

Thermal Fatigue Analysis of an Emergency Core Cooling System Nozzle of a BWR Reactor, by the Finite Element Method

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Recibido el 20 de junio de 2006; aceptado el 10 de enero de 2007.

1. Abstract

The evaluation of the fatigue cumulative usage factor for the High Pressure Core Spray (HPCS) nozzle of a Boiling Water Reactor (BWR) reactor is developed in this paper. This fatigue phenomenon is originated mainly due to the sudden injection of cold water inside the reactor vessel through the before mentioned nozzle. In this case, there is a thermal shock which produces high stresses. Therefore, a numerical methodology is applied, based on the requirements of ASME Code. Firstly the thermal and transient stress fields are calculated with the Finite Element Method and secondly the total cumulative usage factor of the HPCS nozzle is evaluated following Miner's criterion.

Key words: thermal stress, fatigue analysis, Miner's criteria, transient thermal-stress analysis, fatigue usage factor.

2. Resumen (Análisis de fatiga térmica en una boquilla de enfriamiento de un reactor BWR, por el método del elemento finito)

El objetivo del presente trabajo es desarrollar una metodología para la evaluación de daño acumulado en boquillas de inyección de agua de emergencia en recipientes a presión mediante el elemento finito de acuerdo a lo establecido en el código ASME. Éstas son utilizadas en sistemas de protección en reactores de agua en ebullición (BWR), siendo el principal objetivo bajar la temperatura del núcleo cuando éste aumenta arriba del rango de operación permisible por medio de una inyección de agua tratada. Sin embargo, debido a la diferencia de temperaturas entre la pared del reactor y la boquilla, existe un choque térmico, éstos generan esfuerzos térmicos altos que varían cíclicamente, lo cual corresponde al caso de fatiga de bajo número de ciclos. En consecuencia, esto genera un daño acumulado que de no controlarse puede conducir a falla. Esto es evaluado con la regla Miner.

Palabras clave: estrés térmico, análisis de fatiga, regla de Miner, factor de fatigas por uso.

3. Introducción

One of the main problems that the world is facing is the lack of clean energy for satisfying energy needs all around the world avoiding enhanced greenhouse effects and global warming. Furthermore, the nuclear programs are a good option to deal with this problem, they would be reactivated. So, while nuclear option is reactivated the users are taking actions like "License Renewal" and "Power Update" [1, 2 and 3]. Therefore, there are two important issues to study in components important to safety of a Nuclear Power Plant, for dealing with the mentioned issues (1) the continuous and precise monitoring of the cumulative damage in critical components or locations and, (2) the knowledge about the shape and geometry of defects and flaws, material deterioration, etc (ageing). In both cases, the evaluation of

consumed life and remaining life is required. So, fatigue analysis is an important tool for developing them.

Mexico has a Nuclear Power Plant named Laguna Verde (LVNPP) with two units with Boiling Water Reactors (BWR-5). In this paper, as an example, the consumed life of the HPCS nozzle (its internal diameter is 9.67 in) of a BWR generic is analyzed. Accordingly, a methodology for thermal stress fatigue analysis is proposed. It is used in conjunction with the Finite Element Method (FEM) and the ASME Code Section III. For this purpose, the Palmer-Miner's criterion of cumulative fatigue damage [4] is used. Although, this criterion is for Linear-Elastic materials and several simplified considerations are taken into account, the results obtained are considered acceptable. In the open literature, there are many cases where its validity is demonstrated as for example [5]. It is important to mention that the Mexican regulatory guidance indicates that LVNPP must use the ASME Code, due to the fact that the reactor proceeds from the United States of America. For this purpose, an accurate evaluation of the transient stress field is required. In this paper, the thermal fatigue analysis of the first twelve water injections is reported, besides the flexibility introduced by the adjacent pipe is taken into account in the calculations. The transient pressure is not considered because a nozzle is considered as thick shell so its effect is negligible. It is important to mention that thin shells are susceptible to pressure transients, while they are not affected by temperature transients.

