STRESS ENGINEERING SERVICES INC.®

www.stress.com

Power Plant Fitness-For-Service

Pressure Part Integrity: Steady and Cyclic Loading

Running utility boilers for unusual cyclic conditions places new demands on boiler operators, requiring new and pro-active measures to manage the risk of equipment failure. These summary notes illustrate some aspects of the problem for boiler pressure parts.

Boiler design code not relevant for cyclic loading

Conventional and HRSG Power boilers are designed to Section I of the ASME Boiler and Pressure Vessel Code. This code Section does not deal with cyclic loading and therefore the possibility of fatigue and creep/fatigue failures can be high, particularly in regions of high heat flux, internal fouling, wastage, stress concentrations etc. The role of water chemistry is critical. Water chemistry is sensitive to cyclic loading and requires special measures.

Increased operational requirements

It is not uncommon for units originally intended for base load operation to be operating now in cycling and even two-shifting mode. This can mean that the original intended cyclic life is used up many times over. This may or may not mean that failures are inevitable. Some effects of cycling are identified and possible ways to characterize and manage the risk.

Need to optimize effectiveness of inspection

The absence of design calculations for cyclic loading means that high risk components and locations have to be identified based on stress analysis, plant history and experience in similar plants. This is essential for effective planning of inspection since 100% inspection of pressure parts is not feasible.

Risk management requires full use of monitoring, inspection, testing and assessment.

The objective of component risk management is to:

- Avoid failures
- Avoid unnecessary repairs and replacements

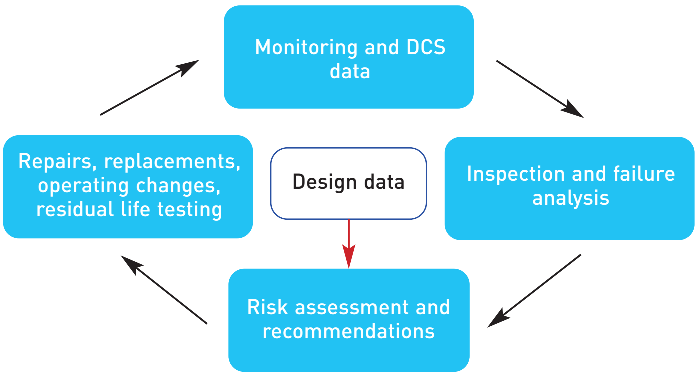
Considering the range of components, problems of access, and the differing failure modes, the methods used will vary from component to component. For example superheater and reheater tubes, wastage and oxide thickness are a critical parameters requiring measurement; metal temperature can be estimated from performance calculations, oxide thickness and terminal tube temperature. For headers and piping, direct temperature monitoring is necessary. A typical range of inspection techniques includes borescopic inspection, replicas and UT of welds and tube ligaments.

Knowing the risks means rational and defensible decisions.

The ability to compare risks of failure means that decisions for inspection, repair, down rating etc have a solid basis. This is important when attempting to understand the meaning of "exceeding minimum rupture life". A probabilistic definition of acceptable risk may be used to define inspection intervals which decrease over time, and which can be justified in terms of the risk of failure between inspections.

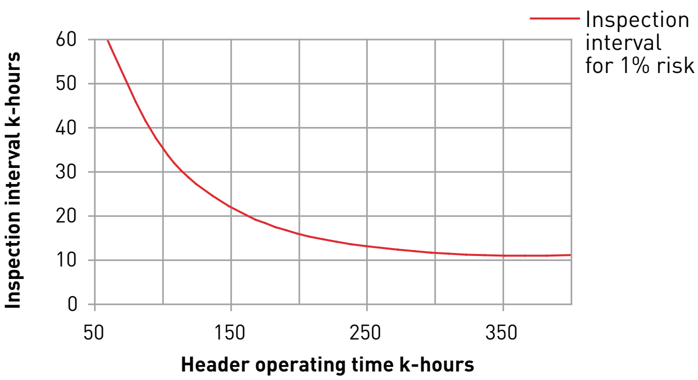
The Process is dynamic and should be updated when changes occur.

