summarized below.

5.1.1 Pressurizer Surge Line Design

A review of the surge line piping for all B&W plants showed that all lowered loop plants have the same nominal dimensions and configuration. The lines consist of approximately 50 feet of 10 inch diameter schedule 140 austenitic stainless steel pipe. The lines are insulated with a reflective/mirror insulation having similar characteristics. The end nozzles connect the surge line to the hot leg and to the pressurizer. In the lower horizontal piping run, a one inch diameter nozzle made of austenitic stainless steel connects a drain line to the surge line. With the exception of TMI-1, snubbers are used as seismic restraints. The TMI-1 line does not contain any seismic snubbers, restraints, or supports. The Crystal River plant uses variable spring hangers as dead weight supports. The surge lines in all other lowered loop plants are free hanging. As long as displacements are within the range of free travel of the snubbers and spring hangers, these supports will have a negligible effect on thermal stratification-induced stresses in the surge line.

5.1.2 Plant Operations

B&W reviewed the plant operational aspects which affect the magnitude and number of thermal cycles applied to the pressurizer surge line. This included a review of applicable plant operating procedures and data, as well as interviews of plant operators. The operational review concentrated on the heatup/cooldown and initial RCS pressurization phases, since the highest potential for significant thermal stratification conditions exists during these phases. They concluded that all of the B&W plants basically operate in a similar fashion with some minor differences. During power operating conditions and during operating conditions where the RCS temperature is near "Hot Standby", all of the plants operate in a similar fashion and the thermal stratification potential is relatively small. During design basis transient events, the transients imposed on the surge line are virtually identical for all of the lowered loop plants.

B&W noted that the reactor vessel operational P/T limits, in accordance with 10CFR50 Appendix G, provide the upper limit of the surge line thermal stratification potential during the heatup/cooldown and initial pressurization phases, and that these limits are a function of the effective full power years (EFPY) of operation. The magnitude of the thermal stratification gradients as well as the actual number of heatup/cooldown cycles were grouped on the basis of the periods of the applicable Appendix G limits. Actual plant data was reviewed to confirm that the B&W plants have operated below the reactor vessel P/T limits. Based on the plant data and the measured data from the instrumented Oconee Unit 1 surge line, B&W was able to define the number and magnitude of thermal stratification cycles for the generic design basis. Based on the P/T path taken by each of the plants during past heatups and cooldowns, the magnitude of future thermal stratification cycles was developed to form the basis for evaluating future surge line fatigue.

5.1.3 BNL Evaluation

Based on a review of the information provided by B&W, BNL concluded that the lowered loop plant configuration and plant operations were sufficiently similar to justify the development of generic design basis transients as well as a generic structural and fatigue evaluation. The evaluation of the revised design basis transients development and of the stress and fatigue evaluation is presented in the following sections.

5.2 Revised Design Basis Transients

The development of the revised design basis transients involved the monitoring of surge line data at Oconee Unit 1, the development of surge line thermal stratification and thermal striping correlations, the review of operational histories, and the formulation of revised transients.

5.2.1 Monitoring Program and Stratification Correlations

Based on comparisons of dimensions of the lowered loop surge line plants, B&WOG concluded that a single plant could be instrumented to provide typical thermal stratification data. Oconee Unit 1 was selected and instrumented with 54 thermocouples and 14 displacement instruments affixed to various parts of the lines. The instrumentation package was installed during the January 1989 refueling outage. Temperature measurements were recorded at either 20 second or one minute intervals during heatup, cooldown, and various power operation conditions. The measured data was processed and used to develop correlations to predict surge line temperature versus time based on global plant conditions including pressurizer and hot leg temperature, surge line flow rate, and reactor coolant pump and spray valve status. Prediction correlations were developed for stratification temperatures in the horizontal piping as well as for temperatures at the nozzles. The stratification correlations were used in conjunction with the synthesized plant transients to develop temperature profiles for use in the stress analysis.

5.2.2 Development of Thermal Striping Correlations

B&W developed thermal striping correlations based on experimentally observed striping data. Based on a review of the literature on striping experiments, B&W found that experiments performed in the HDR facility at Battelle Institute, Karlsruhe, FRG were conducted under conditions that most closely matched those of the pressurizer surge lines. The HDR tests were performed in a large-diameter (15.6 inch), insulated metal pipe using plant-typical fluid conditions. The pipe was extensively instrumented with fast-response thermocouples. B&W obtained the complete set of measurements from the "PWR" subseries of tests. The data was processed to determine interface characteristics as well as striping frequencies and amplitudes. B&W used the ordered overall range method to count striping cycles and to develop distributions of cumulative frequencies of occurrence versus striping amplitude. The maximum striping amplitude for each test was compared and correlated with the governing fluid conditions. The maximum striping amplitudes of the final correlation were increased by 10% to allow for uncertainties.

5.2.3 Development of Revised Design Transients

In developing the revised design basis transients, B&W considered past operational information. An information base of plant operating data, operating procedures, surveillance procedures, and operational limits was collected from utility and B&W records. Discussions with plant operators provided additional information. The revised surge line design basis transients were based on the original design basis transients with some modifications and additions. For all transients, the surge line conditions were redefined to include stratification and striping. The most significant transients which produce the largest top to bottom temperature difference and contribute most to the cumulative fatigue in the surge line are plant heatup and cooldown. These transients were completely redefined. Heatups were categorized into five transients with three representing past operations and two representing future operations. Hot leg and pressurizer temperature versus time plots were developed for each heatup transient. The transients varied in terms of pressurizer to hot leg differential temperature with the most severe transient based on the pressure-temperature limits which satisfy the vessel fracture toughness requirements of 10CFR50 Appendix G at two effective full power years. The number of occurrences for each type of heatup transient was determined by reviewing plant data and taking conservative estimated fractions of the most severe heatups to total number of heatups. For each heatup, operational events that affect surge line flow were identified by a review of plant data and procedures. The number of events per transient was based on the reviews with additional random flow events added. The thermal stratification and thermal striping correlations were used to generate the surge line thermal response to the events. For the most severe heatup transient, B&W estimated a maximum pressurizer to hot leg temperature differential of 400°F. The maximum value of stratification (top to bottom surge line temperature difference) was 397°F. B&W followed similar procedures to redefine the cooldown and other design basis transients. The final results of this effort provided the input for the stress and fatigue analysis of the surge line for each lowered loop plant.

5.2.4 BNL Evaluation

BNL reviewed the methodology described in the BAW-2127 report and raised several questions which were discussed during the February 1991 audit. B&W provided copies of detailed calculations on thermal stratification and striping correlations for review. From the information provided, it was clear that the B&W effort was extensive and thorough. Although the calculations were not checked in detail, the overall approach was found to be reasonable and conservative. Comparisons of predicted stratification to plant measurements showed the prediction correlations to conservatively overpredict stratification response. The striping correlations were based on an envelope of test results and striping amplitudes were further increased by 10% to account for uncertainties. The development of the revised design basis transients considered bounding operating limits as well as typical conditions observed during plant operation.

5.3 Stress and Fatigue Evaluation

The stress analysis effort involved the development of structural mathematical models of the surge line and nozzles, the loading of the models to generate the internal forces, moments and stresses for the thermal stratification conditions and a stress and fatigue evaluation which considered appropriate combinations of stresses generated by other loads to demonstrate compliance with ASME Code Section III requirements.

5.3.1 Model Development and Analysis

The ANSYS computer program was used to develop an "extended" mathematical piping model of the pressurizer surge line. The model included the pressurizer, surge line, hot leg, reactor vessel, and steam generator. The attached equipment was included so that correct anchor movements and component flexibility would be correctly simulated. The ANSYS program was chosen because of its capability to analyze a piping system with a top-to-bottom temperature variation in the piping elements. Since the variation can only be applied linearly, however, B&W developed "equivalent linear temperature profiles" to represent the nonlinear profiles indicated by plant measurements. Nonlinearity coefficients were developed to generate equivalent linear temperature profiles which give the same pipe cross-section rotation as the nonlinear profile. The nonlinearity coefficient was found to be a function of top and bottom temperatures and fluid interface elevation. B&W developed a mathematical formula for nonlinearity coefficient as a function of these variables.

