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Online Creep and Fatigue Monitoring in Power Plants

M. Sc. thesis work

Examiners: Professor Risto Raiko, Professor Pasi Peura

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Abstract

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Increasing wind and solar power production and deregulation of electricity market have significantly changed electricity market environment in many areas such as Germany, Ireland and parts of USA. Consequently, demand for electricity production using combustion boiler units has been experiencing increasing fluctuation. This has been causing increasing amount of variable load operation and on-off cycles for these boilers. Such operation has undesired effects on condition of boiler pressure part and therefore operability and economic efficiency of whole boiler unit.

Objective of first part of this work is to study mechanisms of creep and fatigue occurring in pressure vessels. Then, problems arising from cyclical operation of power boiler pressure part are introduced. Steam turbines are also briefly covered. The latter part of the work discusses possibilities for computer-assisted real time monitoring of boiler condition. More detailed description of a computer application made as a part of this thesis work is also given. One part of the work was to study, if there is need for such applications at the market.

Using information provided by a real time monitoring application, it is possible to reduce problems related to creep, thermal stresses and following fatigue. There are reports indicating that underestimating costs related to cyclical boiler operation may have considerable financial consequences. Therefore it would be beneficial to have estimations on such costs. Several available commercial software products include features that assist in making these estimations.

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Lisääntynyt tuuli- ja aurinkovoiman tuotanto sekä sähkömarkkinan säännöstelyn poistuminen ovat muuttaneet sähkömarkkinaa monilla alueilla, esimerkiksi Saksassa, Irlannista sekä osissa Yhdysvaltoja. Tämän seurauksena polttoprosesseihin perustuvien voimakattiloiden tuotannon tarpeen heilahtelu on lisääntynyt, mistä johtuen niiden ajokuormat vaihtelevat enemmän ja ylös- ja alasajoja tapahtuu aiempaa useammin. Tämänlaisella ajotavalla on ei-haluttuja vaikutuksia kattilan painerungon kuntoon ja sitä kautta koko kattilayksikön toimivuuteen ja taloudelliseen tehokkuuteen.

Tämän työn alkuosan tavoitteena on tutkia voimakattilan painerungon virumiseen ja väsymiseen liittyviä mekanismeja. Tämän jälkeen voimakattilan syklisestä ajotavasta johtuvia ongelmia on esitelty yksityiskohtaisemmin. Höyryturbiineja on käsitelty myös lyhyesti. Työn loppuosa käsittelee tietokoneavusteisen ja reaaliaikaisen kattilan kunnon seurannan toteuttamista. Tämän työn kiinteänä osana on ollut tällaisen ohjelmiston toteuttaminen, jota on kuvattu tässä työssä. Yksi osa tätä työtä oli myös tutkia, onko tällaiselle tuotteelle markkinoita.

Reaaliaikaisen seurantaohjelmiston tuottamaa tietoa käyttämällä on mahdollista vähentää virumiseen, lämpöjännityksiin ja siitä johtuvaan väsymiseen liittyviä ongelmia. On olemassa näyttöä siitä, että kattilan sykliiseen ajamiseen liittyvien kustannusten aliarvioinnilla on merkittäviä taloudellisia seurauksia. Tästä johtuen arviot näistä kustannuksista ovat erityisen hyödyllisiä. Moni tarjolla oleva kaupallinen ohjelmisto tarjoaa ominaisuuksia tällaisten arvioiden tekemiseen.

Preface

This thesis work has been written as a part of development project undertaken by Metso Automation Corporation. The objective of the project was to produce new version of creep and thermal fatigue monitoring application for Metso DNA platform. The thesis work was written to be a guide on various themes related to online condition monitoring so that usage and further development of the application would be more effective. For the writer this was achieved even if it required many excursions outside of the comfort zone which wasn´t always easy.

Guidelines for this work were discussed and decided in collaboration with Maria Nurmoranta and Markku Rintala from Metso Automation and Professor Risto Raiko from TUT, who also is examiner of this thesis. I´d wish to thank both for co-operation. I want also to thank Professor Pasi Peura from TUT for examining the thesis.

I got huge amount of help and advice regarding the application development from the people at Metso Automation. There was no day at the office when I wouldn´t have learned something new. Thank you.

Last but not least I would like to thank my family: my parents for encouraging me to be curious since I was a child and my wife-to-be Maarit for supporting me through the studies.

Table of Contents

ABBREVIATIONS AND DEFINITIONS

ASME	American Society for Mechanical Engineering. Professional non-profit association that promotes field of engineering.
BCC	Body centered cubic, type of atom configuration found in many metals
BLM	Boiler Life Monitoring, a software product developed by Metso Automation Corporation
BPVC	Boiler and Pressure Vessel Code is a set of instructions for designing boilers and pressure vessels published by ASME.
BS 7910	British standard 7910 is a fitness for service procedure for pressure vessels. At the moment, corresponding EN-standard supersedes it where applicable. Latest version was released in 2014.
Creep	Time-dependent deformation of material under constant stress in elevated temperatures of around 30% of melting point or more in Kelvin
EFOR	Equivalent Forced Outage Rate is a statistics to express unplanned unavailability of equipment. It is determined as percentage of unplanned outage hours of the total hours of the availability of equipment.
EN-12952	A set of standard published by European Committee of Standardization to be used as guideline for pressure equipment design and fabrication so that requirements of European Union Pressure Equipment Directive are met
FAD	Fracture assessment diagram. Such diagrams are used by some fitness for service procedures for fracture analysis.
Fatigue	Phenomenon which causes a material fail when repeatedly exposed to stresses under tensile strength.
FCC	Face centered cubic, type of atomic configuration found in many metals.
FEM/FEA	Finite element method/analysis. Numerical method for solving boundary value problems for differential equation. Typically used for solving problems in the field of mechanical engineering.

FITNET	A fitness for service procedure for pressure vessels that was developed by a committee formed by the European Commission. Is not under further development.
HRSG	Heat recovery steam generator. Equipment used to recover residual heat of an process by transferring it to a fluid such as water. Typical use is to recover heat from hot gas turbine flue gases to produce steam.
Incipient crack	An "incipient crack" is a material separation which can be detected with optical aids or non-destructive testing methods. (Suomen standardisoimisliitto, 2012)
NDT	Non-destructive testing. General term for different methods for assessing structural integrity of materials without altering properties of the material.
Metso DNA	DNA stands for Dynamic Network of Applications. It is a software system used for process automation, control, operation and data collection.
PED	Pressure Equipment Directive is directive that sets minimum requirements to national pressure equipment legislation in European Union.
R5	A set of methods for assessing power boiler pressure part condition. It is developed and maintained in collaboration of companies Serco Technical Services, ANSTO, Rolls-Royce and EDF Energy.
RSE	Remaining sequence of extremes. Residual sequence of stress extremes produced by range-pair cycle counting method.

1. INTRODUCTION

Many electricity markets have been changing during last decade due to a few great global trends. This naturally causes changes in business environment of power generating industry and poses new technical and economical challenges to electricity producers. These challenges arise from changes in electricity generation, consumption and markets.

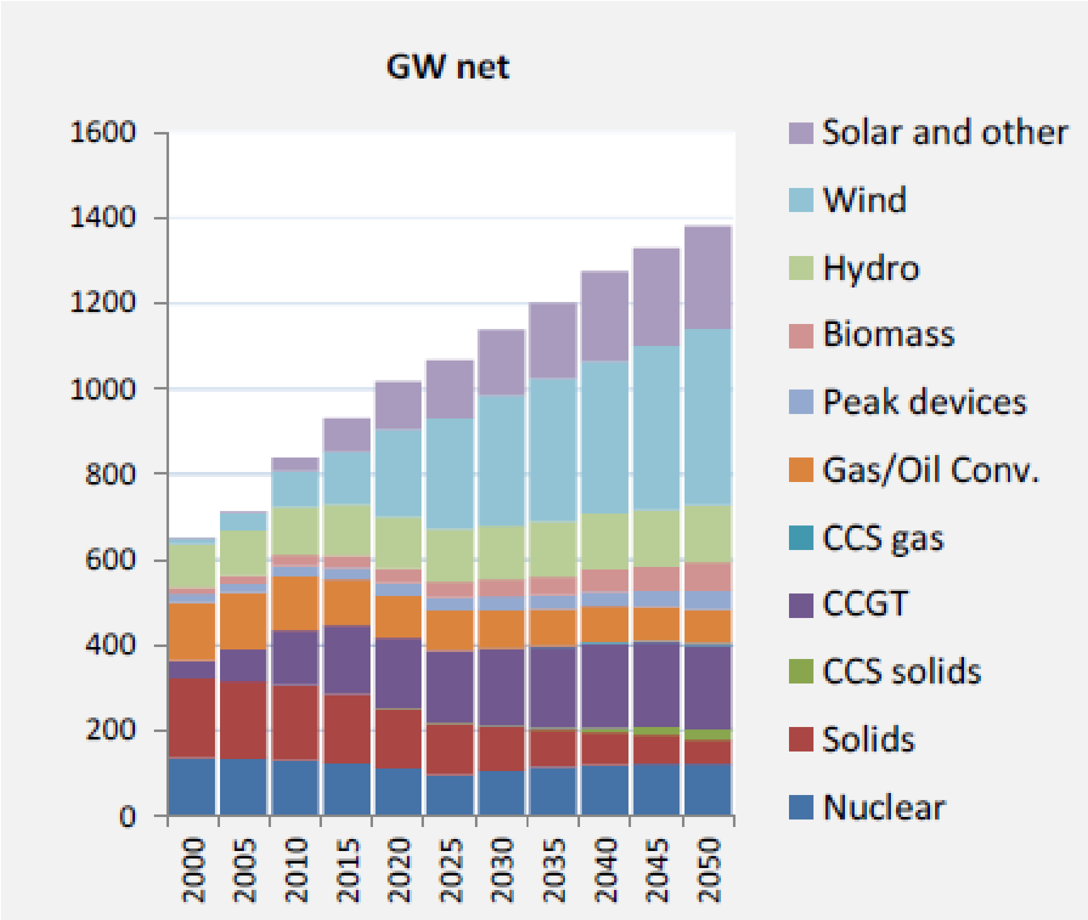

Figure 1-1 Estimated installed power capacity in EU28 countries 2000-2050. Source: (VTT, 2009)

At the moment, many countries of the world are investing in low-emission power generation in form of wind and solar power generation. Additionally technologies like those for harnessing energy of waves in the sea are already in pilot stage. These technologies own great potential in amount of power they can generate but are also more or less affected by cycles of nature and thus outside of human control. At the moment, this effect is significant only in some of the leading countries in the world but the rate at which new wind turbines and photovoltaic systems are built is increasing in many countries. (VTT, 2009)

Human society of today is such that it is dependent on continuous and adequate supply of power at every single moment and thus cannot be fully satiated by means of wind or solar power. In the past, at the moment and in the future there must be means of power generation that can adjust to changing power needs in a quickly manner. Today this often means usage of combustion-based power generation. Increasingly, such boiler units are operated cyclically following fluctuations of energy prices and production of wind and solar power. Such mode of operation may have significant impact on condition and availability of these plants. Especially this concerns many older boiler units not originally designed for such operation.

Object of this thesis work is to provide understanding on these effects and means to better anticipate them to make it possible to react before problems arise. Firstly phenomena behind boiler pressure part service life degradation are introduced in chapters 2 and 3. Some methods for assessing these phenomena using mathematical procedures are also reviewed. Online boiler condition monitoring systems are discussed in chapter 4. In addition to boiler pressure vessel, creep and fatigue assessment of steam turbines is also briefly covered.

2. MATERIALS AND DAMAGE MECHANISMS OF POWER BOILERS

This chapter introduces physical mechanisms behind creep and fatigue occurring in power boiler pressure vessels. Firstly, structure and properties of metals and specifically steel are described. The focus is placed on properties relevant to creep and fatigue. Then calculation of power boiler pressure vessel wall stresses is introduced.

Using the information on the structure of materials, fatigue and creep are introduced. Fatigue is a problem arising especially from on-off cycling of a boiler. Creep is generally the limiting factor of boiler pressure parts lifetime at boilers that are operated continuously for long time. Creep also causes ruptures when a material is overheated to temperatures over design values. Damage caused by corrosion is remarkable for some types of boilers but is excluded from the scope of this work.

Several boiler design codes have been introduced to be used by designers to ensure that all the important things are taken into account when designing, fabricating and adopting pressure vessels into use. Examples of such codes are Boiler and Pressure Vessel Code (BPVC) published by ASME (American Society of Mechanical Engineers) and EN-12952 standard published by European Committee for Standardization. These codes provide guidelines for fabrication, dimensioning, inspection and maintenance of pressure equipment as well as other information relevant to those working with such devices. In some parts of USA, Canada and some other countries complying with BPVC may be even required by law (Babcock & Wilcox, 2005). Estimating damage caused by creep and fatigue is also included in these codes and standardized procedures for making such calculations are described in this chapter.

2.1 Metallic materials

Generally, when selecting construction material for a boiler pressure vessel several factors must be taken into account. Material must have adequate characteristics for the intended usage including mechanical properties, thermal diffusivity, corrosion and oxidation resistance, creep resistance and many more. All this should be achieved within certain budget making the selection eventually some kind of compromise. Generally, material of choice is some type of steel. In this chapter microstructure and mechanical properties of different steel types are reviewed. Focus is placed on properties and phenomena relevant to fatigue and creep calculations. Finally different types of steels used in boilers are described.

2.1.1 Structure of metallic materials

Metallic atoms have one to three electrons on the outermost electron shell. As an atom typically attempts to change into an energetically stable form with zero or eight atoms on the outer shell, metals tend to lose electrons to become stable. Metallic atom loses these electrons and 'gives' them to a non-metal when bonding such elements such as oxygen or carbon. This is how an ionic bond is formed. When metallic atoms bond with each other, another type of bonding is formed. As these atoms have each excess of atoms, they have individually weak bond between them. When grouped however, they lose the electrons of the outer valence and the remaining metallic cations are arranged in a regular pattern. These cations have positive electric charge so they repel each other but the negatively charged electrons given away by the atoms glue them together. These electrons have great degree of freedom when moving between cations making most metals great electricity and heat conductors.

Structure of metallic and other crystalline materials can be illustrated with balls representing atoms packed together in three dimensions. These balls can be organized in several ways and 14 different structures are found in natural materials. Most common metals including steels, however, have one of the three common configurations. (NDT Resource center)

Body-Centered Cubic (BCC) Structure has atoms ordered in a cubic configuration with one atom in the center of the cube. Each corner atom is shared with other cells. The picture below illustrates this configuration.

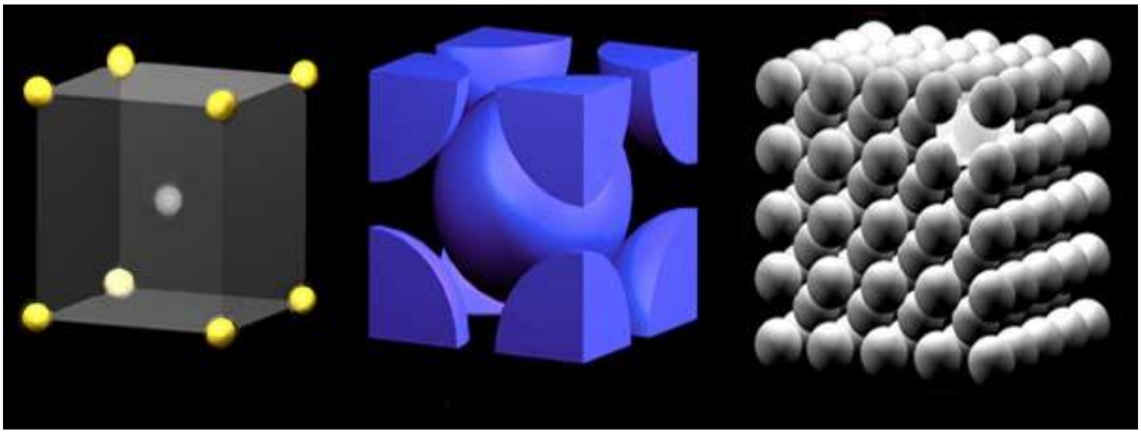

Figure 2-1 Body-Centered Cubic structure. Source: (NDT Resource center)

Metals having this configuration include lithium, sodium, chromium, alpha iron and tungsten. BCC-structure has so-called packing factor of 0,68 meaning that 68% of a unit cell space is filled with an atom. In the following will be seen that this isn´t maximum fill rate for spherical objects.

Face Centered Cubic Structure (FCC) has an atom in each corner and one on each face. When building atom layers with this structure, atoms are placed in empty space between atoms of the previous layer. Next layer is then built so that it´s orientated with the first layer.

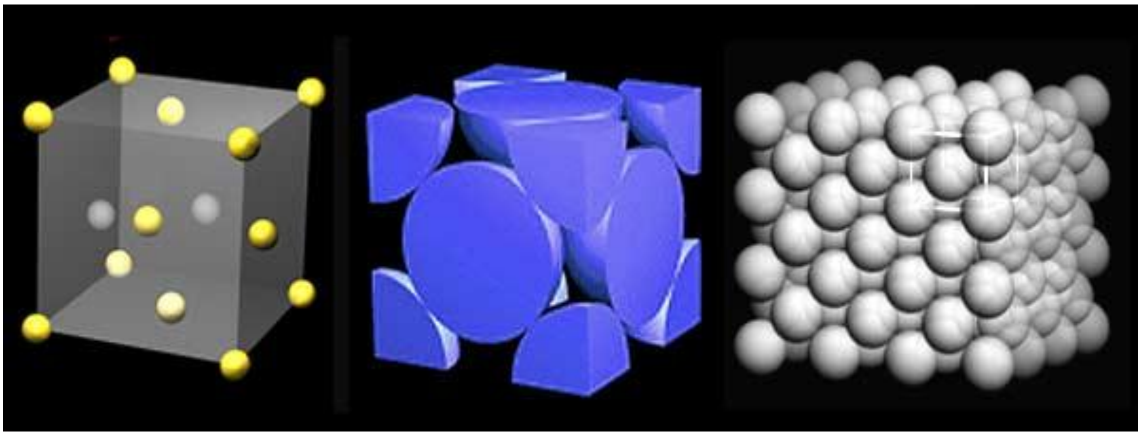

Figure 2-2Face Centered Cubic structure. Source: (NDT Resource center)

This structure has packing factor of 0,74, which is the maximum value found in natural materials. Some of the metals with this structure are aluminum, copper, gold, nickel, platinum and silver. (NDT Resource center)

Hexagonal Close Packed Structure (HCP) is another packing structure with packing factor of 0,74. In this structure, atoms fill empty space between ones in layer below but are differently aligned as in FCC. This results in hexagonal unit structure of the material.

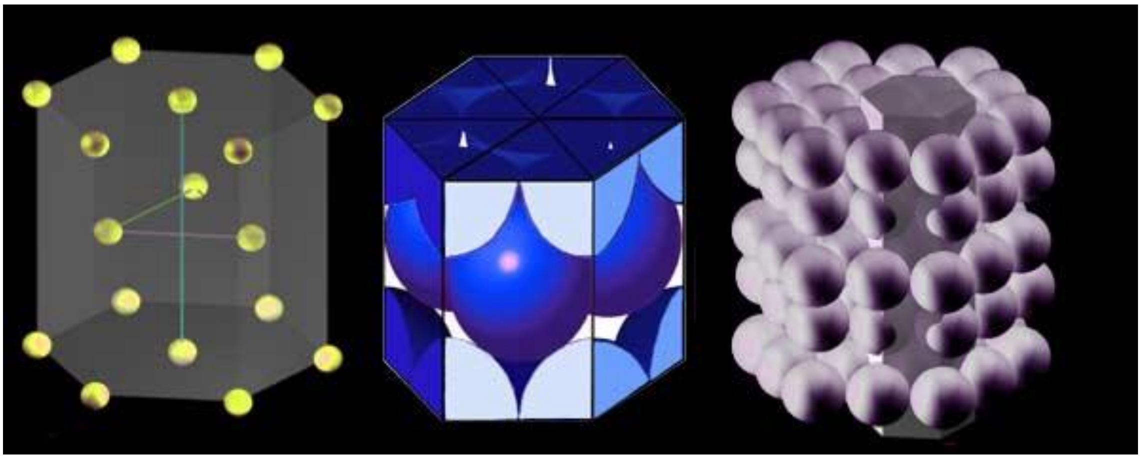

Figure 2-3 Hexagonal Close Packed Structure. Source: (NDT Resource center)

Some metals with this structure are elemental metals beryllium, cadmium, magnesium, titanium, zinc and zirconium (NDT Resource center).

When several of these unit-structures are stacked and lined up together, a metallic lattice system of which a metallic crystal consists. Many of the mechanical properties of metals are greatly affected by the configuration of atoms. As seen later in the text, type of the unit-structure a material assumes is not affected only by atoms it consists of but also by temperature. (NDT Resource center)

If it is assumed that each atom occupies a cubic space of size a_o so that all the material space is occupied by these cubes, then force F causes stress that equals F/a_0^2 on the cube causing strain equalling$(a - a_0)/a_0$. At first the strain-stress relationship is linear with the slope equal to elastic modulus E. At this region the bond returns to starting position if the stress is released similar to a spring. As stress is further increased a maximum is reached and eventually the bond is broken and plastic deformation forms. Due to short intervals on which inter-atomic forces work, the strain required to break the bond is quite small. Calculations show, that ideal strength of a bond gives a material result

$$\frac{\sigma_{ideal}}{E} \approx \frac{1}{15} \qquad (1)$$

However, no macroscopic piece material has been observed to achieve this value and typically yield strength of material is far below this strength. Reasons behind this are described in 2.1.2. Yield strength is the stress a material can stand without the effects becoming permanent. Stress that is less than yield strength is called elastic stress. When such the stress is removed, the material returns to its original form. When the stress exceeds yield strength, the bonds break and reform allowing atom planes to slip over each other. This kind of deformation is permanent and is called plastic deformation. Material with closely packed structure such as FCC needs less energy for such deformation than one with more loosely packed structure such as BCC. Therefore, tightly packed materials often more easily deformed making them also more ductile than metals with more sparsely ordered atoms. (Ashby & Shercliff, 2007)

2.1.2 Dislocations in metals

Few things are perfect and metals are not an exception. Macroscopic piece of metal rarely consists of a single crystal but a great amount of them instead. Reason to this is that when molten metal begins to solidify it begins simultaneously in several points called nucleation points. A crystal is formed from each nucleation point and when the solidification progresses further, they won´t melt into each other but discernible border called grain boundary forms between them. This is one explanation to the fact, that strength of a material is typically very different from that determined by the atomic bond strength. While it is technically possible to control nucleation so that even large objects may be formed of a single crystal, it typically is not economically feasible. A notable exception to this would be special applications such as turbine blades which are operated under very demanding conditions. Decreasing size of grains improves yield strength of steels. (Honeycombe & Bhadeshia, 1995, ss. 24-25) (NDT Resource center)

There are also numerous possible intra-crystal defects that affect properties of material. Point defects can be missing atoms, irregularly placed atoms or atoms of other element. Even if word ‘defect’ is used, in atoms of other element may be intentionally added into molecular lattice to improve characteristics of the main material. If an atom replaces an atom of main material, the system is called a ‘substitutional solid solution’. In some cases the foreign atom is so small that it takes place between the atoms of the lattice. This kind of configuration is called ‘interstitial solid solution’. (Ashby & Shercliff, 2007, p. 121)

Linear defects are whole groups of atoms that are positioned irregularly in the lattice. There are two general groups of line defects: edge dislocations and screw dislocations. Actual dislocations are typically mixes of these two but this detail is not really relevant to form understanding on the impact they cause on material properties.(Ashby & Shercliff, 2007, p. 122)

Edge dislocations have an extra half-plane of atoms in the lattice. Around this half plane, the metallic bonds are locally distorted. The half plane border is called slip plane. When shear stress is applied parallel to this plane, the dislocation can be moved if the stress is high enough. Another type of line dislocation is screw dislocation. Difference to edge dislocation is that it moves perpendicular to the shear stress applied. (Ashby & Shercliff, 2007, pp. 122-123)

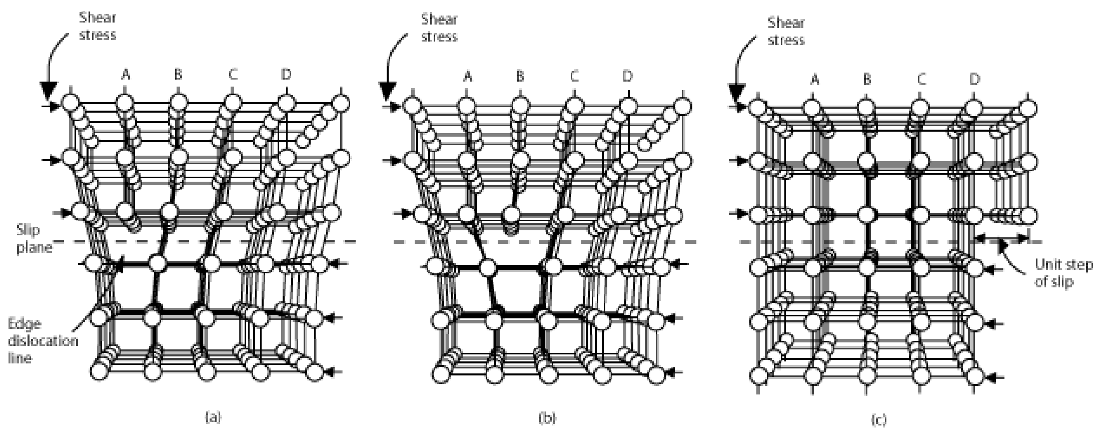

Figure 2-4 Movement of edge dislocation Source: (NDT Resource center)

What makes these line dislocations significant is that breaking atomic bonds is easier where the atoms are densest. This means that deforming material with such dislocations requires less energy than one would expect when observing bond strength. Deformation caused by moving a single dislocation is small, order of 10^{-10} m, but in real materials there is huge number of them and when they all move, the deformations become macro-scopic. (Ashby & Shercliff, 2007)

2.1.3 Altering properties of metals

As dislocations cause materials to deform more easily and consequently fracture, it has been objective of metallurgist and engineers to discover ways to lessen this effect. Metallic lattice has some natural resistance to dislocation movement so, that

$$\tau b = f \tag{2}$$

where τ is the shear stress applied to material, b is the distance the dislocation is moved by stress and f is the resistance, which is a property intrinsic to atom configuration. However, the lattice itself can be altered in a few ways to increase the resistance. In (Ashby & Shercliff, 2007) this is represented by a concept of obstacles placed along the slip plane. Distance between each obstacle is given by L. Each obstacle exerts pinning force of magnitude p on moving dislocation. Now the resistance is increased as

$$\Delta f = \frac{p}{L} \tag{3}$$

and the stress increase required to move the dislocation distance b is

$$\Delta \tau = \frac{p}{bL} \tag{4}$$

As the pinning force is elastic effect, it is proportional to Eb^2. This is justified by the fact that b^2 is the area on which the force affects and elastic modulus E has units of force. Now then the dislocation movement over distance b is countered by stress

$$\tau = \frac{\alpha E b}{L} \tag{5}$$

where α is dimensionless constant describing the strength of the obstacle. In the next sections methods to add such obstacles to a material are described. (Ashby & Shercliff, 2007)

2.1.3.1 Solution hardening

Effect called solution hardening is achieved through adding atoms of another element into parent metal resulting in solid metallic solution. This process is called alloying and the elements added are called alloying elements. In some cases, such atoms may also be unwanted impurities and have undesirable effects on the resulting material. As the atoms have different size and shear modulus, the crystalline lattice is distorted. Average concentration of solute is defined as atom fraction

$$c = b^2/L^2 \tag{6}$$

where b is size of solute atom and L is spacing of solute atoms. When combined with equation (5), shear stress required for dislocation to move past the atom is obtained:

$$\tau_{ss} = \alpha E c^{0,5} \tag{7}$$

where α is dimensionless constant and E is elastic modulus. Examples of such alloys are brass, bronze and steel.

2.1.3.2 Precipitate and Dispersion Hardening

Another way to add particles into a metallic matrix is by a process known as precipitate hardening. As solubility of an element is temperature dependent, quickly cooling saturated solution results in supersaturated phase due to lacking diffusion of solute. When such material is heated to a temperature that is moderate when compared to solvus temperature, diffusion is increased and the solute forms a phase of its own. Given high enough concentration of alloying material, the solution becomes saturated as the mix cools down and small solid particles of solute element eventually form. The process of precipitate forming occurs in three stages. The strength contribution increases at first but with enough time in elevated temperatures the effect is decreased. This is because with time the precipitate particles tend to increase in size to reduce the interaction area with the two phases. This process is sometimes referred to as Oswald ripening. (Hertzberg, 1996, p. 138)

Particles added to a material obstruct dislocation movement in bulk material by forcing them to squeeze past the alloying particles or forcing them through the matrix-precipitate interface. The way dislocations interact with precipitates is affected by their size and structure. If the lattices of matrix and precipitate are relatively coherent, the dislocations tend to move through the phase boundary. This causes the strengthening contribution to be proportional to difference of the lattice parameters of the phases so that

$$\tau \propto G\epsilon^{\frac{3}{2}} (rf)^{\frac{1}{2}} \tag{8}$$

where G is shear modulus, ϵ is mitsfit strain proportional to difference of lattice parameters, r is particle radius and f is volume fraction of precipitate particles.

