

STRESS ANALYSIS OF A 900 MWe PRESSURIZER SURGE LINE INCLUDING STRATIFICATION EFFECTS

C. Ensel¹, A. Colas¹ and M. Barthez²

¹FRAMATOME, France

²Electricité de France

1. INTRODUCTION

Several surge line temperature monitoring programs have been applied to different French PWRs, since 1981. Stratification was observed for the first time on Dampierre 4 surge line. In 1984, a temperature monitoring program performed on CRUAS 2 pressurizer surge line, a three loop 900 MWe unit, confirmed that such a line is stratified in steady state, due to its long horizontal portion and its horizontal nozzle on hot leg (see figure 1). This phenomenon is generic to all French 900 MWe surge lines and was not considered in design stress report. As local transients in the line are modified and bending moments increased by stratification, it has an impact on fatigue damage of lines.

Obviously the first problem was to determine transients affected by stratification and to characterize the fluid temperature profile in different cross sections during these transients. Then using a simplified 2D-1D method developed by FRAMATOME, avoiding a three-dimensional modelisation of the line, a complete stress analysis of a surge line was performed, including the stratified transients and consequently increased bending moments.

This paper presents the whole approach leading to a stress report including stratification effects.

2. THERMAL HYDRAULIC TRANSIENTS.

2.1. Thermal hydraulic test results

Temperature monitoring program in the CRUAS 2 unit was aimed at obtaining fluid temperature profiles in different cross-sections during transients. Therefore, some cross-sections were instrumented on their outer surface, with several thermocouples around the circumference. This program concluded that a 900 MWe pressurizer surge line is stratified in steady state and during low flow rate transients. The highest temperature difference between hot and cool water layers was recorded during heat-up in steam bubble mode and cool-down and was equal to the temperature difference between pressurizer and hot leg : $T_{\text{pressu}} - T_{\text{HL}} = 110^{\circ}\text{C}$.

Nevertheless this program was not sufficient to characterize fluid temperature profiles during all transients. Thermal hydraulic tests were also carried out on a half-scale plexiglass model of CRUAS surge line named EXPRESS, experiment supported by EDF CEA and FRAMATOME. Temperatures measured with thermocouples located around different cross sections of the EXPRESS

mock-up agreed with fluid temperature profiles obtained from the CRUAS 2 measurements. These tests revealed that fluid temperature profile in a stratified cross-section is mainly correlated to the Froude number depending on :

- the flow rate in the line,
- the temperature difference between pressurizer and hot leg.

For each instrumented cross-section of EXPRESS, a Froude number threshold Fr_T is determined by experiments : above this threshold, there is no stratification in the considered cross-section. Moreover, in presence of stratification, the temperature difference between upper and lower water layers in the horizontal portion is close to the temperature difference between pressurizer and hot leg.

2.2. Determination of transients with stratification.

Some of the thirty transients of the design list occur with a low flow rate, inducing then a stratification in the line. This stratification may vanish, under a flow rate increase, inducing thermal shocks in cross-sections. These shocks are determined in five representative sections located in high stress zones (elbow, weld, see figure 1). Knowing pressurizer and hot leg temperatures, flow rate variations versus time, the Froude number is computed versus time, during transients.

Therefrom, stratification conditions can be determined in the five sections, during all transients :

- Each time the Froude number exceeds the threshold Fr_T in a section, stratification disappears instantaneously. It may be caused by a flow rate increase from pressurizer to hot leg and conversely. Induced thermal shocks are described on figure 3 (respectively case (a) and (c)).
- After a flow rate increase from hot leg, surge line being at hot leg temperature, stratification is supposed to be restored in a second by a low flow rate from pressurizer (see induced shock on case (b) figure 3).
- After a flow rate increase from pressurizer, surge line being at pressurizer temperature, it was observed on the plexiglass mockup that stratification is restored after several tens seconds, in the 90° elbow under pressurizer (section E). During most of transients, stratification is restored when flow rate returns to normal operating condition : 6 m³/h from pressurizer to hot leg. In this case, the 90° elbow is stratified again after 100 seconds (case (d) figure 3).

