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A techno-economic probabilistic approach to superheater lifetime determination

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Abstract
In the commonly used approach, the lifetime of a superheater is estimated by characteristic values of the production parameters and the operating conditions. In this approach, a lower bound for a superheater lifetime is based on some arbitrary safety factor that does not necessarily reflect real life, where unexpected failures do occur.

The method proposed here suggests coping with this reality, by employing a techno-economic probabilistic approach. It comprises the following two models:

- *A probabilistic time to failure evaluation model that considers the variability of the lifetime determining parameters.*
- *A model to optimise values of technical parameters and operating conditions and to determine a superheater's optimal replacement policy, based on life cycle cost considerations.*

The proposed probabilistic time to failure evaluation model can help to identify the most influential parameters for planning for a minimal probability of failure. It is applied to a unique problematic steel T22 superheater of rather specific parameters: corrosion rate, the Larson Miller Parameter (LMP), diameter and wall thickness. Sensitivity analysis has shown that the dominant factor affecting variation in superheater lifetime is the variation in the LMP, while the effect of the other parameters is quite marginal. Decreasing the standard deviation of the LMP (by keeping a more uniform material) lowered the probability of failure. This resulted in a practical recommendation to perform periodical checks of the parameter wall thickness. We also tested the effect of changing the nominal values of these parameters on the lifetime distribution. Hence, we suggest that the selection of the nominal values should be based on life cycle cost considerations; and propose a model to calculate, for any given combination, the average life cycle cost.

The latter model, the optimal parameters combination model, optimises the combination of changes in all the superheater's parameters by minimising the average life cycle cost associated with the superheater. Demonstrating the usefulness of the proposed approach, in a problematic case, suggests that it can be beneficially employed in the more general case whenever the planned lifetime of a design is threatened.

Keywords: superheater, lifteime determination, parameters, probalistic approach

1. Introduction

A superheater, in a power generating plant using steam turbines, is a group of pipes with their surface exposed to the hot gases in the boiler furnace. For increasing the steam turbine efficiency, the steam flow is further heated by the superheater to very high temperatures – well above the boiling point of water. Life of superheater pipelines depends on production tolerances and variations in operational conditions. These conditions might increase the chances of shortening the lifetime of a specific segment of the pipeline. Under certain circumstances, failures may take place even within a relatively short period of between 5 – 10 years.

In the commonly used deterministic approach, the lifetime of a superheater is estimated by characteristic values of the production parameters: wall thickness and external diameter; and the operating conditions: stress and temperature. Since design lives of 10 to 30 years are common, some means of extrapolating the data to long life is necessary. A common method of doing this is the use of time-temperature parameters that relate the stress and temperature to the time to failure. The most widely used and long time known parameter is the Larson-Miller parameter (LMP) (Larson & Miller 1952),

$$LMP = T\,[C' + \log t_r] \tag{1.1}$$

Where C' is a constant. C' is approximately equal to 20 when the temperature T is expressed in degrees Kelvin and the time to failure t_r is expressed in hours. By knowing the LMP for a given stress, it is possible to determine the time to failure at a given temperature. In this approach, a lower bound for a superheater lifetime is based on some arbitrary safety factor that does not necessarily reflect real life, where unexpected failures do occur.

In order to cope with this reality, we propose here a probabilistic approach that comprises two models:

- A probabilistic time to failure evaluation model.
- An optimal parameters combination model.

In the probabilistic time to failure evaluation model, presented in Section 2, the variability of the various lifetime determining parameters (wall thickness, external diameter, stress and temperature) is taken into account. This model can help to identify the most influential parameters for planning for a minimal probability of failure.

Application of the model to a specific practical example, a problematic steel T22 superheater, is demonstrated in Section 3. The effect of changing the nominal values of the parameters on the lifetime distribution was tested. It followed that the selection of the nominal values should be based on life cycle cost considerations.

Hence, the optimal parameters combination model, suggested in Section 4, is based on life cycle cost considerations. The model selects optimal values of design parameters and operating conditions and determines an optimal replacement policy. The model calculates, for any given combination, the average life cycle cost, and its usefulness is demonstrated by applying it to the example superheater.

2. Probabilistic time to failure evaluation model

2.1 Background

Structural reliability models usually assume some theoretical lifetime distribution (Weibull etc.). We propose a different probabilistic model which calculates the lifetime distribution as a function of tolerances in design parameters and working conditions. This probabilistic time to failure evaluation model is based on the Larson-Miller formula (see equation (1.1)). However, unlike Larson-Miller, who treat stress and temperature as constants, our model takes into account variations in stress and temperature during the lifetime of the superheater.

Failure of a pipe is mainly a result of creep. Corrosion accelerates creep by increasing stress due to the thinning of the pipe's wall. Changes in wall thickness also affect the metal's temperature. Thus, the model incorporates variation of all those parameters as a function of time.