If non-coherent interface cause the dislocations to loop around the precipitate and the increase in strength is affected by size and distribution of particles:

$$\tau = Gb/l \tag{9}$$

where G is shear modulus, b is particle size and l is distance between particles. (Hertzberg, 1996, pp. 140-141)

Another way of adding foreign material into metallic material matrix is to add particles of high melting point into molten metal. When the base metal solidifies, the particles are trapped inside. This process is called dispersion hardening. Such structures are typically more stable in high temperatures than those formed by precipitate hardening. For example, by adding different metal oxides to the matrix, high temperature properties of material may be increased greatly. Alloys used at corrosive or oxidative high temperature applications such as gas turbine blades are produced this way. (Hertzberg, 1996, pp. 143-144)

2.1.3.3 Work hardening

Density of dislocations is moderate in unworked metal but when plastically deformed, the density rises by several orders of magnitude. As dislocations impede each others´ movement, metal is strengthened when the density of dislocations is increased. Another effect of this is decrease of ductility which must be taken into account when choosing material. Knowledge of this phenomenon has been used by blacksmiths for a long time. This is called strain- or work hardening, cold-working or strain hardening. (Hertzberg, 1996)

Work hardening a material causes internal stresses to occur in the metallic lattice. These stresses increase the energy stored in the lattice. However, this kind of state makes the material energetically unstable. Therefore work hardened materials under elevated temperatures tend to have these stresses relieved as the temperature increases internal energy of the material even more. Working a material in elevated temperature so that the resulting structure recrystallizes spontaneously is called hot working. The temperature at which hot working occurs is around one-third of the melting point of material. (Hertzberg, 1996, p. 128)

In a hot worked material the atoms begin to find place in less strained regions via diffusion. As a result of this process called grain growth, the bigger grains with less surface area for diffusion per volume begin to have net gain of atoms increasing their size even further. As it is discussed later in this text, this process decreases toughness of material. On the other hand, large grain size gives increased resistance against creep. Also internal stresses of grains are relieved through recovery and recrystallization. Recovery means reorganization and annihilation of dislocations in a crystal whereas in recrystallization new, defect-free crystals are formed and old stressed ones are destroyed. As these processes decrease amount of dislocations, they generally decrease strength and increase toughness of material. (Ashby & Shercliff, 2007)

2.1.3.4 Grain boundary hardening

As dislocations do not move easily from one grain to another, decreasing grain size is an effective way to impede dislocation movement. This is observed as increase of material strength given by Hall-Petch equation as

$$\tau_{gb} = \frac{k_p}{\sqrt{D}} \tag{10}$$

where k_p is Petch constant and D is diameter of grain. In typical materials the grain size is order of 10-100μm, which does not affect movement of dislocations to significant extent. When grain size is decreased to under micrometer scale, nano- and microcrystalline materials are obtained. In these scales the dislocation movement is actually affected by the grain boundaries. However, for very small grain size the relation gives too large values. In lower temperatures fine grain size may increase strength. On the other hand, creep rupture strength of material is usually decreased with grain size, which is often undesirable in boiler applications. (Babcock & Wilcox, 2005, ss. 7-2)

2.1.4 Steels

In this work special attention is given to different steel grades and their characteristics as they are the most important materials in pressure vessel construction. This is due to relatively low cost, high strength and ductility, good availability and possibility to alter its properties for many different purposes. Steel is a general name for iron alloyed with carbon and possibly other elements. Carbon content of steel may vary between from nearly zero up to 2 percent. Iron alloys with over 2 percent carbon content are considered cast iron. Typically steels contain also many other elements that are introduced in 2.1.4.2. As steel is used for many safety-critical applications, several standards have been established to provide guidelines for production and characteristics of various steel grades to ensure safety of equipment and uniformity between products of different steel producers. Production of steel and fabrication of steel vessels is not discussed unless relevant in the context of this work. (Honeycombe & Bhadeshia, 1995)

2.1.4.1 Structure of steel

Body-centered cubic oriented iron crystal lattice is called alpha-iron. In such crystal alloyed carbon atoms reside in midpoints of cube edges and face centers. Such structure is called ferrite. In FCC oriented iron crystals called gamma-iron carbon atoms reside at mid-points of cube edges producing structure called austenite. Carbon atoms are larger than the interstices in these structures so that they distort the lattice. This also results in limited carbon solubility in iron: in α-iron solubility is about 0,025% and in γ-iron slightly over 2%. (Honeycombe & Bhadeshia, 1995)

In metallurgy, bodies consisting of a homogenous material are called phases. Two or more elements occurring together form systems of phases structure of which often depends on temperature and concentrations of constituents. Such systems are often mapped in phase equilibrium diagrams that show which equilibrium structures are formed as a function of temperature and solute concentration. Usually the diagram depicts metastable equilibrium of iron and iron carbide FeC_3 often called cementite. In equilibrium iron-carbon system forms graphite but in practice, graphite is not easily formed in steels with low carbon content. On the diagram shown at Figure 2-5, it can be seen that austenitic steels sometimes used in high-temperature parts of power plants doesn´t form normally under 760 degrees Celsius. However, this temperature may be lowered by adding appropriate alloying elements to produce austenitic steels that are stable at lower temperatures. Even if alloying elements change the points of the diagram, the different phases are usually retained and the points of their formation are only changed. (Honeycombe & Bhadeshia, 1995)

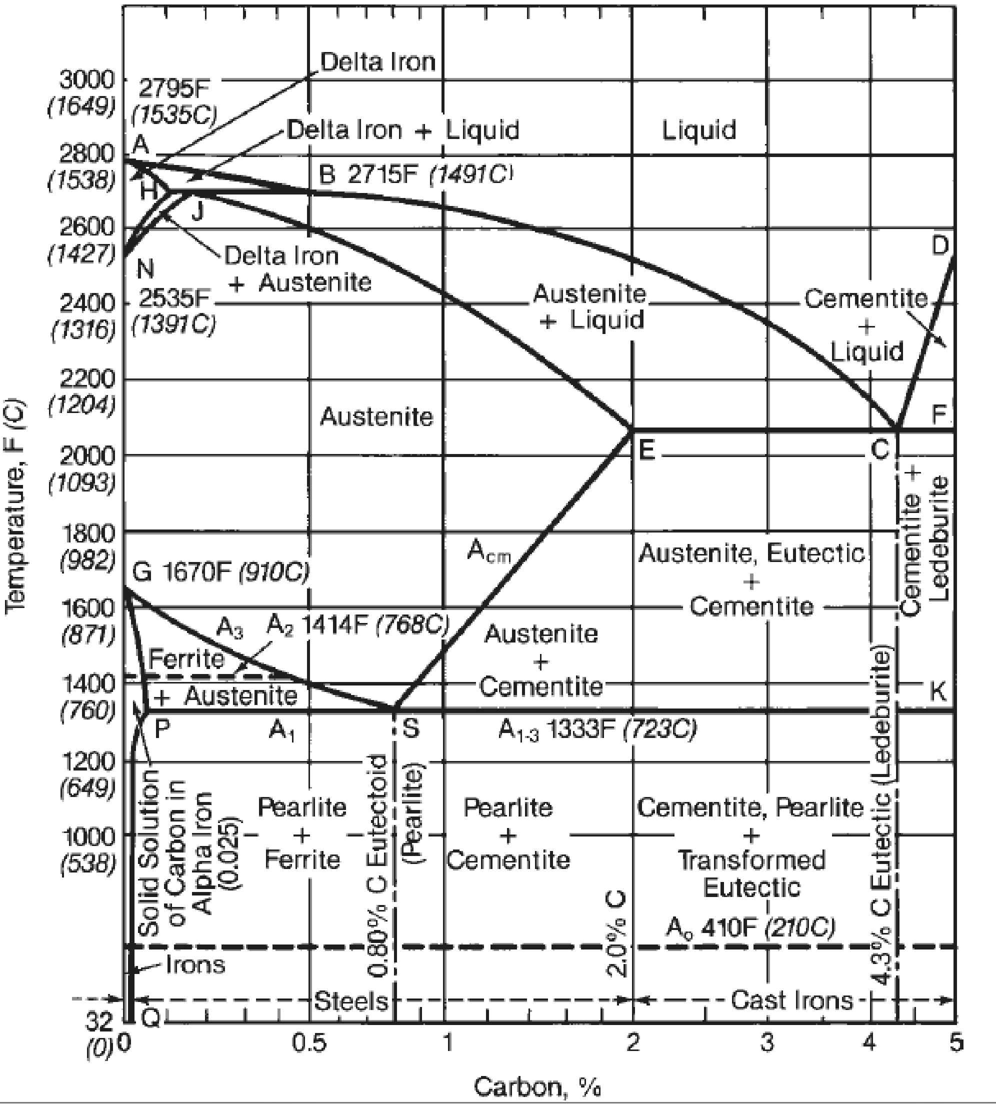

Figure 2-5 Carbon-iron equilibrium phase diagram (Babcock & Wilcox, 2005, ss. 7-3)

Steel with 0,8% of carbon is called eutectoid steel that, when cooled from lower critical transformation temperature A_1, forms only one phase. If steel with carbon content between 0,025% and 0,8% is cooled the resulting steel is a mixture of ferrite and cementite. Cementite (Fe_3C) includes the excess carbon not absorbed by the BCC structure. Cementite is relatively hard substance and thus steel hardness generally increases with carbon content. With carbon contents over 0,8% the end result is a system ferrite and cementite called pearlite. (Honeycombe & Bhadeshia, 1995)

It is notable that equilibrium diagram represents transformations that have long time to occur. In actual processes that last from few seconds to several days information on equilibrium alone isn´t enough to describe it. For this reason the transformations are also described with time-temperature-transformation (TTT) diagrams. Such diagram is shown below for eutectoid steel. When steel is cooled quickly to 220°C or less, phase called martensite is formed instead. Martensite has body-centered tetragonal crystal structure that is greatly distorted by carbon inside the structure giving it high strength and hardness. Martensite is considered a metastable phase and as such is not shown on phase diagrams for equilibrium. (Honeycombe & Bhadeshia, 1995)

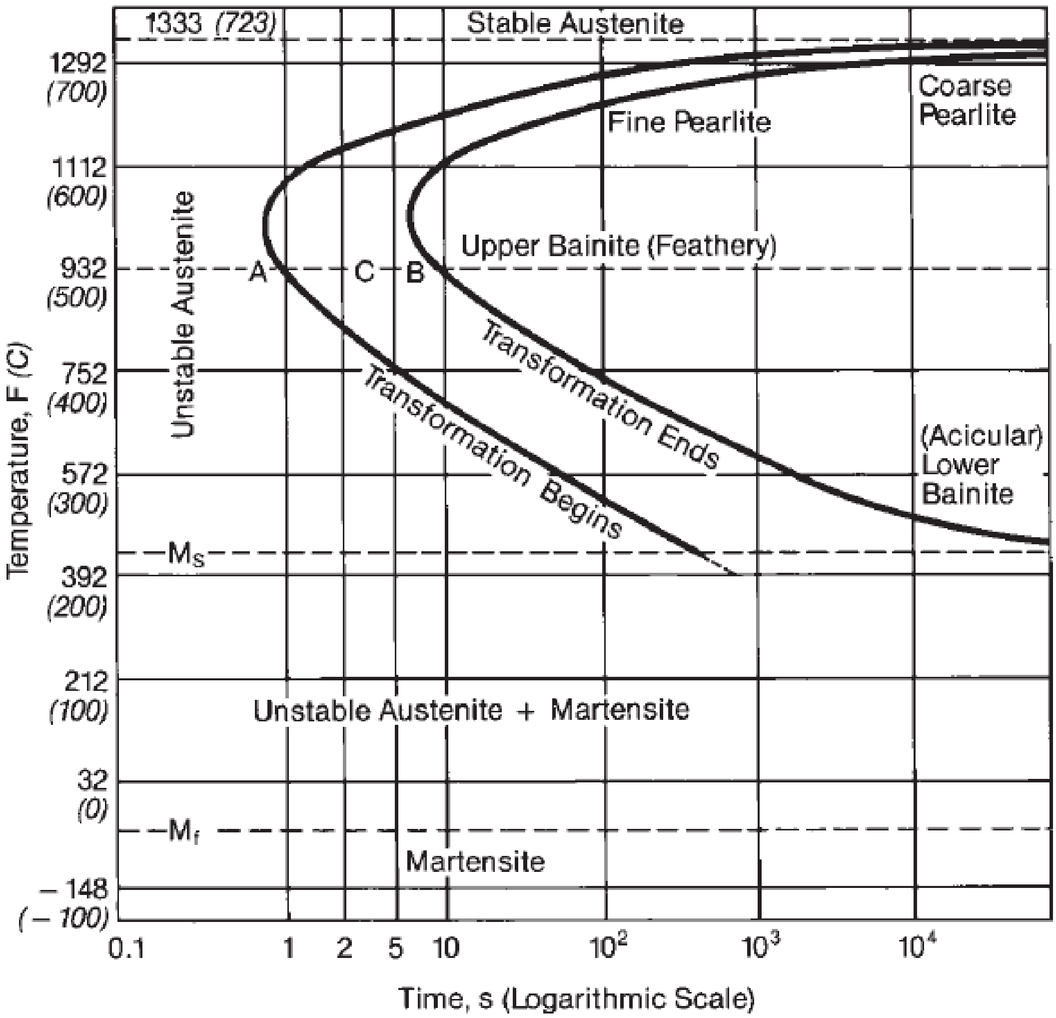

Figure 2-6 TTT diagram for eutectoid carbon steel (Babcock & Wilcox, 2005, ss. 7-5)

If eutectoid austenitic steel is quickly cooled to range of about 220-550, over temperatures at which martensite forms, bainite is formed instead. Bainitic structure consists of clusters of ferrite plates separated by cementite particles. Types of bainitic structure are further divided into upper and lower bainite. Upper bainite forms at temperatures of 400-550°C and consists of ferrite plates that have thickness of around 0,2μm and length of 10mm. These plates are usually separated either by boundaries or cementite particles depending on the concentration of carbon. If the temperature is lower, 250-400°C, lower bainite is formed instead. In this form, very small carbide particles form inside the ferrite plates giving such materials good toughness. Larger carbide particles of upper bainite, on the other hand, are known to nucleate voids and cracks and therefore its formation may be undesirable. (Honeycombe & Bhadeshia, 1995, ss. 119-120)

Most of the carbon precipitates into cementite during transformation and if concentration is increased enough, it forms sheets separating ferrite crystals. As it can be seen in case of martensite and bainite, not only composition of alloy affects characteristics of steels but also method of fabrication and heat treatment it is given. Thus, steels with exactly the same chemical composition may have very different characteristics. (Honeycombe & Bhadeshia, 1995, ss. 115-135)

2.1.4.2 Alloying elements at steels

Characteristics of steel are greatly affected by alloying elements it has been imbued with. Not only amount of alloying element make difference but also their interaction with each other during heat treatment. In addition to simply affecting thermo-mechanical properties of steel, certain alloying elements either rise or lower temperatures at which austenite forms. This makes fabrication of austenitic steels stable at room temperature possible. Some elements, most notably carbon and nitrogen, induce solution hardening effect to the material. Carbides and nitrides formed by these elements with different metallic atoms also contribute to precipitate and dispersion hardening.

Carbon is the most important alloying element that increases strength and creep resistance of steel. However, ductility of steel decreases when carbon content is increased so that steels used for boiler construction usually don´t exceed 0,15% in carbon content to retain needed ductility. As carbon is present in any material classified as steel, word alloy steel is used for grades with other alloyed elements in addition to carbon. Steels without any additional elements are often referred to as carbon steels. In steels, carbon is an interstitial solute atom as its size is much smaller than that of iron. The location a carbon atom assumes depends on the lattice structure of the iron. γ-iron has larger interstitial spacing available explaining larger solubility of carbon when compared to α-iron. As seen at previous chapters, when the iron becomes supersaturated with carbon, carbides are formed to induce precipitate hardening into steel (Honeycombe & Bhadeshia, 1995, s. 5)

Manganese (Mn) is another alloying element that is nearly always present in steels to some extent. As size of Mn atom is near that of iron, it is present in steel as substitutional solid solution element. It acts as a solid solution hardener and forms sulfides with residual sulfur in molten phase. These sulfides replace iron sulfides that would otherwise be formed and reduce strength of the material. Manganese sulfides also have higher melting point which improves malleability of steel. Manganese is an austenite former and lowers the critical cooling rate required for martensite to form. (Babcock & Wilcox, 2005, ss. 7-5 - 7-8)

Molybdenum is often used as alloying element for power boiler superheater steels. It increases strength, elastic limit, resistance to wear and hardenability. It allows steels to be heated to higher temperatures without loss of hardness and increases creep strength. It also decreases steel´s susceptibility to corrosion in reducing environment. (Babcock & Wilcox, 2005, ss. 7-5 - 7-8)

Chromium is important element in production of stainless steels. It is highly soluble in iron and forms stable and very adherent oxide on the material surface giving it great oxidation resistance. It increases strength of material in both low and high temperatures by forming carbides. Steels with chromium content over 12% are considered stainless steels. In such contents the chromium oxide (Cr_2O_3) film on the surface is extensive enough to prevent oxidation of the metal. (Babcock & Wilcox, 2005, ss. 7-5 - 7-8)

Nickel increases toughness of the material and, in contents exceeding 5%, corrosion resistance. More importantly it is used in combination with chromium to produce austenitic alloys that are stable in room temperature. Austenitic alloys have good creep strength, good resistance to corrosion and high temperature oxidation. One of the commonest austenitic stainless steels is 18Cr8Ni (AISI type 300) that also has lowest nickel content that produces stable austenitic structure in room temperature. High temperature strength of austenitic steels is improved by precipitation hardening of intermetallic phases such as $Ni_3(AlTi)$. Addition of nickel and chromium produces several phases with iron. Most notable one is sigma(σ) phase, that typically forms in elevated temperatures and has tetragonal structure. It exists in wide range of compositions and adding chromium encourages sigma-phase formation in contents exceeding 17% while nickel retards it. Molybdenum and titanium further accelerate formation. Sigma-phase forms in grain boundaries of austenitic structure and it may significantly weaken mechanical properties and cause embrittlement. Ferritic steels with high chromium content suffer from this in temperatures under 600°C being the main reason for absence of ferritic stainless steels in power boiler construction. Austenitic steels also suffer from sigma-phase embrittlement but to a lesser extent. (Honeycombe & Bhadeshia, 1995, ss. 264, 270), (Babcock & Wilcox, 2005, ss. 7-13 - 7-14)

Titanium and niobium are used in production of stainless steels so that they form carbides instead of chromium allowing it to remain in element form. Such carbides also increase creep strength of the material. With nitrogen, they also form fine nitride particles that may be used for dispersion strengthening. (Honeycombe & Bhadeshia, 1995, ss. 259-261)

Nitrogen acts as precipitate hardener in austenitic steel. Unlike carbon, it does not deplete chromium from the steel. Up to 0,25% of nitrogen may be added to Cr-Ni austenitic steel. Such addition may nearly double proof stress of the material. Nitrogen also forms nitrides with various metals to provide precipitate or solid solution hardening. However, in some cases this may be detrimental to the creep strength. (Honeycombe & Bhadeshia, 1995, ss. 253, 262)

Cobalt improves creep strength and in austenite it is a strong solid solution strengthener forming carbides for increased strength. Vanadium is used in high temperature steels to amplify effects of molybdenum. Aluminum is used for deoxidation and grain refining. Tungsten forms carbides and increases creep strength. Copper is sometimes added in small amounts to increase corrosion resistance at low-temperature applications, most notably in steels used for steam drum construction. Boron improves hardenability and stabilizes bainite when alloyed with molybdenum so that strength and stability of Cr-Mo alloy steels is improved. Silicon increases strength and acts as degasifying agent. (Babcock & Wilcox, 2005, ss. 7-5 - 7-8)

2.1.4.3 Usage of steel in boiler pressure part

Production and inspection of steels used in pressure vessel construction is highly standardized. Therefore, naming and requirements placed on different steel grades varies. Examples of such codes are European standards EN10216-2 (pipes) and EN-10028-2 (plates). BPVC also has extensive rules regarding these matters. Table 2-1 lists some common steel grades used in boiler pressure vessel construction.

Low temperature parts such as steam drums and structural parts of a power boiler are usually made of carbon steels with carbon content with 0,20 to 0,35% and often some manganese. Killed varieties of such steels are used meaning that no gas is left inside the metal during production.

Low and medium alloy steels with Cr content of up to 11,5% and lesser amounts of other elements are used where carbon steel is not suitable due to higher temperatures, increased oxidation or corrosion. Where improved strength in elevated temperatures is needed, low alloy steel with molybdenum is often used for temperatures under around 525°C. Often some chromium is added to these steels for increased oxidation resistance as well as some other elements such as vanadium or silicon. For even higher temperatures of up to 600°C, amounts of chromium and molybdenum may be increased. One such common steel variety with 2-2,5% of chrome and 0,9-1,1% molybdenum (EN-specification 10CrMo9-10 or SAE Grade 22). Further increase of chromium increases oxidation resistance at cost of weakened strength. Mn-Mo and Mn-Mo-Ni alloys have good toughness and strength to weight ratio and are generally used for larger boiler components such as nuclear pressure vessels. (Babcock & Wilcox, 2005)

Table 2-1 Some common boiler pressure vessel steels. Source: (Alin, 2014), (Babcock & Wilcox, 2005)

SA-specification	Similar European standard specification	Type	Common usage
SA-106C, SA-516-60	P265GH	Carbon-manganese steel	Steam drums, economizer and low-temperature superheater headers
SA-299A/B	P355GH	Carbon-manganese steel	Steam drums
SA-213T12, SA-335P12	13CrMo4-5	Low-alloy ferritic steel	Convective superheater tubes and headers
Grade 22 (SA-213P22, SA335P22)	10CrMo9-10	Low-alloy ferritic steel	Superheater tubes and headers
(SA-213T91, SA-335P91 (ASME Grade 91)	X10CrMoVNb9-1	Martensitic high-alloy steel	Superheater and reheater tubes and headers up to 621°C
ASTM grade 304H	X6CrNi18-11	Austenitic stainless steel	Superheaters and reheaters up to 700°C

For increased strength at temperatures of up to 621°C, so-called Grade 91steel has been developed in USA (ASME specifications SA-213T91 and SA-335P91). This steel with nominal composition of 9Cr-1MoV steel has 8-9,5% of chromium, 0,9-1,1% of molybdenum small amount and vanadium to increase high temperature strength and resistance to creep. Martensitic microstructure resulting from careful tempering and quenching that gives these steels increased strength, toughness and stability in high temperatures. High strength is especially beneficial when building high temperature headers as thinner wall construction decreases thermal stresses. Grade 91´s European standard counterpart is grade X10CrMoVNb9-1. Lately new alloy commonly known as grade 92 has been adopted to use in some higher-temperature applications. The major change to grade 91 is addition of tungsten for improved creep resistance. (Babcock & Wilcox, 2005)

As the strength of grade 91 steel lies in microstructure, care must be taken in material production, fabricating parts and welding when using it. During early years of its usage, cases have been reported where heat affected zone of the base metal has been undergone changes in microstructure and subsequently ruptured by creep long before designed lifetime. There were also failures due to erroneous heat treatment of base material during fabrication. (Shibli, 2003) However, grade 91 is today routinely used without problems (Alin, 2014).

Ferritic and martensitic stainless steels with chromium content exceeding 10% of chromium content are not usually used in boiler pressure vessel construction due to bad weldability and formation of sigma-phase in elevated temperatures causing embrittlement. Therefore, in temperatures over 621°C austenitic steels are only common choices of material. They generally have high contents of chromium and nickel and sometimes cobalt for increased creep strength. They have good high temperature strength, oxidation resistance and large grain size for good creep strength but their usage is limited due to high cost. Austenitic steels also have larger coefficients of thermal expansion and smaller thermal diffusivity making them more prone to thermal stresses. (Babcock & Wilcox, 2005)

2.2 Stress and fatigue

Stress is defined as the internal force between two adjacent elements of a body, divided by the area over which it is applied. If stress exceeds yield strength of material, plastic deformations begin to occur while exceeding of tensile strength (in case of tensile stress) the material breaks. Therefore designing a safely operable pressure vessel boils down to making the vessel in which stresses never exceed tensile stress, or in practical cases, yield strength. Fatigue is a phenomenon where a material fails when repeatedly stressed at magnitudes under tensile strength.

So-called engineering strain caused by stress exerted on material is defined as ratio of change in material length to original length:

$$\epsilon = \frac{\Delta L}{L_0} \tag{11}$$

This simplified approach is widely used in engineering practice. However, it does not take into account the decrease of the area the stress is exerted on. General stress-strain relation for a material may be obtained from empirical equation

$$\epsilon_a = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{K'}\right)^{\frac{1}{n}'} \tag{12}$$

where first term is linear-elastic part of the strain and second term non-linear elastic and plastic part. K’ and n’ are constants obtained from experimental data. (Stoppato;Mirandola;Meneghetti;& L., 2012, s. 231)

2.2.1 Pressure vessel wall stresses

Before development of modern computers, exact stress calculations were either expensive and time-consuming or impossible to perform. Therefore boiler design codes had a set of rules for construction that were experienced to provide safe operation of the plant. Design like this is called ‘design by rule’. Usually these rules include quite a big safety margin. Nowadays it is possible to calculate stress fields in components very accurately using methods like finite element method (FEM) to gain better insight on the requirements placed on a boiler part. This makes it possible to build boiler parts with smaller margins of safety and therefore decreased material costs. Such design methodology is called ‘design by analysis’. Several boiler and pressure vessel construction codes include rules for such design. (Babcock & Wilcox, 2005)

Stresses occurring in a material may be categorized in three groups. Primary stresses are ones that are caused by external loading and are not self-limiting meaning that stress is not relieved upon deformation of material. In case of pressure vessels, stress caused by internal pressure is often the most important source of primary stress.

Vessels that have small wall thickness when compared to other dimensions are often referred to as a membrane shells. General form of membrane stress is

$$\frac{\sigma_1}{r_1} + \frac{\sigma_2}{r_2} = P/h \tag{13}$$

where σ_1 is longitudinal stress, σ_2 is hoop (tangential) stress, r_1 is longitudinal radius r_2 is circumferential radius, P is pressure and h is thickness. For cylindrical shell such as pipes and headers the stresses are obtained as

$$\sigma_1 = \frac{Pr}{2h} \tag{14}$$

$$\sigma_2 = \frac{Pr}{h} \tag{15}$$

where r is cylinder radius. Power boiler tubes and headers maybe considered to be such vessels so that equations for membrane shell primary stresses may be used. (Babcock & Wilcox, 2005, ss. 8-4 - 8-6)

Secondary stresses are stresses caused by differential thermal expansion or constraints caused by adjacent material or other boiler components. They are usually local and do not necessarily affect bursting strength of the vessel but they must be considered when making calculations for fatigue.

When elements of a material are under temperature gradient, elements in higher temperatures are compressed and those in lower temperature are stretched. For general cylindrical shell, thermal stresses are obtained as

$$\sigma_r = \frac{\alpha E}{(1-\mu)r^2}[\frac{r^2 - a^2}{b^2 - a^2}\int_a^b Trdr - \int_a^r Trdr] \tag{16}$$

$$\sigma_s = \frac{\alpha E}{(1-\mu)}[\frac{2}{b^2 - a^2}\int_a^b Trdr - T] \tag{17}$$

$$\sigma_t = \frac{\alpha E}{(1-\mu)r^2}[\frac{r^2 + a^2}{b^2 - a^2}\int_a^b Trdr - \int_a^r Trdr - Tr^2] \tag{18}$$

where a is inside radius, b outside radius and T is temperature. (Babcock & Wilcox, 2005, ss. 8-6)

For cylindrical pressure vessel walls, which have expansion contracted in two directions, magnitude of radial direction thermal stress is obtained as

$$\sigma = \mp \frac{E\alpha\Delta T}{1-\mu} \tag{19}$$

where E is modulus of elasticity, α is coefficient of thermal expansion and μ is Poisson´s ratio. This equation gives maximum value for fully restrained case and therefore gives a conservative estimate on stresses occurring at the wall.

Peak stresses are local stresses caused by geometry changes. Peak stresses are important when evaluating fatigue life as usually failures due to fatigue occur in points where peak stresses are biggest. Such points are also called stress concentrations. Such concentrations occur at geometry incontinuities such as connections between power boiler steam circuit headers and pipes.

There are several theories for calculating the stress needed for material to yield and eventually fail. Three rather simple and commonly used theories are briefly described in the following.

Maximum stress theory considers a failure to occur when one of the principal stresses exceed tensile strength of the material. While this model is not very accurate, it is easy to apply and safely usable if sufficient safety factors are used. Several ASME boiler codes use this theory. (Babcock & Wilcox, 2005)

Maximum shear stress theory or Tresca theory considers a failure to occur when the largest difference between any two principal stresses exceed material yield strength. In other words when

$$|\sigma_1 - \sigma_2| > S_y \text{ or } |\sigma_2 - \sigma_3| > S_y \text{ or } |\sigma_1 - \sigma_3| > S_y \tag{20}$$

This theory is rather simple and more accurate than maximum stress theory especially with ductile materials. This theory is used by stress and fatigue calculations of EN-12952-3 standard.