3. HEAT EXCHANGE COEFFICIENT.

Assuming the surge line at pressurizer temperature, when stratification appears from the hot leg, the lower part of cross-sections is subjected to a cold thermal shock. As cooler water flows in a layer, through the lower part of the cross-sections, it is difficult to assess a value of the heat exchange coefficient. A three-dimensional thermal hydraulic computation has been performed, by TRIO computer code, on a simple model of the surge line, including a 4.5 meter long horizontal pipe connected to a vertical pipe through a 90° elbow. This model is initially subjected to the pressurizer temperature and then stratification is restored with cooler water coming from the hot leg. Given :

- mean velocity in the cooler water layer,
- interface level between the two layers,
- heat exchange coefficients,

thermal hydraulic computations are completed for different values of flow rate and temperature difference between pressurizer and hot leg, and thus for

several Froude number.

In the considered cases (ΔT from 22°C to 110°C the pressurizer temperature being equal to 345°C, flow rate from 4 m³/h to 70 m³/h) the heat exchange coefficient can be estimated as the highest value between :

- heat exchange coefficient in natural convection,
 - heat exchange coefficient in forced convection,
 - heat exchange coefficient in mixed convection,
- computed with the cooler water velocity and the hydraulic diameter D_H of the cooler water layer.

In case of a stratification due to a hot water layer feeding by pressurizer, the upper part of the cross-section is subjected to a hot thermal shock. The flow rate in the hot water layer Q_{hot} is given by : $Q_{pressurizer} = Q_{hot} + Q_{cold}$ where the flow rate in the cold water layer Q_{cold} is obtained from Froude number and previous finite element analyses. The hydraulic diameter of the hot layer is deduced from the cold layer one obtained from Froude number.

4. MECHANICAL ANALYSIS.

The 900 MWe surge line being stratified in steady state, thermal hydraulic transients generate two types of cyclic loads :

- thermal stresses due to shocks,
- stratification moments usually not considered in design stress reports.

A mechanical analysis methodology developed by FRAMATOME and presented in ref [1] allows the impact of these combined loads on fatigue damage to be evaluated. This method, avoiding a three-dimensional computation, is based on a two-dimensional computation of thermal stresses in a stratified cross-section and on a one-dimensional computation of the line loaded with a mean temperature and a curvature in its stratified portion, giving stratification bending moments in the line.

Since the number of transients with stratification is important, sensitivity studies were performed, using this methodology, in order to simplify the analyses.

4.1. Mechanical sensitivity studies.

* As observed on the EXPRESS mockup, stratification interface is sloped along the horizontal portion, one of sensitivity studies demonstrated that a unique temperature profile in all stratified cross-sections, with an interface located in the middle, leads to similar or higher stratification bending moments. Such a profile was assumed in our analyses.

* In order to reduce the transient number analysed with the 2D-1D method, a temperature difference threshold ΔT_0 between pressurizer and hot leg is determined. For a typical transient, the alternating stress intensity is computed for different values of ΔT , the threshold ΔT_0 corresponding to the endurance limit. Below ΔT_0 , stratification has no consequence on fatigue damage. The analysed transient is described on figure 4 : the line is initially stratified with a temperature difference between hot water and cooler water equal to ΔT . The stratification is then removed under a high flow rate increase from pressurizer. The entire line is at pressurizer temperature during 900 seconds. The stratification is then restored when the

flow rate decrease to the normal condition value : 6 m³/h. Three ΔT value are considered : 30 - 50 - 100°C. The alternating stress intensity is computed in the 90° elbow under pressurizer (section E figure 1), including a longitudinal and circumferential welds. Results are the following:

ΔT °C	S_P^{th} MPa	S_P^{Mt} MPa	$\frac{S_P^{Mt}}{S_P^{Mt} + S_P^{th}}$	S_{alt} MPa
30	209.9	57.8	0.22	152.
50	361.	107.	0.23	293.
110	733.3	215.6	0.23	750.

The endurance limit being equal to 180 MPa, the value of ΔT threshold is :

$$\Delta T_0 = 35^\circ\text{C}$$

Below this threshold, additional bending moments due to stratification have no impact on usage factor and are not considered in the fatigue analysis. However thermal stresses are taken into account because they might represent a minimum stress combined with an other transient. They are computed following RCCM section B3600.

4.2. Fatigue damage analysis.

The 90° elbow (section E) is the most exposed to fatigue damage :

- the presence of longitudinal and circumferential welds generate stress concentration,
- this elbow is subjected to the highest stratification bending moments of the line,
- for each small flow rate increase coming from pressurizer, stratification vanishes in this section but not necessary in all the line.

So the fatigue damage analysis is presented only in this elbow. Following RCCM regulation, stress indices of the elbow, the flushed longitudinal weld and the circumferential as welded joint should be combined, leading to $C_2 = 1.96$, and $K_2 = 1.98$. As the circumferential weld is located at the end of the elbow, ovalization effect is reduced. The stress index C_2 is computed at this end section with a three-dimensional model of the elbow under bending moment : $C_2 = 1.2$.

