FEM ANALYSIS AND CREEP LIFE ESTIMATION OF PIPE COMPONENT SUBMITTED TO HIGH PRESSURE STEAM

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Abstract. *In industrial plants, the overheated steam system accounts for collecting the high pressure steam generated by power boilers and distributing it to the turbo-generators employed in electric energy generation. In the studied plant, a total of twelve failures in T-type pipes of the overheated steam system have occurred over the past eight years. These failures were characterized as creep cracks in bent regions of the pipes, where there is a suspicion of high stress concentration. Among the existent damage mechanisms, creep is one of the most important in components operating at high temperatures. In recent years, the use of finite element analyses have aided the assessment of components in creep conditions, due to increased availability of computing resources. This research is aimed at studying the active stress and creep life of T-type steam pipeline made of 1.25 Cr - 0.5 Mn steel (wt. pct.) under high pressure and temperature. This component was considered critical, because of its failure history and suspicion of stress concentration. FEM modeling of the component was performed and the stresses were analyzed for three distinct operational conditions. The next step was the estimation of the creep life for each operational condition. Finally, a design improvement of the component was proposed in order to raise the creep life. Herewith, it was possible to observe the component's sensitivity to stress and temperature variation in its operational conditions.*

Keywords*: Steam pipelines, T-type pipe, Finite Element Method (FEM), Stress Analysis, Creep.*

1. INTRODUCTION

Around the world, thermoelectric plants and refineries are getting old, and are being used beyond their primary lifetime project. From this fact has sprung the need to perform analyzes of their conditions in order to guarantee their safe operational continuity (Auerkari, 2004). It is necessary to know the potential degradation mechanisms and their characteristics so as to consistently analyze a plant. Among the existing damage mechanisms, creep is one of the most severe for components submitted to high temperatures (Furtado, 2002). Creep is a permanent and time-dependent deformation, which occurs when a particular material is submitted to a constant stress at a high temperature (Viswanathan, 1989). This is usually an undesired phenomenon because it limits the component's life under certain working conditions. Niu (2008) performed a Finite Element Method (FEM) analysis of the creep failure of a steam pipeline system and a conical reduction working at high temperatures. The ABAQUS software along with Kachanov-Rabotnov's failure theory (Kachanov, 1986) was used. Steam pipelines working at high pressures and temperatures are widely utilized in chemical industries as well as in generating energy. Under those working conditions, creep is a significant factor, and it can be a cause of failures in pipelines. It is very important to identify the spots where major damages occur, aiming at more accurately estimating the pipeline service life, as well as planning a reliable maintenance strategy for pipeline systems at high temperature (Neubauer and Wedel, 1983).

In an important Brazilian refinery, twelve failures in pipeline extensions of the overheated steam system have being observed over the past eight years. Those failures are characterized as creep cracks in the bent regions of the T-type pipes, where there is a higher stress concentration, as shown in Fig. 1.

Figure 1. Detail of the internal creep crack in a T-type pipe replaced during maintenance

Due to failure occurrence, restrictions have been imposed on the operational conditions, and steam system temperature and pressure have been reduced. A project improvement of the components that presented problems can result in their extended lifetime, increased reliability of the refinery steam system, and a reduction in maintenance costs as well.

The objective of this work is to evaluate the efficiency rate of the restrictions applied, through the analysis of those parts submitted to creep failure by finite elements. Moreover, this work also aims at making improvement propositions concerning the existing pipes so as to increase their lifetime.

2. A SURVEY ON CREEP

The project of components for process plants and generating energy usually estimates a 100,000-hour lifetime. However, these plants continue working after overpassing the project estimation, which leads to the need for a detailed valuation as well as the required follow-up of its conditions. Hence, creep data extrapolation collected in laboratory has become inevitable. Even if long-term data are available, the variations in work conditions and in the properties of the different materials used make it indispensable to run short-term laboratory tests and to use extrapolation techniques. These techniques have their aim at incorporating time, stress and temperature factors in one single equation (Kamimura, 2009). The temperature and time grouping in one single term, according to Larson and Miller's proposition, is the most commonly used method (Taminger, 1999).