Distortion energy theory or Von Mises criterion states that failure occurs when so-called Von Mises stress exceeds yield strength:

$$\sigma_e = \frac{\sqrt{2}}{2}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} = S_y \tag{21}$$

Von Mises criterion is the most accurate of these three theories but also the most cumbersome to use. (Babcock & Wilcox, 2005)

2.2.2 Fatigue

In everyday life one example of fatigue is breaking a credit card in two by bending it repeatedly. First time it resists and bends only a little but little by little it yields more and ultimately breaks. In countries adopting railroad early there were several failures of train coach axles in cases, where they should have lasted according to the knowledge of 19th century engineers. In Germany these events were investigated and fatigue was found in context of mechanics and material sciences. Even after that, several occurrences show that taking fatigue into account may not always be easy or obvious thing to do in mechanical engineering.

Basically fatigue is described as damage to material caused by repetitive loading and unloading. A sequence of loading and unloading is often referred to as a cycle. When determining damage caused by a cycle to material, the most determining factor is the difference between maximum and minimum stress of the cycle called stress amplitude:

$$\sigma_a = \frac{\Delta\sigma}{2} = \frac{\sigma_{max} - \sigma_{min}}{2} \tag{22}$$

where σ_{max} is maximum stress and σ_{min} is minimum stress of the cycle. As tensile stress cycles tend to be more damaging than compressive ones, mean stress σ_m of the cycle is also a significant factor:

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2} \tag{23}$$

Often stress cycle is described by R-value defined as

$$R = \sigma_{min}/\sigma_{max} \tag{24}$$

R-value of -1 describes cycle with zero mean stress. R-value of zero means cycle with minimum stress of zero.

Fatigue may be further divided to low-cycle fatigue and high-cycle fatigue. In high-cycle fatigue the amplitude of stress and strain are within elastic limit of material and the amount of loadings required for failure to occur is large. In low-cycle fatigue the stress causes partially plastic deformations at least in the beginning before the work hardening takes place. The amount of cycles needed for failure is relatively small when compared to high cycle fatigue. In power boiler pressure part, low-cycle fatigue is usually mechanism of interest and especially deformations caused by thermal stresses and large pressure fluctuations occurring at startups and other load changes are the ones causing most damage. Usually amount of 100000 cycles to failure is considered as borderline between low-cycle and high-cycle fatigue.

For many materials such as steels there is certain stress amplitude under which fatigue is not caused. This stress value is called fatigue strength or endurance limit. For metals this value is usually around one-third of tensile strength. Some other materials, however, do not have such point.

Two points of view to estimating and describing fatigue are introduced in the following clauses. This work has focus on metals and thus mechanisms concerning them are investigated here. (Ashby & Shercliff, 2007)

2.2.3 Crack-initiation controlled fatigue

In a crack-free material under fatigue, most of the time before fatigue failure is spent generating a crack. After one appears in the material, relatively small amount of cycles is needed to turn a crack into a fracture.

As was shown in 2.1.1, the dislocations have preferred directions of intra-granular movement. Cyclic loading results in gathering of dislocations in crystal surface as they are moved little by little through the crystal. This is demonstrated by scanning electron microscope photograph below.

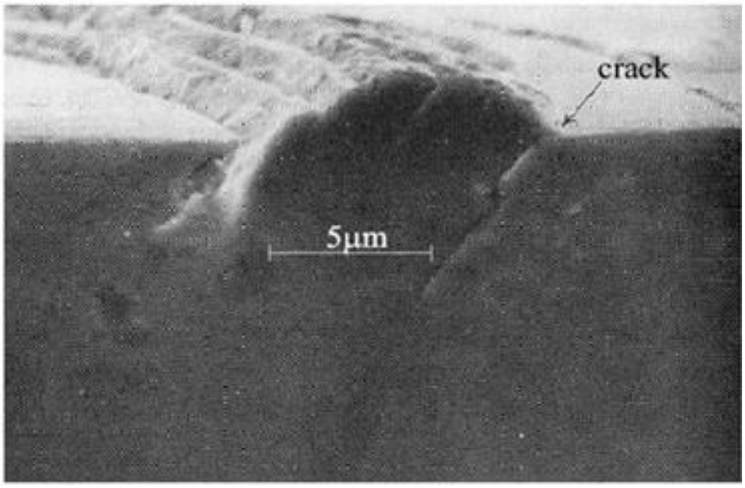

Figure 2-1 Gathered dislocations at metal surface Source: (Suresh, 1991)

As the dislocations gather, intrusions and extrusions will form to the material surface. Small cavities formed by this microscopic roughness act as stress concentration points which, if sufficiently loaded, become initiation points of microscopic cracks.

Two empirical laws have been observed to describe crack initiation behavior. The first one describes high-cycle fatigue and is called Basquin´s law:

$$\Delta\sigma N_f^b = C_1 \tag{25}$$

where b and C_1 are constants of values around 0,007 and 0,13. N_f is the number of cycles required for a crack to initiate. As the load cycle is in elastic range, the strain may be given by

$$\Delta\epsilon = \frac{\Delta\sigma}{E} = \frac{C_1}{EN_f^b} \tag{26}$$

where E is modulus of elasticity.

As stress is increased, the Basquin´s law is no longer valid and another empirical equation is used. Independently found by Manson and Coffin, equation sometimes referred to as Coffin´s law states that

$$\Delta\epsilon_{pl} = C_2/N_f^c \tag{27}$$

where $\Delta\epsilon_{pl}$ is plastic part of the strain. Exponent c is typically larger than that of Basquin´s law and is typically around value of 0,5. Fatigue behavior as a function of strain is sometimes expressed as so-called Manson-Coffin curve of which general form is

$$\epsilon_a = \frac{\sigma_f'}{E}(2N_l)^b + \epsilon_f'(2N_l)^c \tag{28}$$

where constants $\sigma_f^{'}$, $\epsilon_f^{'}$, b and c are determined by best fitting of experimental results. The curve given by the equation is usually expressed in double-logarithmic form. (Stoppato;Mirandola;Meneghetti;& L., 2012)

When given in graphical form (25) and (27) are typically combined to give a double-logarithmic cycle stress range versus N curve. Such curve is called S-N-curve or Wöhler-curve, after the German engineer who discovered fatigue.

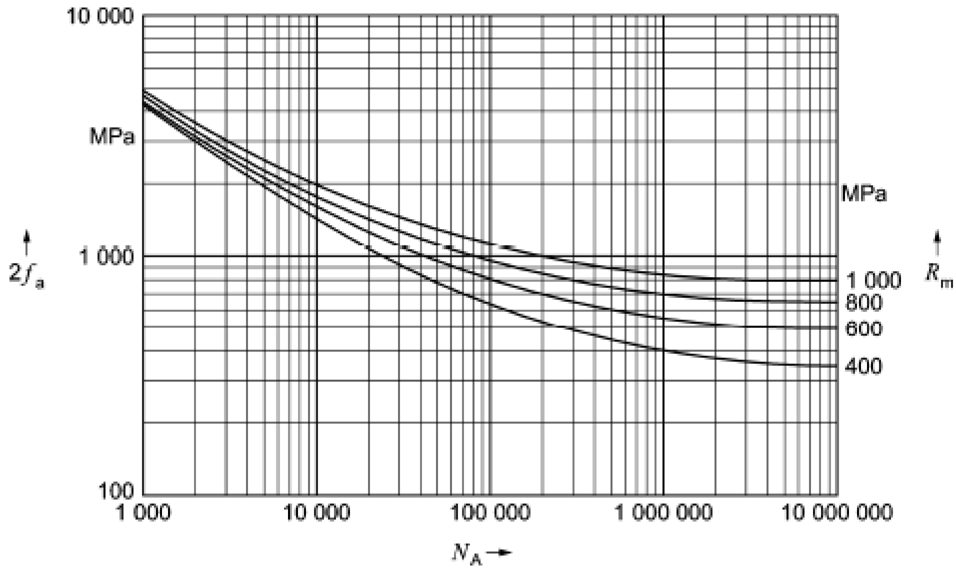

Figure 2-2 S-N curve for ferritic steels of variable strength (Suomen standardisoimisliitto, 2012, s. 144)

Generally, when using S-N curves and Manson-Coffin curves it should be noted that methods used in determining them may vary. For example, curves provided with EN 12952-3 standard and ASME boiler codes are based on unnotched laboratory data specimens while those of British Standard PD 5500 are based on welded objects. Consequently, different correction factors should be used with different curves to account for things such as notch effect, effects of environment and scatter of experimental data and probabilistic nature of fatigue. (Dooley, 2006)

One more thing to consider when assessing fatigue caused by a stress cycle is that Basquin´s and Coffin´s laws are used to calculate fatigue for cycles with zero mean stress and S-N-diagrams are typically calculated with such an assumption. However, as mean stress is increased, fatigue damage caused by a cycle is increased. For tensile mean stress the empirical law of Goodman and Miner has been proposed:

$$\Delta\sigma_{\sigma_{sm}} = \Delta\sigma_{\sigma_0}\left(1 - \frac{\sigma_m}{\sigma_{ts}}\right) \tag{29}$$

where $\sigma_{ts}$is tensile strength. The statement of the rule is that with mean stress σ_m a cycle with amplitude of $\Delta\sigma_{\sigma_{sm}}$is as damaging as a load cycle with amplitude $\Delta\sigma_{\sigma_{sm}}$and zero mean stress. (Ashby & Shercliff, 2007)

When material experiences several load cycles, damage by them cumulates. Simplest method of determining this cumulative damage is to simply sum them over different stress levels so that

$$\Delta D_F = \sum_{i=1}^{k} \frac{n_i}{N_i} \tag{30}$$

where ΔD_F is total damage fraction, n_i is amount of stress cycles of stress difference i and N_i is amount of cycles at stress level i to failure. This rule is called Miner´s rule. While not exactly accurate due failing to take probabilistic nature of fatigue and effect of sequence of load cycles into account, many more complex models don´t improve accuracy in proportion to increased complexity.

2.2.4 Crack propagation controlled fatigue

Macroscopic metallic structures including power boiler pressure vessels have invariably some microscopic cracks in them. Especially welding with high local temperatures easily causes formation of such cracks and leaves internal stresses to material. Small cracks may be observed through various non-destructive methods (NDT) but they have limits in resolution. Thus, it is safe to assume that such material has small cracks smaller than the resolution. When stressed, cracks, notches and incontinuities in material cause the area on which the force affects to be smaller than nominal area of the material and so are stress concentrations formed. If material is assumed to have a crack of length c, then cyclic stress intensity range is

$$\Delta K = K_2 - K_1 = \Delta\sigma\sqrt{\pi c} \tag{31}$$

and the range increases with time for some cyclic stress due to crack growth if it exceeds threshold cyclic stress intensity ΔK_{th}. Paris law gives crack growth rate as

$$\frac{dc}{dN} = A\Delta K^m, \Delta K > \Delta K_{th} \tag{32}$$

where c is crack length, N is amount of cycles and k and M are constants. If ΔK exceeds fracture toughness, the material will rupture in single cycle. Therefore even if the material under stress is macroscopically elastic, locally material around these cracks may undergo plastic deformations. When designing equipment that is to be stressed cyclically, one must define threshold intensity and make sure that it won´t be exceeded during usage. (Ashby & Shercliff, 2007, pp. 192-194)

2.3 Creep

Creep, also sometimes referred to as cold flow, is a physical phenomenon where atoms of solid matter under stress move around in temperatures under melting point causing strain and eventually rupture of material. As before, this chapter has its focus on crystalline substances and metals in particular. Atoms with enough thermal energy move around to vacancies within crystalline structure of steel. Such diffusion causes atoms in dislocation planes to move around and allowing dislocations to be unpinned from position allowing the dislocation to move around due to stress affecting the material until it is pinned again after which the cycle repeats. Such deformation is sometimes referred to as climb and it occurs at temperatures above 35% of melting point. (Ashby & Shercliff, 2007, pp. 275-304) .

Figure 2-3 shows the three different regimes typically used to describe creep on time-strain curve. At primary creep regime strain is caused by dislocation climb and is usually small. The decreasing strain rate is due to changes of microstructure that impede dislocation movement.

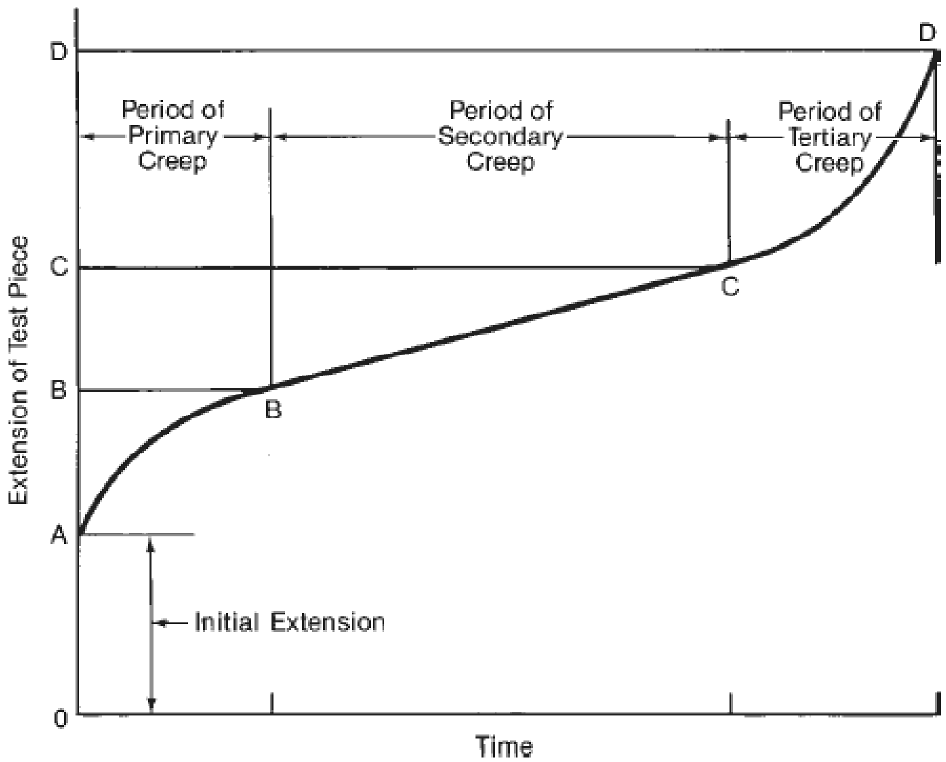

Figure 2-3 Classic time-strain curve of creep at constant load. Source: (Babcock & Wilcox, 2005)

Secondary or steady-state creep regime is mostly the one of interest in case of boiler applications. Depending on temperature, either dislocation climb or creep due to diffusion is the driving mechanism here. Here strain hardening is caused by recovery of crystalline structure. Tertiary creep begins taking place when the material begins to neck due to excessive amount of voids in crystalline boundaries. Regime of tertiary creep is very fast and fracture occurs rather quickly once necking begins to occur. Therefore, tertiary creep is generally of little interest when making design considerations. (Rhoads)

Strain rate caused by power-law creep occurring at secondary and tertiary creep regimes may be generally expressed as

$$\dot{\epsilon_{ss}} = C'\sigma^n e^{\left(-\frac{Q_c}{RT}\right)} \tag{33}$$

where Q_c is activation energy of creep, C' is a constant and n is between 3 and 8. (Ashby & Shercliff, 2007)

For macroscopic deformations to occur in material there must also be interaction between crystals. Diffusion occurs between crystals where grain boundaries act as sources and sinks for vacancies and atom: atoms at grain boundary and enough energy may then jump from grain to grain to fill such vacancy. Strain rate caused by this mechanism to a crystal in parallel to stress is analogous to viscous flow and may be expressed as

$$\dot{\epsilon_{ss}} = C\frac{\sigma}{d^2}D_0 e^{-\frac{Q_d}{RT}} \tag{34}$$

where *C* is constant and exponential term is about 18 for metals. Notable is inverse relationship to square of grain diameter *d* meaning that deformation is greatly accelerated in materials with small grain size. Therefore many high-temperature applications favor steels with large grain size and some special applications such as gas turbine blades utilize blades made of single crystal to avoid this kind of creep altogether. As atoms diffuse from crystal to crystal, they leave vacancies in the boundary causing voids to nucleate on boundaries normal to stress. Given enough time, these voids may then link and at some point fracture between such grain boundaries may occur. Generally, temperatures of above 70% of melting temperature is required this mechanism to take place (Rhoads).

For design purposes, material´s ability to resist creep should be known. Usually this is done by applying constant tensile stress on a material in constant temperature and strain is measured. For example, EN standards considering high temperature steel applications requires times for 1% elongation and rupture to be measured. Creep rupture strength is defined as stress at which rupture occurs in specific time and temperature range in atmospheric conditions. Usually values of rupture strength are shown on stress-logarithmic time curve.

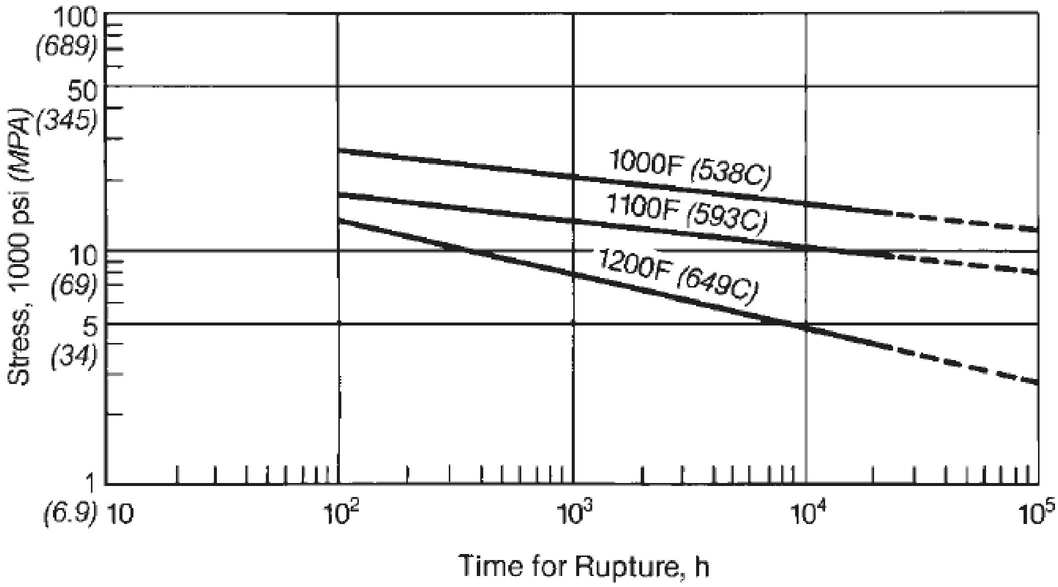

Figure 2-4 Creep rupture curves for 2-1/4Cr-1Mo steel (Babcock & Wilcox, 2005)

Often these measurements are done in various temperature regimes and stresses for more accurate predictions. Because power boiler components may be used for several years, results of shorter test times are extrapolated for longer time predictions. One common and rather simple way for extrapolation is by using Larson-Miller parameter (LMP). It is defined as

$$LMP = T(\log t_r + C) \tag{35}$$

where T is temperature in Kelvins, t_r is creep rupture time and C is a constant of order of 20. LMP may then be plotted against hoop stress of component. Using the plot creep life fraction may then be determined using Robinson´s Rule of Life Fractions. It states that in varying conditions creep life is given by

$$\mathrm{C} = \sum_{i=1}^{n} T_{op,i}/T_{fi}\,, i \tag{36}$$

where $T_{op,i}$ is time of operation in stress-temperature condition i and T_{fi} is time to rupture in those conditions. Probability of creep rupture is expected to be very high when the equation equals 1. This method does not even try to be precise but it attempts to put remaining lifetime in a band probable values. Method described here also includes inherent source of error as it doesn´t take variations of material properties. Such variations are caused by oxidation and corrosion, both of which are quite common in boiler areas where creep occurs. (Babcock & Wilcox, 2005, ss. 45-12)

2.4 Interaction of degradation mechanisms

As fatigue damage occurs in locations of notches and incontinuities of material, phenomena creating them should be taken into account if accurate fatigue predictions are wanted. In power plants, oxidation, creep, erosion and corrosion are all such phenomena. At boilers that are changed to operate more cyclically towards the end of their lifetime, the creep cracks caused by creep due to long-term base load operation may begin propagate rather fast.

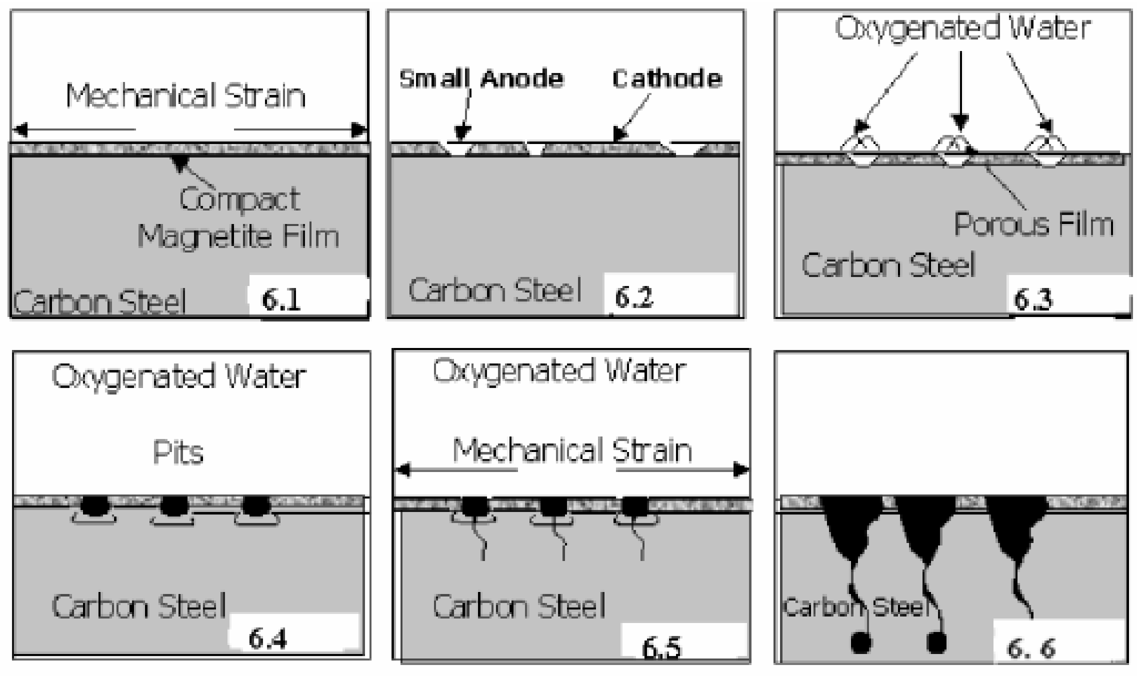

Figure 2-5 Oxidation induced cracking in ferritic steel. Source: (Sing, 2006)

In ferritic boiler materials, protective magnetite layer is formed on inner tube side of water piping due to chemical treatment by hydrazine or similar chemical. In case this layer is cracked, bare steel surface is revealed and porous iron oxide replaces magnetite. This kind of oxide then accelerates corrosion locally by forming cracks that are again widened by load cycles to increasing corrosion rate even more. This kind of corrosion is prevalent in economizer furnace tubing and steam drum water side. (Storesund, 2007)

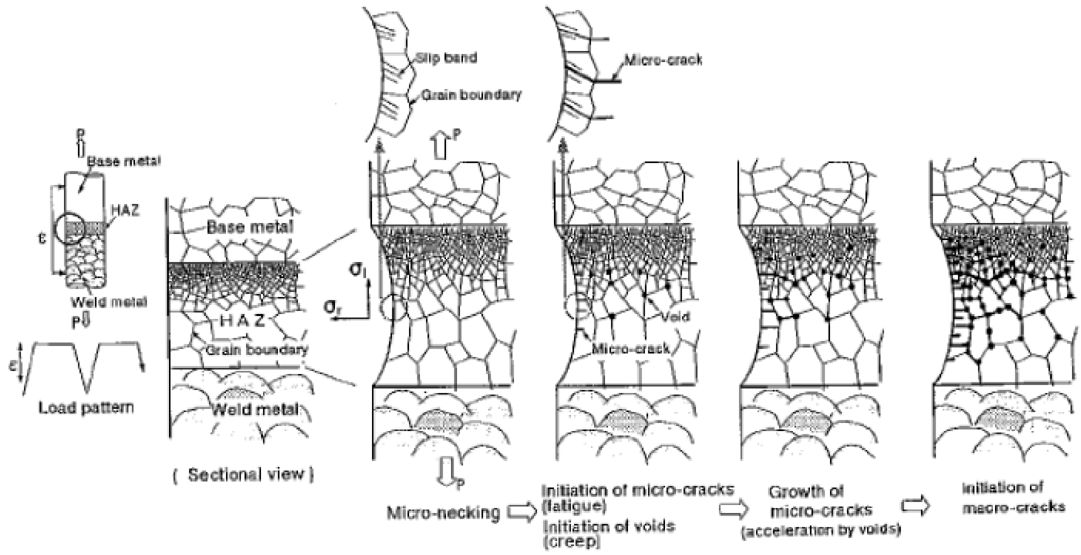

Figure 2-6 Creep fatigue in weld heat affected zone. Source: (Storesund, 2007)

Similarly to oxidation, also creep enhances effect of fatigue. Especially true this is in heat affected zones of welds where material grain size has been decreased. At such areas, voids are formed by creep. Consecutive load cycles then cause these voids to connect into microscopic cracks that finally form macroscopic ones. Figure 2-6 illustrates this effect. (Storesund, 2007)

2.5 Material selection for boiler design

High temperatures of power boilers have many implications on pressure vessel design. Operating temperatures are often in regimes where creep takes place and effects of corrosion and oxidation are accelerated. Therefore, material with adequate resistance against these effects must be chosen. Thermal conductivity must be taken into account especially for heat transfer components such as superheaters and components experiencing thermal stresses. Coefficient of thermal expansion should be within certain limits and taken into account especially when joining components by welding and planning for high energy piping. With previously mentioned properties in mind, a material with adequate strength and ductility is chosen. Usage of chosen material must be also justified from an economical point of view. (ASM International, 2002)

For carbon-manganese steels used for steam drum construction, creep begins to occur at temperatures from 350°C to 400°C. Ferritic alloy steels that are used for boiler construction have varying range of this temperature. Low alloy steels experience creep already at 400°C while high alloy steels begin to deform at temperature of almost 500°C. For stainless austenitic grades used for some superheaters this temperature is well over 500°C. From a practical point of view creep is defined as a time-dependent strain under constant stress. In power boilers, creep is a problem mainly in high temperature components such as radiation superheater and reheater areas (Babcock & Wilcox, 2005)

Materials are selected with previous points and forces predicted to effect upon the vessel in mind. Such forces are caused by internal pressure, vessel supports and forces exerted by other parts joined to the vessel. Basically dimensions are so determined that stresses exerted upon the vessel won´t exceed yield strength. Especially cold startup of a boiler causes large thermal stresses on pressure part causing low-cycle fatigue which should be taken into account where applicable. Sometimes it is advantageous to use more expensive high-strength materials for lower vessel wall thickness to decrease temperature gradients formed by operation transients. Water quenching is another startup related problem that much be tackled in design by designing sufficient drainage for the vessel. In addition to design for strength, the material must have adequate qualities at high temperatures. Some resistance against corrosion and oxidation are also often needed. (Babcock & Wilcox, 2005)

Usually a factor of safety is applied on the dimensions due to notch effect of incontinuities introduced to material before or after manufacturing and material imperfections discussed in chapter 2.1. Such imperfections occur especially in welds and it is reasonable to assume that microcracks smaller than resolution of inspection technique used exist in material. Especially weld toes are prone to fatigue cracking. For this reason, specific standards for planning, implementing and inspecting welds have been introduced. (ASM International, 2002)

2.6 Creep and fatigue calculation according to EN-12952

European standard EN-12952 has been developed to be a guide for designing and building water-tube boilers so that they fulfill requirements posed by EU directives, especially Pressure Equipment Directive 97/23/EC. This work has its focus on part 3 of the standard, *Design and calculation for pressure parts of the boiler*, and on part 4, *In-service boiler life expectancy calculations*. Part 3 describes guidelines for designing boiler pressure part including designing and calculating fatigue durability of components. Part 4 describes calculation of boiler creep and guidelines for implementation of boiler life expectancy calculations. It also places requirements on accuracy and validation of measurements for online calculations. It also includes methods for data compression to be used with stress extreme calculation. This chapter briefly describes methods of calculation proposed by this standard. Purpose of this chapter is to give general idea of the procedure and not to go into details. (Suomen standardisoimisliitto, 2012)

2.6.1 Stress and Fatigue Calculation

Fatigue calculation procedure proposed by the standard may be used either for calculating allowable transients and stress fluctuations to assure an adequate number of startups the equipment can endure or alternatively for estimating exhaustion caused to the equipment by operation history. Latter case is explained here but fundamentals are the same for both. The standard states that the procedure is conservative due its simplicity in nature. If more exact calculations are wanted, usage of more complex methods like finite element method is allowed for acquiring more accurate results. The procedure calculates time to crack initiation and does not concern crack propagation. Part 3 of the standard also has rules depicting, when the fatigue calculation can be omitted. Rules include requirements for similarity of welds, design of equipment, expected amount of startups, expected thermal transients and geometry of vessels.

