PERIODIC REMAINING LIFE EVALUATION PROGRAM OF PWR PRESURIZER SURGE LINE ACCOUNTING FOR THERMAL STRATIFICATION EFFECT

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Abstract

Pressurizer surge line contains high temperature, high pressure and high radioactive reactor coolant. It is of nuclear class I and seismic category I. It is one of the important equipment keeping the integrity of primary pressure boundary. Generally, the fatigue usage factor of surge line is comparatively high, owing to its operating temperature and pressure transients and its thermal stratification cyclic loads. NRC issued Bulletin 88-11 relating to surge line thermal stratification problem almost twenty years ago. From then on, lots of research has been done and prove that: thermal stratification of fluid in the surge line is likely to occur when the flow velocity during an insurge or outsurge is low and temperature difference between the pressurizer and the hot leg is large. Therefore the potential for thermal stratification is greatest during heat-up and cooldown because the difference between the pressurizer and hot leg temperature is then the largest. Consequently, SNERDI established a program to perform temperature measurement for surge line and fatigue re-evaluation of it accounting for thermal stratification effect for a 300MWe PWR NPP during its start of commissioning. Refer to the temperature records of the measuring points relating to the plant heatup and cooldown, thermal stratification phenomenon can clearly be observed. And then we modified the original design thermal transients for the surge line, included the thermal stratification and thermal stripping effects, and reevaluated it following ASME III NB-3650. Its maximum design-basis fatigue usage factor during its design life is bellow 1.0. From the design safety point of view, it is enough to evaluate the surge line according to the maximum design-basis transients including thermal stratification, thermal stripping and thermal shock effect. But from the LTO & AM point of view, the actual fatigue usage factor which is a function of plant operation rather then the design assumptions is important and necessary for the preparation of the plant operation beyond its design life. Owing to the difficulty to replace the surge line, it is very important and useful to reevaluate the surge line remaining life each a certain period according to the result of on site temperature measurement during the commission. And it can be one of the foundations of the surge line life management. Accordingly, SNERDI put forward another program to perform temperature measurement for surge line and fatigue reevaluation of it accounting for thermal stratification effect for a PWR NPP of several years of operation. Subsequently, based on the temperature measurement program, existing thermal stratification data base and improving analysis methods, the periodic remaining life evaluation program of PWR Pressurizer surge line concerning thermal stratification effect can be successfully achieved.

Keywords: pressurizer surge line, thermal stratification, fatigue, life assessment.

1.0 DESIGN AND OPERATING TRANSIENTS MODIFICATION ACCOUNTING FOR THERMAL STRATIFICATION

Thermal stratification was observed and measured on many PWR NPPs both in the U.S. and France. And it is identified as a concern which can affect the structural integrity of piping systems in nuclear plants. The purpose of U.S. NRC bulletin 88-11 is to (1)request that addressees establish and implement a program to confirm pressurizer surge line integrity in view of the occurrence of thermal stratification and (2) require addressees to inform the staff of the actions taken to resolve this issue. And the addressees are all holders of operating licenses or construction permits for pressurizer water reactors(PWRs). The 300MWe NPP designed by SNERDI is two loop pressurized water reactor. Each of its SRC loop contains a steam generator and a reactor coolant pump. The SRC system also includes the pressure vessel and the pressurizer connected to the loop B hot leg through the surge line and its auxiliary equipment necessary for reactor coolant pressure control and overpressure protection.

The reactor coolant pressure control is carried out by the action of electric heaters and spray valves. The spray system is fed from two cold legs and is connected to the pressurizer through the spray nozzle. A small continuous spray flow is provided through the flow requlating valve to reduce thermal stresses and thermal shock when the spray valves are opened.. The surge line has an as long as over 17m long horizontal section of pipe with the height difference between the pressurizer nozzle and hot leg nozzle near 0.1m. The owners of the 300MWe NPP designed by SNERDI were asked by the nuclear safety bureau to clarify the surge line thermal stratification issue. Accordingly SNERDI established a research program to perform temperature measurement of surge line and fatigue life reevaluation of it accounting for thermal stratification effect.

