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

# REVIEW OF BABCOCK AND WILCOX OWNERS GROUP (B&WOG) PRESSURIZER SURGE LINE THERMAL STRATIFICATION BAW-2085 DATED MAY 1989

## INTRODUCTION

The pressurizer surge line (PSL) in pressurized water reactors (PWRs) is a stainless steel pipe, connecting the bottom of the pressurizer vessel to the hot leg of one of the coolant loops. The out flow of the pressurizer water is generally warmer than the hot leg flow. This temperature differential (delta T) varies with plant operating activities and can exceed 400°F during the initial plant heat-up. Thermal stratification is the separation of hot/cold flow streams in the horizontal portion of the PSL resulting in a temperature differential between the top and bottom of the pipe. Since thermal stratification is the direct result of the differences in densities between the pressurizer water and the hot leg water, the potential for stratification is increased as the system delta T increases and as the insurge or outsurge flow decreases. Stratification in the PSL was found recently and confirmed by data measured from several PWR plants.

The original design analyses of the surge line did not include any stratified flow thermal loading conditions. Instead, it assumed a complete sweep of fluid along the line during insurges or outsurges resulting in uniform thermal loading at any particular piping location. This analysis does not reflect actual thermal conditions in the PSL and may overlook undesirable piping deflections and the stresses may exceed design limits. In addition, the striping phenomenon, which is the oscillation of the hot and cold stratified boundary that may induce high cycle fatigue in the inner pipe wall, needs to be analyzed. Accordingly, assessment of stratification effects on the PSL is necessary to ensure piping integrity and conformance with ASME Code, Section III.

## STAFF EVALUATION

Since stratification in the PSL is a generic concern to all PWRs, an NRC Information Notice, No. 88-80, was issued on October 7, 1988. Subsequently, NRC Bulletin 88-11 for the same concern was issued on December 20, 1988. Babcock & Wilcox (B&W), on behalf of the B&W Owners Group (B&WOG), has performed a generic bounding evaluation report, BAW-2085 (Reference 1). Additional information was also provided in Reference 2. The purpose of the report is to:

a. Describe the B&WOG program and plans for addressing both the surge line thermal stratification and the striping issues.

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b. Present the results of the preliminary work done to date to justify continued operation (JCO) until the final program results are available. This is expected to be completed by December 31, 1990.

B&W reported that the thermal striping program has not been completed and only preliminary results are available. Upon completion of the striping program, a final report will be prepared which will provide the technical basis for the 40-year life of the plants. Comparison of calculated PSL thermal displacements with the Oconee 1 measured data will also be performed in the final report.

The following is the staff's evaluation of the B&W efforts and the information provided in References 1 and 2.

During the hot functional testing of the B&W plant at Muelheim-Kaerlich (M-K) in West Germany, the PSL was instrumented and temperature readings were taken during start-up which confirmed that stratification existed in the PSL. As a result, B&W designed a program to instrument a domestic plant to determine the magnitude of the stratification effects, since the M-K plant is different from the domestic plants in terms of power level, PSL layout, pipe diameter and thickness.

Later the scope of the program was expanded to include surge line movements as well as data for evaluating thermal striping.

Based on the M-K data, B&W concluded that the surge line stratification depends on the following factors:

a. Surge line flow rate and flow direction.
b. Cooling of the fluid (ambient loss).
c. Boundary thermal conditions (hot leg and pressurizer temperatures).

Since all B&W domestic plants (7 plants, 10 units) have the same surge line configuration, with the exception of Davis-Besse, B&W performed two bounding fatigue evaluations:

a. Oconee 1
b. Davis-Besse

The Davis-Besse plant surge line has a long horizontal run from the hot leg to a 7.25-foot vertical drop near the center of the surge line span to another long horizontal run of pipe which connects to the bottom of the pressurizer. Hence, the overall run of the pipe is essentially divided into two horizontal runs by the 7.25-foot vertical section. This vertical rise near the center of the surge line will reduce the transmission of the stratification gradients downstream.

In all other plants, a 13-foot vertical drop of pipe exists much closer to the hot leg resulting in a very short horizontal section of 21 inches connecting to the hot leg nozzle. Therefore, two separate fatigue evaluations were performed. The surge line for each configuration is a 10-inch schedule 140, stainless steel pipe.

The Oconee 1 surge line was modeled using the ANSYS finite element computer code. The loadings consisted of pressure, seismic, deadweight, and thermal expansion, from the original stress report, and were combined with the additional thermal stratification loads. The temperature ranges used in the analysis were obtained from the M-K measured data, since no plant-specific data were available at the time of the bounding evaluation.