Using the extended mathematical piping model and calculating the nonlinearity coefficients for the Oconee data, a verification run was performed. The measured temperatures were applied to the model and displacements were determined. The comparison of calculated to measured displacements showed very good agreement. B&W stated that this verified the accuracy of the model and the nonlinearity correction method.

B&W used this model to analyze the three most critical thermal stratification conditions that occur during the most severe heatup transient. Top-to-bottom temperature differences were 397°F, 393°F, and 386°F. Additional analyses were performed for seven other thermal stratification conditions plus the unstratified 100% power condition. With these 11 sets of internal forces and moments, B&W was able to set up an interpolation scheme to determine internal forces and moments everywhere in the surge line for all temperature conditions.

5.3.2 Stress Analysis and Code Evaluation

Reevaluation of the surge line for thermal stratification involved satisfying ASME Code Section III NB-3600 allowable stress limits for primary plus secondary stress intensity range (Equation 10) and cumulative fatigue usage limits for peak stress intensity range (Equation 11). For the most critical thermal stratification cycles, the Equation 10 stress limit of $3S_m$ was exceeded. As an alternative, the Code permits a simplified elastic-plastic fatigue analysis by applying a penalty factor, K_e, to the peak stress (Equation 14) provided that the load sets meet the stress limits of Equation 12 and 13 of NB-3653.6 and the thermal stress ratcheting equation of NB-3653.7. B&W was able to demonstrate compliance with Equation 13 (primary plus secondary stress intensity excluding thermal expansion) and thermal stress ratcheting, but was not able to meet the Equation 12 (secondary stress range due to thermal expansion) limit of $3S_m$ in the elbows using the simplified formulas and stress indices given in the Code. B&W then attempted to remove the conservatism in the Code stress indices by developing new C_2 and K_2 stress indices for the surge line elbows based on finite element analysis. The computer program ABAQUS was used to generate an elastic-plastic finite element model of the elbows and apply in-plane and out-of-plane bending moments. Using the definitions of secondary and peak stresses and taking the higher of the two loading conditions, B&W defined generic stress indices of $C_2 = 1.58$ and $K_2 = 1.47$ compared to values of $C_2 = 2.33$ and $K_2 = 1.0$ from formulas given in Table NB-3685.1-2 of the Code.

Using the internal forces and moments from the most severe thermal stratification conditions and the redefined generic elbow stress indices, three of the four surge line elbows still exceeded the Equation 12 stress allowable. B&W then applied these forces directly to the elastic-plastic finite element model and used the same method to calculate maximum secondary stress as was used to generate the C_2 stress index. The resulting calculated secondary stresses were shown to be less than the $3S_m$ allowable.

5.3.3 Fatigue Analysis and Code Evaluation

For the ASME Code fatigue evaluation, B&W considered the stresses due to stratification induced moment loadings as well as localized peak stresses induced by through-wall temperature gradients DT_1 and DT_2 due to fluid flow, thermal striping, and nonlinear temperature profiles. Peak stresses due to thermal striping were determined from the striping temperature data given in the design basis transients. The temperature distribution through the wall thickness was determined from an ANSYS finite element model. The time-dependent wall temperature was simulated as a "cut-sawtooth" wave. From the experimental data, B&W determined that the fluctuations have a period of approximately 1.0 seconds. To cover a range of periods which could be expected, thermal analyses were performed with periods of 0.5, 1.0, 2.0 and 4.0 seconds. For each period, the extreme temperature profiles were determined and the linear and nonlinear through-wall temperature gradients were calculated, leading to the maximum peak stress intensity range.

Peak stresses due to the nonlinearity of the temperature profile are the result of the difference between the actual nonlinear and the "equivalent linear" temperature profiles used in the structural loading analysis. B&W referred to this temperature difference as DT_4. An ABAQUS finite element analysis was performed for the two most severe measured top-to-bottom temperature profiles. The analyses indicated that the maximum peak stress intensity occurs at the inside radius of the pipe cross section. From these results, B&W developed a correlation to calculate DT_4 as a function of top-to-bottom temperature difference and fluid interface elevation, and give the maximum peak stress intensity in the pipe as a function of DT_4, top-to-bottom temperature difference and fluid interface elevation.

B&W performed a fatigue analysis in accordance with the 1986 Edition of ASME Section III NB-3600 as required by Bulletin 88-11. Since all plants had been designed to earlier Code Editions, a Code reconciliation was performed. The findings indicated that for the 1986 Code: 1) more sophisticated formulas are used for stress indices, 2) allowables are equal to or smaller than the earlier allowables, 3) the fatigue curves go up to 10^{11} cycles compared to earlier curves which only went up to 10^6 cycles.

B&W calculated the "main fatigue usage" which they defined as the usage factor due to all thermal stratification conditions which are characterized by a top-to-bottom temperature difference. The absolute values of the peak stress ranges from the following contributions were added:

1. Moment loading range due to thermal stratification.
2. Moment loading range for the 30 occurrences of OBE.
3. Internal pressure range.
4. Additional localized peak stress due to nonlinearity of the top-to-bottom temperature profile (DT_4).
5. Maximum stress between the peak stress due to thermal striping and the one due to fluid flow (through-wall temperature gradients DT_1 and DT_2).

B&W performed a sort of all the total peak stress intensity values and built a selection table for the combination of the thermal stratification peaks and valleys into pairs in such a way that stress ranges were maximized. For each pair of conditions, the alternating stress intensity was calculated as a function of the peak stress intensity range and of the Equation 10 primary plus secondary stress intensity range. The usage factor associated with each alternating stress intensity value was calculated in accordance with the 1986 ASME Code extended fatigue curves (up to 10^{11} cycles). The summation of all usage factors for each pair gave the total "main fatigue usage."

In addition to the main usage factor, B&W evaluated the additional fatigue contributions due to the highly cyclic thermal striping ranges, the additional OBE ranges not associated with stratification, and the additional fluid flow conditions not associated with stratification. Contributions due to OBE and fluid flow were found to be very small. Fatigue usage due to thermal striping was found to be in the range of 0.10 and 0.15 depending on the specific plant. B&W combined the main usage factor with the additional fatigue usage contributions to calculate the total cumulative usage factor for each of the six B&W lowered loop plants. The values were different for each plant because the number of occurrences of the events in the design basis transients is unique to each plant. The results showed that all cumulative usage factors were below their allowable of 1.0. The highest usage factor was 0.82 and occurred in the vertical elbow at the bottom of the surge line riser to the hot leg in Oconee Unit 2.

5.3.4 Nozzle Evaluation

In addition to the piping analysis, B&W performed detailed stress analyses of the pressurizer and hot leg nozzles. For both nozzles, axisymmetric thermal and thermal stress analyses were performed using the ANSYS finite element computer code. The loadings consisted of thermal gradients, internal pressure, and external piping loads. Since the pressurizer nozzle is vertical, there were no significant thermal stratification loads. The hot leg nozzle is horizontal and is subject to direct thermal stratification which produces circumferential temperature gradients. The stresses due to these gradients were determined by the use of the ANSYS harmonic element STIF 25 which can handle an axisymmetric structure with nonaxisymmetric loading. The nozzles were evaluated in accordance with the requirements for Class 1 components of the ASME Code, Section III, 1986 Edition. For both nozzles the linearized primary-plus-secondary stress intensities exceeded the $3S_m$ limit. However, the Code requirements were satisfied by performing a "simplified elastic-plastic analysis" as defined in NB-3228.5. Cumulative fatigue usage factors were calculated for each plant. All plants met the 1.0 allowable for both nozzles. The highest usage factors in the pressurizer nozzle was 0.41 in Oconee Units 2 and 3. In the hot leg nozzle, the highest usage factor was 0.62 in TMI Unit 1, Crystal River Unit 3, and ANO Unit 1.