1.1 SURGE LINE TEMPERATURE MONITORING FOR THERMAL STRATIFICATION

The first work is to establish a program of temperature monitoring of surge line in order to obtian the actual and detail data representing the stratification phenomena. The pressurizer surge line monitoring program utilized externally mounted temperature sensors. The temperature sensors were attached to the outside surface of the pipe at various circumferential and axial locations. And all the recorded data can give a good picture of how the top to bottem temperature distribution varies along the longitudinal axis of the pipe each two minutes. Two 300MWe NPPs adopted this monitoring program. One is before its commissioning, and the other is about six years after its first ten year interval.

Lots of research has been done and prove that: thermal stratification of fluid in the surge line is likely to occur when the flow velocity during an insurge or outsurge is low and temperature difference between the pressurizer and the hot leg is large. Therefore the potential for thermal stratification is greatest during heat-up and cooldown because the difference between the pressurizer and hot leg temperature is then largest. So the temperature distributions during heatup and cooldown conditions were carefully recorded for the two NPPs, and thermal stratification phenomenon can clearly be observed for both. There is an example of its temperature record shown in the picture 1-1 bellow. And an example of its temperature difference record shown in the picture 1-2 bellow.

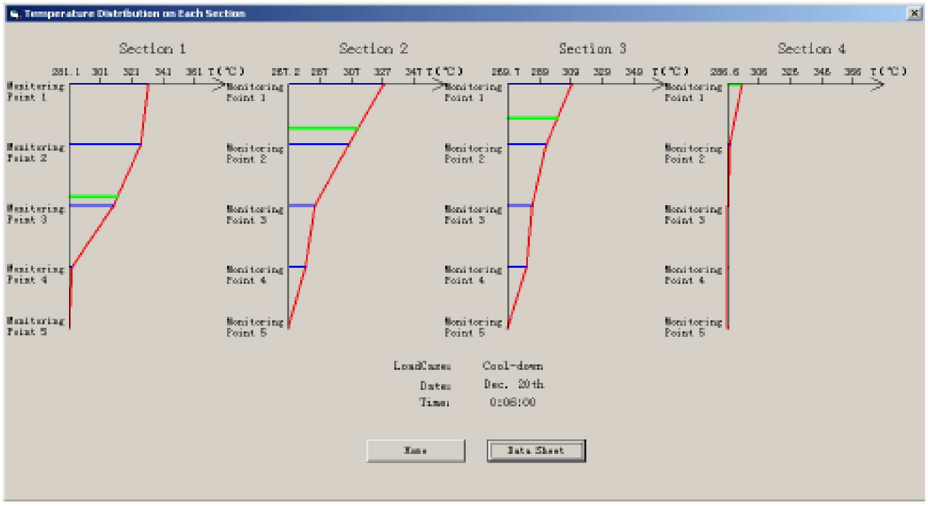


FIG. 1. An example of temperature record

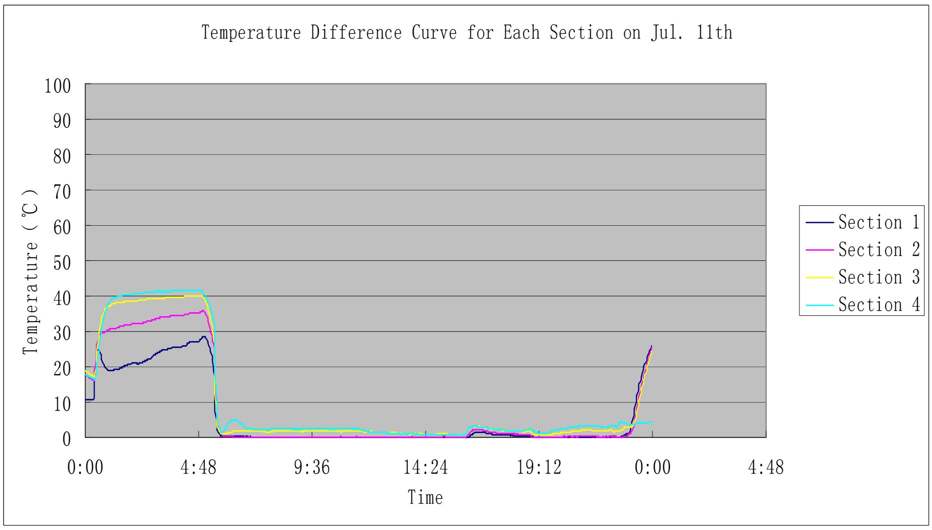


FIG. 2. An example of temperature difference record

1.2 DESIGN AND OPERATING TRANSIENTS MODIFICATION

The following work was to develop transients applicable to the above mentioned NPPs which include the effects of stratification. The transients were developed based on the originally established desgn transients and were refined through the use of monitoring results, plant operating procedures, operator interviews and applicable data or experience of similar NPPs. The similarities rely on the surge line layout, the plant operating procedures and the piping and support configurations.

