Assessment of Remaining Useful Life of Power Plant Steam Generators – a Standardized Industrial Application

Ulrich Kunze[1] and Stefan Raab[2]

[1,2]*Siemens AG – Energy Sector, Erlangen, 91050, Germany*
ulrich.kunze@siemens.com
stefanraab@siemens.com

ABSTRACT

The Web based condition monitoring and diagnostic system "Boiler Fatigue Monitoring" enables on-line assessment of cumulative boiler creep and low cycle fatigue according to the European standard EN 12952-3/4 issued in 2001.

The application is employed as autonomous module as well as fully integrated into the Siemens process control system SPPA-T3000 and is becoming more and more a standard part of the power plant instrumentation and control (I&C).

The Fatigue Monitoring System (FMS) is a standard industrial application for both, new built power plants and retrofits of existing units of any kind. The system is not limited to Siemens I&C systems, it is possible to integrate FMS also into power plants with I&C systems of other suppliers. FMS is also capable for calculating the remaining lifetime for boilers designed according to the American standard ASME VIII-2.

1. INTRODUCTION

Steam generator lifetime monitoring and assessment of the remaining useful life (RUL) is a standard application in power plants. Since market requirements changed towards increased flexibility, power plants are operated more cyclic compared to the past. This makes fatigue monitoring systems even more important to immediately get known to impacts of start-ups or shut-downs onto the remaining lifetime of the boiler components.

Therefore, today fatigue monitoring systems for boilers are becoming more and more standard installations in new power plants and are often subject of upgrading activities.

The basis for the assessment of the RUL is the European standard EN 12952-3/4 issued in 2001, which contains simplified rules to calculate creep and low cycle fatigue. These simplified rules are conservative but have the advantage to be easy to use.

Only 3 years after the release of EN 12952-3/4 the first boiler fatigue monitoring system (FMS) was installed for continuous operation in a new combined cycle power plant in Germany.

FMS is a module of web4diagnostics, the Web-based diagnostics system for power plants. FMS is used in both power plants as an on-line diagnostics system – it has since been installed around the world in more than 50 power plant units, in part with integration in the power plant's office network – as well as in the Siemens Intranet as a Web-based data archive and as tool for data analysis and evaluation.

Previously, this system was a supplement to the operational instrumentation and control (I&C), where the I&C data acquisition was used through a link to the I&C – but otherwise without any further connections. This has changed dramatically.

Today, the "boiler fatigue monitoring" module is fully integrated into the SPPA-T3000 process I&C system and is a standard industrial application. However, it can be combined with any other I&C system via OPC data connection.

2. FUNDAMENTAL PRINCIPLES OF BOILER FATIGUE MONITORING

Many highly-loaded components of the water and steam piping systems with limited service life are implemented in power plant boiler construction. In particular, these are the feedwater heater, superheater, attemperators, headers, piping and internal boiler lines.

The theoretical service life of a component is precalculated for a specific design loading. Operating conditions outside of the design conditions can result in premature failure of the component.

The actual anticipated time until failure of the component at the current operation time is known as remaining useful life

(RUL). The sum of prior operating time and RUL may be greater or less than the theoretical service life due to past operating conditions outside of the design conditions. The residual life is calculated as the difference between theoretical service life and (material) fatigue.

Fatigue results from

- Creep fatigue and/or
- Low-cycle fatigue.

2.1. Creep Fatigue

Creep fatigue designates the fatigue of a component as a consequence of creep damage. Creep damage always occurs when the component is operated above the grain recovery temperature characterizing the material. Creep fatigue results at the most heavily loaded area of the component, generally the area of a cutout. Peak stresses occur here which can result in plastic deformation of the material. The allowable service life is dependent on the component temperature such that the service life is limited at a constant load and decreases with increasing temperature.

2.2. Low-Cycle Fatigue

Low-cycle fatigue is the fatigue of a component as a result of cyclic strain loading. Cyclic strain loading occurs when the part is subjected to pressure changes and/or fluctuating fluid temperature distributions. Thermal stresses resulting from locally transient temperature distributions are superimposed on the compressive loads. Each cycle in the resulting stress (load cycle) leads to utilization of the low-cycle fatigue resistance (low-cycle fatigue) and thus finally to stress cracking at the most highly-loaded point.