2.2 Time dependent parameters

a) Wall thickness (W)

The thickness varies due to internal and external corrosion. This is described as follows:

$$W(t) = W(0) - K_1 t \tag{2.1}$$

Where W(t) is the thickness at time t and K_1 is the rate of decrease of thickness or rate of corrosion.

b) External diameter (D)

The external corrosion is not uniform over the pipe. This variation is described similarly to the variation in thickness as follows:

$$D(t) = D(0) - K'_1 t \tag{2.2}$$

Where D(t) is the diameter at time t and K'_1 is the rate of external corrosion.

c) Stress (σ)

The stress (σ) is associated with wall thickness (W), diameter (D) and operating pressure (P) by the following approximated Lame equation:

$$\sigma = P(D\text{-}W)/2W \tag{2.3}$$

By substituting the values of D(t) and W(t) as per equations (2.1) and (2.2) for W and D, and simplifying the result by assuming that $K_1 \approx K'_1$ (this is a fair assumption as the rate of corrosion is a function of the material and the severity of its environment. The material is the same and the external and internal environments are very similar, one gets the time dependency of σ as:

$$\sigma(t) = (P/2)\{[D(0)\text{-}W(0)]/[W(0)\text{-} K_1 t]\} \tag{2.4}$$

d) Temperature (T)

The variation in temperature is approximately a linear function of the variation in wall thickness as follows (French 1983):

$$T(t) = T(0) + K_2(W(0) - W(t)) \tag{2.5}$$

Where T(t) is the temperature at time t and K_2 is the rate of change of temperature due to the change in wall thickness.

2.3 The Larson Miller Parameter (LMP)

As stated above, the LMP (equation 1.1) associates the lifetime of a pipe and its temperature, assuming constant stress and temperature throughout.

An empirical equation relating LMP and stress σ is given by Viswanathan (1989):

$$LMP = A\text{-}B\ln\sigma \quad (2.6)$$

Where A and B are constants of the material.

Therefore, the lifetime of a superheater pipe (time to failure t_r) can be described as a function of temperature T and stress σ by:

$$t_r(T,\sigma) = 10\exp\{[(A\text{-}B\ln\sigma)/T]\text{-}20\} \quad (2.7)$$

2.4 Assessing the time to failure

If a superheater is exposed for a period of time Δt to a given temperature T and a given stress σ (both constant at Δt), the time to failure $t_r(T,\sigma)$ under these conditions will be given by equation (2.7).

If the 'life fraction' of the pipe, which is consumed during Δt, is Δr we get:

$$\Delta r = \Delta t / t_r(T,\sigma)$$

Since the model takes into account the time dependency of temperature and stress, the 'life fraction' consumed up to time t becomes:

$$r(t) = \int_{\tau=o}^{t} \frac{1}{t_r(T(\tau)\sigma(\tau))} d\tau$$

And the time to failure is the time t that satisfies: $r(t)=1$

$T(\tau),\sigma(\tau)$ are calculated according to the formulae of paragraph 2.2; $t_r(T,\sigma)$ is calculated according to paragraph 2.3. Any standard program performing numerical integration can compute the integral above.

2.5 Evaluation of the time to failure distribution, $t_r(T,\sigma)$

The $t_r(T,\sigma)$ distribution is too complicated to be expressed analytically and should, therefore, be estimated by Monte-Carlo simulation.

Since each of the parameters comprising $t_r(T,\sigma)$ has a known distribution, the simulation program can draw a certain value for each parameter, for which a specific value of t_r is calculated. The simulation thus proceeds until an 'empirical' distribution of t_r values is obtained. If the number of draws or simulation runs is sufficiently large, the 'empirical' distribution becomes a good estimate to the real time to failure distribution.

3. Application of the approach to a specific case

3.1 Parameters of the example

The proposed probabilistic time to failure evaluation model presented in Section 2 was applied to a steel T22 superheater, under given operating conditions: temperature and pressure (which affects stress). This superheater is not representative of all designs and is of rather specific characteristics: corrosion rate, LMP, diameter and wall thickness. The simulation is based on those characteristic parameters and the operating conditions as presented in Table 1.