4. Description of the problem

The HPCS system is part of the Emergency Core Cooling System (ECCS) and its main purpose is to provide water inside the Boiling Water Reactor when there is a piping break in such a way that the heat generated remains under control, avoiding fuel damage. It has to be kept in mind that the reactor design conditions establish that the wall of the nozzle is at 528 °F (548.5 °K) like the vessel, at normal conditions, and when the HPCS system is demanded, water from the suppression pool or from a condensate tank is injected at 40 °F (27.4 °K). It is considered, from a theoretical point of view, that this transient occurs suddenly. In order to avoid a thermal shock, the nozzle is provided with a jacket or thermal sleeve. However, the joint of the nozzle and the jacket is under high stress low cycle fatigue, due to this location is not protected by the thermal sleeve, besides it has a change of geometry which produces a high stress concentration.

Nozzles are one of the most important components of the Reactor Pressure Vessel in a Nuclear Power Plant because they are very sensitive to thermal fatigue. In this paper, twelve injection cycles have been considered and these cycles could have been developed at either lower or higher conditions than those foresight at the

design. Furthermore and for the reasons already mentioned at the beginning of this paper, it is important to know accurately the accumulated damage. Due to the fact that stress amplitudes for thermal shock are high then the nozzle will sustain adequately, only a reduced number of cycles. Clearly, this is a problem in which a transient temperature field is coupled with a stress field in a complicated geometry. In order to evaluate the phenomenon, FEM was used. For this purpose, the computing infrastructure available was a Pentium PC with 8 Mbytes in RAM and 512 Mbytes of capacity in its hard disk. ANSYS Code was used for all the calculations and when the stresses are obtained, the ASME Code [6] is applied in order to obtain the Cumulative Usage Factor, which must be less than 1.0 in accordance with Miner's rule and no crack is considered at the nozzle.

5. Methodology

Considering, the computational resources mentioned above, as well as the nozzle geometry, an axisymmetric model was developed. Accordingly, the analysis was divided in three main steps.

1. THERMAL-TRANSIENT HEAT TRANSFER ANALYSIS, in which the following parameters are considered: the temperature of the injected water, the operating temperature of the reactor which remains constant, and the temperature of the surrounding atmosphere of the nozzle, as well as the forced convection heat transfer on the external boundaries of the nozzle.
2. A STRESS ANALYSIS, which evaluates the stresses caused by the transient temperature gradient during each time step.
3. A THERMAL FATIGUE ANALYSIS which is developed applying ASME Code III requirements in conjunction with Miner's criterion for the evaluation of the cumulative usage factor.

6. Analysis of the problem

In first instance, a stationary analysis was done, its purpose was to simulate the operating conditions before the water injection. Following this, the transient analysis was performed. Thus, after each step, in which the transient thermal field was calculated, the stress evaluation was carried on. Besides, the arrangement of nozzle with its piping system establishes two analysis conditions. In the first case, only the nozzle was considered, in the second case, it was assumed that the adjacent piping, which has an "L" shape, gives an extra flexibility. These reduced the severity of the transient stress field. Accordingly, the geometry between the end nozzle and the first support was considered in the calculations. Therefore, an equivalent straight pipe was calculated, in such way that