The heatup and cooldown transient was first modified mainly based on the monitoring data, historical records and applicable information of similar NPPs to include a number of sub-events which have been defined to reflect stratification effects for each cycle.

Then for each of the normal and upset transients, except for heatup and cooldown, the surge line fluid temperature was modified from the original design assumption of uniform temperature to a stratified distribution, according to the predicted temperature differentials between the pressurizer and hot leg. These transients have been characterized as either insurge/outsurges or fluctuations.

1.3 DATA BASE FOR TEMPERATURE MONITORING AND EVALUATION RESULTS

A computer program which is based on database was developed to preserve, manage and analyze the monitoring results. It can produce the following functions:

1) To show a diagrammatic curve of temperature difference versus time within any specified period of time for each monitoring section. Fig 1-3 is an example. It can reflect the extent and the variation of stratification.

2) To show a diagrammatic curve of temperature versus time within any specified period of time for each monitoring point. Fig 1-4 is an example. It can reflect the range of temperature change and its change rate.

3) To show the temperature distribution and stratification indication at any specified time for all monitoring sections. Fig 1-1 is an example. It can reflect the hot-to-cold interface and severity of stratification.

4) To categorize stratification cycles using the rainflow cycle counting method. And delta T change range and its relating occurrences can be provided.

5) To provide a database for all monitoring results.

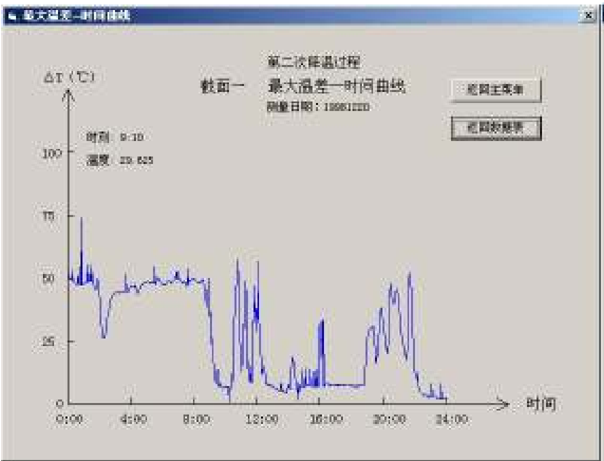


FIG. 3. Section temperature difference versus time

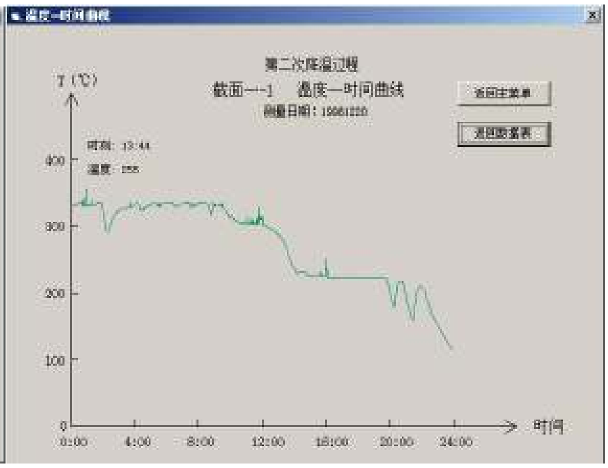


FIG. 4. Temperature versus time for a point

With the increasing accumulation of transient data, this program could play an important role in the life assessment of the pressurizer surge line.