5.3.5 BNL Evaluation

BNL reviewed the stress analysis and Code evaluation methodology and results described in the BAW-2127 report and raised a number of questions which were discussed during the February 1991 audit. B&W provided copies of the detailed calculations on the piping and nozzle stress analyses for review. BNL reviewed selected portions of the piping stress analysis in detail. Based on the review, BNL found the B&W stress reevaluation effort to be comprehensive and complete. Thermal stratification effects including global bending stresses, local stresses due to the nonlinear temperature profiles, and cyclic stresses due to thermal striping were considered. Calculations were found to be clear and well organized. Assumptions were reasonable and generally conservative. The accuracy of the mathematical piping model was checked against data taken at Oconee and showed good agreement in predicting displacements. The fatigue analysis considered stress intensity ranges due to all global and local stratification loads as well as other cyclic design loads. Absolute values of peak stresses due to different loads were combined by conservatively assuming that maximum stresses occur at the same location on the pipe cross-section.

There was, however, one significant issue of concern. BNL disagreed with the B&W methodology for calculating a revised C_2 stress index for the surge line elbows. The methodology was discussed with B&W during the February 1991 audit and calculations were further reviewed in detail. The analysis involved the application of in-plane and out-of-plane bending moments to ABAQUS elastic and elastic-plastic finite element models of the surge line elbows. Based on the results of these analyses, new elbow stress indices were calculated as follows:

For peak stress:

K_2C_2 = Maximum stress anywhere in the elbow divided by the nominal (straight pipe) stress at the surface.

For secondary stress:

C_2 = Maximum stress at mid-thickness in the elbow divided by the corresponding nominal (straight pipe) stress at mid-thickness.

The K_2C_2 value was based on an elastic analysis while the C_2 value was based on an elastic-plastic analysis with a correction factor for displacement-controlled loading. B&W took the larger of the in-plane and out-of-plane stress index values and obtained $C_2 = 1.58$, $K_2C_2 = 2.33$ (or $K_2 = 1.47$). Using ASME Code tables, these values would be $C_2 = 2.33$ and $K_2 = 1.0$. The B&W indices, therefore, would predict significantly lower secondary stresses but the same peak (equation 11) stresses. In differentiating between secondary and peak stresses, B&W referred to the Code definition of peak stress (NB-3213.11) as "that increment of stress which is additive to the primary plus secondary stresses by reason of local discontinuities or local thermal stress including the effect of stress concentrations. The basic characteristic of a peak stress is that it does not cause any noticeable distortion and is objectionable only as a possible source of a fatigue crack." B&W also noted that Figure NB-3222-1 defines a "secondary" expansion stress intensity P_e as "stresses which result from the constraint of free end displacement. Considers effects of discontinuities but not local stress concentration." B&W argued that the maximum stress in the elbow has all the characteristics of a local stress concentration. Their review of the stress analysis results around the circumference and through the elbow thickness indicated that the highest stress intensity was highly localized. B&W also stated that the elbow behaved in a linear fashion after the highest stressed locations entered the plastic domain and that these stresses had a negligible impact on elbow distortion. B&W therefore felt justified in treating surface stresses as peak stresses and the average through-wall stresses (mid-thickness stresses) as secondary stresses.

With the redefined "generic" C_2 stress index, three of the four elbows still did not meet the equation 12 stress allowable. B&W performed additional elastic-plastic finite element analyses for the critical loading case to demonstrate that the elbows meet the expansion stress intensity limit. These analyses took advantage of the lower stress indices for in-plane bending (1.30) and torsion (1.0) and demonstrated acceptable results. However, the basic definitions of secondary and peak stresses were the same as discussed above. Secondary expansion stress intensity was based on mid-thickness stress.

BNL disagreed with the B&W interpretation of the definition of secondary and peak stress in an elbow. The Code (NB-3682) defines the C stress index as the maximum stress intensity due to load L divided by the nominal stress intensity due to load L. This presumably means maximum stress intensity anywhere in the cross-section, not a mid-thickness stress intensity. The B&W definition of secondary stress completely neglects the circumferential bending stresses that develop in an elbow. These stresses are considered only as peak stresses by B&W. It does not appear that the circumferential bending stresses in the elbow walls should be considered peak stresses. Peak stresses are generally associated with localized geometric or material discontinuities that effect the stress distribution through a fractional part of the wall thickness or with local thermal stresses that produce no significant distortion. In the case of elbows, the circumferential bending stresses affect the entire wall thickness and produce distortion (ovalization) of the elbow cross-section. NB-3222.3 defines expansion stress intensity as "the highest value of stress, neglecting local structural discontinuities, produced at any point across the thickness of a section by the loadings that result from restraint of free end displacement." The Code stress index tables (NB-3681(a)-1 and NB-3685.1-2) provide further evidence that the maximum elbow stresses should be treated as secondary stresses. The C_2 value of 2.33 computed from the table formulas agrees exactly with the B&W finite element model maximum stress at the elbow surface. The K_2 value of 1.0 indicates that no stress concentration factor needs to be applied to elbows for determining peak stress.

The use of Code stress indices instead of the redefined B&W stress indices would have a significant impact on the ASME Code stress and fatigue evaluation. If Code stress indices were used, for the most severe thermal stratification load conditions, the range of thermal expansion stress intensity would exceed the $3S_m$ limit (Equation 12). The higher Code C_2 stress indices would also increase the primary plus secondary stress intensity value calculated in Equation 10. For severe load sets, which require the simplified elastic-plastic analysis method of NB-3653.6, the penalty factor, K_e, which is based on Equation 10 stress will increase. This will result in larger alternating stresses (Equation 14) and higher fatigue usage with potential for exceeding the 1.0 allowable.

In order to assess the consequences of this issue, BNL also consulted with ASME Code piping expert, Everett Rodabaugh. He indicated that the Equation 12 $3S_m$ allowable may have significant margin because various tests have shown that piping systems can have substantial fatigue capacity even if Equation 12 is not met. Nevertheless, since meeting the $3S_m$ expansion stress limit is a current Code requirement, BNL recommended that B&W initiate an ASME Code inquiry to determine whether the B&W interpretation of C_2 stress index is acceptable or whether not meeting the Equation 12 allowable is permissible for this application.

BNL and Mr. Rodabaugh agreed that the fatigue usage allowable of 1.0 for the life of the plant must be met. BNL therefore recommended that B&W reevaluate the fatigue usage using the Code table stress indices. If the allowable was exceeded, B&W should investigate and justify alternate approaches to demonstrate that Code requirements for fatigue and expansion stress are met.

5.4 Structural Reevaluation of Surge Line Elbows

In order to address the BNL concern, B&W performed additional analysis to reevaluate the surge line elbows. The revised methodology was presented and discussed during meetings held at B&W offices in October 1991 and in January 1992. As expected, B&W found that when the Code stress indices were used for the elbows, the fatigue usage factor exceeded the 1.0 allowable. Therefore B&W proposed an alternate approach based on elastic-plastic analysis. The methodology was presented at the first meeting and agreement on the overall approach was reached. At the second meeting, B&W presented additional details of the analysis and preliminary results. The final results of the reevaluation were documented in BAW-2127 Supplement 2 which was issued in May 1992. A summary of the reevaluation methodology and the BNL evaluation is given below.