By grouping the temperature (T) and time (t) in the form T (K_1 + log t), it is possible to draw a curve of stress in function of this new parameter for a given material. For steels, the constant K_1 usually is 20, although it may vary between 10 and 40. The well-known Larson-Miller parameter can be obtained from the dependency of the rupture time (t_r) in relation to stress and temperature. The rupture time expression is obtained from laboratory data and can be written as Eq. (1), where A_2 and B_2 are determined from the experimental results.

$$t_r = A_2 \exp(B_2/T) \tag{1}$$

Equation (1) can also be written in logarithmic form as Eq. (2), which can be rearranged in the form of Eq. (3) or Eq. (4), where LMP is the Larson-Miller parameter and K_1 is a constant.

$$\log t_r = \log A_2 + (B_2/2.3T) \tag{2}$$

$$B_2/(2.3) = T(\log t_r + \log A_2) \tag{3}$$

$$LMP = f(\sigma) = T(\log t_r + K_1) \tag{4}$$

3. STUDY PROCEDURES

Firstly, the finite element model characteristics such as dimensions, boundary conditions and loading of the component that presented creep failures were determined. Three operational conditions, which had been chosen with the objective of evaluating the sensitivity to pressure and temperature variations in the work range of steam system pipes, were analyzed. **Condition no. 1**, or Limited Operation condition, has a working temperature T = 510º C and pipe pressure P = 9.8 MPa (100 Kgf/cm^2). This condition corresponds to the operational restriction established after cracks occurred in the T-type pipes. The so called **Condition no. 2** is the original condition of the pipeline Project, with T = 530º C and P = 10.8 MPa (110 Kgf/cm^2). A simulation of operational conditions that were more severe than the project condition was performed, using T = 540º C and P = 11.8 MPa (120 Kgf/cm^2). This hypothesis is **Condition no. 3**, or condition of Extrapolated Operation.

After FEM modeling using the software COSMOS, the analyses of the acting stresses under the three conditions described were performed. From those results, lifetime estimation under creep conditions was then performed. In order to accomplish this, the calculation method suggested under API RP 530 (2003) was used. The combination of sample creep tests and creep damage analyses employing finite elements has been used by several authors, such as Hyde (2006), Hall and Haydurst (1991) and Tabuchi (2005).

Finally, the modification proposals for the studied component were presented. In order to make possible to compare the performances of the modified components and the original model these proposals were modeled with finite elements and then the stress analysis and creep life estimation was done in a similar manner. The modification proposals were analyzed in the Limited Operation (**Condition no. 1**) and Project (**Condition no. 2**) conditions. The Extrapolated Operation condition was not studied in this stage because it is only a hypothetic condition. The performed analyses were static and linear, and a solid element model was adopted. The analyzed component was a 14-inch T-type pipe employed to remove the condensed vapor of the high pressure steam pipeline. The shape and dimensions of the studied component are given in Fig. 2.

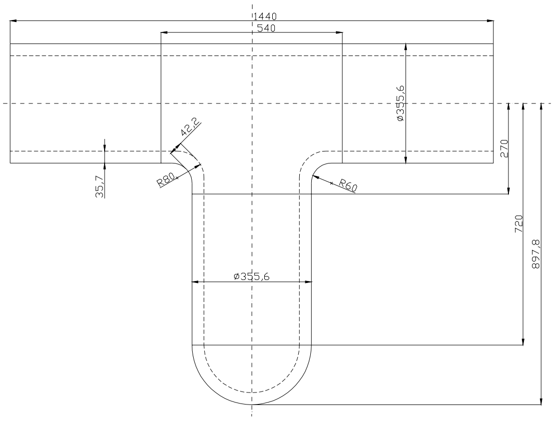

Figure 2. Layout of the 14-inch nominal diameter T-type pipe

The welded junctions were considered as being uniform and having the same properties as the pipe material. ASTM A 335 Gr. P11 steel was used, corresponding to UNS K11597 under the UNS designation. This material has as its main alloy elements 1.25% Cr and 0.5% Mo. According to ASME Section II Subpart 1, this material's yield stress is approximately 205 MPa. Its chemical composition is listed in Tab. 1.

