A Manual For Life Assessment Of Power Boilers In Brazil: Its Development And Application

H. C. Furtado, CEPEL – Centro de Pesquisas de Energia Elétrica, C.P. 2754, 20001-970 Rio de Janeiro, Brazil and I. Le May, Metallurgical Consulting Services Ltd., P.O. Box 5006, Saskatoon, SK, Canada S7K 4E3

The paper describes the development of a guide for the assessment of steam generators for the Brazilian power industry. It is based on the established principle of three levels of assessment. Some observations are presented concerning the application of the assessment procedures, it being noted that Level 1 assessment does not generally apply for all components evaluated. Information is provided concerning the costs and cost-benefits of such assessments.

1. INTRODUCTION

Traditionally, thermal plants for electricity generation have been built on the basis of a design life, and inspection has been made on a regular and periodic basis with the plant shutdown intended primarily for the inspection. The design life is different from the useful life, which is expected to be considerably greater. The task of the designer is to ensure that the plant is designed to have safe operation over the design life, and the approach is necessarily conservative. Those operating the plant are concerned with the extension of the plant’s useful life so that it can operate safely and with a minimum of interruptions to the continued production of electricity.

Unplanned shutdowns occur from time to time and their frequency is generally high for the period following the initial start up of the plant, falling with time to some steady state value, and then rising as the plant ages and approaches its design life. This gives rise to the traditional bathtub curve shown in Figure 1 [1], which applies not only to power stations but to most other pieces of equipment from automobiles to refineries.

For equipment operating at high temperature, where processes of time-dependent deformation (creep) are present, the design life has generally been 100,000 h (11.4 years), although 250,000 h design lives may be used today. The 100,000 h design life results, in part, from the fact that this is the basis on which high temperature data for design for creep conditions are normally established.

A great many of the thermal plants operating worldwide are approaching or have already exceeded their design lives, many units having been in service for times greater than 40 years, but the economics of scrapping them and building new power stations in their place are seldom favourable.

In order to keep aging plant in operation, life extension strategies have been developed by a number of agencies [2, 3]. With a thorough evaluation of an aging plant and replacement of critical components that are found by inspection and analysis to have been damaged significantly, the economic life of plants can be extended and the frequency of unplanned outages reduced as illustrated on Figure 2 [4]. A thorough assessment of a power plant is often considered at around the end of the design life as shown in Figure 3 [5]; however the trend today is to conduct inspections on a continuing and planned basis.

Figure 2  Schematic showing the effect of a life extension program on reducing the level of forced outages [4]

Figure 3  Schematic representation of damage parameters, showing when a major assessment is often made

2. BACKGROUND

The thermal power plants installed in Brazil had a capacity of approximately 3 GW in 1999. The situation is similar to that in many other countries in that there are a great many aging thermal power plants, as of 1999 approximately 63% having been in operation for more than 25 years. In recent years the new
generating capacity that has been brought into service has been largely of the hydroelectric type. This has resulted in many thermal stations that were formerly used for base load generation now being operated at peak load times only, causing accelerated aging and degradation. The intention is to extend the useful life of thermal power plants by from 25 to 30 years, to produce a total useful life of from 50 to 60 years or more. All boilers are subject to the Federal law with respect to pressure vessels, the relevant standard, NR13 [6], requiring regular inspections to be made. However, because the major part of the power generation in Brazil has been and continues to be hydroelectric in nature, there had been relatively little effort to apply the techniques for damage assessment and life extension of thermal plants by most companies responsible for electricity generation.

In Brazil, most of the earlier efforts in integrity evaluation were undertaken in the petrochemical sector [7]. However, considerable study of damage mechanisms in Cr-Mo steels has been made [8], and the philosophy and methodology of damage assessment and life extension in high temperature plant have been promoted extensively through the efforts of the Brazilian Society of Mechanical Engineers, as well as through a Multinational Project on the Evaluation of Integrity and Life Extension of Industrial Equipment (PROMAI) [9].

In view of the fact that CEPEL (Centro de Pesquisas de Energia Elétrica), the main research and technology centre for Eletrobras, which is the Brazilian company that has been the holding company for many of the Brazilian power producing companies, had been conducting inspections and assessments of many of the thermal power stations in Brazil, a project was initiated through which CEPEL would develop a set of guidelines for the assessment of thermal power plants. The manual was completed in 1999 [10].

3. ORGANIZATION OF THE MANUAL

The manual, "Guia de Avaliação de Integridade em Usinas Térmicas", contains the following main sections:
1. Introduction
2. Terminology
3. Planning for Integrity Evaluation
4. Methodology Proposed for Integrity Evaluation
5. Criteria for Selection and Execution of Tests
6. Criteria for the Evaluation of Test Results
7. Costs and Benefits
8. Conclusion of the Integrity Evaluation
9. Extension of Useful Life
10. Appendices
11. References

3.1 Planning

The planning of the integrity evaluation of a power plant depends on a knowledge of its operating history and conditions as well as those of its key components, together with information concerning their current condition. Priorizing components for inspection can be based on history, their original design, the time for replacement during service in case of a failure, and their thermal and mechanical loading. Several approaches to this may be followed and are outlined in the manual.