2.0 FATIGUE ANALYSIS AND LIFE ASSESSMENT

According to IAEA document, there are six ageing mechanisms that tend to reduce the life of the reactor coolant system piping components. They are thermal fatigue, thermal ageing, primary water stress corrosion cracking, vibrational fatigue, boric acid corrosion and atmospheric corrosion. And thermal fatigue is the major ageing mechanism for surge line and its nozzles. From the design safety point of view, it is enough to evaluate the surge line according to the maximum design-basis transients including thermal stratification, thermal stripping and thermal shock effect. But from the LTO & AM point of view, the actual fatigue usage factor which is a function of plant operation rather then the design assumptions is important and necessary for the preparation of the plant operation beyond its design life. Owing to the difficulty to replace the surge line, it is very important and useful to reevaluate the surge line fatigue life each a certain period according to the result of on site temperature measurement during the commission. And it can be one of the foundations of the surge line life management.

2.1 THERMAL TRANSIENT LOAD SETS FOR FATIGUE ANALYSIS

Design or operating transients and thermal stratification phenomena can induce different types of thermal fatigue load sets. For 300MWe PWR NPP, there are many different types of stratification cases only for heatup and cooldown conditions. Its reactor has 11 normal operating conditions besides heatup and cooldown, 3 test conditions and 12 upset conditions, and almost each of them has its own relating stratification case. For pressurizer surge line, distinct spray operating conditions are specified 6 times during plant heatup and 7 times during plant cooldown. Accordingly, the load sets were categorized and combined in order to not only reduce the complexity of calculation and analysis, but also to reflect the effect of different type of load sets on the fatigue analysis result. And then a number of typical load sets which can cover all transient conditions which should be concerned in the analysis were concluded.

Key parameters of the transient load sets were selected based on their effects on the range of stress change, and sensitivity analysis for each parameter was performed to help the categorizing and combination of the transient load sets. The key parameters for normal and upset thermal transient are: temperature difference and its change rate, pressure difference, temperature distribution, pressure distribution and flow rate. And the key parameters for thermal stratification case are: average temperature of each section, top-to-bottom temperature difference of each section, hot-to-cold interface position and relating pipe inside pressure. All these key parameters are refer both to surge line and reactor coolant system hot leg line.

It is not always the same that load sets combination is performed simply based on the requirements which allow the load set with large temperature and pressure difference to envelop the load set with smaller one and allow the load set with high temperature changing rate to envelop the load set with lower one. Cases such as load set with large temperature difference but low change rate, or load set with high average temperature of section but small top-to-bottom temperature difference of section, often occur and make the combination more difficult. Consequently, the effects of pressure, varied moment and thermal transient on the stress level for each pair of load set should be analyzed before the combination, and reasonable transient load sets which can reflect the actual conditions to the extent of moderate conservatism would be available for the fatigue analysis.

2.2 ANALYSIS MODEL

The integrated reactor coolant loop/supports system model is used to perform the fatigue analysis of the surge line and its nozzles. The analytical model mainly includes the stiffness and mass characteristics of the reactor coolant loop piping, the pressure vessel, two steam generators, two pumps, pressurizer, surge line, component supports and some secondary piping. Fig 2-1 shows an isometric line schematic of this mathematical model. And Fig 2-2 is the 3D PDS model of the main loop which includes the pressurizer and surge line. PIPE 728 computer program is used to construct the model and perform the analysis. PIPE 728 (Integrated Piping Analysis System) analyzes piping systems of power plants for static and dynamic loadings, and computes and evaluates the combined stresses in accordance with the ASME Boiler and Pressure Vessel Code, Section □ NB/NC/ND-3650. PIPE 728 was validated according to the requirements of SRP 3.9.1.