Table 1. Chemical composition of ASTM A 335 Gr. P11 steel (wt. pct.).

Element	C	Mn	P	S	Si	Cr	Mo
Composition	0.05 – 0.15	0.30 – 0.60	0.025	0.025	0.50 – 1.00	1.00 – 1.50	0.44 – 0.65

The applied load was the internal pressure for all the analyzed conditions. Other possible loadings, like bending moments or concentrated loads, were not considered. These loadings vary for each component, depending on its location in the pipeline system. For a study at this level of detail, it is necessary to verify *in loco* the existing supports, acting loads, pipeline path and other details for each T-type pipe. However, such a detailed study is beyond the scope of this work. By adopting a common comparison basis, it is possible to evaluate the influence of the operational conditions on the component in a general way, making acceptable the simplifying hypotheses.

4. DEVELOPMENT

4.1. Boundary conditions

The boundary conditions are very important in any FEM analysis. In this work, four constraint analyses were done in order to verify their influence on the stresses developed in the T-type pipe: 1) symmetry constraint at both endings of the component; 2) freely supported extremities with restriction to axial twist at both endings; 3) one clamped and other freely supported ending; 4) one clamped other free ending. In comparing the von Mises maximum stress to the stress distribution on the component regions next to the endings, a 20%-maximum variation was observed in the values. These regions are shown in detail in Fig. 3. In comparing the same parameters throughout the model, a variation below 1% was observed among all the studied boundary conditions.

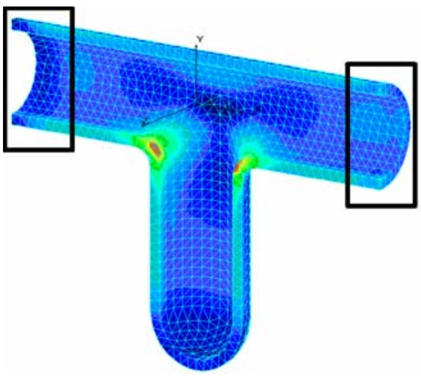

Figure 3. Study of the boundary conditions of T-type pipe

In analyzing Fig. 3, it is possible to observe, as expected, that the major stress concentration occurs at the pipeline derivation curve, where creep failures occurred. There were no significant variations in the stress analyzed, independently of the boundary condition used. Thus, it has been possible to come to the conclusion that there is no influence of the boundary condition on the region of interest for the model used. The boundary condition chosen to proceed with the analysis was clamping in one ending and free support in another. That restriction recreates the condition that may likely occur.

4.2. Stress analysis

Figure 4 shows the von Mises stress for **Condition no. 1**. The stress values vary from 10.1 MPa to a maximum von Mises stress of 134 MPa at the interest region. At the straight line pipes, the average stress was 50 MPa. In order to calculate the service life, the found stresses were divided into four equally-spaced intervals: 10.1 to 41.1 MPa; 41.1 to 72.2 MPa; 72.2 to 103.3 MPa and 103.3 to 134.3 MPa. Figure 5 shows the von Mises stress for **Condition no. 2**. The encountered stress values varied from 11.2 to 148 MPa. For the life calculation the found stresses were divided into four intervals: 11.2 to 45.4 MPa; 45.4 to 79.6 MPa; 79.6 to 113.8 MPa; and 113.8 a 148.0 MPa. At the straight line pipes, the average stress was 55 MPa for this condition. Figure 6 shows the von Mises stress for **Condition no. 3** (extrapolated condition). The encountered stress values varied from 12.2 to 161 MPa. For the life calculation the found stresses were divided into four intervals: 12.2 to 49.6 MPa; 49.6 to 86.9 MPa; 86.9 to 124.3 MPa; and 124.3 a 161.7 MPa. At the straight line pipes, the average stress was 60 MPa for this condition.