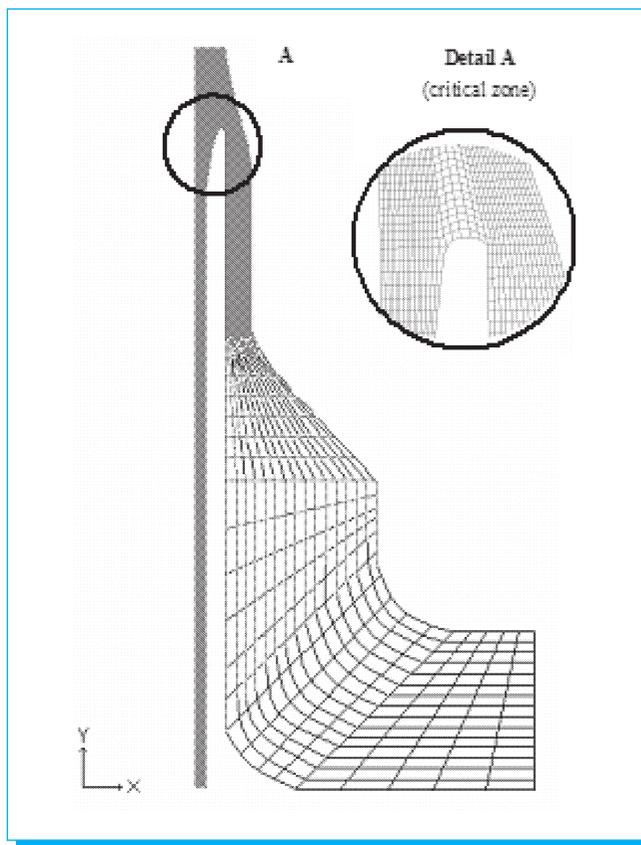


Fig. 1. Mesh used in the nozzle analysis.

both geometries, the proposed and the "L" shape, have an equivalent stiffness and, afterwards, this was considered in the axisymmetric finite element model.

In both cases, the element selected for the FEM analysis was PLANE75 axisymmetric, in order to take advantage of the computing equipment capacity. It is a linear rectangular axisymmetric element which can be used in the thermal analysis coupled with the stress analysis. It has four nodes and each one has three degrees of freedom [7]. The material of the reactor pressure vessel wall is SA 503 ASTM (low alloy carbon steel) and the material of the nozzle and thermal sleeve is SB 166 and SA 336.

6.1. Analysis of the HPCS nozzle

The mesh used for the nozzle analysis has 2 575 elements, in which 1 225 of them were located on the critical zone, which is the zone where the thermal sleeve and the nozzle are joined (Figure 1). Note that the elements of the sleeve and above the shoulder nozzle are smaller. For this reason, the grid mentioned above is shadowed in this area.

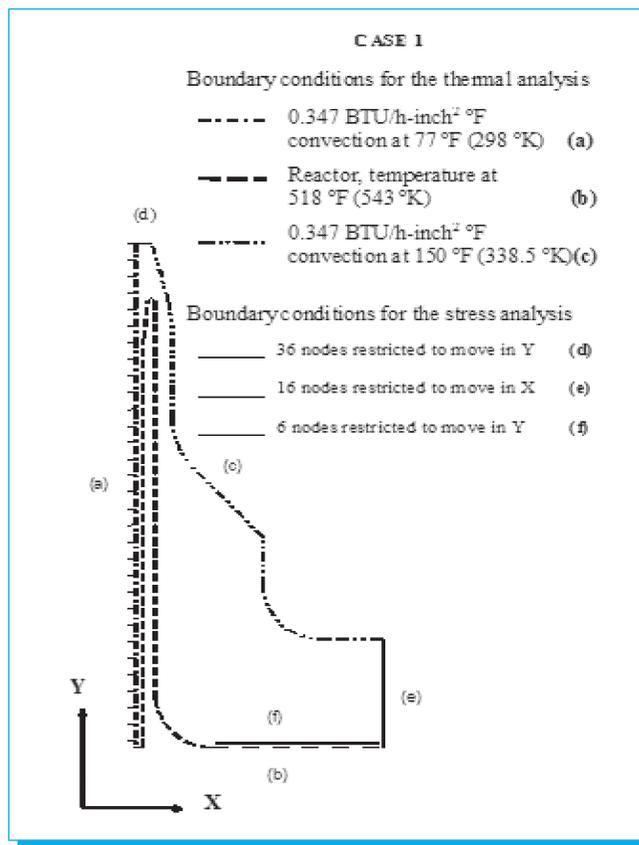


Fig. 2. Boundary conditions for the thermal and stress analysis of the case 1.

Figure 2 shows schematically the boundary conditions for the thermal and stress analysis. Firstly, the internal wall reactor and the sleeve is at 518 °F (543 °K), the wall that directs the water to the reactor is subjected to a forced convection of 0.347 BTU/h-inch² °F at 77 °F (298 °K), and the external nozzle surface is subjected to a forced convection of 0.347 BTU/h-inch² °F at 150 °F (338.5 °K). For the stress analysis, thirty-six nodes at the end that is next to the piping system were restricted to move in the "Y" direction. Besides, in the nozzle's end, which is joined to the reactor, 16 nodes were restricted to move in the radial direction of the nozzle.