The standard proposes approximate calculation methods for membrane stresses of cylinder-to-cylinder and cylinder-to-sphere connections. Here only cylinder-to-cylinder connections are considered. The calculation uses Tresca stresses for determining principal stress in connection used in calculation. Stresses that are radial and axial to cylindrical main body (larger boiler part like header) are basically those compensating for fluid pressure. Magnitude of these stresses equal internal pressure of vessel. Stress that is tangential to both main body and its branch compensates for internal pressure and thermal stresses arising from radial temperature differential over the vessel wall. That is,

$$f_1 = f_{tang,p} + f_{tang,t} \tag{37}$$

$$f_2 = f_{rad} = -p \tag{38}$$

$$f_3 = f_{ax} = -p \tag{39}$$

Where $f_{tang,p}$ is stress compensating for pressure and $f_{tang,t}$ is stress compensating for thermal stresses. Equation (14) is used for calculating $f_{tang,p}$ and equation (19) for calculating $f_{tang,t}$.

Tresca stresses of cylindrical membrane for equation (13) are obtained as

$$\Delta f_{12} = f_{tang} + p \tag{40}$$

$$\Delta f_{23} = 0 \tag{41}$$

$$\Delta f_{31} = -(f_{tang} + p) \tag{42}$$

As it can be seen from equations (40) to (42), largest principal stress fluctuation is given any time by (40), which is then used in calculations for fatigue. The standard states that in case bending stresses become notable, they must be taken into account using some other method. (Suomen standardisoimisliitto, 2012)

As equations presented here are for cylindrical shells with no openings, effect of cylinder-to-cylinder connection should be taken into account by using stress concentration factors. Stress concentration factors are probably the most important single source of error in whole EN-standard fatigue calculation. Magnitude of this error is discussed in 2.6.3. The standard gives two options for determining stress concentration factor for the equations presented here. First option is to determine the factor using finite element method while another is to use methods presented in the standard. Separate factor is determined for membrane stress and thermal stress. In addition to stress concentration factors, the standard provides additional coefficients for different weld types. For example, full penetration weld is considered to have only 90% of calculated stress when compared to welded-on branch. As an alternative to stress concentration factors, the standard allows also usage of so-called notch factors whenever some other stress analysis method is used. These factors work rather similarly as stress concentration factors.

Feature of note with the stress calculation is, that it places limits on compressive and tensile stresses for ferritic and martensitic materials in order to protect water side magnetite layer from cracking. The standard states that for boiler components which may have liquid water inside, the thermal stress shall never exceed 200MPa or go below -600MPa. (Suomen standardisoimisliitto, 2012)

Fluctuations of stress form hysteresis loops on stress-strain diagram and a load cycle is considered to close when corresponding loop closes. Notable is, that inside such a loop several smaller fluctuations usually take place, such as ones presented in Figure 2-9. The standard utilizes range-pair method for gathering cycles from stress data. (European committee for standardization, 2011)

The counting method used by the procedure is called range-pair method. It works so that it compares succeeding stress extreme values to find values that are relative extremes by Boolean formula:

$$\begin{gathered}(x_4 > x_3 \ and \ x_1 \leq x_3 \ and \ x_2 \leq x_4) \\ or \ (x_4 < x_3 and \ x_1 \geq x_3 \ and \ x_2 \geq x_4)\end{gathered} \tag{43}$$

where x_i are sequential stress values. The formula is illustrated by Figure 2-7. If the formula gives true value, x_2 and x_3 configure a load cycle and are removed from the sequence of extremes.

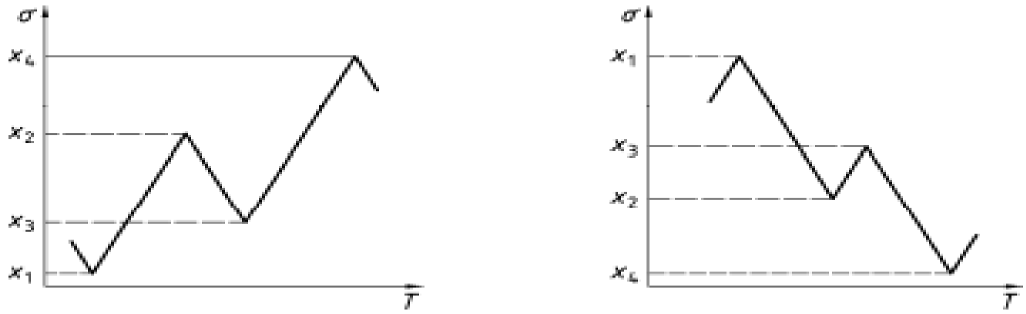

Figure 2-7 Load cycle condition formula illustrated. Source: (European committee for standardization, 2011)

Cycles with stress range less than material elastic range may be omitted when calculating low-cycle fatigue. The procedure is repeated for the sequence until no load cycles are found anymore and all that remains is remaining sequence of relative extremes (RSE). Typical form of a RSE is a range of increasing amplitude oscillation followed oscillation with decreasing amplitude. This sequence shall be retained and new stress extremes shall be added to it.

Figure 2-8 shows an example case of range-pair counting. The first sequence shows RSE of previous calculation followed by new extremes. Separated by a dashed line, new extremes have been added to RSE. Point ‘a’ depicts the minimum point of RSE. One characteristics of RSE is that the sequence of increasing oscillations may never contribute to further load cycles. Therefore, the analysis of those extremes may be omitted. The next sequences show, how the extremes are eliminated by repeatedly applying the algorithm shown by equation (43). Note that the bolded parts of the lines are removed. The final sequence shows the resulting new RSE.

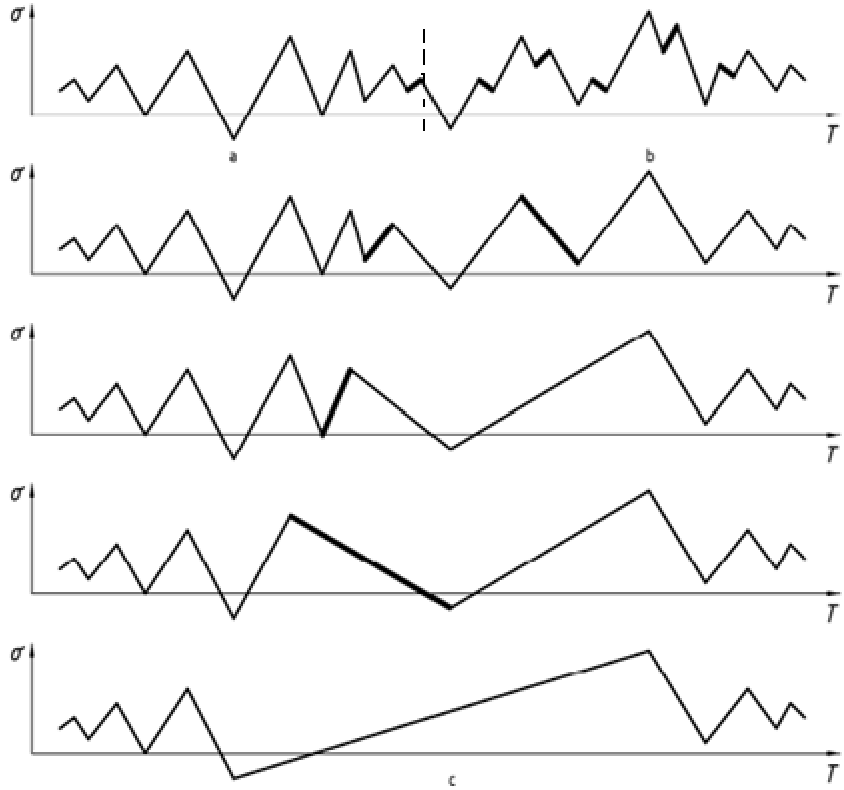

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Figure 2-8 Cycle counting example Source: (European committee for standardization, 2011)

For stress cycle with maximum stress $\widehat{\Delta f_{12}}$ and minimum stress $\widetilde{\Delta f_{12}}$, the stress range is calculated as

$$2f_a = \widehat{\Delta f_{12}} - \widetilde{\Delta f_{12}} \qquad (44)$$

Additionally, the cycle is given reference temperature for determination of material properties. It´s value is weighted sum of temperatures at the time of maximum and minimum stress with maximum point weight of 0,75 and minimum point weight of 0,25.

Figure 2-9 shows a simplified power boiler operating sequence on two kinds of stress-strain curves. The lower figure shows the sequence in chronological sequence with load cycles identified by using equation (43). The upper figure shows the same data in so-called hysteresis loop form that shows all the load cycles in compact form.

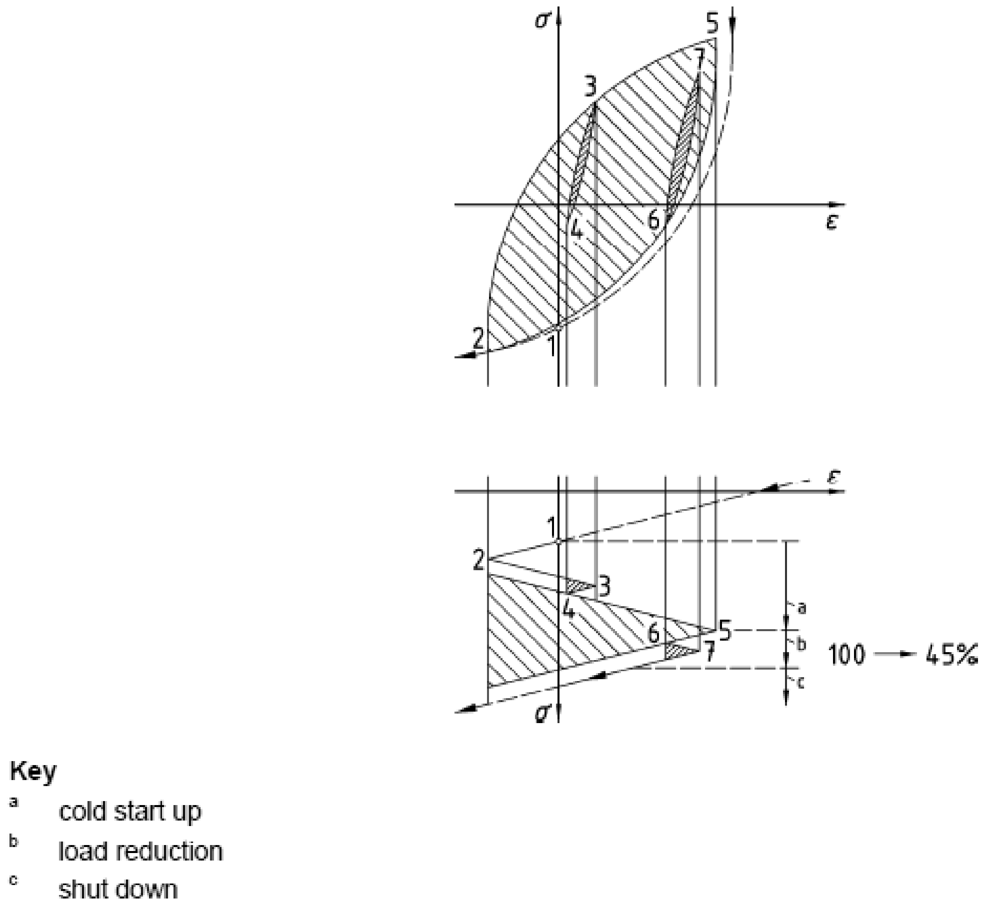


Figure 2-9 Cycle counting with range-pair method Source: (European committee for standardization, 2011)

Finally effects of non-zero mean stress and decrease in fatigue strength caused by elevated temperatures are taken into account by appropriate calculations shown in annex B of the part 3 in the standard the S-N curve provided with the standard doesn´t take these matters into account. The procedure adds safety factor of 1,5 for stress and 10 for load cycles to account for experimental nature of the S-N curve.

Fatigue damage caused by a load cycle is inverse value of the cycle number N obtained from the S-N curve. Therefore fatigue caused by a sequence of extreme is given by Miner´s rule

$$\Delta D_F = \sum_i \frac{1}{N_i} + \Delta D_{FRSE} \qquad (45)$$

where ΔD_{FRSE} is estimated damage caused by stress extremes not included in any load cycle and N_i is cycle amount to failure with stress difference.

2.6.2 Determining Creep

Annex A of part 4 of the standard includes calculation of in-service creep damage for the boiler. It is based on creep rupture data in operating temperature and pressure range and membrane stress of the vessel is used as stress value. Time to creep rupture is taken for each temperature-stress level and time-weighted sum for each time is taken to get total creep damage using equation (36).

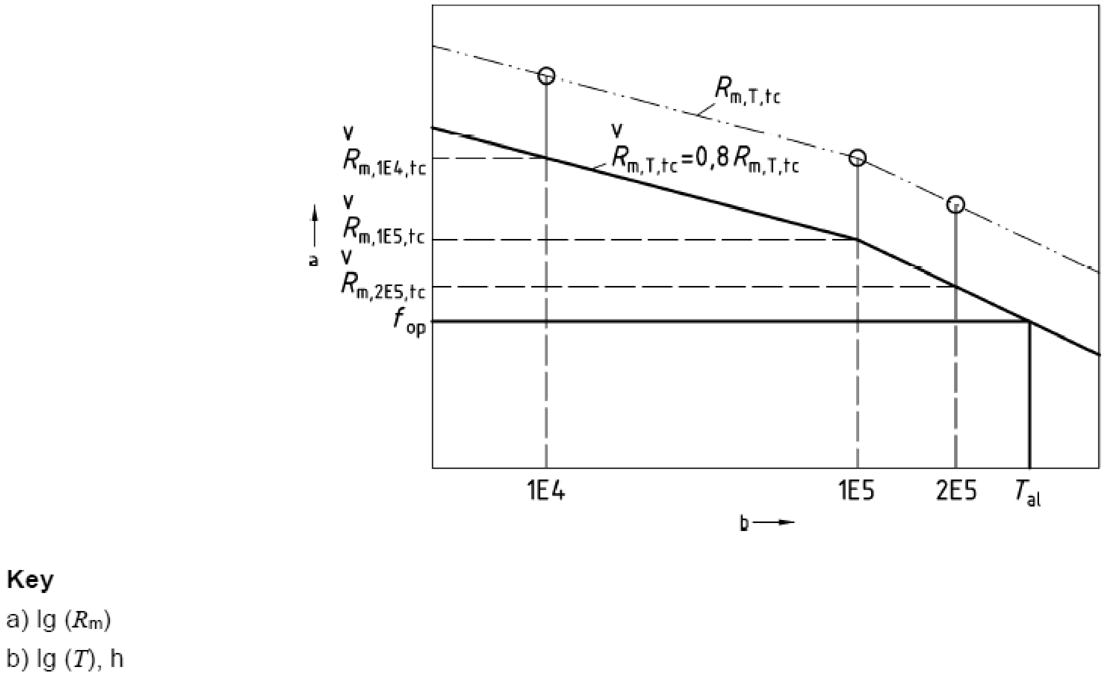


Figure 2-10 Determination of creep rupture time Source: (European committee for standardization, 2011)

Because of probabilistic nature of creep, time to rupture is taken from lower scatter band of creep data. This is achieved through dividing the stress value with factor of 0,8. Usage factor for time increment in operation condition is given by equation (36).

2.6.3 Calculation usefulness and accuracy

As noted before, even the standard itself states that nature of the calculation is estimative and other methods should be used if precise calculations are wanted. Therefore, the procedure alone is not sufficient for boiler condition assessment. Instead, the procedure has been suggested to be used as a guideline for decision making when planning for more detailed assessment. (Hodziz & Hajro, 2012), (Auerkari, ym., 2005). The results given by the procedure could be interpreted more qualitative than quantitative giving answer to questions like ‘has there been significant thermal stresses’ and ‘has the component increased risk of creep rupture’.

For stress calculations, important source of error are the stress concentration factors. In Figure 2-9 there is an example of results obtained from calculation procedure and results of finite element method (FEM) calculation. The standard recommends that these factors should be determined with FEM whenever possible. (Fontaine & Galopin, 2007), (Dwornicka, 2010). This is the case if more accurate stress and fatigue predictions are needed. If general idea about magnitudes of stresses arising from certain operation cycle is needed, it suffices to use the standard with factors provided. (Fontaine & Galopin, 2007).

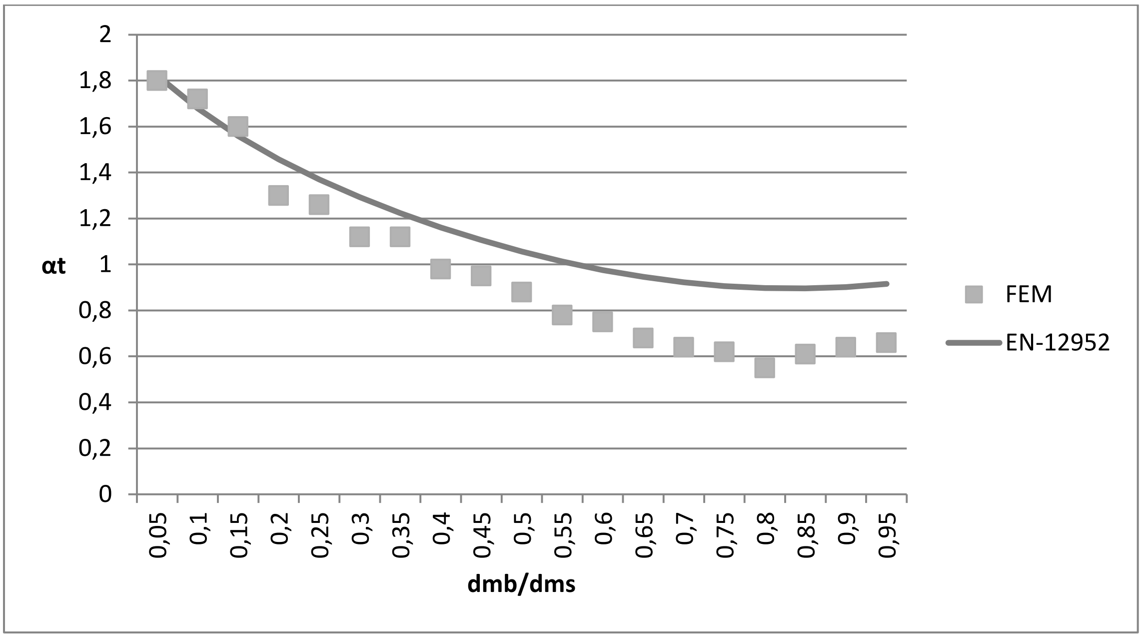


Figure 2-11 Stress concentration factor for weld connection thermal stresses calculated by EN-12952-3 procedure and FEM Sources:(Suomen standardisoimisliitto, 2012), (Dwornicka, 2010)

The graph above shows that the error in thermal stress calculation increases as ratio of pressure vessel main body and branch increases. For ratios of 0,15 and under the difference is rather negligible. With increased ratio, values given by EN-standard are 10-50% higher indicating that the method is conservative. Similar analysis for stress concentrations of primary membrane stresses was not found.

There has also been doubt whether superheater and reheater header quenching caused by condensate water during startups may is handled by the calculation procedure. This especially holds true for horizontally aligned HRSG steam equipment. (Fontaine & Galopin, 2007)

An important point about the fatigue calculation procedure is that time to crack initiation is calculated and dynamics of crack propagation is not taken into account. In some thick-walled power boiler components, especially in steam drums, at least some cracking is bound to happen long before rupture of wall.

Creep calculation methodology of the standard is expected to be on the conservative side due to usage of lower scatter band of creep ruptures by scaling of hoop stresses by factor of 0,8. On the other hand, as mentioned before, it doesn´t take variations of material properties or wall thickness into account. Usage of linear summation where both creep and fatigue are significant is considered as default method by EN 12952-4 procedure. However, the standard also proposes usage of more accurate methods, if needed, and mentions that British standard PD 7910 provides one such method. (European committee for standardization, 2011)

2.7 Other Methods for Boiler Lifetime Calculation

Besides EN-12952 procedure, several other calculation procedures for estimating boiler condition and lifetime have been developed. This chapter briefly describes parts ASME Boiler and Pressure Vessel Code (BPVC) and R5 procedures. Some other procedures not described here include Japanese JNC procedure, French A16 procedure, and now obsolete German TRD-301/508 procedure. In addition to procedures proposed by standards, there are other possibilities for calculation also. An online calculation based on FEM model of a vessel is possible to implement with computation power of modern computers and such systems have also been used since 1990's. One such system has been described in work made by Mukhopadhya and others (Mukhopadhyay;Dutta;Swami Prasad;Kuswaha;& Kakodkar, 1997).

BS 7910:2013 British standard procedure builds on older British standards, R6 procedure originally developed for nuclear plants and European FITNET procedure. At the moment, European standards supersede it where applicable. It contains procedures for assessing acceptability of flaws and fitness for service of welded metallic constructs. The procedure includes corrosion fatigue and creep calculation procedures as well as crack propagation assessment procedures. The revised version of the standard gives three options of different accuracy levels for fracture assessment. All the options use fracture assessment diagrams (FAD) for the assessment. The option 1 uses FAD based only on ultimate tensile strength and yield strength for simplified analysis. Option 2 requires full stress-strain relationship of the material to be known while option 3 requires finite element analysis to be conducted. (Hadley & Pisarski, 2013)

ASME boiler and pressure vessel code Division 1 of section VIII contains rules for simplified stress analysis without consideration of stress considerations and with higher factors of safety. Section VIII division 2 of the code contains rules for more detailed stress analysis and consideration of fatigue and creep so that lower factors of safety may be used. It also includes guidelines for applying FEM in boiler design. III and XI of the code include rules for applying fracture mechanics in design and analysis of vessels made of ferritic steels. Section III uses linear elastic fracture mechanics to determine allowable loadings of a pressure vessel with assumed defect. Subsection NH of section III contains rules for design of nuclear components operated at creep regime. Section XI contains assessment procedure for cracks found in nuclear reactor coolant systems during NDE. Section XI also contains rules for subcritical crack growth due to fatigue. (Babcock & Wilcox, 2005), (Lau, 1999)

'R5- Assessment procedure for the high temperature response of structures' is an assessment procedure for determining fitness for service of pressure vessels and other structures. It is commonly adopted for use in United Kingdom (Ford;Fernandes;& Shibli, 2009). Parts of it have also been incorporated into relevant British Standards. It´s intended to be accurate without usage of finite element methods. The procedure addresses numerous failure modes including inelastic deformation, ratcheting, creep damage, creep-fatigue damage and dissimilar metal weld failure. It has been considered to be very precise method for calculating crack propagation and creep evaluation with good agreement with results obtained with FEM. The procedure concerns both creep crack initiation and propagation. (Siska & Aktaa, 2009)

R5 procedure determines cycle amounts for defect nucleation and propagation of the defect into incipient crack. If N_l is number of load cycles to failure of test specimen at in-service temperature, then load cycles to crack initiation N_i and load cycles to crack propagation N_g may be calculated from empirical equation

$$\ln(N_i) = \ln(N_l) - 8{,}06N_l^{-0{,}28} \quad (46)$$

$$N_g = N_l - N_i \quad (47)$$

which is valid for ductile materials such as typical steels used for boiler construction. The procedure also gives equations for determining the number cycles N_g' it takes to grow an initial crack of size a_i, usually assumed to be size of 20µm, into size a_o:

$$M = \frac{a_{min} \cdot \ln\left(\frac{a_0}{a_{min}}\right) + (a_{min} - a_i)}{a_{min} \cdot \ln\left(\frac{a_i}{a_{min}}\right) + (a_{min} - a_i)}, if\ a_o > a_{min} \quad (48)$$

$$M = \frac{(a_0 - a_i)}{a_{min} \cdot \ln\left(\frac{a_i}{a_{min}}\right) + (a_{min} - a_i)}, if\ a_0 < a_{min} \quad (49)$$

$$N_g' = MN_g \quad (50)$$

where a_{min} equals 0,2mm. If the component is thick-walled and initial crack size exceeds 20 µm, it may be assumed that M equals one. For thin-walled components a_0 is always smaller than a_i due to likely shorter propagation paths. Fatigue endurance of a component with an initial crack is then obtained as

$$N_0 = N_i + N_g' \quad (51)$$

where N_0 is number cycles to failure. (Stoppato;Mirandola;Meneghetti;& L., 2012)

2.7.1 Interaction of fatigue and other damage mechanisms

Linear summation rule of damage for creep-fatigue interaction is employed by R5 procedure. Difference between these methods is that ASME method defines so-called limit damage for materials whereas the R5 method uses sum value of 1 as upper bound limiting value. This is demonstrated in Figure 2-12.

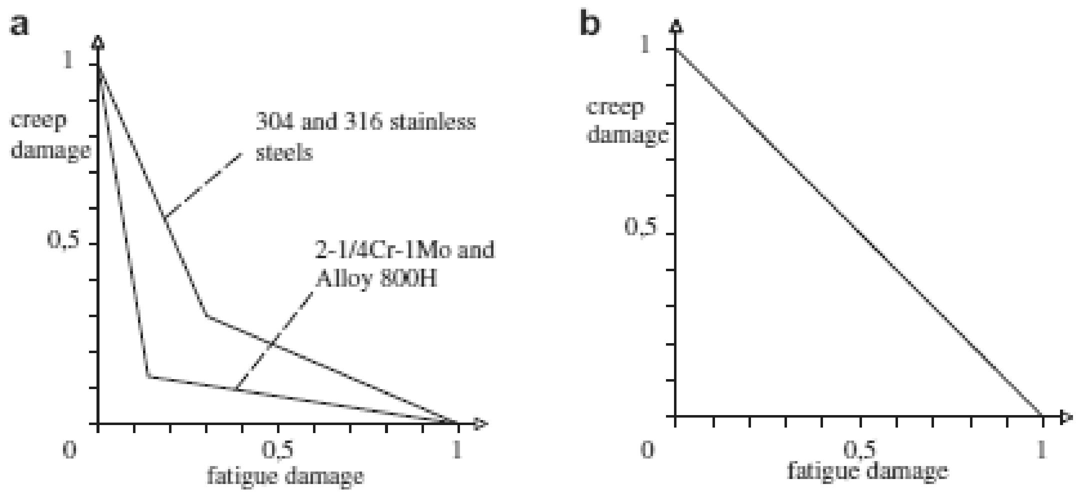


Figure 2-12 Damage summation curves of some steel varieties for ASME (a) and R5 (b) procedures. Source: (Stoppato;Mirandola;Meneghetti;& L., 2012)

ASME BPVC also requires that degradation of pressure vessel walls due to high temperatures must be taken into account when making calculations. Therefore presence of welds, oxidation, corrosion and other changes in steel microstructure must be taken into account. It also uses reduced number of load cycles in case of welded structures. (Stoppato;Mirandola;Meneghetti;& L., 2012, ss. 231-233)

3. POWER BOILER OPERATION

Power boiler pressure vessel life time duration is a sum of many factors. Good design takes these factors into account to produce equipment with needed characteristics including safety and economic efficiency. Matters related to thermal stresses and creep are covered more accurately in 3.2. Finally the single largest cause of thermal stresses in boiler, cyclical mode of operation, is discussed. While some matters discussed in this chapter are not directly related to fatigue and creep monitoring, they act as important motivation for implementing such systems.

3.1 Boiler types

This work places interest on three types of steam generating equipment: steam drum boilers, once through boilers and heat recovery steam generators (HRSG) used in steam circuit part of combined cycle units. All these are categorized as water-tube boilers meaning that water is turned into steam in pipes placed inside the boiler furnace or flue gas outlet. Special circumstances of nuclear reactor boiler equipment are not discussed in the scope of this work.