Components may be prioritized in terms of their being critical or non-critical. A critical component is considered to have the following characteristics:
- A failure would cause shutdown for a considerable time.
- A failure implies risks to employees of the plant.
- Substitution or repair implies high costs and long delay in operation.

A non-critical component would have the following characteristics:
- A failure could result in a significant reduction in capacity, but would not lead to a forced shutdown.
- A failure would not cause to the safety of personnel nor lead to secondary damage.

An alternative method of classification of components is based on whether they can be replaced or not. Components that can be replaced may also require an analysis of remaining life and are subdivided into the following categories:
- Components relating to safety: these include ones that have the potential to cause injury to plant personnel in the case of failure.
- Limited availability of components.
- Long delay in obtaining a replacement.
- Components whose failure would lead to a shutdown of the plant.
- Components that have the potential for early failure.
- Components with poor reliability: those in which there have been many failures causing shutdowns.
- Components in which serious loss of performance is observed, causing deterioration in plant performance.

A risk-based inspection programme is also envisaged, in which a risk ranking of components can be prepared [11].

3.2 Methodology

The well-established approach of having three levels of assessment is followed, the data requirements for the three levels being indicated in Table 1.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Details of Assessment Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ASSESSMENT LEVEL</strong></td>
<td><strong>Level I</strong></td>
</tr>
<tr>
<td>Characteristic</td>
<td>Little detail</td>
</tr>
<tr>
<td>Failure history</td>
<td>Plant records</td>
</tr>
<tr>
<td>Dimensions</td>
<td>Records or nominal</td>
</tr>
<tr>
<td>Condition</td>
<td>Records or nominal</td>
</tr>
<tr>
<td>Temperature &amp; Pressure</td>
<td>Design data or operational records</td>
</tr>
<tr>
<td>Stress</td>
<td>Design or on basis of operating conditions</td>
</tr>
<tr>
<td>Material Properties</td>
<td>Minimum nominal</td>
</tr>
<tr>
<td>Need for Specimens</td>
<td>No</td>
</tr>
</tbody>
</table>

3.3 High Temperature Damage Evaluation

Section 6 of the Manual, titled "Criteria for the Evaluation of Test Results", covers the problems of general loss of thickness, local thinning, pitting corrosion, crack-like defects and high temperature creep damage. Here, the outline of the assessment procedures for creep damage will be detailed.

A Level I approach calls for the following steps:
1. Obtain the design data and operating records for the various components. If there are records of significant failures, move to a Level II assessment.
2. If any condition of temperature or pressure exceeds the design conditions, move to a Level II assessment.
3. Determine the minimum thickness for each component according to the design code, using the tabulated properties for the particular material.
4. Determine the minimum measured thickness for each component from inspection records. Simplified stress analysis using mean diameter is appropriate.
5. If there are calculated minimum thickness values that are less than the minimum permissible, taking the corrosion allowance into account, the component does not meet Level I assessment requirements and must be evaluated by Level II methods.

6. Prior inspection data for cracks, particularly at structural discontinuities, need to be evaluated. If there are any significant cracks, they must either be repaired and eliminated or evaluated using a Level III approach.

7. The operational history must be reviewed. The life fraction used from cumulative damage by creep is estimated on the basis of the design conditions for temperature and pressure, using a cumulative damage relation. Stresses are based on mean diameter and the estimated cumulative damage (or life used up) is compared with the minimum rupture life for the material from the data bank for the code at the design temperature and pressure. If the value estimated for the fraction of life expended is greater than 0.6, a more detailed analysis of creep damage is required using metallographic techniques and hardness measurements.

8. The creep damage can be evaluated using metallographic methods, hardness measurements, or both. If apparent voids are detected after repeated polish-etch procedures, if the microstructure displays severe degradation in terms of carbide spheroidization, or if the hardness is lower than the minimum specified for the particular material, the component needs to be evaluated by a Level II approach.

9. If any significant change in dimension is encountered, the evaluation must be made using Level II procedures.

10. If the component satisfies Steps 1 to 9, a Level I approach is adequate and it can continue in operation until the next inspection period, as defined by the projected rate of damage accumulation.

A Level II evaluation is required when components of a steam generator operating under pressure in situations where the creep damage is not able to satisfy the conditions required for evaluation using Level I. It consists of the following steps:

1. Inspection is required to ensure that there are no cracks present. If cracks are detected, they must either be eliminated or an evaluation using Level III criteria is required.