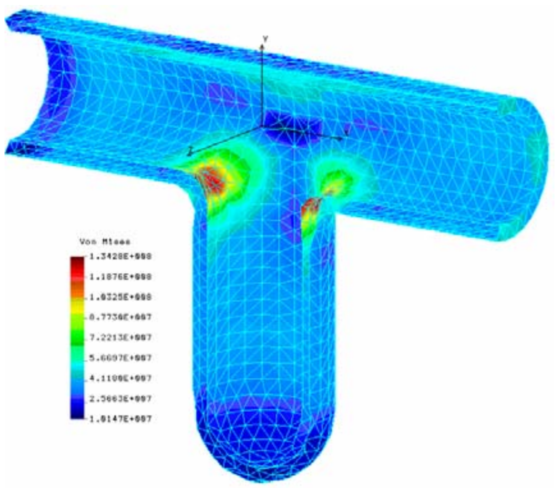

Figure 4. von Mises stress distribution corresponding to limited operation condition (9.8 MPa)

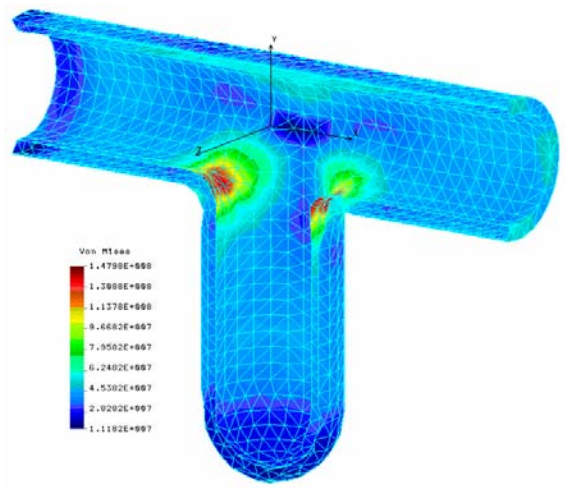

Figure 5. von Mises stress distribution corresponding to project operation condition (10.8 MPa)

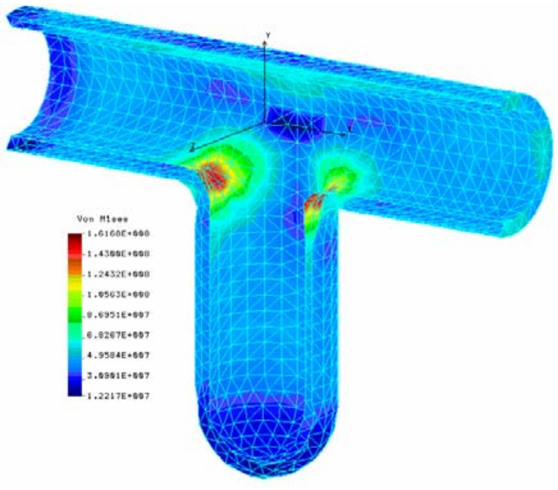

Figure 6. von Mises stress distribution corresponding to extrapolated operation condition (11.8 MPa)

4.3. Analysis of creep lifetime

By using regulation API RP530 (2003) and Eq. (4), the LMP calculation parameters for ASTM A335 Gr. P11 steel are determined, see Eq. (5), where T is the temperature in degrees Celsius and t is the remaining life in hours.

$$LMP = (T + 273)\,(20 + \log t) \times 10^{-3} \tag{5}$$

The value of Larson-Miller's Parameter is obtained based on the acting stress using diagrams presented in the API 530 regulation, according to the employed material. The experiment was aimed at estimating the T-type pipe lifetime under the conditions previously presented. Thus, the term time was determined by Eq. (6).

$$t = 10^{\left[\left(\frac{LPM\,10^{3}}{T+273}\right)-20\right]} \tag{6}$$

The values/results collected from lifetimes are presented Tab. 2 for the evaluated conditions. The stress values listed in the chart correspond to the highest stress value listed in the intervals described in the previous item. Then, with the data contained in that chart, it was possible to draw the life curves for each condition analyzed in a graph lifetime versus acting stress, presented in Fig. 7.