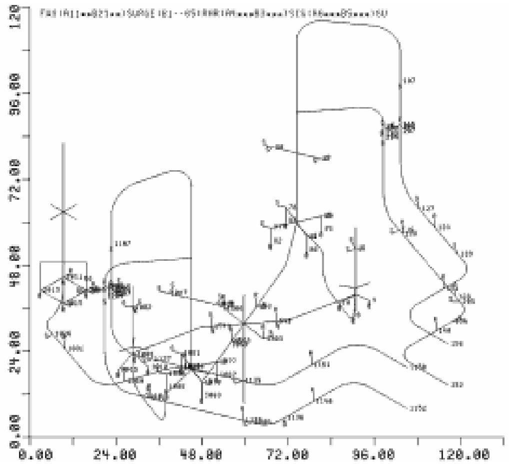


FIG. 5. *Isometric line schematic of the mathematical model*

FIG. 6. *3D PDS model of the main loop*

Due to the effects of thermal stratification, the temperature distribution of the pipe section can be classified as three components: average distribution, linear distribution and non-linear distribution. They cause different types of stress on the section according to the definitions of ASME code. The linearly distributed temperature will cause the global bending of the surge line. And the impact of the global bending on the pipe is analyzed using the ANSYS computer program. Fig 2-3 shows the analysis results for the surge line under the 'bending temperature' (linearly distributed temperature) of 29℃.

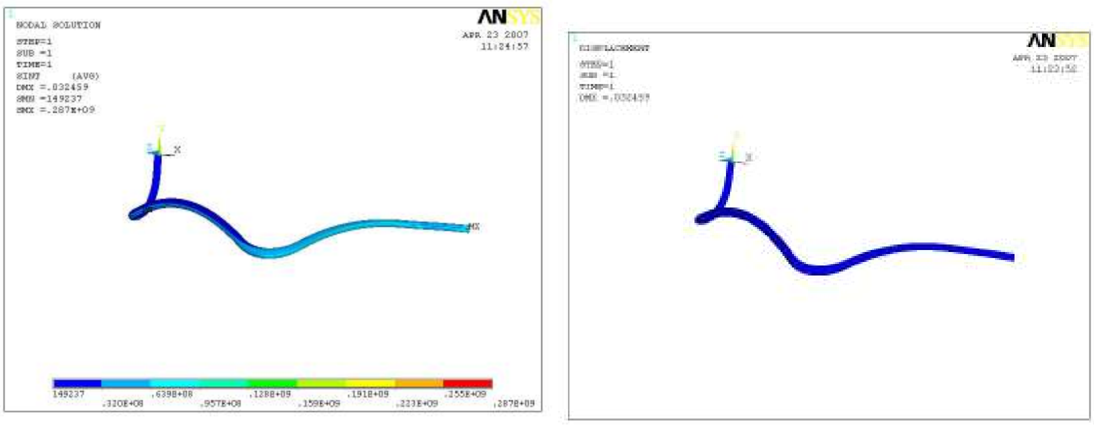
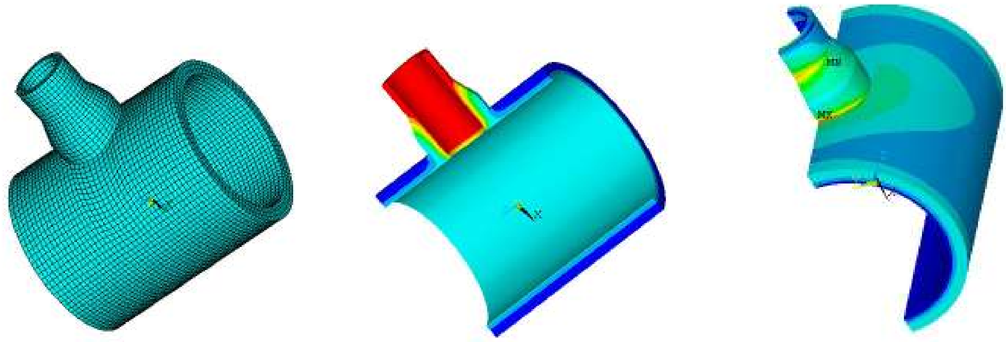


FIG. 7. Analysis results for the surge line under the 'bending temperature' of 29 ℃.