For each critical component or assembly, the estimate of risk needs to be updated when new data becomes available. This ensures that any unforeseen event such as an over-temperature can be assessed quickly and efficiently.



Objective: Avoid failures and unnecessary repairs and replacements

Schematic of information flow in pressure part risk management process.

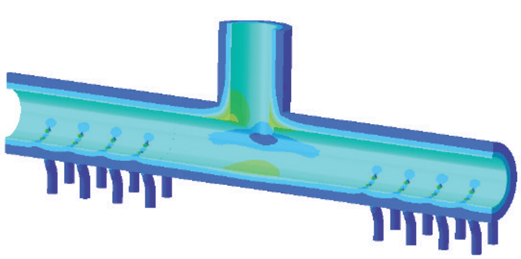


Calculated header inspection interval for uniform risk (material, stress, cycle and temperature dependent)

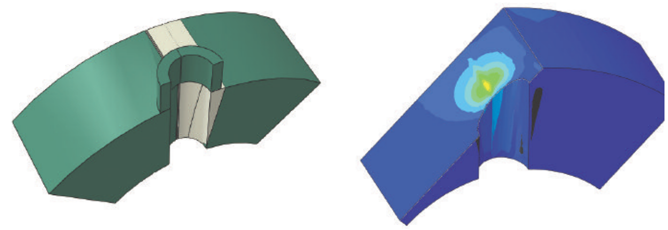
Components

Headers

Header life is a function of steady and cyclic loading, and is sensitive to heating and cooling rates as well as to side-to-side and top-to-bottom temperature differentials. These factors can usually be tracked with carefully placed terminal tube thermocouples, and DCS steam temperature data. Superheater and reheater outlet headers are usually the most critical, but it is not uncommon for a seamwelded platen outlet header to have a comparable risk. A seamweld running through tube ligaments is likely to lead to a significant reduction in life, with or without cyclic loading. As seen below, weld HAZ cracking is likely to occur beneath the surface, so surface inspection of such seamwelds may miss evidence of weld creep damage.



Stress analysis of header showing nozzle and tube penetration stress concentrations



Model of header seamweld through tube ligaments showing an internal region of creep damage in weld HAZ

Scoping calculations for tube ligaments, nozzles and seamwelds under steady pressure loading allow for rapid assessment, but cracking and hogging/sagging behavior due to cycling temperature differentials require detailed finite element analysis. The accuracy of the remaining life prediction increases with the type and quality of the available information.

Design data only Assessment is possible if there is a basis for believing that operating conditions are less severe than design conditions. Ranking of header risk is possible.

Design data + Distributed Control System (DCS) data Life prediction based on minimum properties and typical header temperature variation has some basis.

Design data + DCS + thermocouple data Maximum header temperature is known and steady load assessment based on minimum properties is possible. Probabilistic statements to justify inspection intervals may be made.

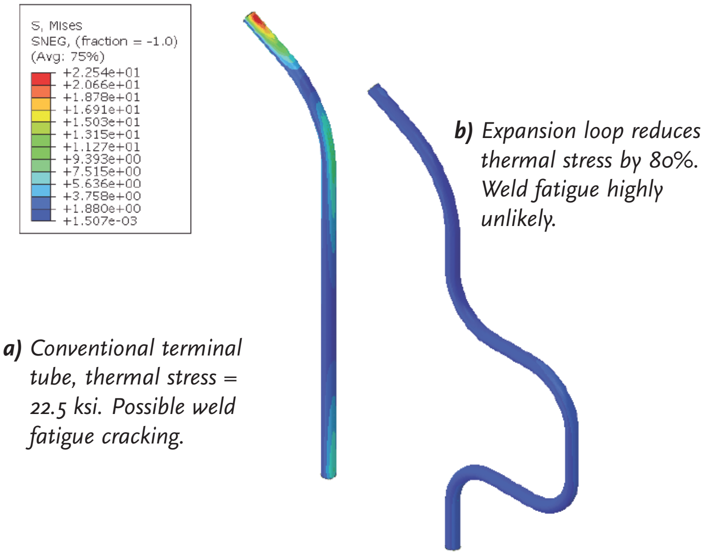
Design data + DCS + thermocouple data (steady and cyclic) + sample material data Remaining life estimates can be performed with the most confidence. What makes life prediction possible is knowledge of the creep properties of header material.