In once-through design all water is vaporized in boiler bank pipes while rising upwards due to convection caused by temperature gradient or in some cases due to pumping. In steam drum design water is only partially vaporized in boiler riser tube outlet and it is led into vessel known as steam drum. In steam drum the water level is kept constant so that steam phase rises to upper part of the drum to be led further into steam cycle while the water phase is led back to feed water line through down comer pipes to be reheated. Steam drum is a large and relatively thick-walled pressure vessel and usually most expensive single piece of the boiler pressure part. Kraft recovery boiler used for pulp mill chemical recovery is also typically of water pipe design. Normally the saturated steam produced is superheated to improve thermal cycle efficiency. (Babcock & Wilcox, 2005)

HRSG is a general term for a device that is used to transfer heat from a fluid to water in order to produce steam. Most HRSGs used in power generation are of steam drum design. In a combined cycle power generation unit the steam pipes of a HRSG are located at gas turbine flue gas outlet. Using the steam produced for electricity generation, thermal efficiency of the unit may be improved up to 60%. Size, design and capacity of HRSGs vary and steam pipes may be either vertical or horizontal and there may be 1-3 different pressure stages. Either natural or forced circulation of feed water may be used depending on the orientation of the steam pipes. (Babcock & Wilcox, 2005, ss. 27-15)

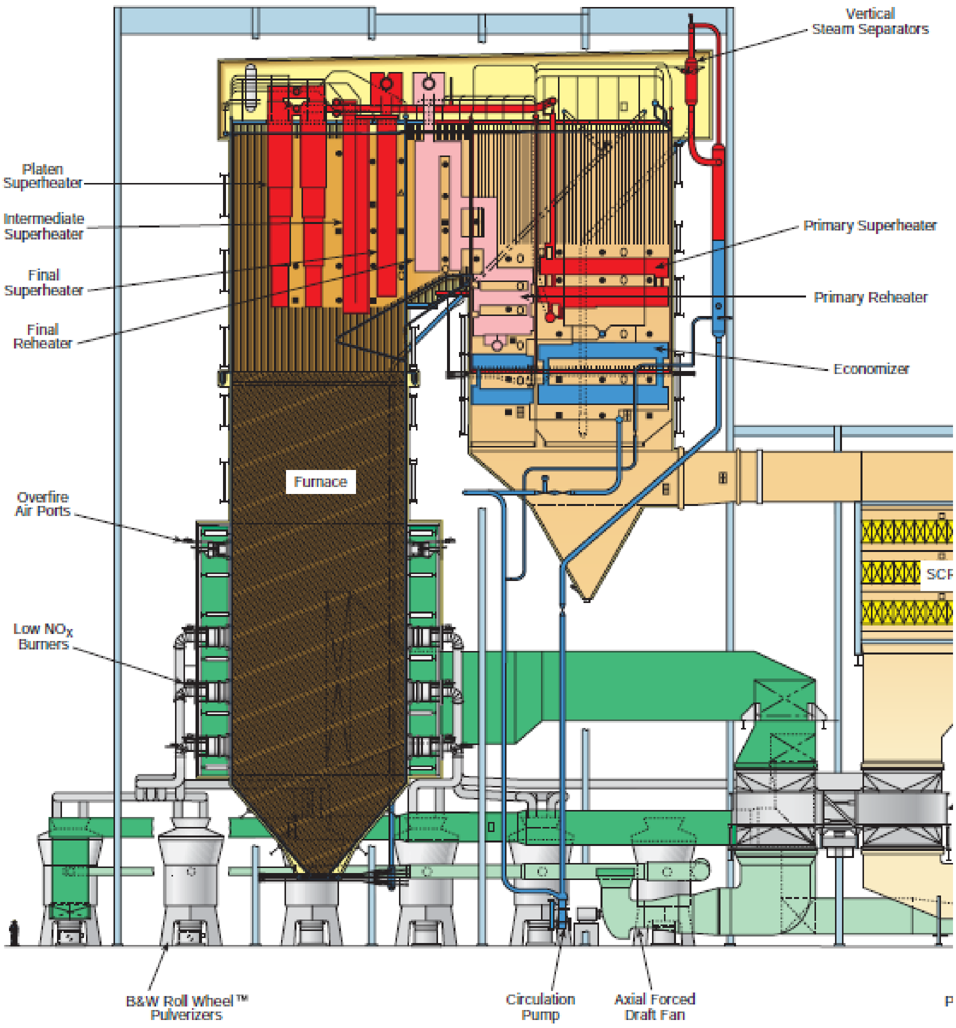


Figure 3-1 Once-through boiler. Source: (Babcock & Wilcox, 2005)

Start up time of combined cycle process is remarkably shorter than that of steam process. Consequently, temperature increase rate of flue gas in HRSG may be 800-1600°C/h while for steam cycle plants the rates are of order 250-800°C/h. Due to fast startup time combined cycle power plants are often operated cyclically so that problems related to thermal stresses are rather common in HRSG pressure part (Babcock & Wilcox, 2005, ss. 27-17). In Europe, HRSGs have been designed for cycling since 1970's by utilizing vertical design with natural circulation and other technical solutions. (Fontaine, 2003).

Figure 3-2 Utility boiler steam drum being lifted inside power plant structure. Source: (Babcock & Wilcox, 2005)

While conventional steam cycle boilers are often designed for base load use, cyclical use has become more usual in areas where deregulation of electricity market and increased use of wind and solar power has caused instability in electricity market. For example, in Germany both new and old coal power plants are being operated cyclically to regulate power grid. (Ford;Fernandes;& Shibli, 2009)

3.2 Power Boiler Pressure Vessel Components

In the following chapters, design of specific power boiler pressure vessel components is briefly discussed in the context of thermal stress and creep. Steam turbines are handled in the chapter 3.3.

Fatigue is especially prevalent cause of failures in HRSGs used at combined cycle power plants and power boilers that are being used cyclically even if not originally designed for it. Combined cycle plants are often operated cyclically as they have short startup times and thus are suitable to be used as regulating plant for electricity generation.

Base-load boilers that are operated relatively steadily and shut down only for maintenance breaks are not expected to suffer from severe fatigue.

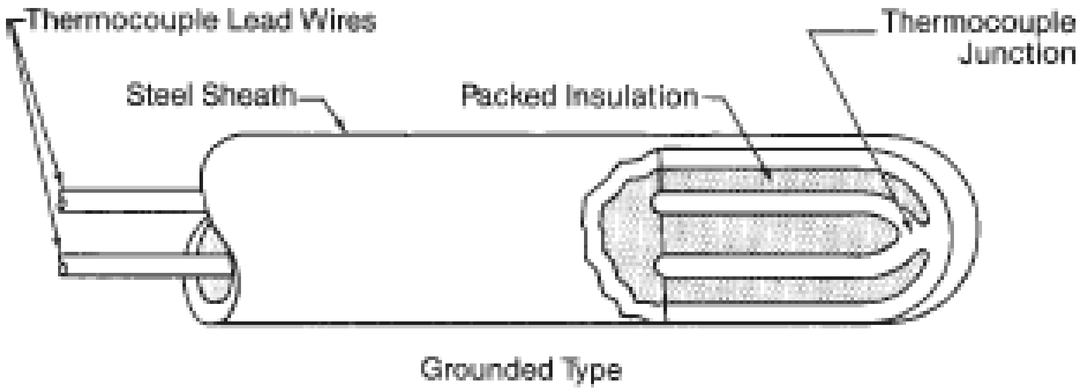
Table 3-1 Typical replacement periods of various boiler components. Source: (Babcock & Wilcox, 2005, ss. 44-12)

Typical replacement period (years)	Component	Cause for replacement
20	Attemperator	Fatigue
25	Secondary superheater	Creep
25	Superheater outlet headers	Creep fatigue
25	Burners	Overheating, corrosion
30	Reheater	Creep
35	Primary superheater, economizer	Corrosion
20	Miscellaneous tubing	Corrosion, erosion, over heating
40	Lower furnace	Overheating, corrosion

Typically fatigue causes cracks in points of pressure vessels' stress concentrations caused by notches and shape changes. Such points are, for example, joints to piping such as steam drum risers and down comers and superheater header's joints to tubes. Oxidation, corrosion and creep often further increase the notch effect.

One possibility to avoid effects of overnight shutdowns is to design minimum load of boiler unit to be so low that shutdown is not needed at all. However, costs and problems related to partial load operation may prevent doing this and other furnace types handle this kind of operation better than others (Lefton;Kumar;Hilleman;& Agan, 2012). Effects of overnight shutdowns on thermal stresses may also be decreased by improving boiler insulation to decrease rate of cooling. Mitigating idle time pressure loss through valves and other potential points of leaks is also desired to decrease needed energy to increase pressure and to regulate steam drum level better. This should also be taken into account when designing steam circuit drainage. Appropriate drainage is important as during startup condensate remaining in superheater and reheater tubes may cause anomalies in steam circulation and potentially over heating of equipment. (Commission for Energy Regulation, 2010)

It has been recommended that array of thermocouples should be installed in different parts of the steam drum to enable online monitoring of temperature gradients. Such pairs shall be installed in each end and middle part of the drum at both steam and water sides. If gradient over radial wall direction is to be monitored, two thermocouples at different radial position can be installed at each of these points. Similar setup may also be used for monitoring of boiler headers. (Babcock & Wilcox, 2005, ss. 43-5)



3-3 Sheathed thermocouple used for steam drum and header inner surface temperature measurement. Source: (Babcock & Wilcox, 2005)

A thermocouple is a device that consists of two electrical conductors made of dissimilar material and joined together at the ends to form a circuit. If temperature of other junction differs from the other, electromotive force is formed causing current to run through the conductors. The current is dependent on the temperature difference so that if temperature of the other end is known and the current measured, temperature of the other end may be calculated. Thermocouples are commonly used for temperature measurement in power industry as they are low cost, simple and durable. In addition to their usage at drums and headers, thermocouples are commonly used for material temperature measurement of superheater and reheater tubes. (Babcock & Wilcox, 2005, ss. 40-7 - 40 - 12)

3.2.1 Steam drum

Steam drum is a thick-walled steel vessel in which steam and water are separated. Water that has been warmed to saturation temperature by the boiler enters the drum from riser piping. Part of the water is then vaporized and is further led to superheater system. Water unvaporized returns to bottom of the boiler via down comer pipes to be mixed with feed water. As steam drum operates in water saturation point, creep and other problems related to high temperature are not of concern in its condition assessment. For this reason steam drums are usually fabricated of carbon-manganese steel.

Generally steam drums have been highly reliable components and they typically last their design lifetime of 25-30 years so that lifetime assessment of steam drums become interesting towards the end of their lifetime for assessing remaining lifetime of the boiler (Coleman, 2004). On the other hand, because of the cost and size of drum, even a small change of failure may bear unbearable risk on operability and cost-effectiveness of boiler unit. Due to thick walls, thermal stresses may form in steam drum walls and in some cases even cause limits on startup rate. Additionally, corrosion fatigue may become a problem around tube joints. (Babcock & Wilcox, 2005, ss. 44-6). It is common practice to equip riser tubes with thermal sleeves especially where ASME boiler codes are applied so that risks related to thermal stress fatigue are in downcomer nozzles instead. (Coleman, 2004)

Figure 3-4 Longitudinal cracking of steam drum downcomer nozzle. Source: (Coleman, 2004)

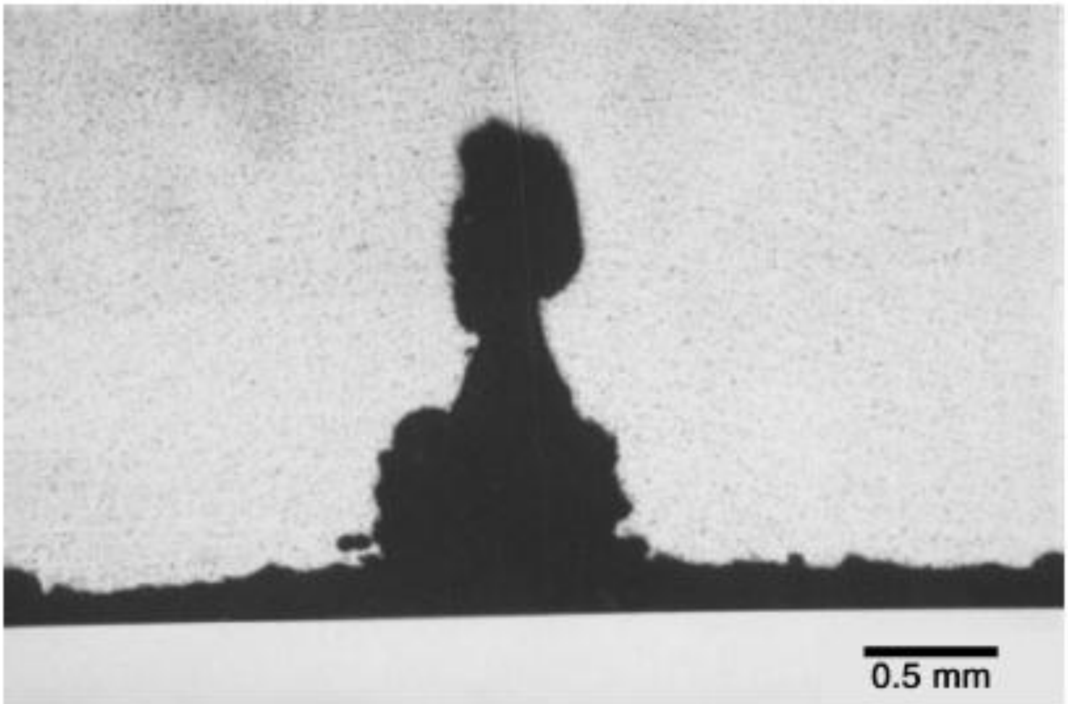


Figure 3-5 Hourglass shaped crack caused by thermal fatigue and subsequent corrosion and oxidation. Source: (Coleman, 2004)

Because upper part of the steam drum has steam and lower part has water, temperature gradient between upper and lower part of the drum may form during shutdown when the boiler is cooled by air fans but the steam temperature inside the drum remains the same. Such gradients also form if drum temperature is rapidly decreased and steam production is decreased resulting in cooling of drum upper part. Such stresses may cause so-called drum humping. Modern boilers usually have two supports so that the bending is not too restrained and the stress relieve itself but this is not necessarily the case, especially with older boiler designs with three or more supports causing constraints on drum deformation. (Babcock & Wilcox, 2005, ss. 43-5)

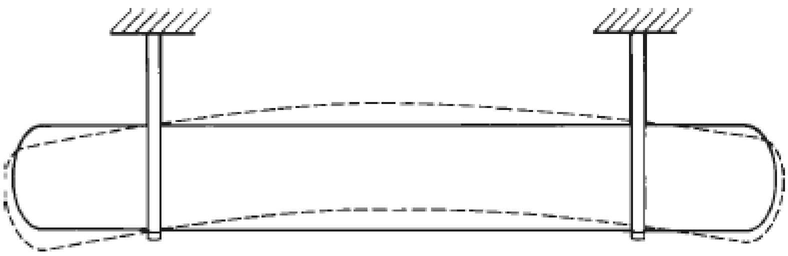


Figure 3-6 Drum humping. Source: (Babcock & Wilcox, 2005)

Also, if the boiler has non-drainable superheaters, soon after start of boiler firing the steam formed in superheaters may begin to flow back into drum and cause thermal gradient between upper and lower part. The thermal gradient between upper and lower part can be lessened by carefully flooding the steam drum during shutdown so that no carryover to superheaters occurs. Effect of such flooding may be further increased by reducing drum pressure before taking out of service (Babcock & Wilcox, 2005, ss. 43-5).

3.2.2 Economizer

Economizers are used in power boilers to utilize low temperature flue gases. In HRSGs it´s the last heat exchangers in the flue gas duct while in conventional boilers it is typically located in convection pass. Economizer warms feed water to saturation temperature before it flows into furnace for vaporizing.

In economizer, thermal stresses may occur in inlet header in cases when the header is located in convection pass. During hot startup, the economizer is warm and cold feed water enters the header as steam drum level is being adjusted for startup. Consequently, thermal shocks may occur especially near the feedwater inlet. A questionnaire made for fossil fuel boiler units in United States and United Kingdom with 50-75% of design life time elapsed revealed that 60% of those units had experienced economizer header cracking (Ford;Fernandes;& Shibli, 2009, s. 137).

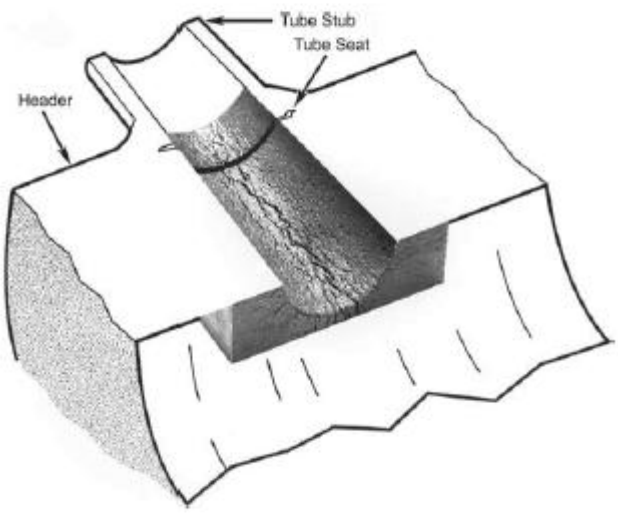


Figure 3-7 Cracking of economizer inlet header due to cold feed water rush occurs first in bore holes nearest to water inlet Source: (Babcock & Wilcox, 2005, ss. 45-18)

Thermal shocks like this may be prevented by pump-assisted circulation of feedwater to prevent temperature stratification in water-steam circuit. By installing a connection between furnace water pipes and feed water line warm water may be introduced to feed water lines to keep them warm so that when startup is initiated the feed water temperature is raised.

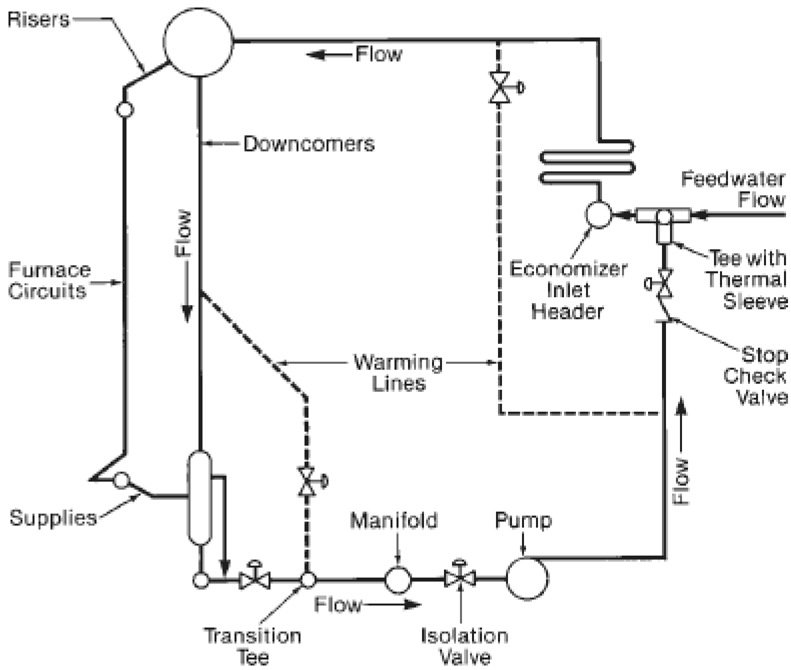


Figure 3-8 water circulation system for mitigation of thermal shocks Source: (Babcock & Wilcox, 2005)

When circulation pump system have been installed in units not originally designed for cyclical operation, the temperature differentials in economizer have been shown to decrease from over 100-200°C to around 50°C by using circulation system like this. (Babcock & Wilcox, 2005)

3.2.3 Superheater and reheater headers

Superheater and reheater headers usually have steam in uniform temperature so that main source of thermal stresses is temperature change due to transients. Headers made of low-alloy steel result in relatively thick-walled headers causing greater thermal stresses. Therefore it has become common practice to build pressure vessels of steels with better high temperature strength such as grade 91. When correctly used, such steels may greatly decrease problems related to thermal stresses.

Very common form of header degradation is ligament cracking. In older power plants with low alloy header materials, occurring of such cracking has reportedly been quite common. Cracking has reportedly been caused by thermal stresses and oxidation. There is some ambiguous data on the exact size of the impact of the boiler operation mode but apparently flow of cold water into header at late stages of startup sequence plays a big role. (Storesund, 2007).

In addition to usage of high strength materials, possibility of weld cracking can be decreased by using forged tee-connections for piping or by decreasing stresses around weld joint by using full-penetration welds. Of course, as with most other solutions, this approach has higher investment costs. Ligament cracking may be decreased by increasing size of ligaments in the header. Superheater headers have also possibility of thermal stresses to arise from improperly functioning attemperation causing subcooled water to hit header walls causing temperature gradients. (Babcock & Wilcox, 2005)

Typical life time of high temperature headers is 25 years. The usual reason for replacement is creep-fatigue cracking especially occurring in tube-to-header connection welds where ligament and weld cracking occur. Cracking may also be caused by inadequate flexibility of tubing. (Babcock & Wilcox, 2005, ss. 44-13 - 44-14)

Reheaters are prone to overheating during startups when steam hasn´t yet reached values appropriate to be admitted to high pressure turbine. If overheating is to be avoided, firing must be increased slower and thus increasing startup time. Additionally, when steam flow is established, the initially cold headers may suffer thermal shocks. These problems may be efficiently removed by building a bypass for HP turbine so that steam enters reheaters from the start. Basically this is done by adding a connection with pressure reduction station and attemperator between high pressure steam line and steam line from HP turbine to reheaters. Such setup may also be installed to IP reheater if needed. (Commission for Energy Regulation, 2010)

3.2.4 Superheater and reheater tubes

Modern high efficiency power boilers may have steam temperatures of up to 600 degrees Celsius and supercritical boilers even over that. Such temperatures place many requirements on the tube material of superheaters and reheaters. Several new high-alloy steels have been developed for this purposes usually containing at least 25% nickel for superior creep and high temperature qualities. Typical lifetime of properly operated superheater tubes is 25 years or 200 000 hours. Depending on the boiler, the limiting factor of this time is either creep or corrosion.

During startup, flue gas temperatures must not exceed values where serious creep begins to take place before uniform and sufficient steam flow through the tubes is established. As a rule of thumb, this temperature is around 480°C for carbon steels and 538°C for alloyed steels. Local overheating may cause rupture in substantially shorter times than designed lifetimes.

Short term overheating occurs due to anomalies in operation such as when water remains in superheater during startup and no steam flow is established. Therefore it is important to make sure that no water remains in the tubes when boiler load is increased. One way to monitor this is to use thermocouples installed in outlet legs of tubing in areas with lowest heat flow such as near boiler walls and division walls as where remaining water is last to boil there. The thermocouple reading should rise sharply peak when steam flow is established to signal that the tube is clear of water. (Babcock & Wilcox, 2005, ss. 43-5)

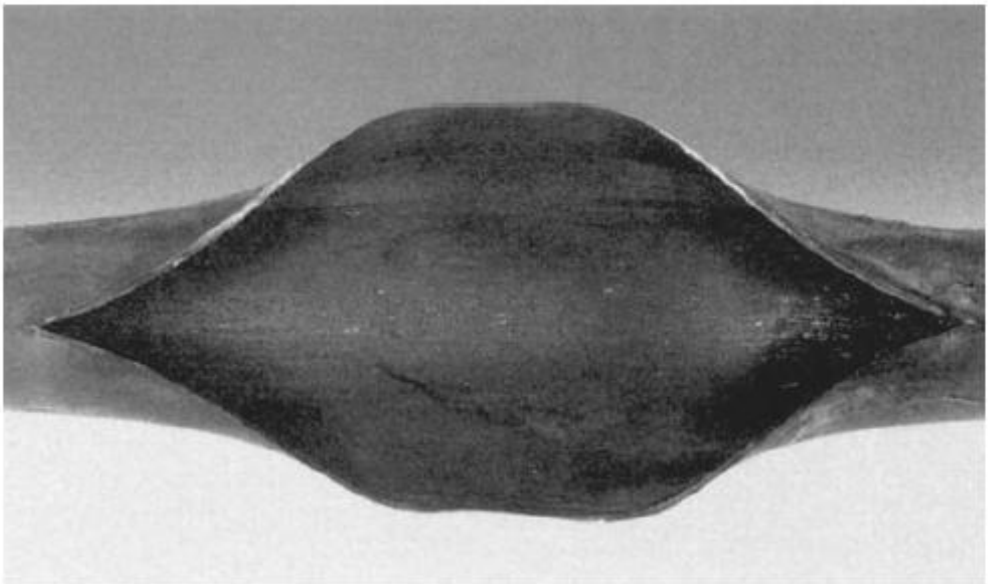


Figure 3-9 Tube ruptured by short term overheating Source: (Babcock & Wilcox, 2005)

Long term overheating occurs over a time during which oxide deposits accumulates on steam side wall decreasing heat transfer capabilities and strength of the tube. Such deposits may be monitored by installing chordal thermocouples in hottest areas. Temperatures at oxide free tubes should be noted and then regularly monitored to identify problematic points. (Babcock & Wilcox, 2005, ss. 42-19)

3.2.5 High energy tubing

Modern high energy tube lines such as tubes delivering steam from superheaters to turbine including turbine throttle valves are nowadays generally designed to last 30 to 40 years of operation before creep ruptures begin to occur. Nowadays, deformations caused by thermal stresses are considered by design of hangers and supports, which should have some built in flexibility. However, interaction of creep and fatigue has still been causing problems with mechanisms, that aren´t fully understood. Cracking in steam tubes occurs especially in attachment welds due to thermal fatigue, improper welding or improper support of tubing. Another problem that may arise with horizontally aligned steam tubes is deformation caused by temperature gradients between upper and lower section of the tube. (Babcock & Wilcox, 2005, ss. 45-9)

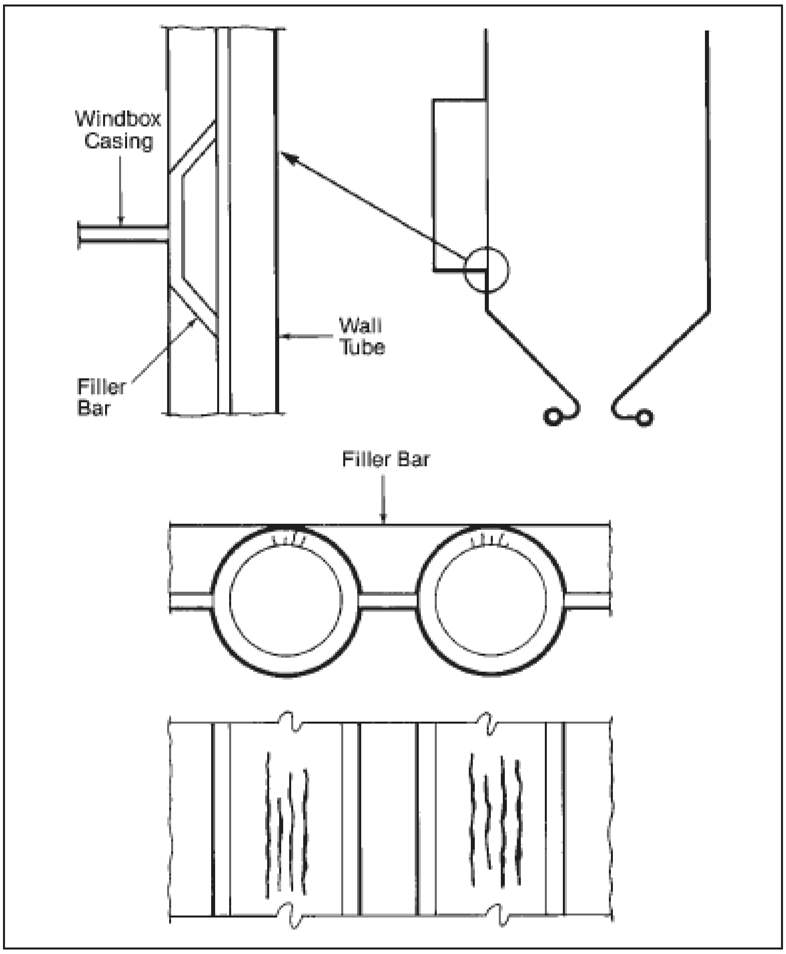


Figure 3-10 Longitudinal cracking in furnace wall tubing. Source: (Babcock & Wilcox, 2005, ss. 45-18)

Another cause of thermal stresses in boilers is subcooling of boiler water in furnace tubing during overnight shutdown. During shutdown boiler cooling in vertical direction is not even and water in lower boiler parts may get cooler than water in upper parts. When water circulation is established, the cooler water enters warmer regions in riser tubes causing temperature gradients and thermal stresses especially where boiler tubing is restrained in some way especially at attachments to lower windbox. These stresses may cause longitudinal cracking in tube inner surface. Such cracking may be prevented by circulating water from down comers back to drum through furnace walls when the boiler is off line. (Babcock & Wilcox, 1999)

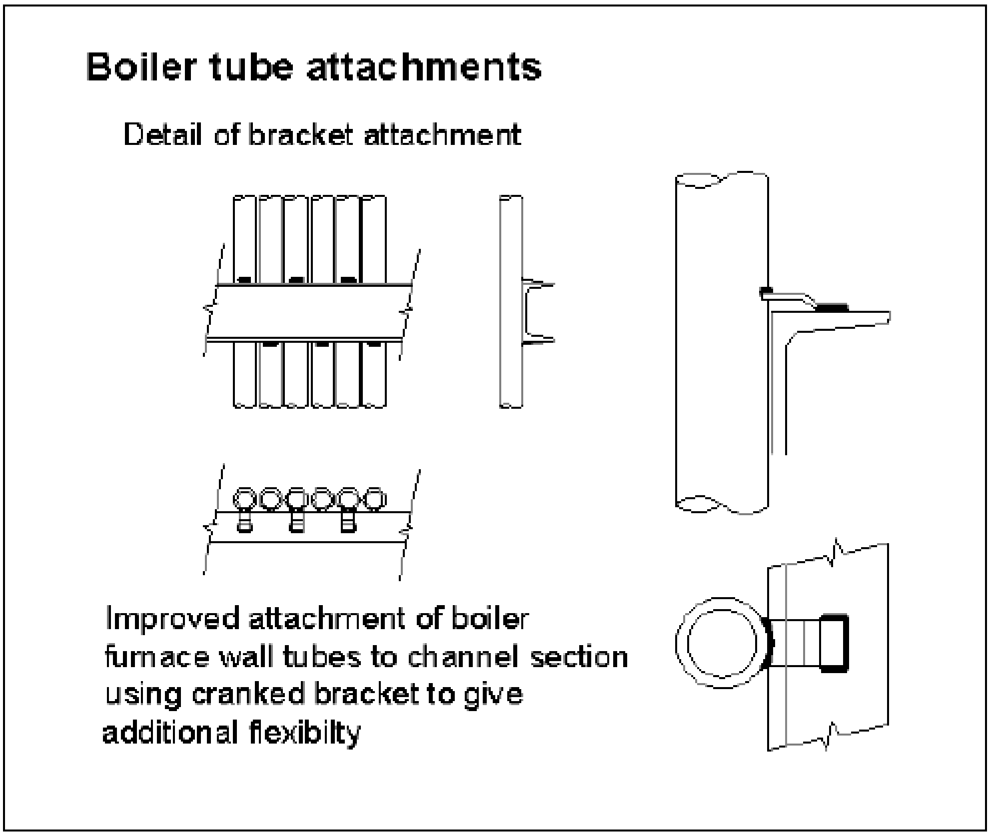


Figure 3-11 Bracketed boiler tube connection. Source: (Commission for Energy Regulation, 2010)

Another problem arising from thermal fatigue is failures of furnace water tubing attachments. One way to reduce these failures is to use more flexible bracket attachments for tubing attachment. (Commission for Energy Regulation, 2010)

3.3 Thermal Stresses and Creep in Steam Turbines

This part of the work handles calculation and monitoring of steam turbine creep and thermal stresses. An overview is given instead of going into too much detail.