The local stress caused by the hot-to-cold interface on the pipe cross-section due to thermal stratification was calculated assuming a step change hot to cold. And the thermal striping stress due to the turbulence in the hot-to-cold stratification layer was also considered taking into account of the attenuation of thermal striping potential. Meanwhile the comment and R&D results in the IAEA-TECDOC-1361 was also used for reference.

A combination of line element model and 3D solid structure model is used to analyze the surge line hot leg tee connection. Fig 2-4 shows the detail 3D tee analysis model and the result of temperature distribution and the result of σ_1 distribution.



a) 3D tee model *b) Temperature Distribution* *c) σ_1 distribution*

FIG. 8. 3D model of the surge line hot leg tee

2.3 EVALUATION OF THE RESULTS

With the thermal transient load sets deducted from the modified design transients based on the temperature monitoring results, Pressurizer surge line fatigue evaluation was accomplished according to the ASME III NB-3650 for each of the two 300MWe PWR NPPs. And the maximum design-basis fatigue usage factor during each design life is bellow 1.0.

But from the design safety point of view, it is enough to evaluate the surge line according to the maximum design-basis transients including thermal stratification, thermal stripping and thermal shock effect. From the owner's point of view, the LTO & AM are playing more and more important roles due to their significance to both safety and economy. And the actual fatigue usage factor which is calculated based on plant operating transient is one of the important and necessary solutions to the evaluation of the component life, especially for the one whose degradation mechanism is mostly thermal fatigue.

For the Pressurizer surge line, we can also get some important information from the result of the fatigue analysis. It is very easy to find that the normal operating transients including heatup and cooldown provide a comparatively small contribution to the usage factor although the significant thermal stratification transients are observed. On the contrary, some upset transients with very conservative assumptions of the stratified temperature for I/O thermal stratification transients provide a comparatively large contribution to the usage factor although most of them are very unlikely to happen. After all, these upset transients are supposed to occur during the up coming expected service life for fatigue life evaluation.

Accordingly, the thermal stratification temperature monitoring program is an practical, feasible and helpful way to support surge line life assessment for the owner. And the owner should keep it in long term efficiency, and save and group the recording data in consistent with the plant operating transients. For the designer who is the lifelong technical supporter for the owner, elaborate transients analysis based on actual operating procedures and temperature monitoring results is necessary and useful to refine the life assessment work, for example that detail local fluid field analysis model with the help of temperature monitoring can be used to reduce the tendency of conservatism within the assumptions of thermal stratification loads.

3.0 CONCLUSION

SNERDI has helped two owners of 300MWe PWR NPP to establish the temperature monitoring system for the Pressurizer surge line and obtained the valuable temperature distribution records which show that significant thermal stratification occurrence exist during the plant heatup and cooldown conditions. It is necessary and practical to establish a periodic remaining life evaluation program of PWR Pressurizer surge line concerning thermal stratification effect for the purpose of plant LTO and AM.

For the fatigue life evaluation, the categorizing and combination of the thermal transient load sets based on the analysis of the selected key parameters of the transients are useful to reduce the complexity of calculation and analysis, and to find the important types of transient who contribute significantly to the analysis result. And consequently, reasonable life evaluation results and effective AM program can be concluded.

With the help of the temperature monitoring system, a database and the relating management computer program is developed in order to preserve, manage and analyze the monitoring results. Meanwhile, the design transient is modified and the operating transients can be refined with the method of detail transient analysis on the basis of temperature measurement.

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