2. Estimate stresses on the basis of the operating conditions and determine the cumulative life expended on the basis of the minimum properties of the material under operating conditions; hence, determine the remaining life. If the remaining life is less than the planned inspection interval, a Level III evaluation is required. The stress analysis can be made using stress analysis equations.

3. The damage by creep can be checked from metallography and hardness. These tests should be made on a number of areas to ensure they are representative. For example, in the case of a header, the tests should be made towards the ends and in the centre, close to welds. In the case of severe carbide spheroidization, microcracks or apparent voids on grain boundaries being detected, or where the hardness is significantly less than the minimum specified for the material concerned, a more detailed analysis is required using a Level III approach.

4. In the case of the detection of distortions, ovalization or significant deformation, an analysis of the creep deformation must be made. The stress distribution resulting from changes in geometry can be used to recalculate the cumulative life expended and the minimum remaining life. The stress analysis can be made using simplified applied mechanics methods. If the safe minimum life is less than the interval to the next planned inspection, the component must be changed or evaluated using Level III criteria.

Level III analysis is required if the steam generator does not meet the required criteria of Level I or Level II. It is also required to evaluate the growth of cracks that have been detected and which may grow in service. The required steps are as follows:

1. All cracks need to be dimensioned precisely and characterized according to their growth mechanism.

2. The cracks need to be evaluated using fracture mechanics methods, including their growth by creep and from creep-fatigue interaction. Recognized proprietary programs, such as R5 and R6 [12] and PCPIPE [13], may be used.

3. Stress analysis may be made using numerical methods to obtain more precise results. Such analysis may require that the effects of stress relaxation be considered as these may be significant during elevated temperature service. Multiaxial stresses and complex geometries as at nozzle connections may be evaluated and a more precise analysis of the effect of pipe bends and of supports may be made than was done previously.

4. Better estimates of the creep damage can be made. These can be made using estimates of metal temperature based on hardness or measurements of the oxide thickness on the steam side of tubes and headers in order to estimate more accurately the cumulative life expended. If this is less than the projected interval to the next inspection, the component may be replaced, re-dimensioned or re-evaluated using Level III methods. Alternatively, creep rupture tests of the material can be made to estimate the remaining life more accurately. This can be compared to the to the time to the next planned inspection. If remaining life is less than this value, the next inspection interval can be reduced or the component replaced. Approximations of damage accumulation using continuum damage mechanics may also be used in the evaluation [5].

5. In the case of distortion, ovalization or local deformation, these may be evaluated using numerical methods to determine the extent of creep deformation and stress redistribution. The analysis needs to ensure that the projected safe life as estimated on the basis of actual stresses, the precise values of thickness and geometry and the current properties of the material, is more than the planned inspection interval.

6. In the case of a component that does not satisfy a Level III evaluation, it must be replaced.

4. CASE STUDIES

In the course of a number of evaluations made using the methodology outlined in the Manual, it has been found that virtually no steam generators have been evaluated completely using the Level I approach only. A few cases where more detailed evaluation was required will be described.

4.1 Superheater and Reheater Tubes

An assessment was made of a 220 MW steam generator unit that had operated for some 50,000h over 23 years, with frequent shutdowns and much of its operation on part load. Liquid penetrant inspection of welds between the stubs of ASME SA213 T22, 15Cr, 1Mo steel and the austenitic tubes of the secondary superheater and reheater did not disclose any problems but, because of a history of problems at such welds in cyclic operation, samples were removed for examination. The secondary superheater tubes were of AISI 347H and the reheater tubes of AISI 304H. The samples examined included shop welds between the stubs and austenitic steel nipples, and field welds between these and the tubes.

Figure 4a shows a junction between a ferritic stub and a nipple of 347H with cracking along the fusion zone on the stub side, while surface cracks were observed on the stub itself adjacent to the fusion zone crack (Fig. 4b). There was cavitation ahead of the cracks. The cracking indicated thermal fatigue caused by differential expansion between the two materials and cyclic operation. The cavitation indicates a local creep mechanism ahead of the crack tips: the cracks would grow to line up with subsurface voids. Intergranular cracking between carbides along the fusion line was also observed, as shown in Fig. 4c. Approximately one-third of the wall thickness was cracked. Similar cracking was observed in other samples. Cracking was also observed at the welds between the austenitic nipples and austenitic tubes (Fig. 4d).
The expected safe life for these conditions is probably little more than 3,000 h. Hence, the recommendation was to effect immediate repairs.