Table 2. Comparison of service lifetimes under distinct operating conditions.

Condition no. 1 9.8 MPa, 510ºC		**Condition no. 2** 10.8MPa, 530ºC		**Condition no. 3** 11.8 MPa, 540ºC	
Stress [MPa]	time [years]	Stress [MPa]	time [years]	Stress [MPa]	time [years]
41.1	873.53	45.4	140.33	49.6	43.83
72.2	83.09	79.6	12.26	86.9	4.55
103.3	16.49	113.8	2.92	124.3	0.96
134.3	5.08	148.0	0.93	161.7	0.31

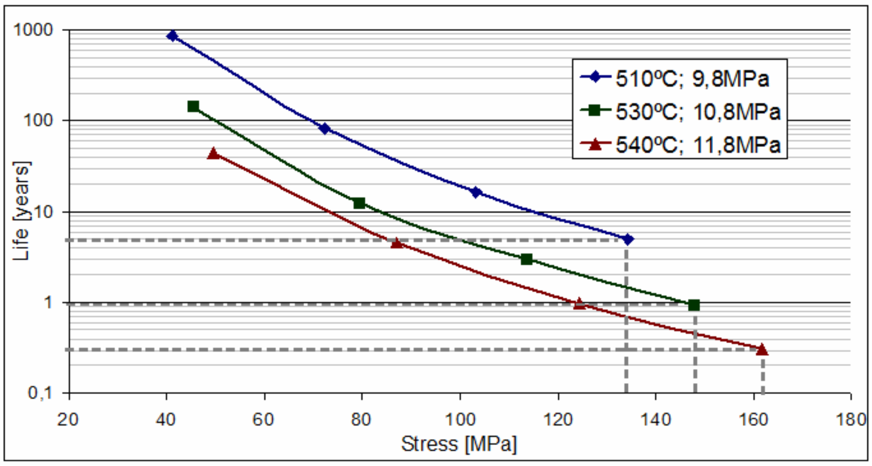

Figure 7. Service lifetime under creep conditions

Based on the analysis of figure 7, it is possible to verify that the component submitted to the Limited Operation condition (510ºC and 9.8 MPa) has a longer life, when compared with the other conditions. There is a relation of approximately 6 to 1 between the lives estimated under the Limited Operation conditions and those of Project (530ºC e 10.8 MPa). Furthermore, it was possible to observe a relation of approximately 3 to 1 between estimated lives under Project (530ºC and 10.8 MPa) conditions and Extrapolated Operation (540ºC and 11.8 MPa). As far as the ranges studied are concerned, lifetime revealed to be greatly affected by stress and temperature variations. A small variation in operational conditions (temperature and pressure) represented a great impact to the component lifetime. Based on the results obtained in this work, it has been possible to detect that the steam operational system restriction determined after failure occurrences can be justified by the significant increase in component lifetime. Nevertheless, it is important to point out that the accurate temperature control present in the system in its ordinary operation is really hard to be performed; 10ºC variations are quite frequent. Due to this fact, a modification in the T-type pipe project was proposed.

4.4. Modification proposal for the T-type pipe project

The decision of project modification used in the steam system aimed at building a component which could result in extended lifetime when compared to the T-type pipe presently used. In order to make this comparison feasible, the same procedure sequence described in the previous item was used, as well as the same parameters: ASTM A 335 Gr. P11 steel, loading, boundary condition and finite elements model.

At first, the modification tested was an increase in the radius of the derivation bend, on the spot where the failures occurred. By applying this modification, a reduction in localized strength with further increase in pipeline T lifetime was expected. The external radius of the derivation bend was increased from 60 mm to 180mm. This alteration resulted in a small increase in the thickness of the bend region, from 42.2 mm to 50.5 mm. The remaining dimensions didn't undergo any changes.