For steam turbine rotors and casing, thermal stresses and creep are considered main causes of crack initiation and propagation. For turbine casing, internal pressure is driving force for creep and for rotor centrifugal forces. Similarly to boiler parts, in steam turbines thermal stresses occur during startup and shutdown whereas creep occurs mainly during steady full load operation. (Ford;Fernandes;& Shibli, 2009)

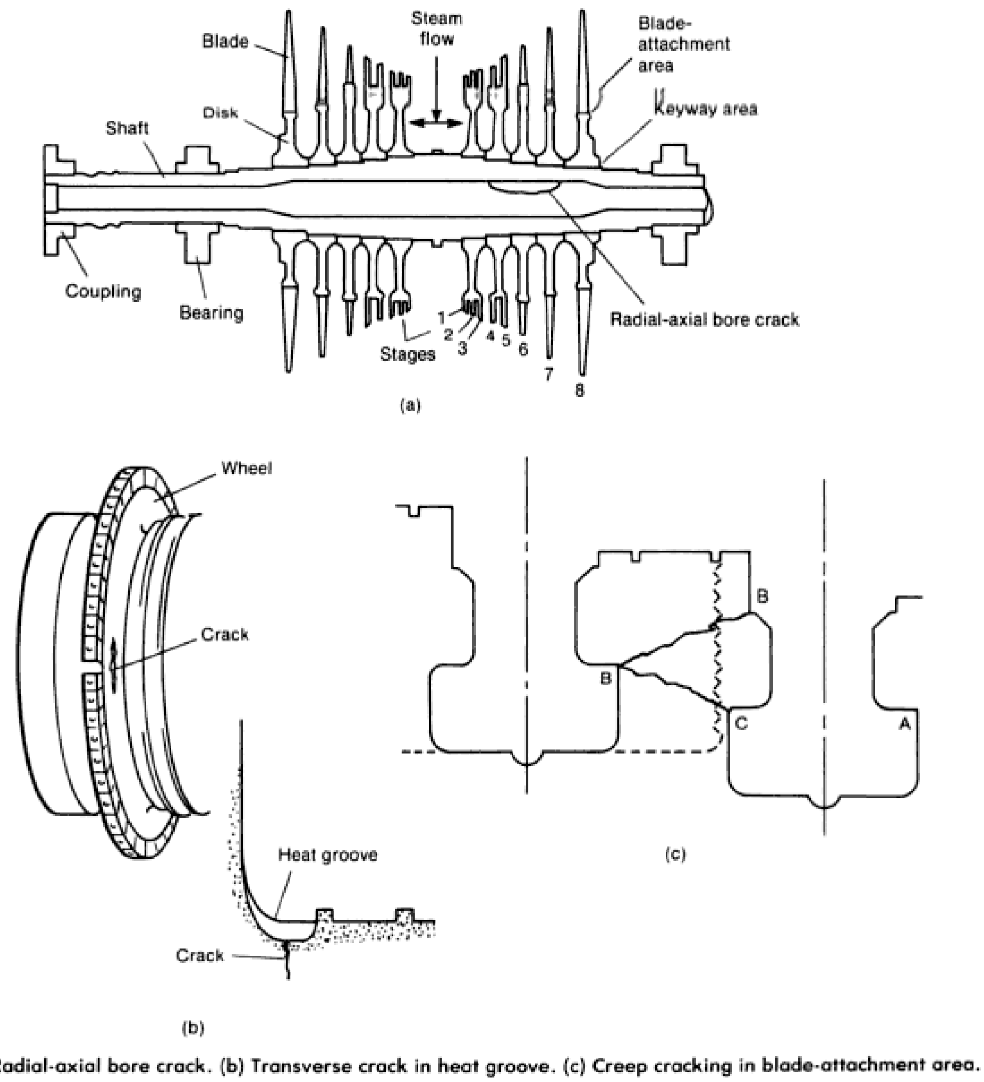


Figure 3-12 Steam turbine configurations and typical cracking locations. Source:(Viswanathan, 1989)

Temperature profile of first rotor stage may be estimated by using information on fluid temperature, thermal properties of material and geometry. As temperature drops at each stage, it may be necessary to calculate this drop for each stage separately. Figure 3-13 depicts one possible procedure for this calculation. (Kant, 1997, s. 414)

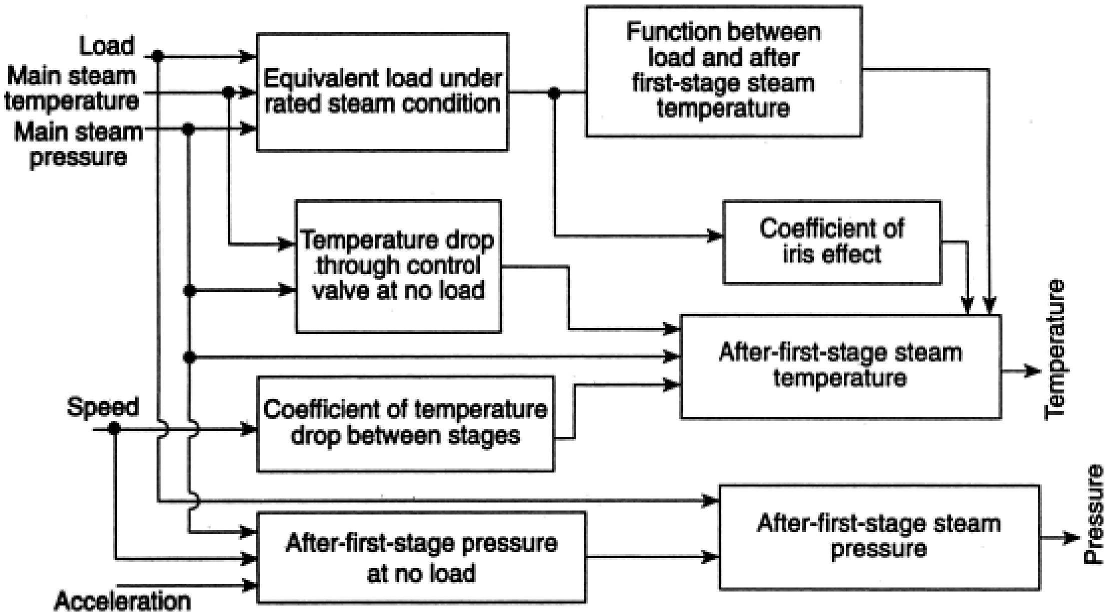


Figure 3-13 Calculation of post-first stage temperature and pressure. Source: (Kant, 1997, s. 414)

Probes for rotor temperature have been developed. One type of such sensor is thermocouple installed inside the wall of turbine inlet so that its reading lags behind steam temperature simulating temperature inside the rotor so that stresses may be then calculated using computer (Ford;Fernandes;& Shibli, 2009, s. 156). Another possibility for rotor surface temperature measurement is to use optical measurements such as infrared devices. They are less susceptible to vibrations than contact-based measurements but must be protected from steam (Rao, 1993, p. 137). For rotors, stresses are concentrated to disc root portions and damage assessment should be done using appropriate stress concentration factors. With inexpensive finite element analysis available, obtaining these factors is technically rather simple. It has been noted that determination of creep-stress behavior of disc roots should be done using long term tests on test bars with similar stress concentrations and that using extrapolated data acquired from unnotched specimens lead to non-conservative results. Linear damage accumulation rule has also been applied to steam turbine calculations. It has been estimated that 70% of linear damage to steam turbines is caused by fatigue and 30% by creep although mode of operation has a great impact on the number. (Prasad;Shukla;& Roy, 2007), (Viswanathan, 1989)

3.4 Power Boiler Cyclical Operation

Mode of operation is the major factor affecting power boiler creep and fatigue damage. Base load plants have been designed to last at least 20 and even 40 years in its maximum capacity and therefore design for creep is a major design parameter instead of ability to tolerate several operation cycles. In this chapter, cyclical boiler operation and related issues and costs are investigated.

A load cycle is often considered to start at full load which is followed by load reduction to lower load or zero load after shutdown. Then the boiler is returned to full load after load increase. Types of cyclical operation may be divided in two categories: load cycling and on/off cycling often referred to as two shifting. In load cycling the plant load is adjusted due to business needs whereas in two shifting the boiler is shut down for some period, often over night or weekend. Power plant start ups are typically further categorized into hot, warm and cold starts to account for conditions in the beginning of start up. Typical offline times preceding warm start have been depicted in Table 3-2. Hot startups occur after offline times less than shown. In cold startup the boiler is in ambient conditions or very near it. As noted before, load changes cause temperature differentials and therefore thermal stresses to various boiler parts causing degradation. Additionally cyclical boiler operation causes losses in form of decreased heat rate, increased usage of fuel during startups and increased need for operator labor. (Kumar;Besuner;Lefton;Dwight;& Hilleman, 2012)

Table 3-2 Typical warm shutdown times for various power generating units. Source: (Kumar;Besuner;Lefton;Dwight;& Hilleman, 2012)

Plant type	Offline time before warm start(h)
Coal, small	4-24
Coal, large	12-40
Coal, supercritical	12-72
Combined cycle	5-40
Gas turbine, large	2-3

Problems related to cycling induced thermal stresses tend to occur only after few years of such operation for boilers originally used for base-load operation which is illustrated by Figure 3-16.(Ford;Fernandes;& Shibli, 2009) (Babcock & Wilcox, 2005, ss. 45-17)

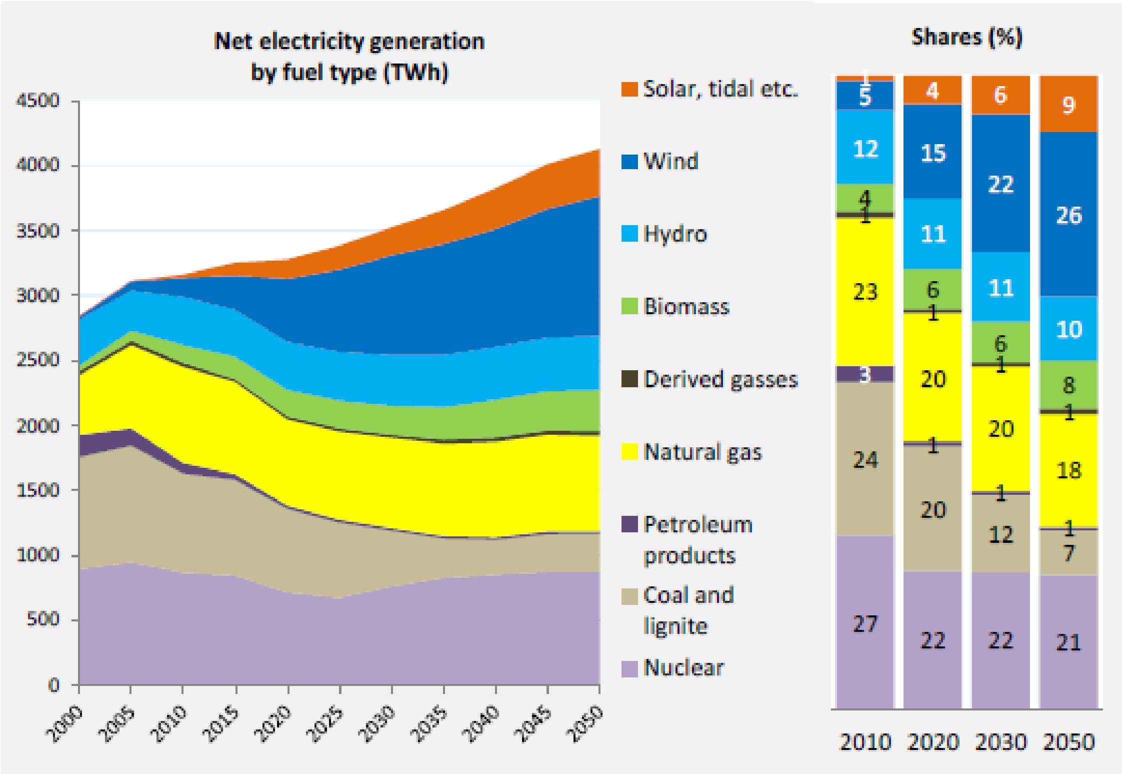


Figure 3-14 Forecast of electricity generation in EU28 countries by primary energy source 2000-2050. Source: (Capros, et al., 2014)

Two large trends have been increasing amount of cyclical operation globally during last decades. These trends have caused boiler units not originally designed for cyclical operation to be cycled due to demands on the power grid balance and therefore posing new kind of demands on maintenance and operation.

The first trend is increased usage of wind and solar power in several countries such as Denmark, Germany, Ireland and Spain. Need to stabilize power grid with conventional power plants utilizing biomass or fossil fuels arise from variations of weather conditions. Uncertainty of weather forecasts further increases difficulty of planning operation. In year 2010, 6% of electricity production primary energy was produced with wind, solar and tidal power whereas in 2020 the amount is estimated to be 19% (Capros, et al., 2014). It has been estimated that 20% penetration of wind power in power grid causes cost of 1-4€/MWh(el.) including costs related reserve power capacity and investments in transmission network. The cost is quite dependent on the need to invest in transmission and geographical distribution of wind turbines. (Holttinen, 2007).

Another trend causing fluctuations to electricity market has been gradual deregulation of electricity market in many countries during last two decades. Fluctuation in prices and demand causes power plants to be operated more cyclically than in regulated market.

Personnel have a significant role when adopting cyclical operation mode in previously base load operated power plant. Improving communication between operators, engineers and other relevant people are considered important for sharing ideas and adopting new mode of operation successfully. Communication between personnel from several power plants can further improve transfer of knowledge and ideas. Also monitoring and reviewing working methods of each shift may be beneficial to find the best practices. Plant operators´ responsibility is greatly increased if the amount of startups is increased from few per year to one or more per week. This also requires quite a different mindset regarding operation and also information on economical and condition-related issues involved cyclical operation. (Commission for Energy Regulation, 2010)

3.4.1 Costs of cyclical operation

Causes of cycling costs may be divided in few categories. Due to accelerated degradation of equipment cost of boiler maintenance is increased and there is possibility that maintenance overhauls become longer. This effect is emphasized in Figure 3-15. Secondly, unexpected failure of equipment causing unexpected boiler shutdown often causes financial consequences due to commitments made to the electricity market. Boiler start ups require start up fuel, may require extra man power and chemicals and decrease long term efficiency. Also, partial load operation decreases effectiveness and may have unwanted effects on boiler condition. (Lefton;Kumar;Hilleman;& Agan, 2012)

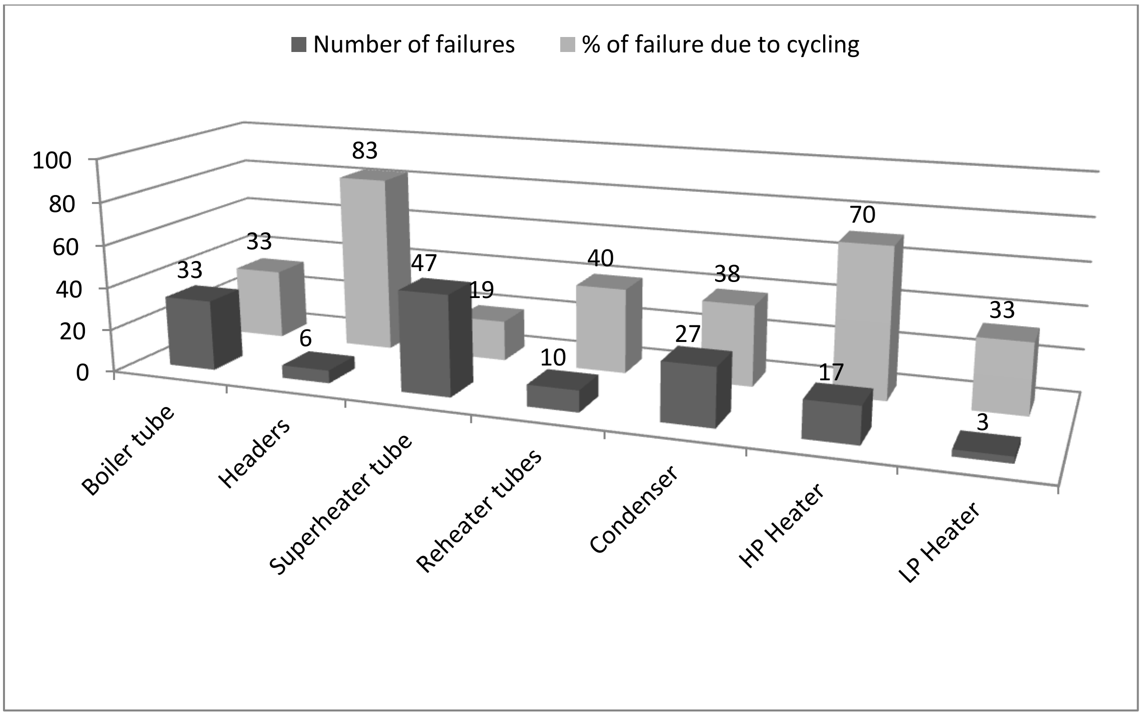


Figure 3-15 Effects of cycling on various boiler components. Source: (Ford;Fernandes;& Shibli, 2009)

One way to measure availability of a boiler is by using equipment forced outage rate (EFOR). It is determined as percentage of unplanned outage hours of the total hours of the availability of the boiler.

Monitoring of cost due to cyclical operation of equipment is important part of operation planning when the objective is to maximize income of a power generation company.

Table 3-3 Typical cost per cycle estimations of power industry in United States. Source: (Lefton & Besuner, 2006)

Unit type	Typical estimate in industry (USD 2006)	Range of potential actual costs (USD 2006)
Small drum boiler	5 000	13 000-100 000
Large supercritical boiler	10 000	15 000 – 500 000
Gas turbine	100	300- 80 000

Common problem with load cycle cost estimations has been underestimation of costs and consequent sub-optimal financial performance. Table 3-3 depicts some approximate values regarding this.

3.4.1.1 Research made by Aptech

American engineering company Aptech has made several publications regarding cyclical operation of power plants especially in USA. This chapter presents some interesting findings from these publications. Research based on operation data collected in USA over 20 years in coal boiler and gas turbine units has been made. (Kumar;Besuner;Lefton;Dwight;& Hilleman, 2012)

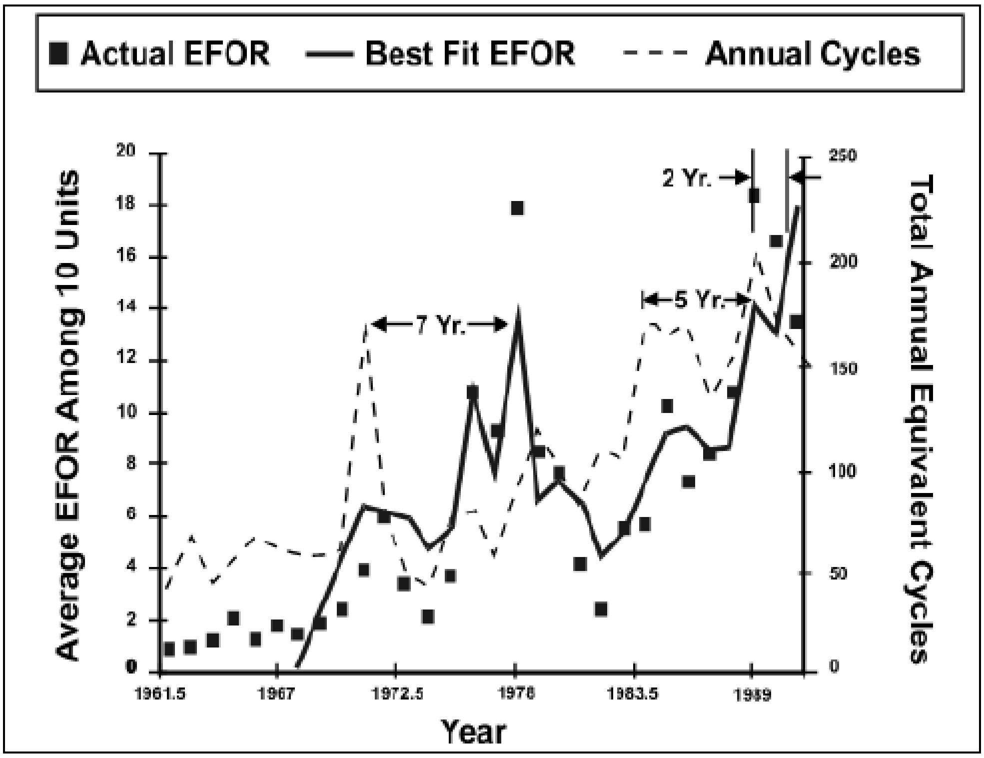


Figure 3-16 Relation of EFOR and cyclical operation. Source: (Kumar;Besuner;Lefton;Dwight;& Hilleman, 2012)

Figure 3-16 shows rather clearly connection between cyclical operation and increase in EFOR and how the impact may be observed with a delay of several years. This set of data would indicate that as cumulated operation time increases, this delay decreases.

Based on the data, lower bound estimates for costs of startups and load changes were calculated. These lower bound values have been collected into Table 3-4. Values presented are for plants with costs in lowest 25% of the whole data. Such units represent those with technical solutions and operation practices most suitable for cyclical operation and may be used as a baseline when considering building new units even if the numbers don´t include possible increased capital costs. Median values for sample data were 50-80% higher and represent better existing equipment originally designed for base load operation. (Kumar;Besuner;Lefton;Dwight;& Hilleman, 2012)

Coal boilers included in the data have subcritical steam cycle. The data on supercritical units was reportedly lacking and thus not included in the table. Such boilers are expected to have values at least equal to large sub critical boilers. For combined cycle plants, it should be noted that HRSGs in Europe are usually of cycling tolerant design and therefore values presented here could represent European units rather well (Fontaine, 2003). It is noted that true costs depend also on value lost due to EFOR and on type of contracts made by the utility company as well as on market price of electricity. (Kumar;Besuner;Lefton;Dwight;& Hilleman, 2012)

Table 3-4 Low bound costs and increase in EFOR for load shifts of power plants. Source:(Kumar;Besuner;Lefton;Dwight;& Hilleman, 2012)

Plant type		**Cold start**	**Warm start**	**Hot start**	**Load change (typical load change of capacity)**
Coal,(25-300MWe)	Cost ($/MW cap)	94	95	58	2.26 (32%)
	EFOR increase	0,0081%	0,0089%	0.0055%	
Coal, over 300MWe	Cost ($/MW cap)	89	61	39	1,99 (35%)
	EFOR increase	0.0098%	0.0075%	0.0056%	
Combined cycle	Cost ($/MW cap)	60	44	31	0,33 (20%)
	EFOR increase	0.0053%	0.0038%	0.0023%	
Gas turbine, large	Cost ($/MW cap)	38	28	22	0,88 (27%)
	EFOR increase	0.0033%	0.0025%	0.0019%	

Due to cyclical operations, heat rate of a boiler unit also tends to increase due to load changes and partial load operation. Table 3-5 shows approximate increases of heat rate due to startups for various unit types. Cost of startup fuel has been eliminated from the numbers. Impact on heat rate of coal boiler units was substantially higher than that of gas turbine and combined cycle units. However, it is noted that the increase may vary from unit to unit due to differences between control systems, operation, test data and several other factors. Hot, warm and cold starts have not been differentiated in this data. (Kumar;Besuner;Lefton;Dwight;& Hilleman, 2012, ss. 33-34)

Table 3-5 Increase of weekly heat rate when one start is made. Source: (Kumar;Besuner;Lefton;Dwight;& Hilleman, 2012)

Plant type	Increase of weekly heat rate per start (%)
Coal, 25-300MWe	0,62
Coal, over 300MWe	0,44
Combined cycle	0,20
Gas turbine, large	0,20

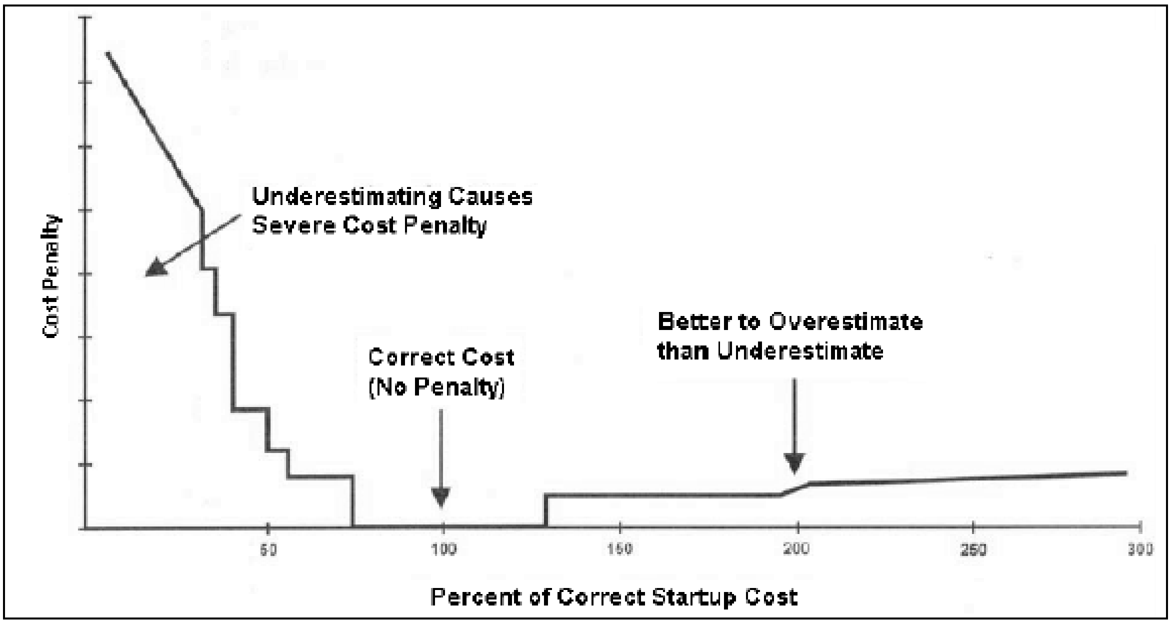


Figure 3-17 Economical losses due to erratic estimation of cycling costs. (Kumar;Besuner;Lefton;Dwight;& Hilleman, 2012)

Figure 3-17 shows an interesting finding regarding the existing assessments of power production planning and predicted costs of startups. Underestimating the costs seems to have much more severe economical consequences than overestimating them. Overestimating the costs by as much as 200% causes only relatively small extra costs when compared to underestimating them. (Kumar;Besuner;Lefton;Dwight;& Hilleman, 2012).

4. ONLINE CONDITION MONITORING OF BOILERS

This chapter introduces concept of computer aided online boiler condition assessment. General overview on such computer application that was developed as a part of this thesis work by using Metso DNA platform is also given.

4.1 Motivation for Online Condition Monitoring

In European Union, the Pressure Equipment directive sets minimum criteria for national legislation for safe usage of pressure equipment such as power boilers (European Commission, 2014). To assure safety, condition of power boiler pressure part is demanded to be assessed at fixed time intervals using destructive and non-destructive testing in order to fulfill these criteria. In Germany, requirements of PED are fulfilled by Pressure Equipment Act accompanied with several guidelines. For example, such guidelines are introduced in some standards proposed by technical association VGB Powertech. Fulfilling the criteria proposed by these guidelines may allow for longer inspection intervals (VGB Powertech, 2012).

According to a report made by Wagner, some of these criteria may be met by using online condition monitoring. Decreased inspection intervals mean lower costs of plant operation and maintenance. For example, VGB Guideline 506 lists stress analysis conducted during operation as one of five core parts of boiler condition monitoring. (Wagner, 2013)

It is not uncommon that a boiler operates outside designed operating range causing potentially damage to pressure equipment. Well-documented operation history with estimates of damage caused by unexpected events helps to indicate such incidences and planning for following actions to be taken to improve availability and safety of the plant. Calculation results could also be used to optimize boiler startup and shutdown sequences for decreased low-cycle fatigue. It could be also possible to include boiler life extending calculation model directly in the DCS as proposed in source (Li;Marquez;& Gooden, 2006). Calculation models may also be used for estimating impacts of certain operation patterns on boiler lifetime which may be useful when estimating economical aspects of cyclical boiler operation. In a study conducted in the field of cyclical operation, it has been stated that there is need for reliable and economical online monitoring sytem. Such system should at least include tools for life management and start/stop cycle management. Also need for improved sensors for strain and temperature gradient measurements is stated (Ford;Fernandes;& Shibli, 2009).