5.4.1 Reevaluation Methodology and Results

The B&W reevaluation was based on the alternate ASME Code criteria given in Section III Subsection NB-3228, "Applications of Plastic Analysis". In this subsection, the Code provides some relaxation of the basic stress limits if plastic analysis is used. Subsection NB-3228.4,"Shakedown Analysis", specifically states that the limits of thermal stress ratchet (NB-3222.5), progressive distortion (NB-3227.3), local membrane stress (NB-3221.2), and primary plus secondary stress intensity (NB-3222.2) need not be satisfied at a specific location if a plastic analysis demonstrates that shakedown occurs and the deformations which occur prior to shakedown do not exceed specified limits. In evaluating stresses for comparison with fatigue allowables, the total strain range which occurs after shakedown shall be multiplied by one-half the modulus of elasticity of the material at the mean temperature value.

In order to demonstrate shakedown, B&W developed an ABAQUS finite element model of the surge line piping which was identical to the original ANSYS model except for the use of elastic-plastic pipe elbow elements. Stress-strain curves for austenitic stainless steel at different temperatures were generated to match the ASME Code yield and tensile values using an exponential stress-strain relationship. Piecewise linear curves approximating these curves were used as input to the analysis. Kinematic strain hardening was assumed for the loading/unloading behavior. The ABAQUS model was verified by comparison to the ANSYS mathematical model. B&W identified the most severe thermal stratification stress loading range that was seen in the previous fatigue evaluation. This severe load range was applied in combination with thermal expansion, deadweight and internal pressure for a total of 13 cycles. The 13 cycles envelope the number of occurrences for all lowered loop plants. According to B&W, the results of the elastic-plastic analysis demonstrated that for the most severe ranges of thermal stratification conditions, shakedown was achieved in four cycles. The maximum accumulated local strain was 1.07% at the most critical elbow location.

The total cumulative fatigue usage in the elbows was recalculated based on the elastic-plastic analysis. As in the original analysis, B&W considered both the "main fatigue usage" due to all stratification conditions and the "additional fatigue usage" associated with thermal striping, OBE stresses not associated with stratification, and non-stratified fluid flow conditions (as discussed in Section 5.3.3 above). Only the main fatigue usage for cycles with Equation 10 stress range intensity greater than the Code $3S_m$ limit needed to be recalculated for this analysis. For these cycles, 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. B&W used detailed elbow models to develop correlation tables 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. Correlation tables were also developed for the plastic penalty factor to be applied to the additional peak stresses. For each thermal stratification cycle, the strain range and the plastic penalty factor were calculated through a conservative linear interpolation between values in the correlation tables to determine the alternating stresses for fatigue evaluation. The results of the fatigue analysis showed that the highest cumulative usage factor for the lowered loop plants was 0.50 for the vertical elbow at the bottom of the surge line riser to the hot leg in Oconee Unit 2. Based on the results of the original evaluation and the results of the elbow reevaluation, B&W concluded that requirements of Bulletin 88-11 were satisfied.

5.4.2 BNL Evaluation

During the October 1991 and January 1992 B&W meetings, BNL determined that the elbow reevaluation approach was acceptable provided that specific concerns regarding implementation of the analysis were adequately addressed. The major concerns and their resolution are summarized below.

The shakedown analysis did not apply an actual load history corresponding to the normal sequence of heatups, cooldowns and other anticipated operating transients. Instead B&W identified and applied the loads corresponding to the most severe peaks and valleys of thermal stratification conditions. They identified PV4 (a peak associated with a heatup) and PV402 (a valley associated with a cooldown) as the most severe loading range from the original fatigue evaluation. Thirteen cycles of this load range were applied in the shakedown analysis. BNL pointed out that since the strains in the plastic analysis are nonlinear and path dependent, the application of an actual load history would be more appropriate. B&W was requested to provide additional justification to ensure that the loads that were applied in the shakedown analysis were indeed bounding. B&W agreed to verify this through the use of a Bree diagram. The results of this additional evaluation were reported in BAW-2127 Supplement 2. A Bree diagram was built for the surge line location undergoing the largest strain. On this diagram, the most severe thermal stratification loads (analyzed in the elastic-plastic shakedown analysis) were shown to be the controlling conditions for shakedown when compared to other conditions during the same heatup transient. In addition all of the stress points corresponding to the peaks were shown to be acceptable. This additional information resolved the BNL concern.

In addition to demonstrating shakedown, ASME Subsection NB-3228.4 requires that the deformations which occur prior to shakedown do not exceed specified limits. The B&W shakedown analysis showed that the maximum accumulated local strain (resulting in permanent deformation) that occurred due to the application of the thirteen bounding load cycles was 1.07%. BNL requested that B&W provide a basis for acceptability of this strain value. In response, B&W noted that ASME Code Cases N-47 and N-196 permit a maximum allowable accumulated local strain of 5%. Code Case N-47 provides rules for Class 1 components in elevated temperature service and Code Case N-196 provides relief from the shakedown requirements of NB-3228. Although these Code Cases were not being specifically applied to qualify the surge line, BNL agreed that they provided a reasonable basis for acceptance of the 1.07% calculated strain.

In the surge line elbow reevaluation, B&W still could not demonstrate that the thermal expansion stress limit of $3S_m$ given in NB-3653.6 (Equation 12) as well as in NB-3222.3 was met. The requirements of NB-3228.4 did not provide relief from this limit. Based on further discussions with B&W and with Mr. Rodabaugh, BNL agreed that demonstrating shakedown appeared to satisfy the intent of this stress limit. However, as a confirmatory item, B&W was asked to initiate an ASME Code inquiry to confirm this. B&W complied with this request and obtained a response from the Code Committee on March 26, 1992 (see Appendix A). The response confirmed that when shakedown is demonstrated in accordance with NB-3228.4(b), the expansion stress criterion of NB-3222.3 does not need to be satisfied. This resolved the issue.

Based on the review of the additional structural analysis and reevaluation of the surge line elbows, BNL concluded that the B&W analysis adequately demonstrated the structural integrity of the lowered loop plant surge lines for the 40 year design lives of the plants with proper consideration given to the effects of thermal stratification. In order to provide additional confidence, BNL recommends that licensees perform augmented volumetric inspections of surge line elbows in order to ensure that the most highly stressed areas (elbow bodies as well as welds) have not sustained damage.

5.5 Plant Specific Applicability of B&WOG Analysis

The BAW-2127 report identified the conditions upon which the generation of the revised design basis transients and the thermal stratification fatigue stress analysis of the surge line were based. These conditions and the licensee actions needed to verify that the conditions are applicable on a plant specific basis are summarized below.

5.5.1 Applicability of Revised Design Basis Transients

The generation of the revised design basis transients for future events was based on the incorporation of operational guidelines which:

- limit the pressurizer to RCS temperature difference during plant heatups and cooldowns (imposed with pressure/temperature limits), and

- prevent surveillance tests that cause rapid additions of water to the RCS from being performed with pressurizer to RCS temperature difference greater than 220°F.

Pressurizer/temperature limits for future heatup and cooldown operations were included as Figure 8-1 of BAW-2127. In order to meet the pressure limit specified for heatup in the 70°F to 150°F temperature range, B&W recommended preheating the RCS. For heatups involving pressurization at lower RCS temperatures, a less restrictive limit was included in Figure 8-1. The fatigue evaluation was based on the assumption that 85% of the heatups for the remainder of plant life meet the recommended limit shown by path CDEN of Figure 8-1, and 15% of future heatups meet the less restrictive path ABEN.

5.5.2 Applicability of Fatigue Analysis

The thermal stratification fatigue analysis was based on the following assumptions:

- o no interference of the surge line with any other structure,
- o surge line movement within the travel range of each snubber,
- o surge line movement within the travel range of each hanger,
- o branch moments at the surge line drain nozzle connection within their respective maximum allowables (for deadweight, OBE and thermal stratification).