3.2 Results for typical conditions and parameters

Table 2: Superheater lifetime distribution under typical circumstances

Superheater lifetime distribution in (000) hours			
Mean	*SD*[1]	P_5	P_{10}
195	95 (49%)	7%	18%

Note:
1. In parenthesis – SD as percentage of mean

It can be seen that the simulation has yielded for a superheater of average temperature of 590°C and pressure of 35 atm (atmospheres), a mean lifetime of 22 years with a standard deviation of nearly 11 years (49%). Under these circumstances, the probability of failure within 10 years is high – 18%. Since the operational conditions were held constant in this example, it is clear that the high standard

Table 1: Typical parameters and operating conditions for superheater of steel T22

Initial thickness W(0)[1]	*Initial diameter D(0)*[1]	*Pressure (P)*[2]	*Initial temp. T(0)*[2]	*Corrosion rate* (K_1)[3]	*Temp. rate* (K_2)[4]	*LMP*[5]
Mean=4.6 mm	Mean=57.1 mm	35 atm (atmospheres)	590°C	$7.6\cdot10^{-6}$-$15\cdot10^{-6}$mm/h	35°F/mm	A=47
SD=0.03 mm	SD=0.2 mm					B=4.33

Notes:
1. A normal distribution is assumed.
2. This is the pressure at the superheater reheater when its metal temperature (not steam temperature) is 590°C. The parameter P is treated as constant; sensitivity analysis for higher/lower values should be performed.
3. A uniform distribution is assumed.
4. Given in Larson and Miller (1959).
5. A and B, of Equation 2.6, are given for steel T22 in French (1983). All LMP values, calculated for these in A and B, vary in the range of about 10% of each other. We assume a uniform distribution in this range.

deviation in lifetime is due only to variations in the superheater's parameters.

3.3 Sensitivity analyses

(a) Effect of the standard deviations of parameters on the standard deviation of lifetime

We have seen above that the superheater parameters: Corrosion rate, LMP, Initial thickness and Initial diameter determine the variability in superheater lifetime. The first two depend on the material characteristics of the superheater, whereas the other two reflect superheater production tolerances. In order to assess how the parameters affect variation, the simulation raffled each parameter (one at a time) while keeping the others at their typical values. Table 3 describes the influence of variation in each parameter on superheater lifetime's standard deviation.

Table 3: Variation of parameter affecting standard deviation of superheater lifetime

Parameter	*Standard deviation (000) hours*
Corrosion rate	10
LMP	94
Diameter	0.5
Wall thickness	2

It follows that the dominant factor affecting variation in superheater lifetime is the variation in the LMP. The variations of other parameters have only a marginal effect.

The effect of decreasing the standard deviation of the LMP by 2% (by keeping a more uniform material) on the lifetime standard deviation and on the probability of failure was examined. It was found out that:

- The standard deviation of the lifetime was similarly decreased.
- The probability of failure within 5 years, P_5, or 10 years, P_{10}, became:

$$P_5=2\%$$
$$P_{10}=16\%$$

That is, there is a considerable improvement during the first 5 years, but marginal improvement for the 10 years period. This calculated improvement suggests a practical recommendation to perform periodical checks of the parameter wall thickness. Such periodical checks are a means to monitor variations in this important parameter, thereby reducing variations in the LMP and extending the superheater's lifetime.

(b) The effect of change in typical parameter value

We refer to changes in the following parameters:

- Corrosion rate (as material dependent).
- Initial wall thickness.
- Superheater's temperature (which in turn, affects the corrosion rate for a given material).
- Operating pressure.

Since we change four parameters, the number of possible options is $2^4=16$. This number is quite large; therefore, the analysis was performed only on a 'one at a time' basis for each parameter. An example is also given for the case of a combined change of two parameters – temperature and pressure, demonstrating its dramatic effect. The results of this sensitivity analysis (including, for convenient reference, the results of Table 2) are presented in Table 4 below. These results are expressed in terms of the mean and standard deviation of superheater lifetime and the probability of failure in 5 years and in 10 years (P_5 and P_{10}).

Notice, however, that an optimal decision regarding the required changes should be taken only after testing *all* the 16 possible options. Hence, in Section 4 we suggest a criterion based on life cycle cost considerations, and a model to calculate, for any given option, the average life cycle cost.

The results in Table 4 clearly show that each single change (perhaps with the exception of pressure) significantly improves the mean lifetime with a lesser effect on the standard deviation. Obviously, the magnitude of the standard deviation greatly affects the probabilities of failure. Consider the decrease in the corrosion rate that increases the standard deviation. Thus, although the decrease in corrosion rate

Table 4: The effect of change of parameter on superheater lifetime

Parameter changed	*Superheater lifetime distribution in (000) hours*			
	Mean	*SD*[1]	P_5	P_{10}
All typical – no change (see Table 2)	195	95 (49%)	7%	18%
Corrosion rate down to $5 \cdot 10^{-6}$mm/h	352	193 (55%)	4%	13%
Wall thickness up to 5.61mm	259	107 (41%)	<1%	8%
Temp down to T=580°C	289	134 (46%)	<1%	10%
Pressure down to P=32 atm	211	93 (44%)	3%	14%
T=580°C + P=32 atm	311	130 (42%)	<1%	5%

Note:
1. In parenthesis – SD as percentage of mean

dramatically improves the mean, the probability of failure in 5 or 10 years is still quite high. However, the combined effect of lowering pressure and temperature results in a dramatic improvement in the mean and a moderate improvement in the standard deviation. These two improvements together, result in the desired effect of significantly lowering the probability of failure even in the 10 year period.