Additionally, better operating procedures for operators could also be established using the data obtained. For example, following procedure proposed by Wagner could be used (Wagner, 2013, p. 8):

1. Determining previous mode of operation and limiting conditions of operation
2. Assessing mode of operation
3. Determine time for which boiler is to be operated in the mode selected and calculate allowable startup rates
4. Determine critical boiler load ranges and optimal use matrix for load ranges needed
5. Develop improvements to DCS based on the data.

In addition to calculations, condition assessment software could also include means to store all documentation regarding condition inspections to give efficient access to all relevant data involved when planning for maintenance. This could be convenient especially where mobility of workforce and know-how is notable.

A study has been made indicating that turbine stress evaluator systems delivered by turbine manufacturers have been considered to be trusted by power plant operators, unlike applications made by third party deliverers. It was assumed that know-how of the turbine manufacturers is regarded as superior when compared to third party suppliers. Also, in cases where turbine has been in operation for long times with no problems it may be seem unneeded to acquire such tools (Commission for Energy Regulation, 2010). The study has not involved boiler monitoring applications it would not be surprising if same kind of attitude is encountered. However, good track record for developing and delivering applications for boiler and turbine processes control and monitoring could have positive effect on marketing such products.

4.1.1 Discussion with Electricity producer Rovaniemen Energia

A brief interview was made with personnel of energy company Rovaniemen Energia regarding maintenance of Suosiola power and district heating boiler. This was done to establish a better picture on practices in pressure vessel inspection and maintenance.

The Suosiola main boiler is a CFB boiler burning mainly peat and wood with option of burning coal as a fuel. Maximum amount of wood is 70%. In full load the boiler produces steam at temperature of 535 degrees Celsius and pressure of 115bar. After the latest improvements to the process the steam production capacity has been increased to 47kg/s. Steam is used for district heating in the city of Rovaniemi and for electricity production using a back-pressure turbine. Measurements for boiler condition assessment have lately been performed by a certified company Inspecta.

The boiler is seldom shut down completely as the minimum load used in warm summer months is sufficiently low for these low-demand seasons. Thus the fatigue caused by thermal stresses is of low concern in the boiler pressure part. Since 2010 the steam drum will be inspected every 4 years using visual and NDT inspections.

Live steam temperature has been kept well within design limits due to careful operation and thus the high temperature superheater tubes made of Cr- and CrMo-steels have not been suffering from ruptures caused by creep. Due to the fuel mix, corrosion is a moderate problem instead. Late increases in amount of wood in fuel mix have not caused increase in corrosion rate so far.

The superheater tubes are inspected annually. First an overall visual inspection is made and tubes with clear abnormalities are inspected. Then a measurement line is established and NDT and further visual inspection on cleaned tube along that line is made with additional random measurement points. It was mentioned, that after boiler begins nearing its design life time, more comprehensive inspections are performed. This includes using replication and destructive testing on superheaters. Latest destructive testing has been made in 2010.

Boiler bank is also inspected yearly. Lately this is made by T-scan inspection developed by Inspecta. T-scan is a quick way for scanning finned boiler walls to get extensive view on boiler tube wall thickness. The data is provided electrically so that it is easy to see for example areas where wall thickness is below a certain limit or changed a lot in comparison to the data of previous inspections.

Inspection results are documented with detailed information on measurement setup including pictures where applicable and include inspector´s notes on differences to previous inspections and other matters. Documents are available in both paper and electrical form.

It was discussed that it could be interesting to be able monitor sudden changes in process temperatures instead just duration times in each temperature class to be able to better track abnormalities in boiler operation. This is a matter to be taken into account when designing reporting and calculation applications for temperature monitoring.

At the moment, online monitoring of fatigue is not very interesting when Suosiola boiler is concerned because of the base load operation mode. Creep monitoring is not very interesting either because corrosion is the main detoriation mechanism of superheaters.

In the future state of the electricity market could move to such direction that increases need for more cyclical operation increasing motivation for fatigue monitoring. In Lapland there have been many ongoing wind energy projects, which could be one driving force for such change.

4.2 General Points on Boiler Condition Calculations

Any calculation result is just as good as model and data it is based on. As seen in 3.4.1.1, underestimating effects of damage caused to boiler by cyclical operation may have severe economical consequences. Therefore fatigue and creep calculation procedures proposed by standards are built in with certain level of conservatism. (European committee for standardization, 2011). As better procedures are taken into use and tested, amount of this conservatism may be decreased without increasing risk of unexpected equipment failure. In general, fatigue and creep online calculations are more or less conservative by nature, especially if no FEM methods are used. This means that results obtained from such calculations should be used as a tool for making estimations of a need for more precise assessment techniques.

Lately boiler industry has been reaching higher and higher steam temperatures and pressures meaning introduction of new boiler materials. Data for such materials may be scarce and acquired through extrapolation causing additional uncertainty in calculations which sometimes may require reviewing results obtained earlier (Wagner, 2013). This also means that it is important to have possibility of recalculation if improved material data becomes available later.

Difficulty of implementing condition monitoring system for an existing power boiler depends on how much operation history of the plant is recorded. If full process data is available the task is rather trivial if good tools are available. If this is not the case, duration spent in full operation and amount plant operation cycles should be determined. This may be done for example using production data to calculate amounts of different startups and load-following operations. Then some baseline fatigue and creep caused by these operations should be determined for assessment of cumulated damage.

Validity of real-time measurement data used by application should be verified to avoid misguiding results. Furthermore, especially creep calculations may be very sensitive to temperature measurement so that accuracy of instrumentation used must be adequate. For example, measurement error of 10°C (or 1,5%) at 600°C may cause error of 10% in creep life estimate of grade 91 steel (Suomen standardoimisliitto, 2009).

Thermal stress calculations are not very sensitive of absolute temperature values. For example, EN 12952-4 standard demands accuracy of 3% for measurements when results are directly proportional to measurement. However, whenever through-the-wall temperature difference is measured with dual thermocouples, the acquired thermal stresses are very sensitive to the difference of measurements and accuracy of the equipment should be guaranteed. For example, in the test case presented in 4.3.3, error of 1K in difference of measurements causes error of about 10K in through the wall temperature difference. If the guarantee cannot be made, the calculation should be made using sequence of measured temperatures. Absolute temperature value has little effect on the results and error of 10K is allowed by the standard. (European committee for standardization, 2011)

4.3 Practical Part of the Thesis: Metso DNA Boiler Life Monitoring

Practical part of this thesis work was a product development project objective of which was to develop online monitoring product for power boiler fatigue and creep. As a result, a product called Boiler Life Monitoring (BLM) has been made. Metso DNA (Dynamic Network of Applications) is a collection of computer applications used for process control, operation and reporting developed by Metso Corporation. The development work was done using tools provided by Metso DNA Historian data storage and calculation environment. Especially topics of chapter 2.6 were utilized for the development work. While other parts of chapter 2 were not so heavily used, knowledge on the subjects increases general understanding on the matter and therefore are seen as useful subjects to be included in this work.

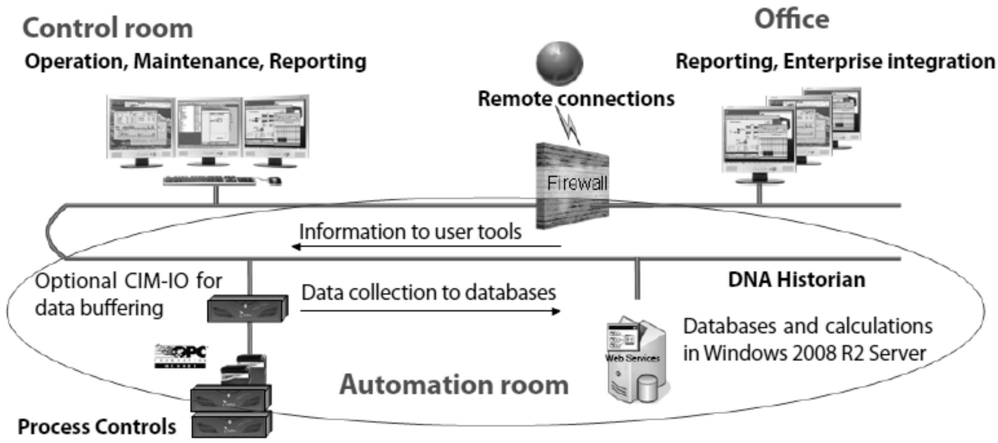


Figure 4-1General overview of Metso DNA Historian product structure. Source: (Metso Corporation, 2011)

The product consists of pressure vessel creep and fatigue calculations and tools for displaying relevant data to plant operators and management. It supersedes an older product of the same name that uses now obsolete TRD calculation procedure. Technical improvements and new user interface have also been implemented. Pilot project of the new product version is in delivery phase at time of writing and thus there is no end user experience yet.

4.3.1 Calculation implementation

The calculation part of BLM is implemented using Metso DNA Historian Calculation Environment, which provides means to easily and efficiently access stored process data, manipulate it and store the results into database. The calculation procedure is based on EN 12952-3 and EN 12952-4 standard´s fatigue and creep life calculation procedures for cylindrical objects with branches. Total accumulated damage is calculated by applying linear damage rule to obtained fatigue and creep damages. Stress and creep calculation is performed every minute using one-minute averaged temperature and pressure data. Validation of measurement data is done by comparing values to preset minimum and maximum values and previous measurement values and checking, whether measurement values have frozen due to equipment failure. Overview of the calculation procedure is illustrated by Figure 4-2.

The stress calculation is based on dual thermo couples installed in component wall to obtain wall temperature gradient reliably. Stress concentration factors for welded branches are determined by using approximate equations provided by the standard so that no FEM model is required. If such factors are readily available from FEM model or other source, calculated values may be overridden with them.

The calculation stores large stress fluctuations into relational database to be used by fatigue calculation. The database also includes material data used by calculation. Fatigue calculation is performed at longer intervals such as one day. It applies range-pair cycle counting method on stresses calculated by stress calculation and remaining sequence of extremes from previous calculation. Analyzed load cycles are stored into relational database. Fatigue calculation also produces long-term averaged and summed data for longer term storage and reporting purposes.

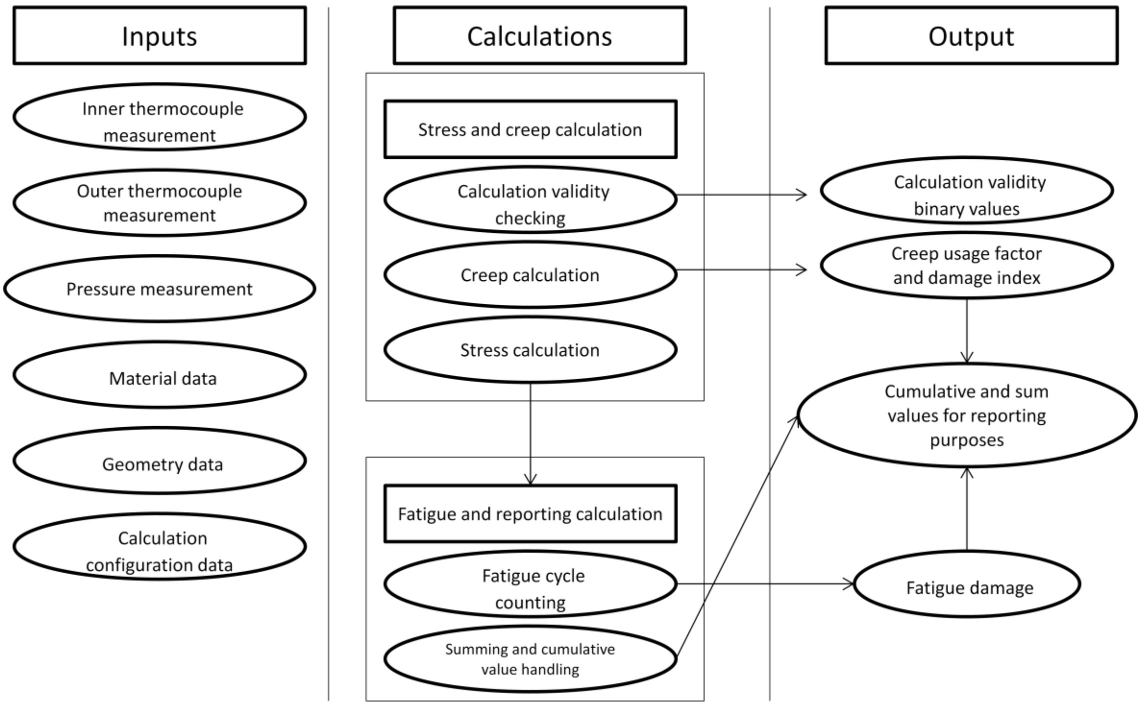


Figure 4-2 BLM calculation procedure

Resulting stress, fatigue and creep values are stored into DNA Historian database. To increase ability to analyze data, temperature change rates, wall temperature differences of thick walled component and measurement and calculation validity binaries of calculations are also stored. For creep damage, the rate of creep life consumption is compared to designed lifetime consumption of component to acquire dimensionless creep damage index that is easier to interpret than decimal number of order 10e-6.

4.3.2 End users

The application is intended to be used by power plant operation personnel who are concerned of pressure vessel condition and want to continuously monitor phenomenon affecting it. It may be used for getting quickly general idea of estimated equipment condition and finding occurrences causing most damage.

For continuous monitoring, operator is provided with Metso DNA Operate display showing real time data from stress and creep calculations and measurements. The data may be shown on a view in which each monitored pressure part component is given a traffic light-style color coding to quickly see what the state of the process is. Alternatively the data may be given as trends of main variables. The way how the information is presented depends on the customer needs and whether the end user is operator or maintenance staff.

For maintenance planning and long term monitoring purposes reports on calculation data and estimated lifetime consumption are provided through web site based Metso DNA Report product. The main reporting tool is customizable web reports that show creep and fatigue values for selected parts of the pressure. The web portal also includes trending capabilities of data stored into Historian database in form of DNA Tracer trends. Figure 4-3 and Figure 4-4 show examples of such trends. The reports include trends and cumulated damage values of the calculation results. Appendix 1 shows report showing fatigue cycles found with range-pair method. DNA Report Diary product may readily be used for documenting pictures and events regarding boiler maintenance and condition assessment made to boiler. Usage for this use might be better promoted to customers interested in computer aided condition management. For example, NDT results and photographs taken during assessment could be stored here. Pressure vessel thickness measurement results stored here may be then better also updated into possible calculations made for thermal stresses.

Appendix 2 shows creep report for superheater tubes and appendix 3 shows superheater header report showing fatigue and creep data of a header. Interactive trends showing calculated values such as stress and temperature gradients may be viewed using hyperlinks on the report.

Deterministic simulations for different boiler operation situations may also be conducted using the product. This may be done for fatigue cycle calculation by inserting time series to the history database. However, testing like this requires some knowledge of Metso DNA Historian tools and calculation configuration as the product has not been designed for this kind of usage in mind. By inserting values for a single calculation round it is rather easy to test stress and creep calculation for single calculation round.

4.3.3 Testing results

Due to lack of real operation data, the calculation was tested using hypothetical operating sequence in which the temperature and pressure are risen in 30 minutes to operating point of 560°C and 160bar. After that the temperature and pressure are decreased back to ambient conditions. The pressure vessel inspected is a superheater header described in Table 4-1.

The superheater outlet temperature is first raised as shown in Figure 4-3. After 12 minutes the rate of temperature increase is held at 20-40 degrees resulting in compressive total stress of -200-(-250MPa).

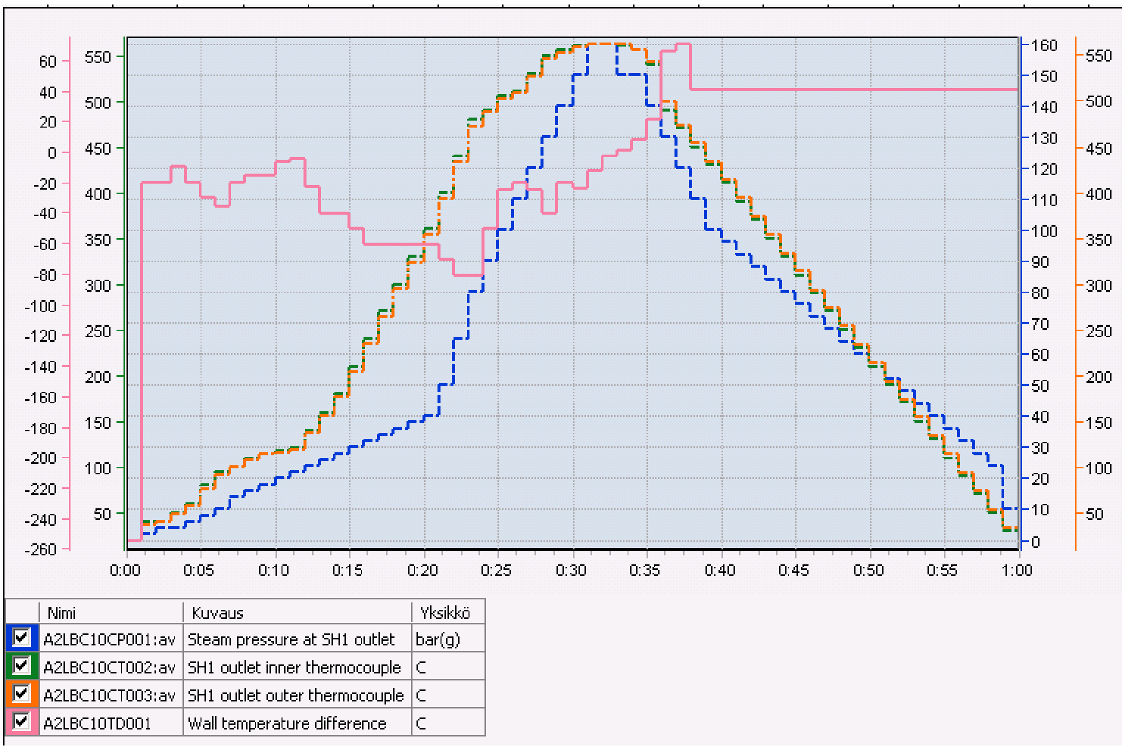


Figure 4-3 Boiler superheater outlet temperatures and pressure

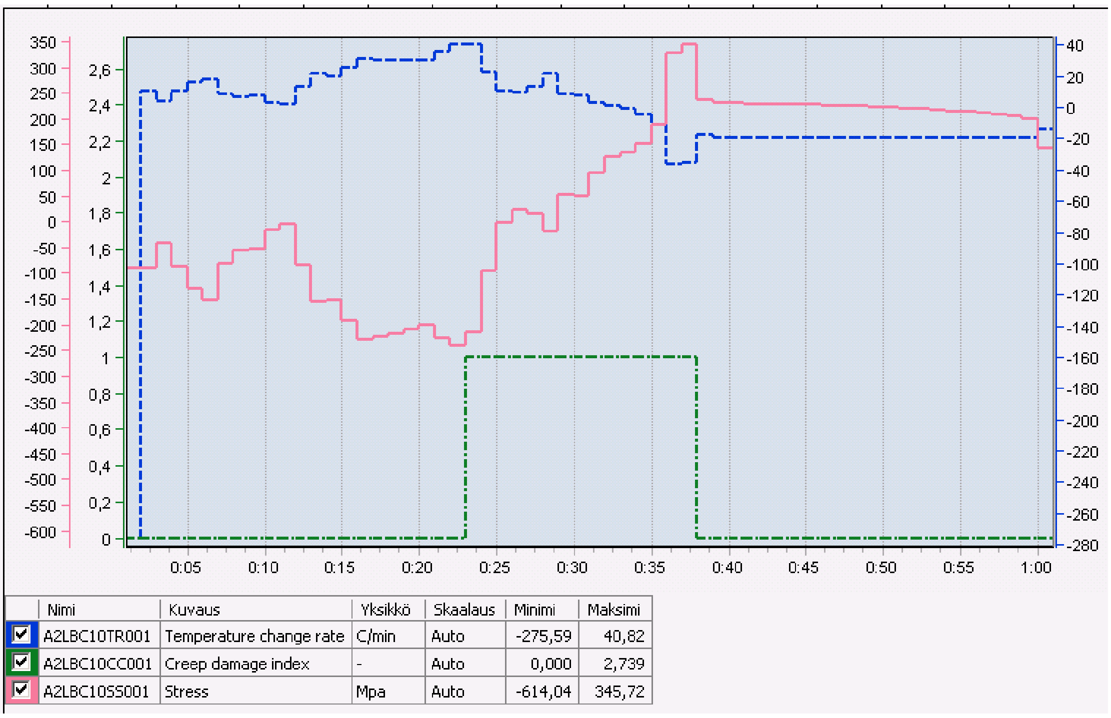


Figure 4-4 Superheater outlet stress, creep and temperature change rate

Table 4-1 Test Superheater header data

Material	SA-335P91 martensitic steel
Outer diameter	273mm
Wall thickness	45mm
Distance of inner thermocouple from shell inner wall	15,6mm
Distance of outer thermocouple from shell inner wall	18mm
Superheater tube outer diameter	44,5mm
Superheater tube wall thickness	5,59mm
Membrane stress concentration factor	3,33
Thermal stress concentration factor	1,47

Around 24 minutes the pressure begins to increase until the full operation is reached. During pressure increase the total stress is increased to near-zero level. At full operation some minor creep deformation occurs as indicated by creep damage index value of 1. Creep damage index is relation of creep lifetime of current operating conditions to design lifetime consumption of boiler component, 200 000h in this case. Value of 1 indicates creep rate of design point whereas value under 1 indentifies that creep deformation occurs at under design rate.

Lastly, the operating temperature and pressure are then decreased for shutdown resulting minor tensile stresses of 60MPa at the beginning when temperature drops more quickly. As material used is grade 91 steel, the pressure vessel was relatively thin and thermal stresses consequently rather low.

4.4 Development Ideas for the Product

This chapter contains some ideas for further development of the BLM product. While there is always a way to improve things, it should be considered whether making improvements and adding features improves customer value in proportion with costs associated with implementing them.

As shown in chapter 4.5, the systems delivered by European companies are very similar while using nearly the same standards. Usage of EN-standard over superseded TRD-standards may be seen as an advantage. Differentiation of products has to be done through advanced data analysis such as startup cost monitoring. However, as these products are probably sold as a part of larger delivery, differentiation won´t be a very big issue most of the time. Therefore concentrating on improvement of core calculation reliability and user interface is probably the most important matter where product development is concerned.

4.4.1 Startup analysis

Many products introduced in chapter 4.5 classify the damage caused to a boiler categorized by different operation types like different load following operations and startups. That way, it is possible for example, to compare damage caused by startups made by different shifts or with different startup speed. For this reason, it could be beneficial to introduce such feature especially in case a potential customer makes comparison between products. Implementation of such system needs classification of operation events based on process data and associating of detected load cycles and fatigue caused to these events event. Metso DNA calculation and reporting tools provide good means for implementing such analysis and reporting the results. At the moment, the product expresses consumed lifetime in hours. For expressing damage caused by fatigue, this is not the best option and expression in a unit such as remaining startups could be a more informative option.

Metso’s application selection already has a startup analysis application for following how well operation has followed predefined startup curves. Possibility to show damage caused by deviation from the curve could be interesting for the end user. EN-12952 standard calculation also allows calculation of allowable temperature change rates for each boiler component so that little or no fatigue. This information could be used for improving existing procedure. Ability to easily compare effects of different startup rates could also be interesting feature. Monitoring temperature change rate of different parts of the process is also useful because usually abrupt changes signal some potentially problematic anomaly in the process has occurred. This is true for the whole process, not only the pressure vessel.

Many products at the market at least promise to provide monetary estimate for the cost of startups and load follows. As seen at chapter 3.4, at least a conservative estimate is important for decision making. Therefore, providing such services could add good value to the end user. Implementing such analysis requires good knowledge on the process and costs associated with operating a boiler but it seems to be possible. One possibility to acquire such knowledge is co-operation with some boiler manufacturer or other specialist.

4.4.2 Alternative and improved calculation procedures

In North America ASME BPVC seems to be de facto calculation procedure whenever some standardized thermal fatigue and creep calculation procedure is used. In United Kingdom R5 and BS7910 procedures seems to have similar position. R5 procedure also is more comprehensive and according to some sources also very accurate. If marketing at those countries is considered, adapting some of these standards could help the effort.

Further studies are needed to assess amount of effort needed for implementing calculations using other procedures. Having the infrastructure for cycle counting and material database already in place the effort might be relatively small. While stress analysis using FEM calculation is very accurate and apparently possible to implement, cost and required expertise for developing one probably outweighs the benefits.

If entire procedure is not changed, one thing that could be improved in current procedure is interaction of creep and fatigue damage. EN 12952-4 does not define any particular creep-fatigue interaction model to be used. Therefore, for example, bi-linear curves used by some BPVC procedures might be adopted.

Effects of wall thinning and notching due to corrosion and oxidation may greatly increase effects of fatigue or cause damage by their own. Mechanisms for taking this into account might improve accuracy of calculation for superheater tubes in high temperatures. For wall thinning this could be easily implemented in system deliveries including corrosion monitoring application that approximates thickness in real time.

4.4.3 Life extending control system

PC-based Siemens WIN_TS turbine monitoring system introduced in chapter 4.5.2.2 has feedback to DCS set points. The same can be done with Metso DNA to implement anti-thermal stress control in addition to conventional boiler conserving mechanisms. However, this places even higher requirements on validity and consistency of data and should be implemented with care. There have also been suggestions for stress monitoring systems implemented purely in DCS. (Li;Marquez;& Gooden, 2006).

4.5 Offering in the market

Several companies offer software solutions for boiler condition monitoring and simulation of effects of different operating cycles. Some such software is introduced here while some more are described in report made by Ford, Fernandes and Shibli (Ford;Fernandes;& Shibli, 2009, ss. 203-208). According to query directed to operators in power industry, no product has reached superior popularity on market. This may be due to the fact, that cheaper systems have rather large margin due to simplifications while more accurate systems tend to have very high development costs resulting in high price. (Ford;Fernandes;& Shibli, 2009)

4.5.1 EPRI BLESS and TULIP

American research organization Electric Power Research Institute (EPRI) has been developing their BLESS (Boiler Life Evaluation and Simulation System) software since 1990 latest version being from year 2008. It is derived from PCCAD failure analysis software and PC CREEP crack growth analysis software originally developed by Babcock & Wilcox Company.

BLESS performs creep and thermal fatigue damage predictions of boiler headers and tubing. Loading histograms of operating events may be viewed. The program is intended to be used by utility engineers for decision making regarding boiler pressure part without need for in-depth knowledge on things such as fracture mechanics. (EPRI, 2008)

The program has ability to make both probabilistic and deterministic calculations and make cost performance analysis of them. Flaws detected during examination of equipment may be analyzed by using BLESS. Information on exact calculation principles of the program was not found. The program is available for purchase at price of $4750. (EPRI, 2008)

Another lifetime assessment product developed by EPRI is ‘TULIP 2.0’ –Tube life probability software. It´s an application made for simulating superheater and reheater tubes and calculating probability of ruptures using continuum mechanics approach. The model used considers effects of fireside corrosion, oxide thickness and other time-dependent variations. For those who are not funding members of EPRI, TULIP 2.0 is available for purchase at price of $19000.(EPRI, 2006)

4.5.2 Siemens

4.5.2.1 Siemens Fatigue Monitoring System

Siemens Fatigue Monitoring System (FMS) calculates cumulative creep and fatigue damage of power boiler based on EN 12952-3/4 standard procedures. It also includes ability to perform calculations according to procedure proposed by ASME BPVC section 2 part VIII. First instance of FMS was installed in 2004 and is certified by German safety inspectorate TÜV. The product may be integrated in Siemens SPPA-T3000 information and communications system and it may also be integrated to other systems via OPC data link. Integration with I&C system allows the calculation values to be used in operator displays and for generating operator alarms. The reporting UI is web browser based. (Kunze & Raab, 2012)

FMS employs dual thermocouples for calculating thermal stresses or alternatively fluid temperature may be used (Kunze & Raab, 2012). Its creep calculation employs temperature class division proposed by EN-12952-4.

4.5.2.2 Siemens WIN_TS

WIN_TS is a software product that sold by Siemens. It uses temperature, pressure and turbine rotation speed measurements for making stress and creep calculations for steam turbine. Parts typically monitored are intermediate and high pressure turbine rotors, high pressure turbine casing and main steam and shutdown valves. Calculation and database for storing results are run in Windows PC environment.

Siemens also offers long-term online monitoring contracts for turbine purchaser. This includes Siemens specialists monitoring turbine so that erratic operation may be identified early so that damage may be prevented. (Brummel, 2006)

Three different turbine startup procedures turbine (slow, normal, fast) are defined and temperature gradient limits are defined for each mode. This is done to give operators information on how quickly turbine operation may be changed if thermal stresses are to be kept under certain level. For cold starts additional gradient limits are set for cold temperature regime in order to avoid brittle fracture. Obtained results are used for calculating optimal set point values for super heating and reheating temperatures used in DCS.