Terminal tubes Terminal tube temperatures are sensitive to steam flow variations, as well as to side-to-side gas temperature variations. Failure is likely to be at the terminal tube-header weld, but high crown seals are also a possibility. The use of expansion loops can eliminate thermal stress due to terminal tube temperature variations. Cracking at terminal tube welds can be predicted with temperature information and a tube finite element model.

Superheater and reheater tubes

The complexity of superheater and reheater tube failure modes is well known. (Cycling and fatigue are unlikely to affect tubes unless there are welded spacers or supports.) Wastage rates are difficult to predict and control. From the point of view of estimating tube risk, the exact mechanisms of wastage are less important than the data, and knowing if the mechanism is likely to continue.

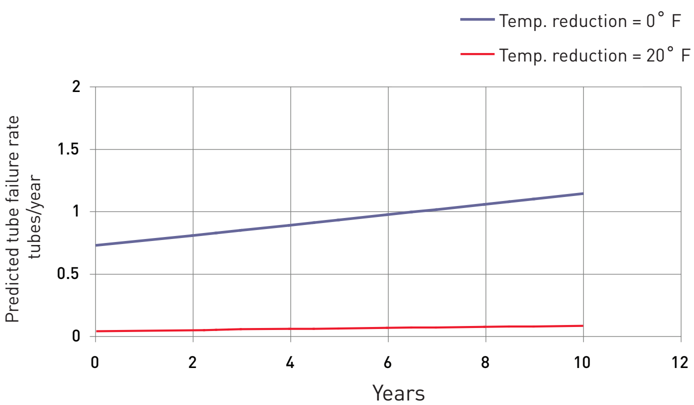
Given basic data, tube risk and minimum remaining may be estimated, and recommendations made for partial or complete replacement the section. In addition, if the current risk of failure is unacceptable and a replacement is not available, a recommen-



a) *Conventional terminal tube, thermal stress = 22.5 ksi. Possible weld fatigue cracking.*

b) *Expansion loop reduces thermal stress by 80%. Weld fatigue highly unlikely.*

dation for a temperature de-rate may be made which effectively reduces risk to zero. Experience has shown that this temperature reduction is often acceptable in terms of generation performance.



Plot of tube risk

Information requirements The following list is typical.

- Schedule of current tube materials, dimensions, length of service and design conditions
- Unit maximum continuous rating (MCR) temperature and pressure
- DCS and/or thermocouple data for outlet of section in question
- Dissimilar metal welds
- Thickness surveys and any evidence of wastage rates
- History (inspection reports, tube replacements, material changes, failure analyses)
- Basic steam flow and thermal performance data for the heat exchanger section

Waterwalls

Waterwall failures in supercritical boilers are generally regarded as the source of most forced outages.

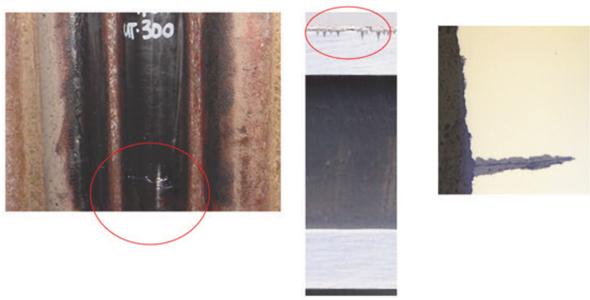
Failure modes are complex and involve combinations of severe environmental and thermal-mechanical conditions. Aggressive external corrosion after conversion to low NOx burner systems has been the main cause of waterwall tube failures and replacements in supercritical units. The response to this by utilities has been the use of coatings and Ni-based weld overlays to prevent wastage in the reducing combustion environment. While weld overlays have been generally successful in controlling wastage, other failure modes have occurred, such as:

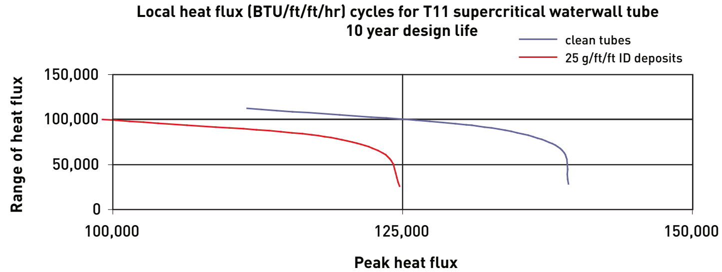
- Fatigue at terminations of weld overlay and other poor field-welded details
- Overheating failures due to factors such as fouling which requires more attention in supercritical than in subcritical units
- Oxide cracking due to thermal-mechanical cycles
- Environmentally assisted creep-fatigue

A typical case is circumferential cracking, usually initiating at multiple sites on the exposed crown of the tube. Both plain and overlaid tubes have suffered from such cracking. In addition to the environmental factors mentioned above, contributing factors are:

- Frequent thermal cycling due to soot-blowing and slag falls
- High local heat fluxes
- Internal fouling leading to high tube metal temperatures

Analysis of creep-fatigue damage quantifies the thermal-mechanical contribution to circumferential cracking, and gives a basis for recommending limits to maximum heat flux and heat flux ranges.





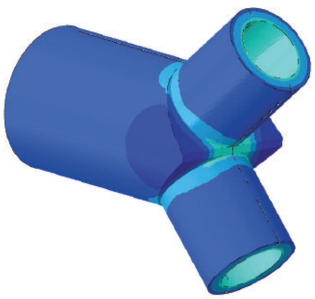
Effect of heat flux cycles and internal fouling on waterwall tube life

Economizer

Economizer inlet headers in the gas stream are potentially at risk from thermal shock leading to fatigue and cracking. Ash build-up, wastage and corrosion problems are the main on-going concerns. Generally economizer reliability is manageable with conventional inspection and maintenance.

Piping and welds

Piping is designed for steady and cyclic loading in the B31.1 code. It is reasonable to expect that piping reliability should be better than for a boiler. Changes in hanger performance over time due to inspection and maintenance difficulties, and excessive piping deflection leading to hanger bottoming out, remain as concerns. A combination of hot and cold walk-down data, combined with a piping analysis, is recommended. This provides a sound basis for hanger maintenance and identification of areas of possible creep-fatigue, and inspection. Any seam-welds, as well as girth welds in areas of high cyclic bending stress, require particular attention in assessing risk. Heavy-walled components such as forged tees and wyes are likely candidates for fatigue and cracking from thermal shock. In many cases, when inspection has revealed such a crack, it has been assessed as a low risk. The component has been allowed to operate with an inspection schedule, with recommendations for temperature de-rate if necessary.



Stress analysis of "wye"

Methods

Inspection: MPI, UT, wall and oxide thickness measurement, borescope, replicas, dimension checks for straightness and swelling.

Monitoring: Primary monitoring tools include strain gages, thermocouples, and DCS systems

Testing: Remnant creep life testing of samples. A decision to use this technique is clearly not taken lightly. As noted below, a pressure part assessment reflects the data available. The creep properties associated with the material specification have a statistical distribution. When this distribution is not good enough to use in some particular case, a material test can greatly reduce uncertainty in creep material properties, *and* in information on the stress and temperature history of the component.

Failure analysis: Information from failure analyses, particularly of tubes, is crucial for understanding the factors in an assessment, and providing data such as wastage rates, estimates of temperatures, weights of internal deposits etc. Indeed one of the objectives of the failure analysis should be to generate the data for tube risk assessment.

Risk assessment: Identification of failure modes. Remaining life and risk calculations.

Recommendations: Inspect and monitor/repair/replace/re-rate.

Conclusions

Identification of critical components, their failure modes and corresponding data is key. This changes the risks of cyclic failures from unknown to manageable. The multi-disciplinary skills and experience available in SES are a necessity in understanding such complex problems and developing solutions.