Against all odds, however, the component radius modification didn't present a stress decrease as expected. Figure 8 shows the stress distribution after pipeline T modification, calculated to a Condition 1 (10.8 MPa and 530ºC). Whereas the most critical spot in the original model reached 148 MPa (Fig. 5), the modified model had stress reaching 195 MPa (Fig. 8).

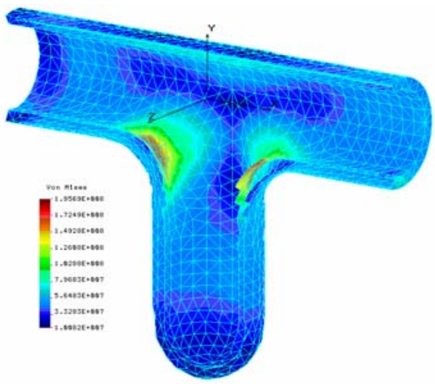

Figure 8. von Mises stress distribution for the first modification proposal subjected to 10.8 MPa

After a number of studies, a new proposition was elaborated, a modification in the pipeline component, keeping a 14”-nominal-diameter T-type pipe as its basis. The major changes regarding the original project were the increases in thickness along part of the three pipeline extensions and the external curvature extension radius. In Fig. 9 a scheme of the modification proposed is presented. Stress analyses were performed for the new pipeline T model proposed, with the same project conditions and operation as the original model. Figures 10 and 11 show the stress distribution for Conditions 1 and 2, respectively. In comparing Fig. 10 with Fig. 4 it is possible to observe a decrease in the maximum stress from 134 MPa to 111.9 MPa. With regard to condition 2, the comparison of Fig. 11 with Fig. 5 shows a decrease in the maximum stress from 148 MPa to 123.4 MPa. It is possible to observe that, based on the modification of the pipeline T project, the maximum stress found for condition 2 (primary project) was even lower than the maximum stress for the limited operation condition.

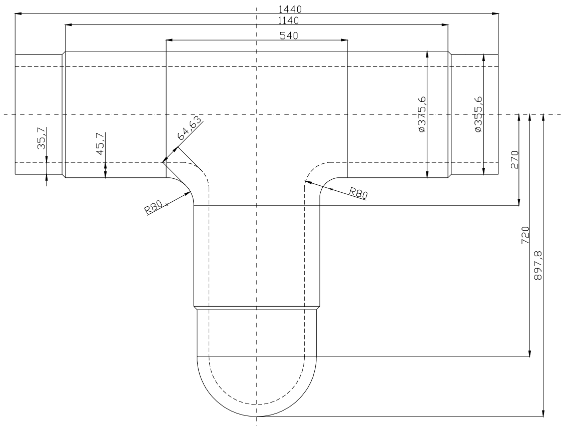

Figure 9. Modification proposal for T-type pipe with nominal diameter of 14 inches

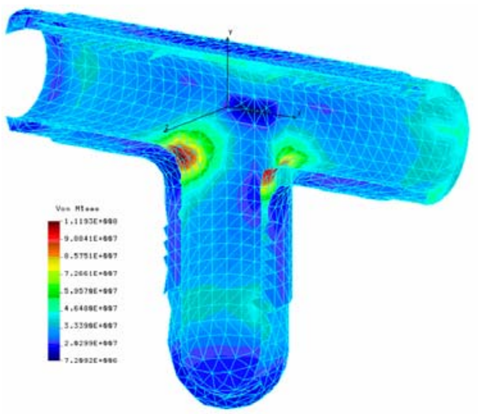

Figure 10. von Mises stress distribution for modified component subjected to 9.8 MPa