5.5.3 BNL Evaluation

The conditions of applicability were discussed with licensee representatives at the B&W audits. The licensees agreed that the B&W proposed operational guidelines will be followed. Operating procedures will have to be revised to reflect these limits. In addition, licensees will review the maximum surge line displacements to ensure that there are no interferences and that travel limits on hangers and snubbers are not exceeded. Each licensee will be responsible for reevaluating the pipe supports and the drain line piping and nozzle. Plants with welded attachments will evaluate them on a plant specific basis. When all of these conditions are met, the licensees will be able to use the B&W generic analysis as the basis for verifying the structural integrity of the surge line.

6.0 CONCLUSIONS

Based on the review and evaluation of the material presented in the B&W reports, BAW-2127 and BAW-2127 Supplement 2, and the additional information provided during the February 1991, October 1991 and January 1992 audits, BNL concludes that the B&WOG program has adequately demonstrated that the bounding surge line and nozzles meet ASME Code stress and fatigue requirements for the forty year design life with consideration of the thermal stratification and thermal striping phenomena. The results of the B&WOG analysis may be used as the basis for licensees to update their plant-specific Code stress reports to demonstrate compliance with applicable Code requirements as requested in Bulletin 88-11.

The generic analysis and results are applicable to the following six B&W lowered loop plants:

Arkansas Nuclear One Unit 1
Crystal River Unit 3
Oconee Units 1, 2, 3
Three Mile Island Unit 1

Licensees are responsible for verifying plant-specific applicability of the B&WOG program and results. This will include verification of analysis assumptions, qualification of supports and attached piping, and revision of operating procedures as indicated in BAW-2127 and summarized in Section 5.5 of this report.

In order to provide additional confidence in the structural integrity of the surge lines, BNL recommends that licensees perform volumetric inspections of critical elbow components as part of future ASME Code Section XI in-service inspections. Inspections of elbow bodies as well as elbow welds should be performed to ensure that the most highly stresses areas have not sustained damage.

7.0 REFERENCES

1. NRC Bulletin No. 88-11, "Pressurizer Surge Line Thermal Stratification", December 20, 1988.

2. B&W Report BAW-2127, "Final Submittal for Nuclear Regulatory Commission Bulletin 88-11, Pressurizer Surge Line Thermal Stratification", December 1990.

3. B&W Report 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", May 1992.

4. B&W Report BAW-2085, "Submittal in Response to NRC Bulletin 88-11, Pressurizer Surge Line Thermal Stratification", May 1989.

5. BNL Letter, G. DeGrassi to S. Hou, "Request for Additional Information on B&W Report BAW-2127, Final Submittal for NRC Bulletin 88-11, Pressurizer Surge Line Thermal Stratification, (FIN A-3869, Task 48)", February 13, 1991.

6. BNL Letter, G. DeGrassi to S. Hou, "Audit of Babcock and Wilcox Owners Group (B&WOG) Pressurizer Surge Line Thermal Stratification Generic Detailed Analysis (FIN A-3869, Task 48)", June 13, 1991.

7. NRC Letter, J. W. Shea to J. A. Taylor, "NRC Bulletin 88-11, Pressurizer Surge Line Thermal Stratification, Safety Evaluation Report", July 24, 1991.

8. BNL Letter, G. DeGrassi to H. Shaw, "B&W Owners Group Pressurizer Surge Line Final Audit Trip Report (FIN A-3869, Task 60)", March 11, 1992.

9. BNL Letter, G. DeGrassi to H. Shaw, "B&W Owners Group Pressurizer Surge Line Final Audit Trip Report (FIN A-3869, Task 61)", September 25, 1992.

APPENDIX A

ASME CODE INQUIRY AND RESPONSE

DONALD F. LANDERS, President

TELEDYNE ENGINEERING SERVICES
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(617) 890-3350 TWX (710) 324-7508

December 30, 1991
7569-2

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

<u>Subject</u>: 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 basis 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 28, 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

Christian Sanna
Assistant Secretary, Boiler & Pressure Vessel Committee
(212) 605-4708

SAFETY EVALUATION REPORT
ON THE
BABCOCK & WILCOX OWNERS GROUP PRESSURIZER SURGE LINE THERMAL STRATIFICATION GENERIC DETAILED ANALYSIS
BAW - 2127

1.0 INTRODUCTION

NRC Bulletin No. 88-11 requested all PWR licensees to establish and implement a program to confirm pressurizer surge line integrity in view of the occurrence of thermal stratification and inform the staff of the actions taken to resolve this issue. Licensees of operating PWR's were requested to take the following actions:

Action 1.a - Perform a visual inspection walkdown (ASME Section XI, VT-3) at the first available cold shutdown which exceeds seven days.

Action 1.b - Perform a plant specific or generic bounding analysis to demonstrate that the surge line meets applicable design codes and other FSAR and regulatory commitments for the design life of the plant. The analysis is requested within four months for plants in operation over ten years and within one year for plants in operation less than ten years. If the analysis does not demonstrate compliance with these requirements, submit a justification for continued operation (JCO) and implement actions 1.c and 1.d below.

Action 1.c - Obtain data on thermal stratification, thermal striping, and line deflections either by plant specific monitoring or through collective efforts among plants with a similar surge line design. If through collective efforts, demonstrate similarity in geometry and operation.

Action 1.d - Perform detailed stress and fatigue analyses of the surge line to ensure compliance with applicable Code requirements incorporating any observations from 1.a. The analysis should be based on the applicable plant specific or referenced data and should be completed within two years. If the detailed analysis is unable to show compliance, submit a JCO and a description of corrective actions for effecting long term resolution.

Although not required by the Bulletin, licensees were encouraged to work collectively to address the technical concerns associated with this issue. In response, the Babcock & Wilcox Owners Group (B&WOG) developed and implemented a program to address the issue of surge line stratification in B&W plants. The first part of the program was documented in an interim report, BAW-2085 dated May 1989. Based on preliminary bounding calculations, B&W concluded that all B&W plants can continue operating safely in the near term until the final analyses could be completed. The staff reviewed the interim evaluation and identified several concerns but concluded that it was sufficient to be used as the technical basis for justification for continued operation for all B&W plants until the final analysis is completed by the end of 1990. The interim report, combined with acceptable plant specific visual inspection results, satisfied Bulletin Actions 1.a and 1.b for all B&W plants.

The B&W final analysis was completed in 1990. The summary and results of the program were documented in report BAW-2127, dated December 1990. The report summarized the work performed to satisfy the remaining NRC Bulletin Action items including the monitoring program and the final ASME Code stress and fatigue evaluations. It covered all B&W lowered loop plants: Arkansas Nuclear One Unit 1, Crystal River Unit 3, Oconee Units 1, 2, and 3, and Three Mile Island Unit 1. The remaining B&W plant, Davis-Besse Unit 1, is a raised loop plant and is undergoing a plant specific evaluation which will be reported in a future supplement to the report.

The staff reviewed the final report and conducted an audit at B&W offices in February 1991. The following sections summarize the staff evaluation of the program.

2.0 STAFF EVALUATION

The B&WOG Program for evaluation of the lowered loop plants was divided into two basic sections: thermal-hydraulics and stress analysis. The thermal-hydraulics portion developed a revised set of surge line design basis transients that account for thermal stratification and thermal striping. It involved the instrumentation and monitoring of surge line temperature and displacement data from a representative plant (Oconee Unit 1). It included an assessment of operating procedures and review of historical plant data from all B&W plants. The stress analysis portion involved the development of structural mathematical models of the surge line and associated equipment. Structural loading analysis was performed using the revised thermal-hydraulic design basis. Stress and fatigue evaluations were performed in accordance with the 1986 Edition of the ASME Code Section III requirements. The major areas of staff review and evaluation are summarized below.