Then the elbow is analysed in two sections (see figure 2):

- the median section (E_1) with combined stress indices of elbow and flush longitudinal weld $C_2 = 1.96$, $K_2 = 1.1$,
- the end of elbow (E_2) with combined stress indices of flush longitudinal weld, circumferential joint as welded and a reduced elbow effect $C_2 = 1.2$, $K_2 = 1.98$.

These sections are subjected to same thermal loads, only stress indices are different. Two azimuths are considered in each section :

- the upper azimuth (E_1^+ , E_2^+) subjected to cold thermal shocks when stratification is vanished and to hot shocks when stratification is restored,
- the lower azimuth (E_1^- , E_2^-) subjected to hot shocks when stratification disappears and to cold shocks when it is restored (see figure 3).

As demonstrated in sensitivity studies, for transients with a temperature difference below 35°C, stratification bending moments are negligible, thermal stresses are computed following section B3600 of the RCCM code, temperatures

in the considered azimuth being estimated using a one-dimensional convection model.

When temperature difference is higher than 35°C, thermal stresses are computed in the cross-section, bending moments being calculated on the one-dimensional model. Bending moment stresses are then estimated following equation (11) of the RCCM code :

$$K_2 C_2 \frac{M_{i,j} D_0}{2 I}$$

As bending moment extrema do not occur with thermal stresses extrema (see an example on figure 5) the bending moment variation $M_{i,j}$ associated to each transient is computed for thermal stress extrema, in order to reduce the margins.

Results are the following : (U.F. = Usage Factor)

<u>SECTION E₁</u> :	E ₁ ⁺	U.F. = 0.28	<u>SECTION E₂</u> :	E ₂ ⁺	U.F. = 0.90
	E ₁ ⁻	U.F. = 0.09		E ₂ ⁻	U.F. = 0.38

5. CONCLUSIONS.

Based on EDF and FRAMATOME experiences, such as temperature measurements on site and mockups, local transients in 900 MWe surge lines were defined, taken into account stratification. Thermal hydraulic computations allow thermal exchange coefficients to be determined in different configurations.

The 90° elbow under pressurizer (see figure 1) is the most exposed to fatigue damage, specially in the end section (E₂) where effects of longitudinal and circumferential welds are combined. The most severe transients are the heat-up and cool-down. During these transients, the 90° elbow is subjected to six 110°C cold thermal shocks on its upper part, produced by flow rates from hot leg. Only three 110°C hot shocks are induced on the lower part by flow rates from pressurizer. The usage factor is then higher in the upper part of this elbow.

REFERENCE :

- [1] Ph. Taupin, E. Thomas-Solgadi, C. Ensel, Method to Assess Mechanical Effects of Stratification Phenomenom in Piping System. SMIRT 10, paper F08/3, Anaheim, August 1989.