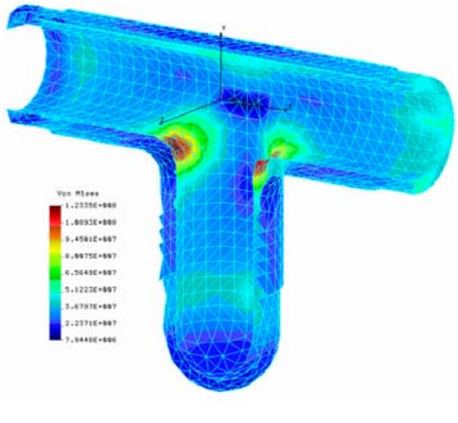

Figure 11. von Mises stress distribution for modified component subjected to 10.8 MPa

Figure 12 shows the variation in creep life by comparing the possible extended lifetime in years with the stress decrease enabled by the new project. By using the new pipeline T Project, a stress reduction of approximately 20% was observed in connection with the original project. In comparing lifetime estimation, an increase of more than 100% was observed when the new project was applied. Figure 13 shows the comparison of the amount of extended lifetime obtained, by adding the limited operation result to the new project in connection with the operation conditions originally proposed. In this case, it was possible to observe a reduction of about 35% in stress levels and an increase of 10 times in lifetime.

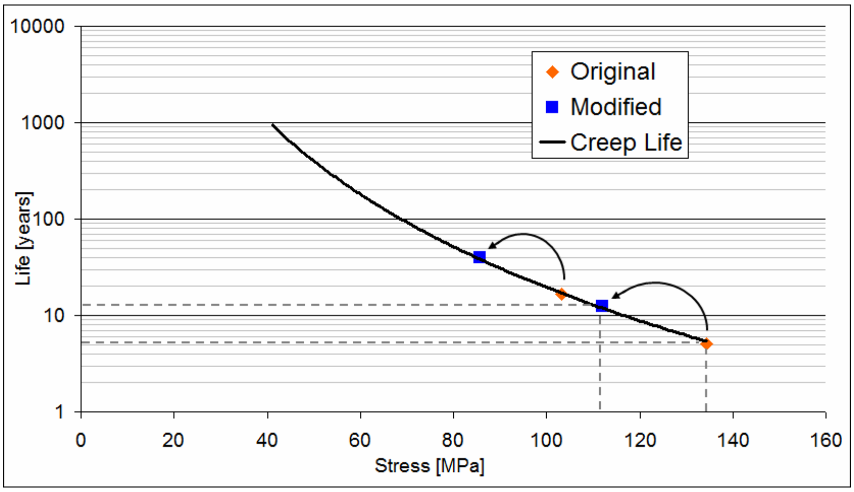

Figure 12. Comparison of service lives of the original and modified models

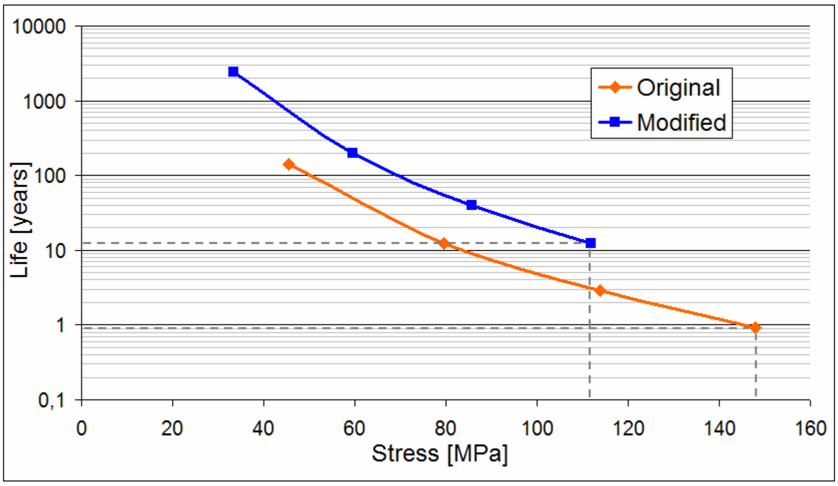

Figure 13. Service life of original model at project condition and modified model at limited operation condition

5. CONCLUSIONS

Based on the performed stress analyses, it was possible to observe that a stress concentration does exist in the derivation curves of T-type pipes. This fact was consistent with the failure description presented by the steam pipeline T system. Moreover, the component critical region to be studied and improved came to light.