2.1 Development of Revised Design Transients

The development of the revised design basis transients involved the monitoring of surge line data at Oconee Unit 1, the development of surge line thermal stratification and thermal striping correlations, the review of operational histories, and the formulation of revised transients. Based on comparisons of dimensions of the lowered loop surge line plants, B&WOG concluded that a single plant could be instrumented to provide typical thermal stratification data. Oconee Unit 1 was selected and instrumented with 54 thermocouples and 14 displacement instruments affixed to various parts of the lines. The instrumentation package was installed during the January 1989 refueling outage. Temperature measurements were recorded at either 20 second or one minute intervals during heatup, cooldown, and various power operation conditions. The measured data was processed and used to develop correlations to predict surge line temperature versus time based on global plant conditions including pressurizer and hot leg temperature, surge line flow rate, and reactor coolant pump and spray valve status. Prediction correlations were developed for stratification temperatures in the horizontal piping as well as for temperatures at the nozzles. The stratification correlations were used in conjunction with the synthesized plant transients to develop temperature profiles for use in the stress analysis.

B&W developed thermal striping correlations based on experimentally observed striping data. Based on a review of the literature on striping experiments, B&W found that experiments performed in the HDR facility at Battelle Institute, Karlsruhe, FRG were conducted under conditions that most closely matched those of the pressurizer surge lines. The HDR tests were performed in a large-diameter (15.6 inch), insulated metal pipe using plant-typical fluid conditions. The pipe was extensively instrumented with fast-response thermocouples. B&W obtained the complete set of measurements from the "PWR" subseries of tests. The data was processed to determine interface characteristics as well as striping frequencies and amplitudes. B&W used the ordered overall range method to count striping cycles and to develop distributions of cumulative frequencies of occurrence versus striping amplitude. The maximum striping amplitude for each test was compared and correlated with the governing fluid conditions. The maximum striping amplitudes of the final correlation were increased by 10% to allow for uncertainties.

In developing the revised design basis transients, B&W considered past operational information. An information base of plant operating data, operating procedures, surveillance procedures, and operational limits was collected from utility and B&W records. Discussions with plant operators provided additional information. The revised surge line design basis transients were based on the original design basis transients with some modifications and additions. For all transients, the surge line conditions were redefined to include stratification and striping. The most significant transients which produce the largest top to bottom temperature difference and contribute most to the cumulative fatigue in the surge line are plant heatup and cooldown. These transients were completely redefined. Heatups were categorized into five transients with three representing past operations and two representing future operations. Hot leg and pressurizer temperature versus time plots were developed for each heatup transient. The transients varied in terms of pressurizer to hot leg differential temperature with the most severe transient based on the pressure-temperature limits which satisfy the vessel fracture toughness requirements of 10CFR50 Appendix G at two effective full power years. The number of occurrences for each type of heatup transient was determined by reviewing plant data and taking conservative estimated fractions of the most severe heatups to total number of heatups. For each heatup, operational events that effect surge line flow were identified by a review of plant data and procedures. The number of events per transient was based on the reviews with additional random flow events added. The thermal stratification and thermal striping correlations were used to generate the surge line thermal response to the events. For the most severe heatup transient, B&W estimated a maximum pressurizer to hot leg temperature differential of 400°F. The maximum value of stratification (top to bottom surge line temperature difference) was 397°F. B&W followed similar procedures to redefine the cooldown and other design basis transients. The final results of this effort provided the input for the stress and fatigue analysis of the surge line for each lowered loop plant.

The staff reviewed the methodology described in the BAW-2127 report and raised several questions which were discussed during the February 1991 audit. B&W provided copies of detailed calculations on thermal stratification and striping correlations for review. From the information provided, it was clear that the B&W effort was extensive and thorough. Although the staff did not check the calculations in detail, the overall approach was found to be reasonable and conservative. Comparisons of predicted stratification to plant measurements showed the prediction correlations to conservatively overpredict stratification response. The striping correlations were based on an envelope of test results and striping amplitudes were further increased by 10% to account for uncertainties. The development of the revised design basis transients considered bounding operating limits as well as typical conditions observed during plant operation.

2.2 Stress and Fatigue Evaluation

The stress analysis effort involved the development of structural mathematical models of the surge line and nozzles, the loading of the models to generate the internal forces, moments and stresses for the thermal stratification conditions and a stress and fatigue evaluation which considered appropriate combinations of stresses generated by other loads to demonstrate compliance with ASME Code Section III requirements.

The ANSYS computer program was used to develop an "extended" mathematical piping model of the pressurizer surge line. The model included the pressurizer, surge line, hot leg, reactor vessel, and steam generator. The attached equipment was included so that correct anchor movements and component flexibility would be correctly simulated. The ANSYS program was chosen because of its capability to analyze a piping system with a top-to-bottom temperature variation in the piping elements. Since the variation can only be applied linearly, however, B&W developed "equivalent linear temperature profiles" to represent the nonlinear profiles indicated by plant measurements. Nonlinearity coefficients were developed to generate equivalent linear temperature profiles which give the same pipe cross-section rotation as the nonlinear profile. The nonlinearity coefficient was found to be a function of top and bottom temperatures and fluid interface elevation. B&W developed a mathematical formula for nonlinearity coefficient as a function of these variables.

Using the extended mathematical piping model and calculating the nonlinearity coefficients for the Oconee data, a verification run was performed. The measured temperatures were applied to the model and displacements were determined. The comparison of calculated to measured displacements showed very good agreement. B&W stated that this verified the accuracy of the model and the nonlinearity correction method.

B&W used this model to analyze the three most critical thermal stratification conditions that occur during the most severe heatup transient. Top-to-bottom temperature differences were 397°F, 393°F, and 386°F. Additional analyses were performed for seven other thermal stratification conditions plus the unstratified 100% power condition. With these 11 sets of internal forces and moments, B&W was able to set up an interpolation scheme to determine internal forces and moments everywhere in the surge line for all temperature conditions.

Reevaluation of the surge line for thermal stratification involved satisfying ASME Code Section III NB-3600 allowable stress limits for primary plus secondary stress intensity range (Equation 10) and cumulative fatigue usage limits for peak stress intensity range (Equation 11). For the most critical thermal stratification cycles, the Equation 10 stress limit of $3S_m$ was exceeded. As an alternative, the Code permits a simplified elastic-plastic fatigue analysis by applying a penalty factor, Ke, to the peak stress (Equation 14) provided that the load sets meet the stress limits of Equation 12 and 13 of NB-3653.6 and the thermal stress ratcheting equation of NB-3653.7. B&W was able to demonstrate compliance with Equation 13 (primary plus secondary stress intensity excluding thermal expansion) and thermal stress ratcheting, but was not able to meet the Equation 12 (secondary stress range due to thermal expansion) limit of $3S_m$ in the elbows using the simplified formulas and stress indices given in the Code. B&W then attempted to remove the conservatism in the Code stress indices by developing new C_2 and K_2 stress indices for the surge line elbows based on finite element analysis. The computer program ABAQUS was used to generate an elasto-plastic finite element model of the elbows and apply in-plane and out-of-plane bending moments. Using the definitions of secondary and peak stresses and taking the higher of the two loading conditions, B&W defined generic stress indices of $C_2 = 1.58$ and $K_2 = 1.47$ compared to values of $C_2 = 2.33$ and $K_2 = 1.0$ from formulas given in Table NB-3685.1-2 of the Code.

Using the internal forces and moments from the most severe thermal stratification conditions and the redefined generic elbow stress indices, three of the four surge line elbows still exceeded the Equation 12 stress allowable. B&W then applied these forces directly to the elasto-plastic finite element model and used the same method to calculate maximum secondary stress as was used to generate the C_2 stress index. The resulting calculated secondary stresses were shown to be less than the $3S_m$ allowable.