6.2. Analysis of the HPCS nozzle and the equivalent straight length

The mesh used in case 2 has 3 800 elements, and is similar to the one considered in case 1. In this case, the mesh in the critical zone has 1 225 elements. Figure 3 shows schematically the boundary conditions. In the case of the thermal analysis, the same boundary conditions were applied as in the first

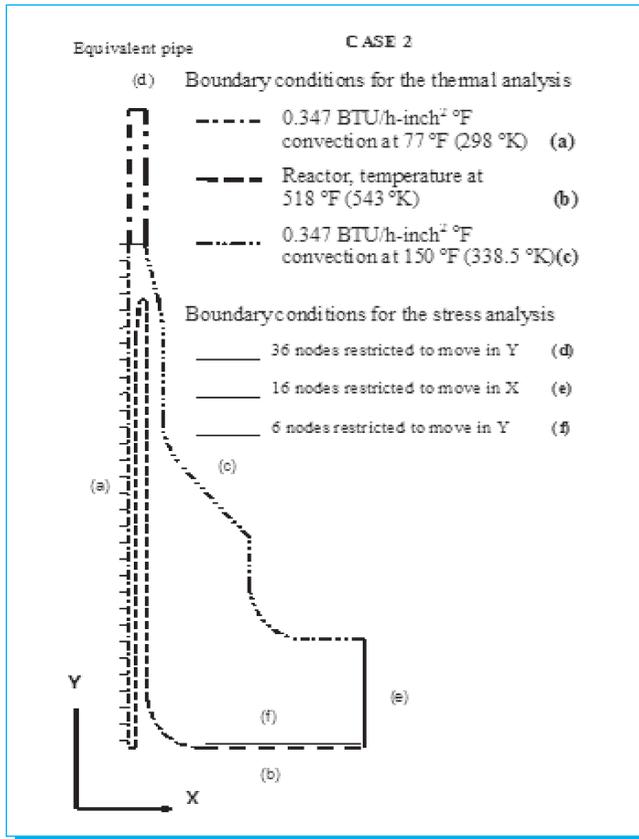


Fig. 3. Boundary conditions for the thermal and stress analysis of the case 2.

case. The external wall of the nozzle and the equivalent straight pipe was subjected to a forced convection of 0.347 BTU/h-inch² °F at 150 °F (338.5 °K). The internal wall and jacket reactor temperatures are 518 °F (543 °K) and there is a forced convection at 0.347 BTU/h-inch² °F at 77 °F (298 °K) in the internal wall of the nozzle and the pipe.

Regarding the boundary conditions for the stress analysis, 36 nodes at the end of the equivalent pipe were restricted to move on the "Y" direction, while 16 nodes at the nozzle's end that is next to the reactor wall are restricted to move in the nozzle radial direction.

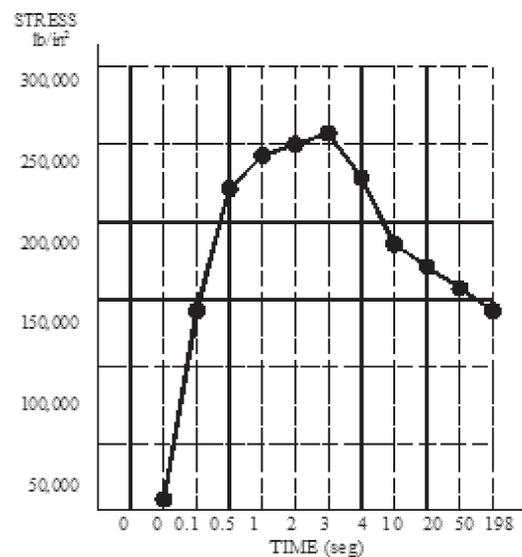
7. Analysis of the results

The temperatures of the reactor and injected water, which were reported during each injection cycle, are shown in table 1. The initial analysis of the transient thermal field, showed that after 198 seconds, the temperature field tends to stabilize. However, the stress variation during the cycle was studied.

Table 1. Temperatures reported in the twelve injection cycles (°F).