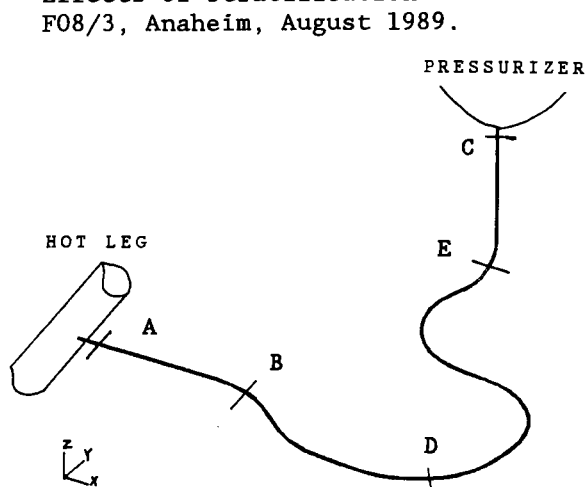


FIGURE 1 : 900 MWe PRESSURIZER SURGE LINE CONSIDERED CROSS-SECTIONS

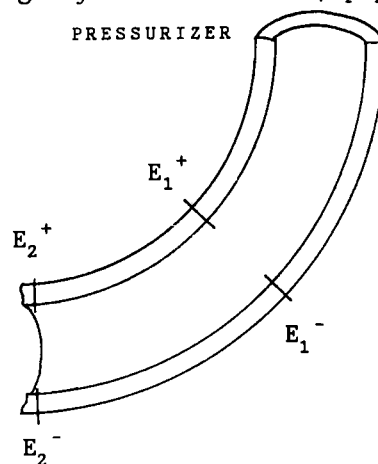


FIGURE 2 : ANALYSED SECTIONS IN THE 90° ELBOW UNDER PRESSURIZER

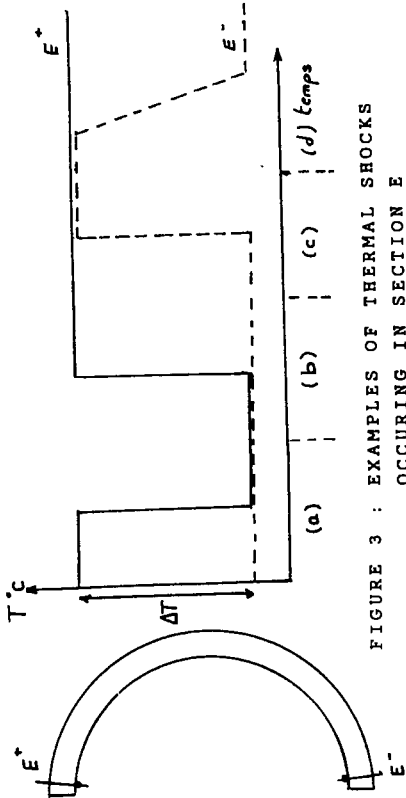


FIGURE 3 : EXAMPLES OF THERMAL SHOCKS OCCURRING IN SECTION E

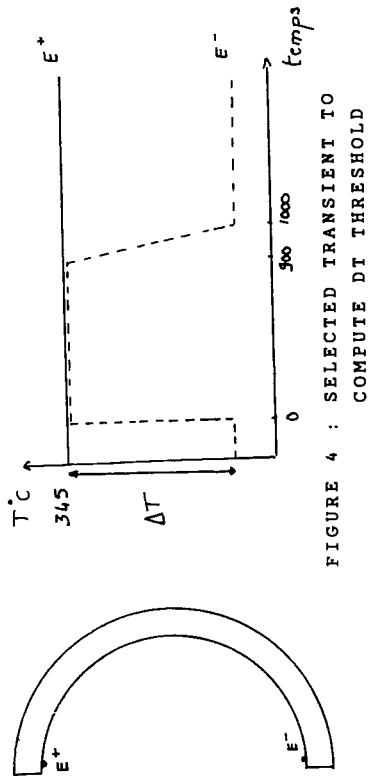


FIGURE 4 : SELECTED TRANSIENT TO COMPUTE DT THRESHOLD

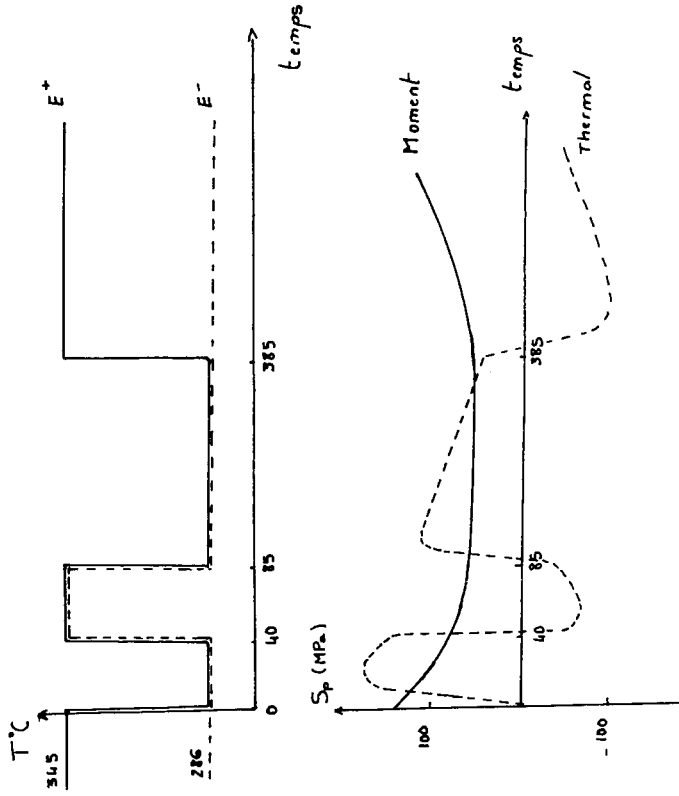


FIGURE 5 : VARIATION OF THERMAL AND BENDING MOMENT PEAK STRESSES IN SECTION E⁺