For the ASME Code fatigue evaluation, B&W considered the stresses due to stratification induced moment loadings as well as localized peak stresses induced by through-wall temperature gradients ΔT_1 and ΔT_2 due to fluid flow, thermal striping, and nonlinear temperature profiles. Peak stresses due to thermal striping were determined from the striping temperature data given in the design basis transients. The temperature distribution through the wall thickness was determined from an ANSYS finite element model. The time-dependent wall temperature was simulated as a "cut-sawtooth" wave. From the experimental data, B&W determined that the fluctuations have a period of approximately 1.0 seconds. To cover a range of periods which could be expected, thermal analyses were performed with periods of 0.5, 1.0, 2.0 and 4.0 seconds. For each period, the extreme temperature profiles were determined and the linear and nonlinear through-wall temperature gradients were calculated, leading to the maximum peak stress intensity range.

Peak stresses due to the nonlinearity of the temperature profile are the result of the difference between the actual nonlinear and the "equivalent linear" temperature profiles used in the structural loading analysis. B&W referred to this temperature difference as ΔT_4. An ABAQUS finite element analysis was performed for the two most severe measured top-to-bottom temperature profiles. The analyses indicated that the maximum peak stress intensity occurs at the inside radius of the pipe cross section. From these results, B&W developed a correlation to calculate ΔT_4 as a function of top-to-bottom temperature difference and fluid interface elevation, and give the maximum peak stress intensity in the pipe as a function of ΔT_4, top-to-bottom temperature difference and fluid interface elevation.

B&W performed a fatigue analysis in accordance with the 1986 Edition of ASME Section III NB-3600 as required by Bulletin 88-11. Since all plants had been designed to earlier Code Editions, a Code reconciliation was performed. The findings indicated that for the 1986 Code: 1) more sophisticated formulas are used for stress indices, 2) allowables are equal to or smaller than the earlier allowables, 3) the fatigue curves go up to 10^{11} cycles compared to earlier curves which only went up to 10^6 cycles.

B&W calculated the "main fatigue usage" which they defined as the usage factor due to all thermal stratification conditions which are characterized by a top-to-bottom temperature difference. The absolute values of the peak stress ranges from the following contributions were added:

1. Moment loading range due to thermal stratification.
2. Moment loading range for the 30 occurrences of OBE.
3. Internal pressure range.
4. Additional localized peak stress due to nonlinearity of the top-to-bottom temperature profile (ΔT_4).
5. Maximum stress between the peak stress due to thermal striping and the one due to fluid flow (through-wall temperature gradients ΔT_1 and ΔT_2).

B&W performed a sort of all the total peak stress intensity values and built a selection table for the combination of the thermal stratification peaks and valleys into pairs in such a way that stress ranges were maximized. For each pair of conditions, the alternating stress intensity was calculated as a function of the peak stress intensity range and of the Equation 10 primary plus secondary stress intensity range. The usage factor associated with each alternating stress intensity value was calculated in accordance with the 1986 ASME Code extended fatigue curves (up to 10^{11} cycles). The summation of all usage factors for each pair gave the total "main fatigue usage."

In addition to the main usage factor, B&W evaluated the additional fatigue contributions due to the highly cyclic thermal striping ranges, the additional OBE ranges not associated with stratification, and the additional fluid flow conditions not associated with stratification. Contributions due to OBE and fluid flow were found to be very small. Fatigue usage due to thermal striping was found to be in the range of 0.10 and 0.15 depending on the specific plant. B&W combined the main usage factor with the additional fatigue usage contributions to calculate the total cumulative usage factor for each of the six B&W lowered loop plants. The values were different for each plant because the number of occurrences of the events in the design basis transients is unique to each plant. The results showed that all cumulative usage factors were below their allowable of 1.0. The highest usage factor was 0.82 and occurred in the vertical elbow at the bottom of the surge line riser to the hot leg in Oconee Unit 2.

In addition to the piping analysis, B&W performed detailed stress analyses of the pressurizer and hot leg nozzles. For both nozzles, axisymmetric thermal and thermal stress analyses were performed using the ANSYS finite element computer code. The loadings consisted of thermal gradients, internal pressure, and external piping loads. Since the pressurizer nozzle is vertical, there were no significant thermal stratification loads. The hot leg nozzle is horizontal and is subject to direct thermal stratification which produces circumferential temperature gradients. The stresses due to these gradients were determined by the use of the ANSYS harmonic element STIF 25 which can handle an axisymmetric structure with nonaxisymmetric loading. The nozzles were evaluated in accordance with the requirements for Class 1 components of the ASME Code, Section III, 1986 Edition. For both nozzles the linearized primary-plus-secondary stress intensities exceeded the $3S_m$ limit. However, the Code requirements were satisfied by performing a "simplified elastic-plastic analysis" as defined in NB-3228.5. Cumulative fatigue usage factors were calculated for each plant. All plants met the 1.0 allowable for both nozzles. The highest usage factors in the pressurizer nozzle was 0.41 in Oconee Units 2 and 3. In the hot leg nozzle, the highest usage factor was 0.62 in TMI Unit 1, Crystal River Unit 3, and ANO Unit 1.

The staff reviewed the stress analysis and Code evaluation methodology and results described in the BAW-2127 report and raised a number of questions which were discussed during the February 1991 audit. B&W provided copies of the detailed calculations on the piping and nozzle stress analyses for review. The staff reviewed selected portions of the piping stress analysis in detail. Based on the review, the staff found the B&W stress reevaluation effort to be comprehensive and complete. All known thermal stratification effects including global bending stresses, local stresses due to the nonlinear temperature profiles, and cyclic stresses due to thermal striping were considered. Calculations were found to be clear and well organized. Assumptions were reasonable and generally conservative. The accuracy of the mathematical piping model was checked against data taken at Oconee and showed good agreement in predicting displacements. The fatigue analysis considered stress intensity ranges due to all global and local stratification loads as well as other cyclic design loads. Absolute values of peak stresses due to different loads were combined by conservatively assuming that maximum stresses occur at the same location on the pipe cross-section.

There is, however, one significant issue that is currently unresolved. The staff disagreed with the B&W methodology for calculating a revised C_2 stress index for the surge line elbows. The methodology was discussed with B&W during the February 1991 audit and calculations were further reviewed in detail. The analysis involved the application of in-plane and out-of-plane bending moments to ABAQUS elastic and elasto-plastic finite element models of the surge line elbows. Based on the results of these analyses, new elbow stress indices were calculated as follows:

For peak stress:

K_2C_2 = Maximum stress anywhere in the elbow divided by the nominal (straight pipe) stress at the surface.

For secondary stress:

C_2 = Maximum stress at mid-thickness in the elbow divided by the corresponding nominal (straight pipe) stress at mid-thickness.

The K_2C_2 value was based on an elastic analysis while the C_2 value was based on an elasto-plastic analysis with a correction factor for displacement-controlled loading. B&W took the larger of the in-plane and out-of-plane stress index values and obtained $C_2 = 1.58$, $K_2C_2 = 2.33$ (or $K_2 = 1.47$). Using ASME Code tables, these values would be $C_2 = 2.33$ and $K_2 = 1.0$. The B&W indices, therefore, would predict significantly lower secondary stresses but the same peak (equation 11) stresses. In differentiating between secondary and peak stresses, B&W referred to the Code definition of peak stress (NB-3213.11) as "that increment of stress which is additive to the primary plus secondary stresses by reason of local discontinuities or local thermal stress including the effect of stress concentrations. The basic characteristic of a peak stress is that it does not cause any noticeable distortion and is objectionable only as a possible source of a fatigue crack." B&W also noted that Figure NB-3222-1 defines a "secondary" expansion stress intensity P_e as "stresses which result from the constraint of free end displacement. Considers effects of discontinuities but not local stress concentration." B&W argued that the maximum stress in the elbow has all the characteristics of a local stress concentration. Their review of the stress analysis results around the circumference and through the elbow thickness indicated that the highest stress intensity was highly localized. B&W also stated that the elbow behaved in a linear fashion after the highest stressed locations entered the plastic domain and that these stresses had a negligible impact on elbow distortion. B&W therefore felt justified in treating surface stresses as peak stresses and the average through-wall stresses (mid-thickness stresses) as secondary stresses.