Injection cycle	Temperature of reactor and nozzle	Temperature of injected water
1	524 (546.3 °K).	60.7 (288.9 °K).
2	445 (502.4 °K).	77.1 (298.0 °K).
3	524 (546.3 °K).	80.2 (299.7 °K).
4	520 (544.1 °K).	80.1 (299.7 °K).
5	523 (545.7 °K).	78.1 (298.6 °K).
6	521 (544.6 °K).	78.2 (298.6 °K).
7	516 (541.8 °K).	77.1 (298.0 °K).
8	526 (547.4 °K).	77.1 (298.0 °K).
9	526 (547.4 °K).	78.2 (298.6 °K).
10	526 (547.4 °K).	79.1 (299.1 °K).
11	527 (548.0 °K).	60.3 (288.7 °K).
12	527 (548.0 °K).	98.4 (309.8 °K).

The stress-time curve of the first injection is shown in graphic 1. Initially, the curve is in an steady state, in which the average stress 686.6 kpsi is under design levels. Afterwards, three seconds after the injection, a maximum stress of 256 670 kpsi is developed. From this point, stress tends to be reduced until steady state is reached again. In all the cases studied, this peak stress was considered for fatigue calculations. In order to get some knowledge, in a first approach, a fatigue analysis was performed considering twelve average cycles with the design conditions. For the first case, the nozzle has



Graphic 1. Stress-Time curve.

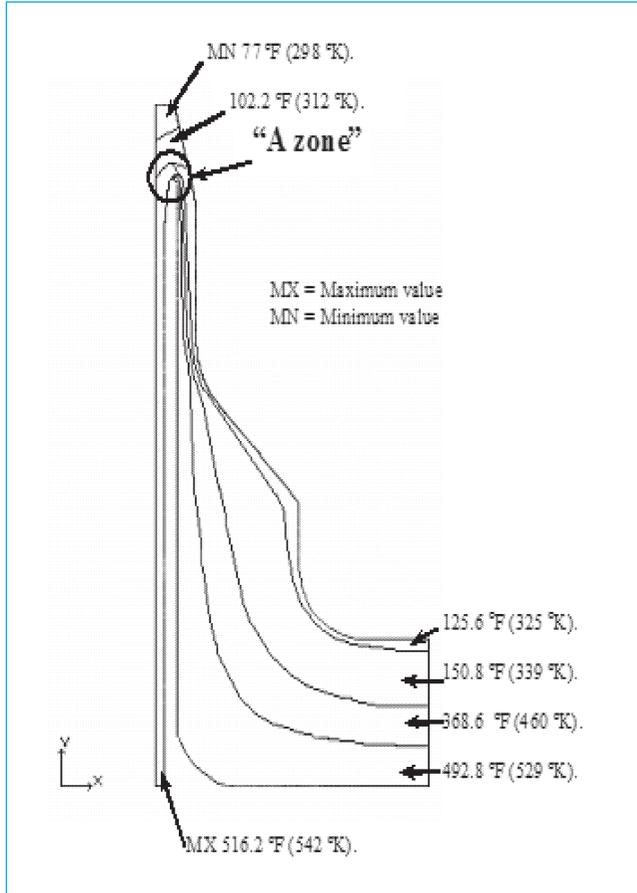


Fig. 4. Temperature gradients.

a temperature field which is in agreement with the boundary conditions and its gradient is not a severe one, except in the "A zone" in which, the nozzle and the sleeve are joined (Figure 4). This implies the development of peak thermal stresses.

The analysis of the maximum principal stress field (Figure 5) confirms that the stress field is almost uniform on the whole nozzle body, except on the identified critical zone. In which the highest peak stress is 256.67 kpsi (1 770 MPa).

The analysis of the temperature distribution of case 2, shows similar conclusions as those obtained for case 1 (Figure 6), the main difference is that the maximum peak stress is lower 160.38 kpsi (1 106 MPa) (Figure 7), although it is developed in the same zone point. In order to explain this result, it must be considered the fact that the temperature distribution in the equivalent pipe, reduces the severity of the temperature gradient in the critical zone. Moreover, these