Clearly, there is no single parameter that can be varied alone and lower significantly the probability of failure, and a combination of parameters may be required. As mentioned before, selecting the optimal combination should be based on minimizing the average life cycle cost. An appropriate model is presented in Section 4.

4. Optimal parameters combination model

4.1 Background

The optimal combination of changes in parameters and operating conditions of the superheater, involves the minimization of average life cycle cost. For each of the optional combinations of the parameters: temperature, pressure, corrosion and wall thickness, an optimal time replacement and an average cost per time unit should be calculated. The life cycle cost for each option is calculated under the assumption that an optimal replacement policy is employed.

A model to determine the optimal replacement time and the corresponding optimal combination of parameters is presented in Section 4.2.

4.2 Optimal selection of parameters and scheduled replacement time

Model description

The breakdown costs for superheaters are known to be very high; hence a preventive maintenance policy with prescheduled replacement time is employed. However, the costs involved in this policy are those associated with replacing a superheater too early, when it is still in good operational condition, versus the costs associated with breakdown before the scheduled replacement time. To address the problem of minimizing those costs under preventive maintenance policy, the proposed model determines an optimal replacement time that relies on a good estimate of the probability of failure of the superheater.

Notations in the proposed model:

- X time to failure of a superheater.
- $f(X)$ probability density function of X, estimated by the simulation.
- $F(t)$ the probability of failure occurring before replacement time t [estimated by the simulation, using the fraction of failure times occurring before t].
- $[1-F(t)]$ the probability for prescheduled replacement.
- $E(X/X<t)$ the expected time of failure occurrence, given it occurred before time t, is estimated by averaging out all the values of $X<t$ given by the simulation.
- C_1 cost of preventive maintenance.
- C_2 – cost of breakdown maintenance.

Both C_1 and C_2 depend on the combination of superheater parameters.

Hence, μ – the expected time between replacements will be:

$$\mu = t(1-F(t)) + E(X/X<t)\,F(t)$$

Therefore, the average cost per unit of time – C_M – will be:

$$C_M = (1/\mu)[C_1(1-F(t)) + C_2\,F(t)]$$

Where the probability F(t) is interpreted as the proportion of cases for which cost of repair is C_2. [1-F(t) is similarly related to C_1].

Any standard one-dimensional search routine can readily calculate the optimal replacement time t for which C_M, the average cost per unit of time, is minimal.

5. Summary and conclusion

The described probabilistic approach, comprising a probabilistic time to failure evaluation model and an optimal parameters combination model, was found to be an effective tool for gaining an insight into the various factors affecting the lifetime of a superheater. The proposed approach can be beneficially used to predict the probability of failure of the superheater at any given time, and to determine the optimal replacement time.

The probabilistic time to failure evaluation model was applied to a specific problematic example of a steel T22 superheater (which is not representative of all boiler designs). It was shown that the example's mean lifetime, given data at typical operating conditions: temperature of 580°C and pressure of 32 atm, is over 20 years. But the high variability of the data result in a large standard deviation and consequently a relatively high probability of failure is 18%, within the first decade of operation.

Sensitivity analysis has shown that the dominant factor affecting variation in superheater lifetime is the variation in the LMP. Decreasing the standard deviation of the LMP (by keeping a more uniform material) lowered the probability of failure. This resulted in a *practical recommendation* to perform periodical checks of the parameter wall thickness. Such periodical checks monitor variations of that parameter, thereby reducing uncertainties in the superheater's lifetime.

The effect of changing each of the superheater's parameters – corrosion rate, LMP, initial wall thickness and diameter – on the lifetime distribution was examined. The analysis was performed on a 'one at a time' basis for each parameter. However, an optimal decision regarding the required changes should be taken only after testing the considerable number of *all* the possible combinations. Hence, a criterion based on life cycle cost considerations, and an optimal parameters combination model that determines (for any given option) the average life cycle cost, were suggested.

The latter model computes the average life cycle cost per time unit as a function of the superheater's parameters, operational conditions and the scheduled replacement time. For any given values of the parameters, it determines the optimal replacement time that minimizes the average life cycle cost. Given that an optimal replacement policy is employed, the optimal parameters set is the one for which the average life cycle cost is minimized.

The usefulness of the proposed approach was demonstrated in a specific problematic example. It identified a specific parameter for which *periodical checks* were subsequently recommended. It also resulted in an optimal replacement policy for the superheater. This success of the proposed approach in a problematic example suggests that it can be readily adapted to a more general context, where the planned lifetime of a certain design is threatened.

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