With the redefined "generic" C_2 stress index, three of the four elbows still did not meet the equation 12 stress allowable. B&W performed additional elasto-plastic finite element analyses for the critical loading case to demonstrate that the elbows meet the expansion stress intensity limit. These analyses took advantage of the lower stress indices for in-plane bending (1.30) and torsion (1.0) and demonstrated acceptable results. However, the basic definitions of secondary and peak stresses were the same as discussed above. Secondary expansion stress intensity was based on mid-thickness stress.

The staff disagreed with the B&W interpretation of the definition of secondary and peak stress in an elbow. The Code (NB-3682) defines the C stress index as the <u>maximum</u> stress intensity due to load L divided by the nominal stress intensity due to load L. This presumably means maximum stress intensity anywhere in the cross-section, not a mid-thickness stress intensity. The B&W definition of secondary stress completely neglects the circumferential bending stresses that develop in an elbow. These stresses are considered only as peak stresses by B&W. It does not appear that the circumferential bending stresses in the elbow walls should be considered peak stresses. Peak stresses are generally associated with localized geometric or material discontinuities that effect the stress distribution through a fractional part of the wall thickness or with local thermal stresses that produce no significant distortion. In the case of elbows, the circumferential bending stresses affect the entire wall thickness and produce distortion (ovalization) of the elbow cross-section. NB-3222.3 defines expansion stress intensity as "the highest value of stress, neglecting local structural discontinuities, produced <u>at any point across the thickness of a section</u> by the loadings that result from restraint of free end displacement." The Code stress index tables (NB-3681(a)-1 and NB-3685.1-2) provide further evidence that the maximum elbow stresses should be treated as secondary stresses. The C_2 value of 2.33 computed from the table formulas agrees exactly with the B&W finite element model maximum stress at the elbow surface. The K_2 value of 1.0 indicates that no stress concentration factor needs to be applied to elbows for determining peak stress.

The potential consequences of this unresolved issue are as follows:

1. If Code stress indices are used, for the most severe thermal stratification load conditions, the range of thermal expansion stress intensity will exceed the $3S_m$ limit (Equation 12).

2. Higher C_2 stress indices will increase the primary plus secondary stress intensity value calculated in Equation 10. For severe load sets, which require the simplified elastic-plastic analysis method of NB-3653.6, the penalty factor, Ke, which is based on Equation 10 stress will increase. This will result in larger alternating stresses (Equation 14) and higher fatigue usage with potential for exceeding the 1.0 allowable.

Further staff discussions with an ASME Code expert indicated that the Equation 12 $3S_m$ allowable may have significant margin. Various tests have shown that piping systems can have substantial fatigue capacity even if Equation 12 is not met. Nevertheless, since meeting the $3S_m$ expansion stress limit is a current Code requirement, the staff recommends that B&W initiate an ASME Code inquiry to determine whether the Code Committee either agrees with the B&W interpretation of C_2 stress index or permits a higher Equation 12 allowable for this particular application.

The fatigue usage allowable of 1.0 for the life of the plant must be met. The staff recommends that B&W reevaluate fatigue usage using the Code table stress indices. If the allowable is exceeded, B&W should investigate alternate approaches to demonstrate that Code requirements for fatigue and expansion stress are met.

2.3 Plant Specific Applicability of B&WOG Analysis

The BAW-2127 report identified the conditions upon which the generation of the revised design basis transients and the thermal stratification fatigue stress analysis of the surge line were based.

The generation of the revised design basis transients for future events was based on the incorporation of operational guidelines which:

- limit the pressurizer to RCS temperature difference during plant heatups and cooldowns (imposed with pressure/temperature limits)
- prevent surveillance tests that cause rapid additions of water to the RCS from being performed with pressurizer to RCS temperature difference greater than 220°F

Pressurizer/temperature limits for future heatup and cooldown operations were included as Figure 8-1 of BAW-2127. In order to meet the pressure limit specified for heatup in the 70°F to 150°F temperature range, B&W recommended preheating the RCS. For heatups involving pressurization at lower RCS temperatures, a less restrictive limit was included in Figure 8-1. The fatigue evaluation was based on the assumption that 85% of the heatups for the remainder of plant life meet the recommended limit shown by path CDEN of Figure 8-1, and 15% of future heatups meet the less restrictive path ABEN.

The thermal stratification fatigue analysis was based on the following assumptions:

- no interference of the surge line with any other structure
- surge line movement within the travel range of each snubber
- surge line movement within the travel range of each hanger
- branch moments at the surge line drain nozzle connection within their respective maximum allowables (for deadweight, OBE and thermal stratification)

The staff discussed the conditions of applicability with licensee representatives present at the February 1991 audit. They indicated that the requirements were understood. They agreed to follow the B&W proposed operational guidelines. Operating procedures will be revised to reflect these limits. Licensees have received the maximum surge line displacements from B&W and are checking for interferences and for travel limits on hangers and snubbers. Each licensee will be responsible for reevaluating the drain line piping and nozzle. Plants with welded attachments (Crystal River and Davis-Besse) will evaluate them on a plant specific basis. The licensee representatives indicated that no problems have been identified to date. The staff found the licensee responses acceptable, but may verify licensee programs and activities in future plant specific audits.

3.0 CONCLUSIONS

Based on the review of BAW-2127 and additional information provided during the February 1991 audit, the staff concludes that B&W has defined and implemented a comprehensive program to address the pressurizer surge line thermal stratification concerns discussed in NRC Bulletin 88-11. The program is applicable to the six B&W lowered loop plants:

Arkansas Nuclear One Unit 1
Crystal River Unit 3
Oconee Units 1, 2, 3
Three Mile Island Unit 1

Licensees are responsible for verifying plant-specific applicability of the B&WOG program and results. This will include verification of analysis assumptions, qualification of supports and attached piping, and revision of operating procedures as indicated in BAW-2127. The remaining B&W plant, Davis-Besse Unit 1 is a raised loop plant which is undergoing a plant specific evaluation. The results of that evaluation will be reported in a future supplement to BAW-2127.

The B&WOG program developed a revised set of design transients which incorporated thermal stratification and thermal striping. The program included instrumentation and monitoring of surge line temperature and displacement data from a representative plant. The stress and fatigue analysis involved the development of structural mathematical models to analyze the global and local stresses resulting from stratified conditions in the line. Structural loading was performed using the revised design transients. Stress and fatigue evaluations were performed in accordance with the requirements of ASME Code Section III, 1986 Edition.

The staff review found the B&W effort to be quite extensive, thorough and of high quality. Assumptions were found to be reasonable and generally conservative. The staff found the methodology acceptable with one significant exception. B&W did not use the ASME Code stress indices as defined in Table NB-3685.1-2, but instead performed a finite element analysis to redefine lower stress indices for the surge line elbows. Although the Code permits stress indices to be defined by analysis, the staff disagrees with the B&W interpretation of the secondary stress index (C_2) for an elbow. The C_2 index was based on the maximum stress at the mid-thickness of the elbow wall. The staff believes that the C_2 index should be based on maximum stress anywhere in the elbow. This definition is consistent with the values obtained from the Code table.

The use of Code table stress indices for surge line elbows may have a significant adverse impact on the results of the B&W evaluation. It is highly probable that the surge line would not meet the Code limits on thermal expansion stress ($3S_m$) and fatigue usage (1.0). The staff, therefore, recommends the following actions:

1. Reevaluate the surge line to all Code requirements using the Code table stress indices for elbows.

2. If thermal expansion stress limits are exceeded, initiate an ASME Code Inquiry to determine whether the Code Committee agrees with the B&W interpretation of C_2 stress index or permits a higher Equation 12 allowable for this particular application.

3. If fatigue usage factor exceeds 1.0, investigate alternate approaches to demonstrate that Code fatigue requirements and expansion stress limits are met.