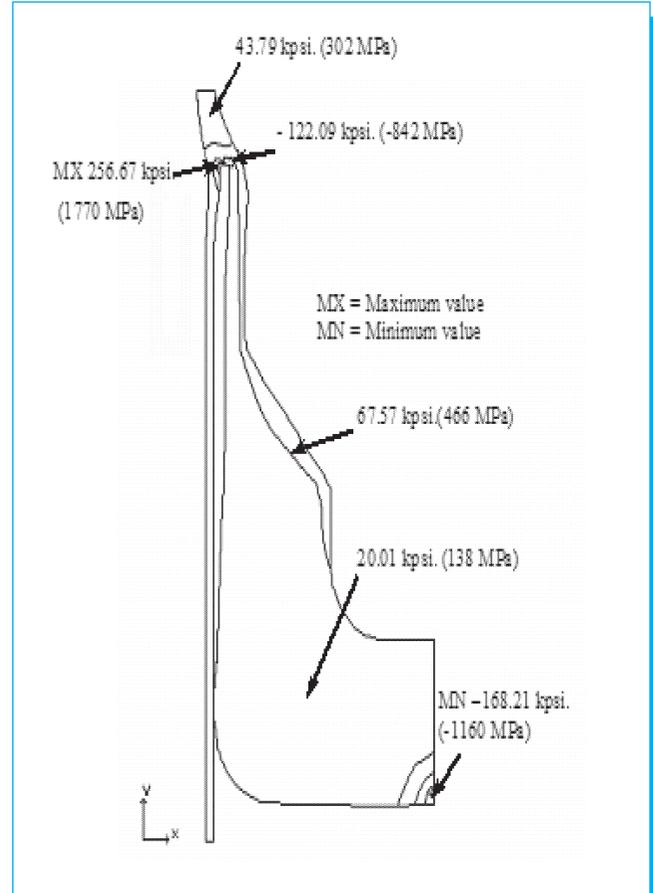


Fig. 5. Thermal stresses.

results confirm that the pipe adds flexibility to the nozzle reducing the peak stresses, with this information, the average cumulative usage fatigue damage was evaluated. In all the cases it was used, the design curve of fatigue for austenitic steels, nickel-chromium-iron alloy and nickel-copper-alloy of ASME Code Section III Division I [6]. Table 2 establishes a comparison among the results obtained for the different cases.

In the case of the design methodology, it seems that a Discontinuity Stress Analysis was performed, and peak stresses were developed in the same location observed in this paper. However, the stresses are lower in this last case due to the fact that a Discontinuity Analysis is conservative because it applies the deformation compatibility criterion among thin or thick cylinders, not considering the exact geometry in transitions or in rounded locations. This explains the difference between the old methodology and modern FEM results.

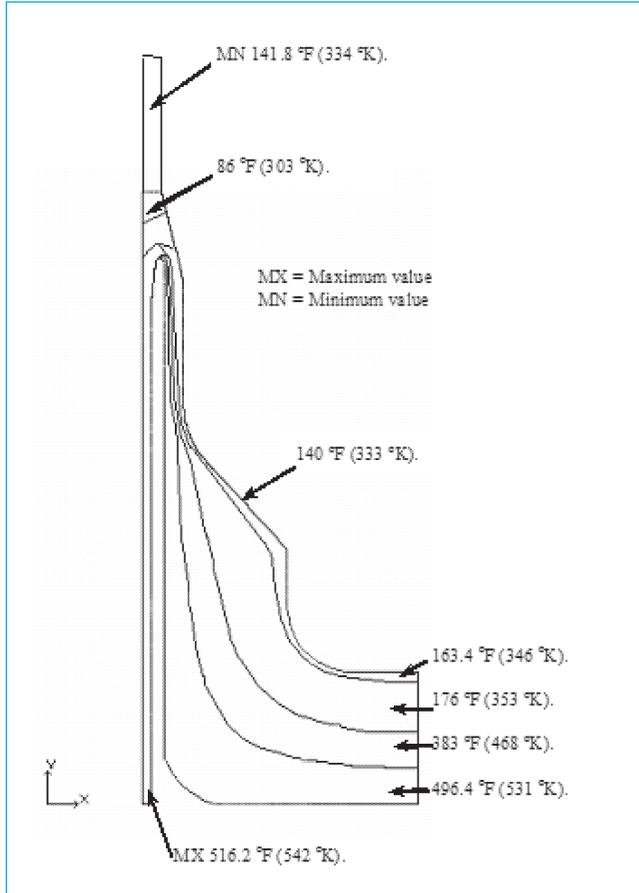


Fig. 6. Temperature gradients of the case 2.