Thermal stratification was assumed to occur over the entire lower horizontal run of pipe. The maximum pipe top-to-bottom delta T, for the three load cases considered (pre-heatup, heatup, and cooldown) was assumed to be 330°F, 422°F, and 306°F, respectively, and was based on the maximum system delta T. Pre-heatup was assumed to occur three times during each heat-up and cooldown cycle.

Stress indices were used in accordance with Section III of the ASME Code, 1977 Edition with Addenda through the Summer of 1979. The Oconee 1 bounding fatigue evaluation predicted expansion stresses from Equation 12 on the vertical elbow from the pressurizer, far in excess of the ASME Code allowable limit of $3S_m$ (50.1 ksi). This is twice the material yield strength at 650°F. Stresses calculated using Equations 9 and 13 are within Code allowables since they are not affected by thermal stratification.

To take advantage of the material behavior in the inelastic range, B&W substituted the cyclic "strain-hardened" yield strength ($S_h$) in place of the static yield strength ($S_y$), and a higher allowable value of $2S_h$ was obtained. The $S_h$ value is defined as the "strain hardened" yield strength of the material at temperature. B&W reported that in its final analysis, it is their intent to meet the ASME Code acceptance criteria of Section NB-3600.

The staff disagrees with this approach of using twice the "strain-hardened" yield strength in place of the Code specified $3S_m$ limit even if this is a preliminary and conservative analysis.

With the exception of Davis-Besse, all other B&W plants have no rigid supports or pipe whip restraints. Even if the Oconee 1 type plants have no supports which resist thermal motion, there is no indication that snubber/spring travel limitations were considered in the bounding evaluation. The staff's recommendation is that thermal displacement of the PSL should be considered at the support locations and it should be verified that adequate snubber/spring travel exists.

The fatigue usage factors for Oconee 1 type plants, excluding the striping effects, were calculated at several locations along the surge line for the thermal stratification load cases, and were combined with those from the stress analysis of record to obtain the total usage factor.

Based on the fatigue life of each part affected by the stratification effects, the allowable number of heat-up/cooldown cycles was calculated.

| Location | Allowable number of cycles |
| --- | --- |
| Hot leg nozzle (carbon steel portion) | 270 |
| Hot leg nozzle (stainless steel portion) | 162 |
| Surge line (straight or elbow) | 153 |
| Surge line drain nozzle | 135 |
| Pressurizer nozzle (stainless steel portion) | 341 |
| Pressurizer nozzle (carbon steel portion) | 396 |

This indicates that the worst case plant, Oconee 2, which has experienced 96 cycles to date, can withstand an additional 39 cycles to reach the allowable limit of 135 cycles for the surge line drain nozzle or a cumulative usage factor (CUF) of 0.71 (96/135). The 0.71 factor does not include the effects of striping.

Based on the average of nine heat-up/cooldown cycles/year, B&W indicated that an additional four years of continued plant operation is justified.

The Davis-Besse surge line analysis was conducted in a similar manner as the Oconee Unit 1 analysis. The design transient inputs for the fatigue analyses were developed by Toledo Edison. Adjustments were made to the M-K data to account for the differences between M-K and Davis-Besse but no plant-specific temperature distribution data or surge line displacements were obtained.

Thermal stratification was assumed to occur over the full length of the lower horizontal pipe run and each transient was assumed to occur three times during the bubble formation. The staff concludes that further investigation is necessary to justify this assumption for the Davis-Besse plant. The staff also believes that, depending on the direction of the flow (insurge or outsurge), thermal stratification may occur in the upper horizontal run of pipe and that the Davis-Besse unique configuration will experience different stratification conditions than the Oconee 1 type plants.

For Davis-Besse, Impell Corporation performed the deflection/stress analysis of the thermal stratification events using the ANSYS computer code and the surge line met the $3S_m$ limit of the B31.7 Code for Equations 10 and 12.

The $3S_m$ limit was based on values from the Certified Material Test Reports (CMTR). Due to the uncertainty of the relationship between product strength and the CMTR values, it is obvious that the use of such values for replacing Code allowables is not acceptable.

B&W performed the bounding fatigue evaluation for Davis-Besse utilizing the output of the Impell analysis. The values, excluding the striping effects, are as follows:

| Location | CUF |
|---|---|
| Hot leg nozzle (branch connection) | 0.619 |
| Hot leg nozzle (carbon steel portion) | 0.704 |
| Hot leg nozzle (stainless steel portion) | 0.343 |
| Surge line (straight or elbow) | 0.063 |
| Pressurizer nozzle (stainless steel portion) | 0.297 |
| Pressurizer nozzle (carbon steel portion) | 0.634 |

Based on the average of three heat-up/cooldown cycles per year which have been experienced by Davis-Besse during the past 12 years, B&W reported that an additional five years of continued plant operation can be assured.