The operational restriction applied to the steam system after the occurrence of creep failures was observed to be effective. With a reduction in work temperature from 530ºC to 510ºC and a reduction in pressure from 10.8 MPa to 9.8 MPa, a significant increase in the lifetime of the component analyzed, of about six times.

Based on the component lifetime results in 3 different operational conditions, the sensitivity of lifetime to stress variation and temperature at the current work range came to light. On the one hand, a small decrease in operational conditions resulted in a 6-time increase in the component lifetime, as mentioned above. On the other hand, when work conditions were simulated as a bit stricter, the service life decreased to a third of the original lifetime.

The modification proposition of the component analyzed in the present work showed a significant lifetime gain with regard to the original model. For the same work conditions, the lifetime of the component which had been modified was twice the original component lifetime. When a slight decrease in operational conditions was applied together with the alteration in the original component, it resulted in a ten-time lifetime increase. Starting with the studies performed, and here presented, an intervention in the component geometry can be a path to be explored aiming at an improvement concerning the inevitable problem of creep failure in elements of steam system pipeline.

5. REFERENCES

Auerkari, P., et al., 2004. “Developments in assessing creep behaviour and creep life of components**”**. Materials at High Temperatures, Vol. 21, Nº. 1, pp. 61-64.

Furtado, H. C.; May I. L., 2004. “High Temperature Degradation in Power Plants and Refineries”. Materials Research, Vol. 7, Nº.1, pp. 103-110.

Kachanov, L. M., 1986, “Introduction to Continuum Damage Mechanics”, Martinus Nijhoff Publishers, Dordrecht, Netherlands, 135p.

Kamimura, R. C., 2009, “Análise de Danos em Alta Temperatura e Avaliação do Parâmetro de Larson-Miller na Determinação de Tempo de Ruptura por Fluência, em Ciclones de Vasos Regeneradores Construídos em Aço Inoxidável Austenítico ASTM TP 304H”**.** Master Thesis. Federal University of Rio Grande do Sul, Porto Alegre, Brazil. 89p. *(in portuguese).*

Taminger, K. M. B., 1999, “Analysis of Creep Behavior and Parametric Models for 2124 Al and 2124 Al + SiCW Composite”. Master Thesis . Virginia Polytechnic Institute and State University, Blacksburg, 202p.

American Petroleum Institute, 2003, “API RP 530: Calculation of Heater Tubes Thickness in Petroleum Refineries”.

American Petroleum Institute, 2003, “API RP 571: Damage Mechanisms Affecting Fixed Equipment in the Refining Industry”.

Viswanathan, R., 1989, “Damage Mechanisms and Life Assessment of High-Temperature Components”. ASM Internacional, pp. 59-70.

Hyde, T. H., et al., 2006, “Finite Element Creep Failure Analyses of P91 Large Tensile Cross-Weld Specimens Tested at 625°C”, Proceedings of the 5th International Conference on Mechanics and Materials in design, Porto, Portugal.

Hall, F. R., Hayhurst, D. R., 1991, “Continuum Damage Mechanics Modelling of High Temperature Deformation and Failure in a Pipe Weldment”, Proceedings of Mathematical and Physical Sciences, Vol. 433, No. 1888, pp. 383-403.

Tabuchi, M., Ha, J. C., Yokobori, A. T., 2005, “Creep Crack Growth Properties Of Welded Joints For High Cr Ferritic Steel”, Proceedings of the 11th International Conference on Fracture, Turin.

Niu, X.-C., et al., 2009. “Creep damage prediction of the steam pipelines with high temperature and high pressure”**.** International Journal of Pressure Vessels and Piping, Vol. 86, pp. 593-598.

Neubauer, B., Wedel, U., 1983, “Restlife Estimation of Creeping Components by Means of Replicas**”,** ASME International Conference on Advances in Life Prediction Methods, New York, pp. 307-314.

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