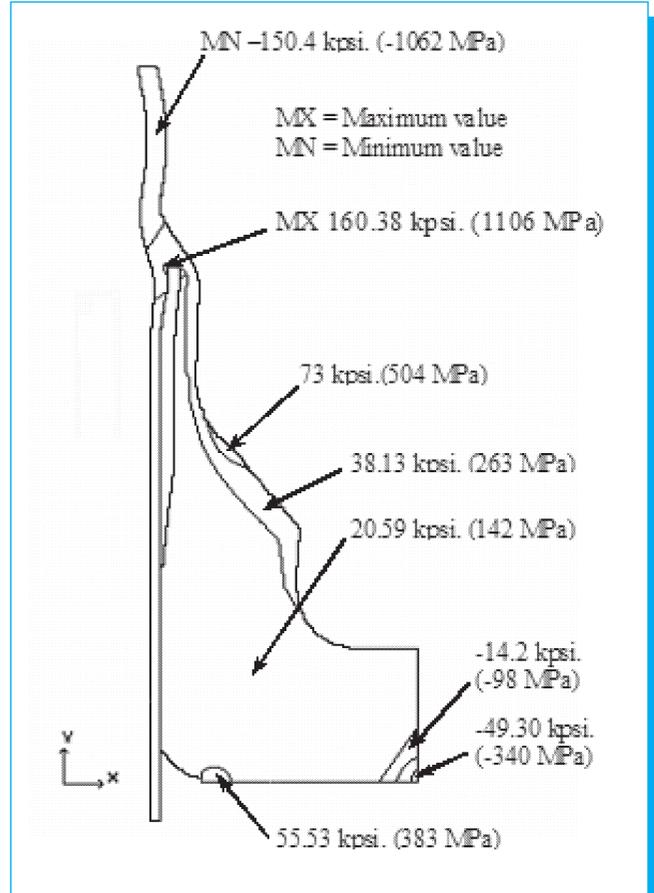


Fig. 7. Thermal stresses of the case 2.

In a second approach, the cumulative damage was evaluated by injection by injection. In other words, the transient thermal stresses were calculated with the information reported by the user (it is shown in table 1). This calculation is a more exact one than that using average values. The analysis of table 1 shows that, the cycle and design conditions are very similar. However, the cycle 2 and 12 are not severe. On the other side, cycles 1 and 11 are critical.

Considering the above mentioned and the methodology proposed in section 3, the cumulative damage was evaluated, the results shown in both cases are similar. However in case 2, the temperature field and the flexibility introduced by the pipe arrangement reduced the severity of the peak stresses. Consequently the accumulated damage is lower.

8. Conclusions

The Finite Element Method permits to develop a precise analysis of complicated geometries, like a "nozzle-thermal

sleeve-piping" component subjected to a coupled Heat Transfer-Stress phenomenon. It is very useful for studying ageing or life extension cases for nuclear power plants. In this paper, it was calculated the cumulative usage fatigue factor for a ECCS nozzle of a BWR reactor, considering a

Tabla 2. Cumulative Usage Factor results.

Methods used	Cummulative usage factor
Using design methodology	11.078 %
Average result by ANSYS (case 1).	7.059 %
Injection by injection analysis by ANSYS (case 1).	6.635 %
Average result by ANSYS (case 2).	4 %
Injection by injection analysis by ANSYS (case 2).	3.759 %

cycle by cycle damage and the flexibility of the adjacent piping. Results show that FEM provides lower values than those obtained with the old design methodology.

The geometry in the critical area, the zone where the thermal sleeve and the nozzle are joined (Figure 1), plays an important role on the stress pattern developed. When a crack is developed, an interaction with the nozzle boundaries will take place and the stress intensity factor at the crack tip will increase, as it was observed in [8]. Besides, local material imperfections and strain rate will affect the direction and stability of the crack propagation [9,10].

Acknowledgements

The grants awarded by CONACYT (3761P-A9608), DEPI (964913) and COFAA are kindly acknowledged.

9. References

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