Turbine casing and rotor thermal stresses are monitored with dual thermocouples to obtain temperature gradient. Calculation is based on non-stationary one-dimensional and rotational symmetric calculation which is solved using series development. Validity of the algorithm used has been verified using finite-element method.

Fatigue calculation is made separately for thermal stresses and stresses caused by internal pressure and centrifugal forces. For parts of which operation temperature does not exceed 400°C, residual stress of 60MPa is considered to remain. Cycle counting method is based on time stamps of maxima, minima and zero values of strain (thermal stress) or stress (internal pressure/centrifugal stress). Stress and strain values are stored only when local maximum or minimum is reached, value increases to or departs zero point or if value is suddenly changed by large amount. S-N curves are then used for obtained load cycles. Creep damage is calculated from stress and temperature measurement. Operation classes are typically divided in 16 temperature and 8 pressure regimes. For each component a 3D-diagram is made where fatigue increase, amount and startup rate is given for each startup type (cold, half-warm, warm and hot).

4.5.2.3 STEAG Energy Services GmbH

SR1 is a boiler thick-walled component lifetime monitoring program system developed by German company Steag. Its procedures are based on EN 12592-3 and TRD 508 standards and the program includes possibility of temperature gradient calculation from steam side measurement.

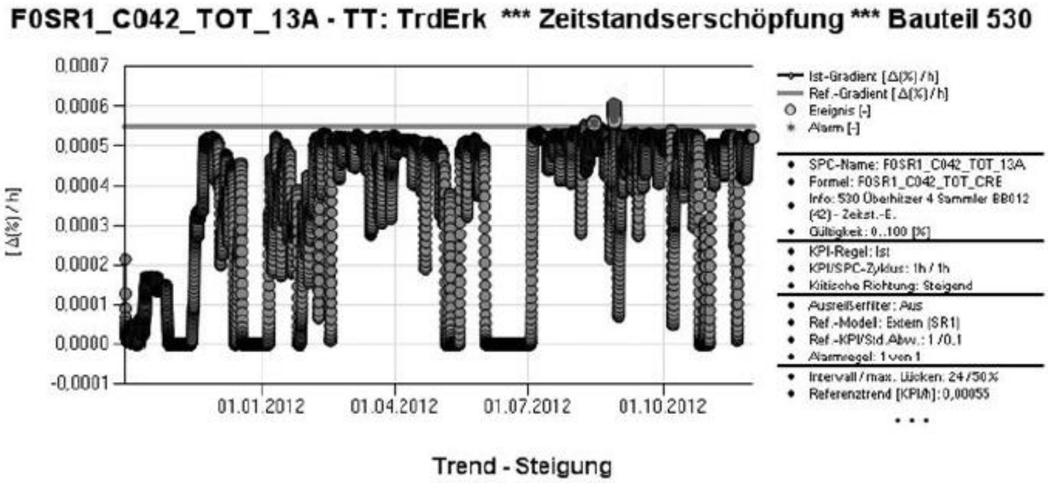


Figure 4-5 Steag SR1 creep damage gradient trend. Note the line depicting design gradient. Source: (Wagner, 2013)

The program includes possibility extrapolate operation cycles of old plant backwards to gain estimate of lifetime fatigue after 5000 hours of operation. The software includes trending and reporting tools as well as extrapolation of data for different operation scenarios. Steag also provides stress monitoring tool for high-energy piping. (Wagner, 2013)

4.5.3 ABB

ABB AG offers Optimax Boiler Life Monitoring package for condition monitoring of thick-walled boiler components and steam pipes. It is based on TRD 301 and 508 rules as well as EN 12952-4 standard. Except for different stress calculation rules, basic set-up seems very similar to STEAG´s SR1 having also TÜV certificate. The program includes possibility of design parameter usage for measurements in case of broken equipment. Modified rain flow algorithm is used for load cycle counting. The program is also able to determine monetary cost for a startup. The Optimax® solutions allow also optimization of operation from boiler life and economical point of view. (ABB AG)

4.5.4 ClearView Monitoring Solutions

Company ClearView Monitoring Solutions offers condition monitoring system for detecting anomalies in different parts of a power plant process. Using historical data, the application establishes normal conditions for a measurement, calculated value or correlations of such values. Distributions of occurrences for them are formed and presented in a map-like form. Allowable limit areas such as alarm limits are also shown. If state of process deviates from this area, an alarm may be generated and red dots are drawn on the map. The system is also able to differentiate between process and instrumentation related problems. (Hartman & Richard, 2009)

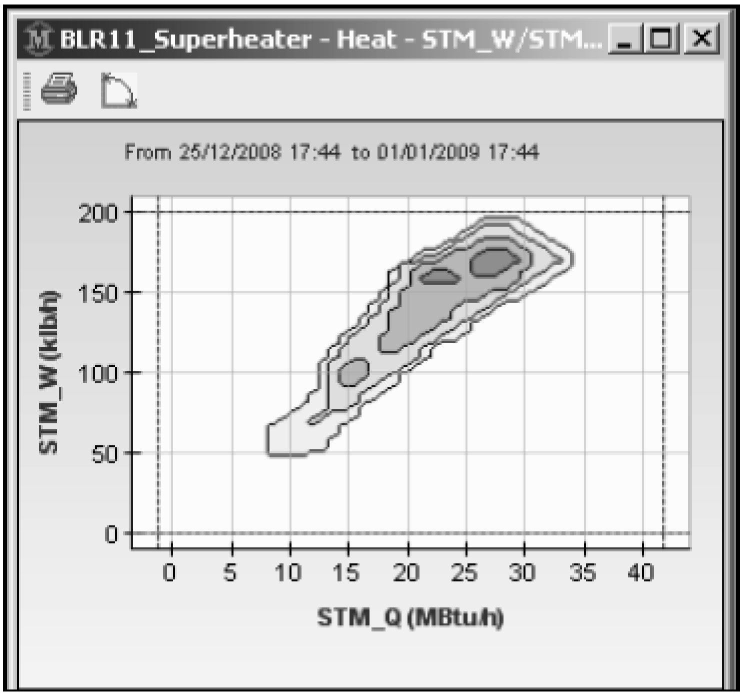


Figure 4-6 An example of measurement relationship map. Source:(Hartman & Richard, 2009)

If the normal state of process is drifted from previous normal due to changes in process or ageing, it will gradually identify these new conditions. The system seems to be suitable for many kind of problem detection and case studies presented indicate successful usage of it. (Hartman & Richard, 2009)

Due to nature of the method, it might be better suited for problems occurring during steady state operation like leaks and other equipment failure. However, such statistical method could be developed for operation transients so that desired startup curves for various process values are established and then monitored in a similar way.

4.5.5 Intertek APTECH

Intertek APTECH is an engineering consultant firm based in USA. They offer PC-based COSTCOM and Combined Cycle Advisor software. COSTCOM is used for calculation of damage caused by operation while Combined Cycle Advisor is for optimizing combined process operation. Algorithm used by COSTCOM classifies operation events using process data. The model used in calculation damage operation events is calibrated using equipment breakage history of the unit or similar units. (Kumar;Besuner;Lefton;Dwight;& Hilleman, 2012)

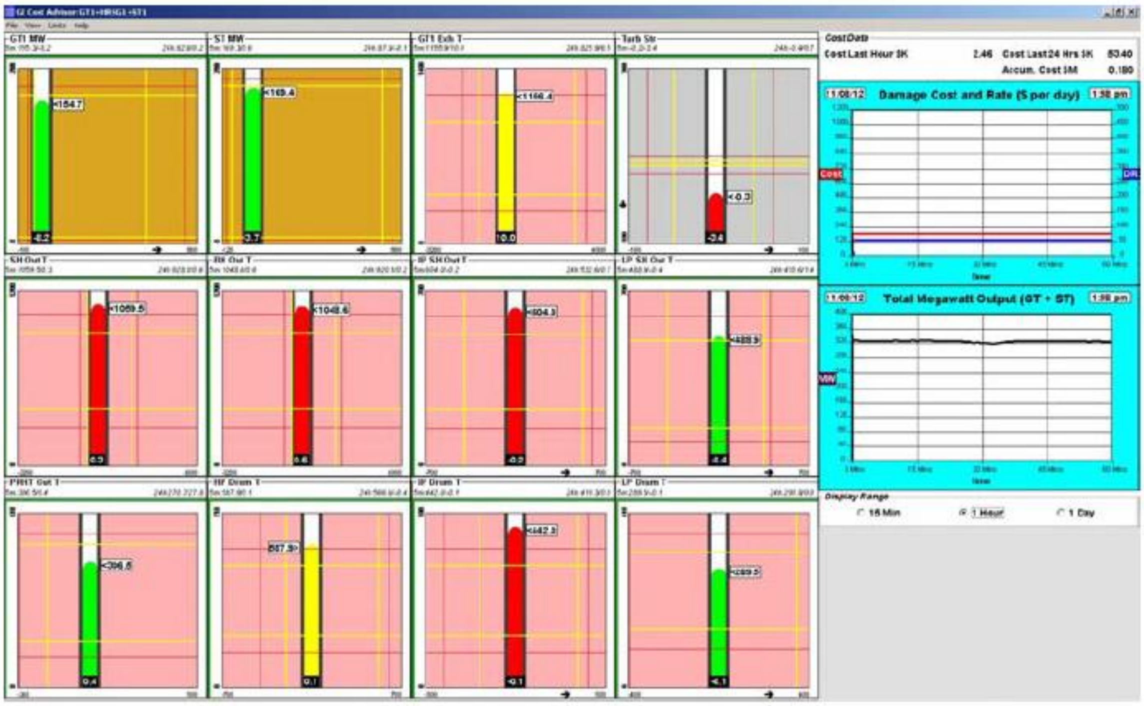


Figure 4-7 APTECH combined cycle advisor. Source: (Lefton;Kumar;Hilleman;& Agan, 2012)

COSTCOM includes operator display showing current state of damage caused. It also indicates how much faster a start up may be executed without risking damage to equipment. The software also indicates monetary costs of operation. The costs due to increased maintenance and operation increased forced outages, increased heat rate, increased use of resources (auxiliary power, startup fuel, chemicals, manpower) and long term efficiency degradation. (Kumar;Besuner;Lefton;Dwight;& Hilleman, 2012)

5. CONCLUSIONS

Implications of creep damage and cyclical boiler operation on power boiler pressure part condition have been investigated. According to research and several reports concerning cyclical boiler operation, it is clear that this often underestimated phenomenon is of great significance for the industry. It has been estimated that in the future, increasing proportion of electricity production will be done by power boilers operated in this manner. Therefore, it is apparent that significance of cyclical operation to the electricity market will increase. Especially important this is for power boilers that have been originally designed for base load operation that have been operated at creep regime for many years.

With all this in mind, it shall not be surprising if increasing customer need for continuous automated thermal stress and creep monitoring systems arise in near future. This holds true especially in electricity markets where prices are prone to fluctuations. Because the problems are especially related with existing older units, retrofitting such units with monitoring system might be reasoned. Therefore good practices for installing system in such plant and estimating fatigue and creep that has already taken place should be established. This requires knowledge of the processes especially if existing process history data is lacking.

Online thermal stress and creep monitoring solution for boiler pressure part has been developed using Metso DNA platform. It is expected to deliver basic needs for monitoring process so that conservative estimates of damage caused by operation are given for boiler operators and maintenance staff. What is perhaps even more important, it helps to identify operation procedures that have increased probability to cause damage.

Some proposals for future improvements have been also made. The most important ones are seen to be improvement of end user experience and operation event based reporting of boiler damage. Assessing possibilities of using other procedures for improved calculation accuracy could be considered. Adapting certain calculation procedures could also facilitate marketing at some regions.

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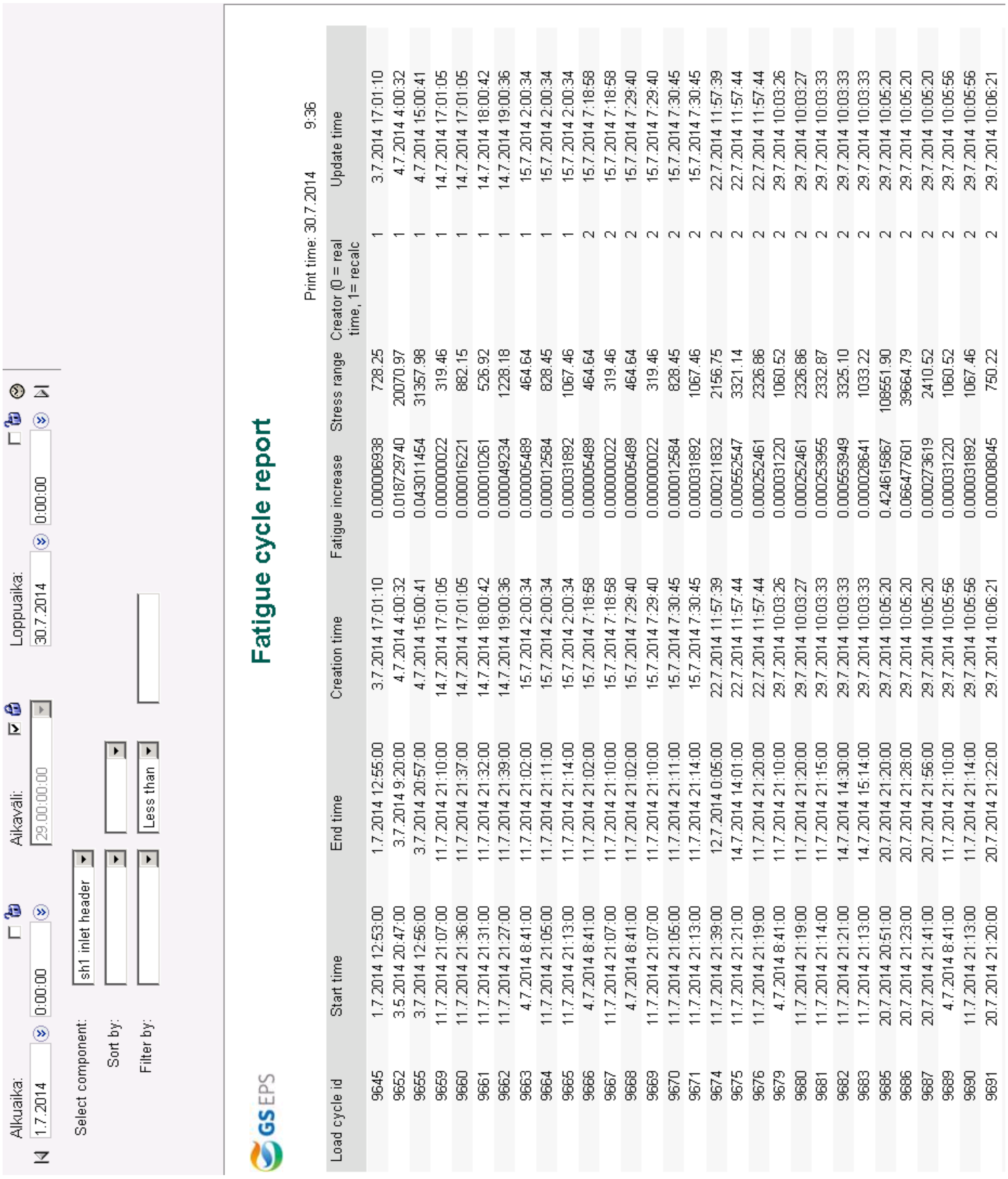
APPENDICES

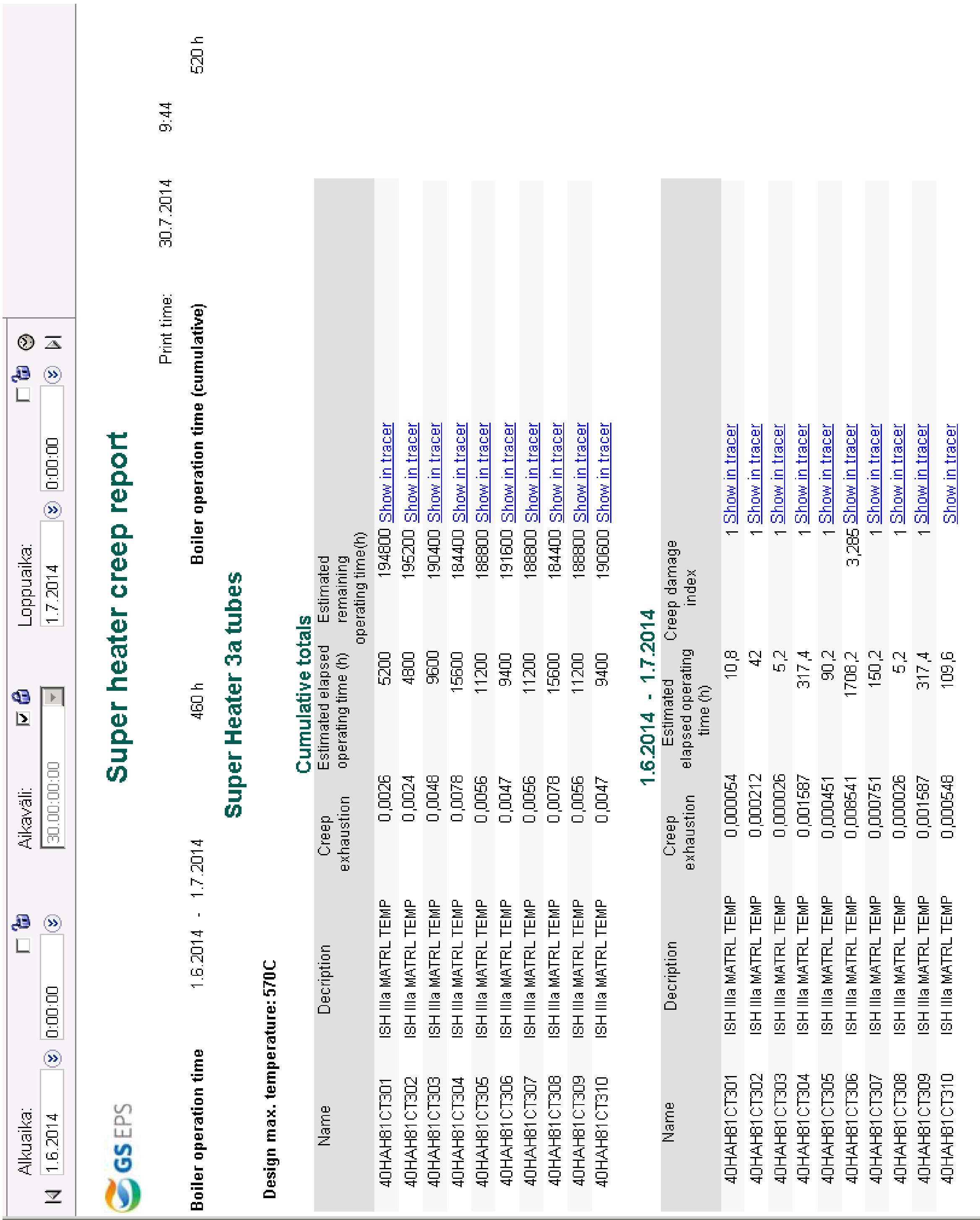
Appendix 1: Metso BLM fatigue cycle report



Load cycle id	Start time	End time	Creation time	Fatigue increase	Stress range	Creator (0 = real time, 1= recalc	Update time
9645	1.7.2014 12:53:00	1.7.2014 12:55:00	3.7.2014 17:01:10	0.000006938	728.25	1	3.7.2014 17:01:10
9652	3.5.2014 20:47:00	3.7.2014 9:20:00	4.7.2014 4:00:32	0.018729740	20070.97	1	4.7.2014 4:00:32
9655	3.7.2014 12:56:00	3.7.2014 20:57:00	4.7.2014 15:00:41	0.043011454	31357.98	1	4.7.2014 15:00:41
9659	11.7.2014 21:07:00	11.7.2014 21:10:00	14.7.2014 17:01:05	0.000000022	319.46	1	14.7.2014 17:01:05
9660	11.7.2014 21:36:00	11.7.2014 21:37:00	14.7.2014 17:01:05	0.000016221	882.15	1	14.7.2014 17:01:05
9661	11.7.2014 21:31:00	11.7.2014 21:32:00	14.7.2014 18:00:42	0.000010261	526.92	1	14.7.2014 18:00:42
9662	11.7.2014 21:27:00	11.7.2014 21:39:00	14.7.2014 19:00:36	0.000049234	1228.18	1	14.7.2014 19:00:36
9663	4.7.2014 8:41:00	11.7.2014 21:02:00	15.7.2014 2:00:34	0.000005489	464.64	1	15.7.2014 2:00:34
9664	11.7.2014 21:05:00	11.7.2014 21:11:00	15.7.2014 2:00:34	0.000012584	828.45	1	15.7.2014 2:00:34
9665	11.7.2014 21:13:00	11.7.2014 21:14:00	15.7.2014 2:00:34	0.000031892	1067.46	1	15.7.2014 2:00:34
9666	4.7.2014 8:41:00	11.7.2014 21:02:00	15.7.2014 7:18:58	0.000005489	464.64	2	15.7.2014 7:18:58
9667	11.7.2014 21:07:00	11.7.2014 21:10:00	15.7.2014 7:18:58	0.000000022	319.46	2	15.7.2014 7:18:58
9668	4.7.2014 8:41:00	11.7.2014 21:02:00	15.7.2014 7:29:40	0.000005489	464.64	2	15.7.2014 7:29:40
9669	11.7.2014 21:07:00	11.7.2014 21:10:00	15.7.2014 7:29:40	0.000000022	319.46	2	15.7.2014 7:29:40
9670	11.7.2014 21:05:00	11.7.2014 21:11:00	15.7.2014 7:30:45	0.000012584	828.45	2	15.7.2014 7:30:45
9671	11.7.2014 21:13:00	11.7.2014 21:14:00	15.7.2014 7:30:45	0.000031892	1067.46	2	15.7.2014 7:30:45
9674	11.7.2014 21:39:00	12.7.2014 0:05:00	22.7.2014 11:57:39	0.000211832	2156.75	2	22.7.2014 11:57:39
9675	11.7.2014 21:21:00	14.7.2014 14:01:00	22.7.2014 11:57:44	0.000552547	3321.14	2	22.7.2014 11:57:44
9676	11.7.2014 21:19:00	11.7.2014 21:20:00	22.7.2014 11:57:44	0.000252461	2326.86	2	22.7.2014 11:57:44
9679	4.7.2014 8:41:00	11.7.2014 21:10:00	29.7.2014 10:03:26	0.000031220	1060.52	2	29.7.2014 10:03:26
9680	11.7.2014 21:19:00	11.7.2014 21:20:00	29.7.2014 10:03:27	0.000252461	2326.86	2	29.7.2014 10:03:27
9681	11.7.2014 21:14:00	11.7.2014 21:15:00	29.7.2014 10:03:33	0.000253955	2332.87	2	29.7.2014 10:03:33
9682	11.7.2014 21:21:00	14.7.2014 14:30:00	29.7.2014 10:03:33	0.000553949	3325.10	2	29.7.2014 10:03:33
9683	11.7.2014 21:13:00	14.7.2014 15:14:00	29.7.2014 10:03:33	0.000028641	1033.22	2	29.7.2014 10:03:33
9685	20.7.2014 20:51:00	20.7.2014 21:20:00	29.7.2014 10:05:20	0.424615867	108551.90	2	29.7.2014 10:05:20
9686	20.7.2014 21:23:00	20.7.2014 21:28:00	29.7.2014 10:05:20	0.066477601	39664.79	2	29.7.2014 10:05:20
9687	20.7.2014 21:41:00	20.7.2014 21:56:00	29.7.2014 10:05:20	0.000273619	2410.52	2	29.7.2014 10:05:20
9689	4.7.2014 8:41:00	11.7.2014 21:10:00	29.7.2014 10:05:56	0.000031220	1060.52	2	29.7.2014 10:05:56
9690	11.7.2014 21:13:00	11.7.2014 21:14:00	29.7.2014 10:05:56	0.000031892	1067.46	2	29.7.2014 10:05:56
9691	20.7.2014 21:20:00	20.7.2014 21:22:00	29.7.2014 10:06:21	0.000008045	750.22	2	29.7.2014 10:06:21

Figure A-1 Metso DNA BLM Fatigue Cycle Report

Appendix 2: Metso BLM superheater tube creep report



Alkuaika: 1.6.2014 0:00:00 Aikaväli: 30.00:00:00 Loppuaika: 1.7.2014 0:00:00

GS EPS

Super heater creep report

Print time: 30.7.2014 9:44

Boiler operation time 1.6.2014 - 1.7.2014 460 h **Boiler operation time (cumulative)** 520 h

Super Heater 3a tubes

Design max. temperature: 570C

Cumulative totals

Name	Decription	Creep exhaustion	Estimated elapsed operating time (h)	Estimated remaining operating time(h)	
40HAH81CT301	ISH IIIa MATRL TEMP	0,0026	5200	194800	Show in tracer
40HAH81CT302	ISH IIIa MATRL TEMP	0,0024	4800	195200	Show in tracer
40HAH81CT303	ISH IIIa MATRL TEMP	0,0048	9600	190400	Show in tracer
40HAH81CT304	ISH IIIa MATRL TEMP	0,0078	15600	184400	Show in tracer
40HAH81CT305	ISH IIIa MATRL TEMP	0,0056	11200	188800	Show in tracer
40HAH81CT306	ISH IIIa MATRL TEMP	0,0047	9400	191600	Show in tracer
40HAH81CT307	ISH IIIa MATRL TEMP	0,0056	11200	188800	Show in tracer
40HAH81CT308	ISH IIIa MATRL TEMP	0,0078	15600	184400	Show in tracer
40HAH81CT309	ISH IIIa MATRL TEMP	0,0056	11200	188800	Show in tracer
40HAH81CT310	ISH IIIa MATRL TEMP	0,0047	9400	190600	Show in tracer

1.6.2014 - 1.7.2014

Name	Decription	Creep exhaustion	Estimated elapsed operating time (h)	Creep damage index	
40HAH81CT301	ISH IIIa MATRL TEMP	0,000054	10,8	1	Show in tracer
40HAH81CT302	ISH IIIa MATRL TEMP	0,000212	42	1	Show in tracer
40HAH81CT303	ISH IIIa MATRL TEMP	0,000026	5,2	1	Show in tracer
40HAH81CT304	ISH IIIa MATRL TEMP	0,001587	317,4	1	Show in tracer
40HAH81CT305	ISH IIIa MATRL TEMP	0,000451	90,2	1	Show in tracer
40HAH81CT306	ISH IIIa MATRL TEMP	0,008541	1708,2	3,285	Show in tracer
40HAH81CT307	ISH IIIa MATRL TEMP	0,000751	150,2	1	Show in tracer
40HAH81CT308	ISH IIIa MATRL TEMP	0,000026	5,2	1	Show in tracer
40HAH81CT309	ISH IIIa MATRL TEMP	0,001587	317,4	1	Show in tracer
40HAH81CT310	ISH IIIa MATRL TEMP	0,000548	109,6		Show in tracer

Figure A-2Metso BLM Superheater Tube Creep Report

Appendix 3: Metso BLM superheater header report

Thermal Stress and Creep Report

Print time: 21.8.2014 12:49

Boiler operation time	1.6.2014 - 1.7.2014	538	h	**Boiler start-ups**	1.6.2014 - 1.7.2014	1
Boiler operation time	1.5.2014 - 1.6.2014	687	h	**Boiler start-ups**	1.5.2014 - 1.6.2014	1
Boiler operation time (cumulative)		35101	h	**Boiler start-ups (cumulative)**		28

Superheater IIIa outlet header

Cumulative total

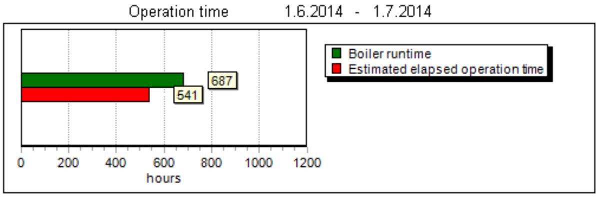
Exhaustion	Exhaustion due to creep	Exhaustion due to fatigue	Estimated elapsed operation time (h)
0,004512	0,000124	0,004388	902,4

Period

	Exhaustion	Exhaustion due to creep	Exhaustion due to fatigue	Estimated elapsed operation time	Total amount of replaced values	Estimated effect of RSE
1.6.2014 - 1.7.2014	0,02447632	0,00237648	0.02209984	0	269	0,0000054
1.5.2014 - 1.6.2014	0.0006046722	0.002149444	0.0005751463	541	607	

Open calculation results in tracer

Operation time 1.6.2014 - 1.7.2014



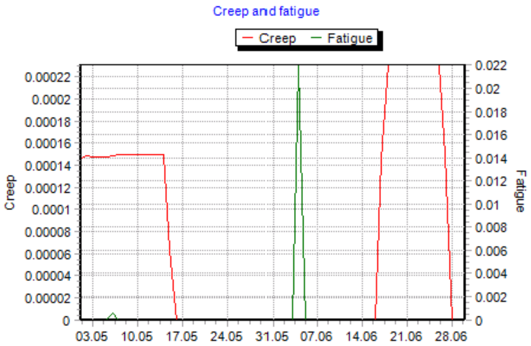


Figure A-3Metso BLM Superheater Header Report