4.3 Microstructural Degradation

Where microstructural degradation is observed, this may have the form of carbide spheroidization, the carbides frequently lying along grain boundaries. It has been observed that there are, in many cases, no apparent voids present along grain boundaries after careful polishing and etching [8, 14] and indeed, after a series of polish-etch steps, even though the remaining life has been exhausted, such spheroidized microstructures have been seen in tubes that have failed in creep [15]. These, and other observations have shown that dependence on a parameter such as the A-parameter [16], giving a measure of the number of cavitated boundaries, is not a reliable measure of creep damage. Thus severe damage, indicating a need for replacement, has been based on (a) the degree of carbide spheroidization, approximating to the classification of Toft and Marsden [17]; (b) the presence of any detected apparent voids produced by carbide-matrix decohesion; and (c) abnormally low hardness values.

5. COSTS AND BENEFITS

Some preliminary studies indicated that the cost of an integrity evaluation of a steam generator is around 2% of the value of the unit, and that the cost of a life extension program for a typical fossil fuel plant is of the order of 20 to 30% of the cost of construction of a new plant. The resulting cost-benefit ratio is very favourable [18,19].

Table 2 shows the costs of four typical integrity evaluations made in Brazil: it illustrates the cost reduction that has occurred with the optimization of procedures.

Figure 6 Remaining safe life as a function of crack depth for a circumferential crack in the weld metal of a steam pipe

- 30 -

Figure 4 Damage at dissimilar metal joints on secondary superheater: (a) Cracking on the fusion line on the stub side (left); (b) Surface cracks on the stub adjacent to the cracking; (c) Intergranular cracking along the fusion line; (d) Cracking between austenitic weld metal and austenitic nipple

The reheater connections showed similar cracking between the ferritic nipple and weld metal (Fig. 5a), with internal intergranular cracking adjacent to segregated carbides (Fig. 5b).

Figure 5 Cracking at reheater joints: (a) Cracking at welds between ferritic stub and austenitic weld metal; (b) Internal intergranular cracking adjacent to segregated carbides in reheater tube

It was clear that the cyclic operation had caused serious problems at ferrite-austenite connections. The extent and seriousness of the cracking disclosed by the sampling indicated a need to replace the connections. The example also demonstrates the danger inherent in operating a boiler designed for continuous operation on a cyclic, peak-load basis. A final point to be made is the difficulty in detecting cracking at ferrite-austenite connections using standard NDE procedures: the removal of samples for destructive examination at appropriate intervals is the only secure evaluation method.

4.2 Cracking in Steam Line

During the evaluation of a power plant used for peak load operation, internal cracking was detected by ultrasonic inspection at the butt welds in a vertical steam pipe connecting the primary and secondary superheaters. There was also external cracking at a hanger support welded to the upper part of the pipe and from which the latter was suspended, caused from the frequent thermal cycles. The internal cracks were at backing rings in the 300 mm O.D. pipe, of wall thickness 23 mm. The operating conditions were 13.8 MPa and 400°C. The most severe crack detected was approximately 9 mm deep, with a circumferential length of 130 mm.

In order to determine whether the plant could be restarted or whether immediate repairs were called for, an analysis was made of the probable crack growth during further cyclic operation. The analysis was made using the PCPIPE program [13], which involves time dependent fracture mechanics and takes account of cyclic operation. Figure 6 shows the remaining life estimated on the basis of the crack being in the weld metal, which appeared to be the case from the ultrasonic measurements, and for 35 h operating cycles, which was the historical cycle time for the unit.
Table 2  Costs of Four Typical Assessments

<table>
<thead>
<tr>
<th>Unit</th>
<th>Unit A</th>
<th>Unit B</th>
<th>Unit C</th>
<th>Unit D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installed Capacity (MW)</td>
<td>163</td>
<td>36</td>
<td>80</td>
<td>50</td>
</tr>
<tr>
<td>No. of inspection points</td>
<td>2,444</td>
<td>748</td>
<td>1523</td>
<td>1247</td>
</tr>
<tr>
<td>Year</td>
<td>1995</td>
<td>1996</td>
<td>1997</td>
<td>1999</td>
</tr>
<tr>
<td>Total Cost (US$)</td>
<td>294,898</td>
<td>48,388</td>
<td>74,705</td>
<td>36,471</td>
</tr>
<tr>
<td>Cost/MW (US$)</td>
<td>1,257</td>
<td>1,344</td>
<td>934</td>
<td>729</td>
</tr>
<tr>
<td>Cost/Inspection Point (US$)</td>
<td>83.8</td>
<td>64.7</td>
<td>49.1</td>
<td>29.3</td>
</tr>
</tbody>
</table>

6. CONCLUDING REMARKS

Various codes or guides for the assessment of plants operating at high temperature are in preparation worldwide. However it has been found useful to develop such a code for the Brazilian power industry without waiting for the finalization of others. The exercise has provided experience for those involved and the code is written in the language that is understood by the plant employees. It has been applied and found to be helpful in reaching logical decisions in practice, together with providing justification for recommendations made.

7. REFERENCES