Subsequent to the bounding evaluations discussed above, temperature measurements were obtained during the February 1989 heat-up of Oconee Unit 1, and indicated much smaller pipe top-to-bottom delta T. As a result of these PSL temperature measurements, the bounding fatigue evaluation was reviewed for consistency. The measurement program initiated at Oconee Unit 1 determined surge line temperatures and thermal displacements during plant heat-up and steady state operation. The temperature differences assumed for the bounding evaluation of a delta T of 422°F and a delta T of 330°F were found to envelope the actual delta T's of 280°F and 250°F, respectively, at most critical locations. No upsets or complete cooldowns have occurred yet; therefore, measurements for these types of transients are not available to integrate into the bounding evaluation. Temperature data were also obtained at the outside surface of the surge line and detailed heat transfer analyses were necessary to approximate the conditions at the inside surface to adequately evaluate the striping phenomenon.

To account for the effects of the non-linear temperature profile and the lower pipe top-to-bottom delta Ts, which were obtained by the temperature measurements, at Oconee 1, the peak stress ranges calculated in the bounding analysis were refined as follows:

1. Scaled down in accordance with the lower top-to-bottom delta T's.

2. Increased by a factor to account for the increased pipe rotation due to the non-linearity of the temperature profile. (This factor is based on a finite element analysis comparing the actual measured temperature profile versus the assumed linear temperature profile.)

3. Added the corresponding peak stress for the maximum thermal striping phenomenon.

Based on the above refinements, the resulting alternating stress range predicted that the worst component for the Oconee, Unit 1, PSL drain line nozzle can still withstand the limiting number of 135 heat-up and cooldown cycles, as predicted by the bounding evaluation. Similarly, the Davis-Besse PSL at the hot leg nozzle can still withstand the limiting number of 57 heat-up and cooldown cycles.

B&W reported that a thorough treatment of thermal striping has not been evaluated yet and to account for the thermal striping effects to PSL, input from the Oconee Unit 1 measurement program will be utilized. Thermocouples were installed around the outside circumference at nine locations along the surge line. Heat transfer analysis will be performed to determine the fluid temperature amplitude and the period of oscillation at the inside surface of the pipe.

These data will be evaluated and a more detailed striping fatigue analysis will be performed based on the evaluation of the Oconee 1 measured data. Results of this effort will be submitted to the staff in a topical report in December 1990. An interim assessment of the cyclic thermal stresses due to striping has been made. Preliminary results from this striping evaluation indicate that the fatigue impact on the surge line is approximately 10% of the allowable usage factor with the maximum contribution occurring during the early part of plant heat-up.

Based on the information available in the public domain (BWR feedwater nozzle tests, liquid metal fast breeder reactor tests, Argonne National Laboratory tests, HDR project tests), an estimate of the oscillatory behavior of the fluid at the stratified interface was made. Oconee test data also supports this interim set of characteristics for assessing the striping phenomenon.

CONCLUSIONS

Based on its review, the staff concludes that the information provided by Babcock and Wilcox in references 1 and 2 is inadequate and not entirely acceptable for justifying operation for the 40-year life of the B&W plants. The staff concludes that further technical justification is required to meet the ASME Code acceptance criteria of NB-3600.

The staff has identified the following concerns:

a. The ASME code acceptance criteria of Section NB-3600, Equations 9 to 14, need to be satisfied as applicable. The approach of using twice the "strain hardened" yield strength or using the CMTR values in place of the Code specified limits may be non-conservative and is not acceptable.

b. All supports, including pipe whip restraints, should be considered in the bounding evaluation for the effects of thermal constraint.

c. All supports, including pipe whip restraints, require plant-specific confirmation of their displacement capabilities, including clearances, and that they fall within the bounds of the analysis.

d. You should compare your calculated PSL thermal displacements with the Oconee 1 measured data to demonstrate the validity and conservatism of the bounding analysis.

REFERENCES

1) Babcock and Wilcox Report, BAW-2085. "Pressurizer Surge Line Thermal Stratification," dated May 1989.

2). Babcock and Wilcox letter from Daniel F. Spond to Terence L. Chan (NRC), OG-854. "Pressurizer Surge Line Thermal Stratification," dated September 29, 1989.