3. Codes and Regulations

Since 2001, EN 12952 has applied for the design and monitoring of boilers in Germany and many other (European) countries (for design: Part 3 and for continuous monitoring: Part 4; cf. Fig. 1).

EN 12952 supersedes the Technical Rules for Steam Boilers (TRD) which served for many years as the basis for design and monitoring, but which are also closely related.

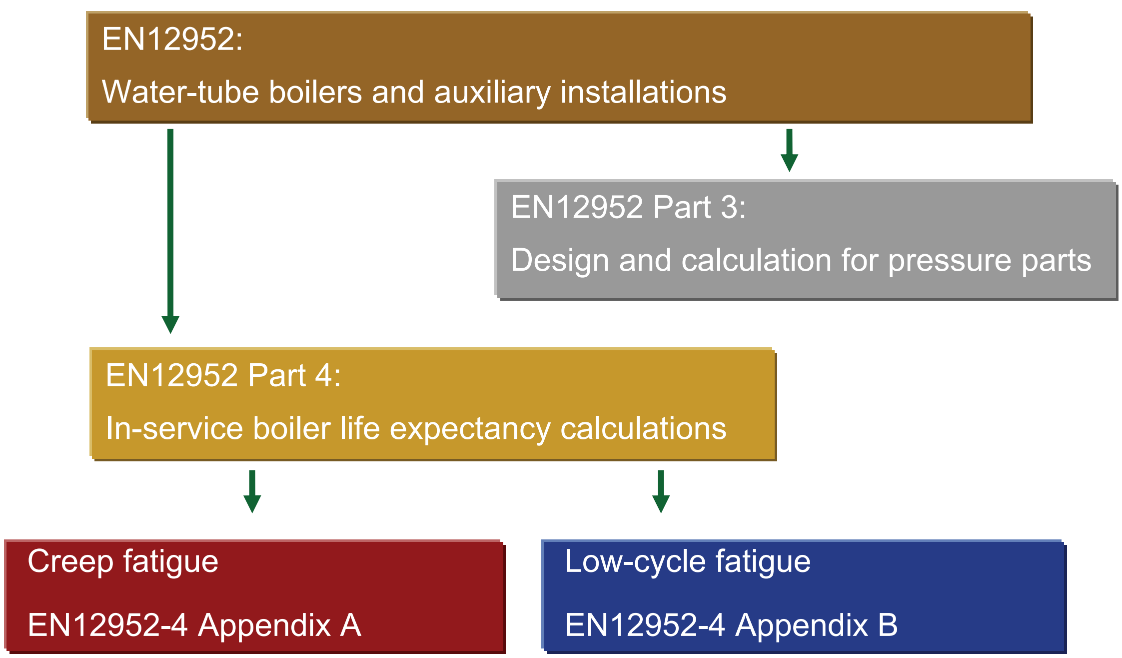

Fig. 1 Fatigue calculation in accordance with EN 12952

4. Design Loading for Steam Boilers

During the design of a steam boiler, it is checked whether the selected design including the intended materials will withstand the loading warranted by the manufacturer.

This verification is performed by the boiler manufacturer.

The manufacturer assumes a service loading combination for subsequent operation for this purpose, comprising, for example, the following typical parameters:

- Service life: 25 years or 200,000 h
- Cold starts (120-h outage): 50
- Warm starts (weekend outage): 1250

- Hot starts (overnight outage): 5000

as well as further possible operating cases.

The anticipated fatigue is calculated for the critical areas (components) of the steam boiler based on EN 12952-3, which results accounting for the design service loading combination. This must always be less than 100%. The boiler manufacturer will generally design the boiler so that there is some reserve with regard to the design service loading combination.

However, these design conditions will be deviated from during operation. It is frequently the case that the power plant is initially in base load operation due to its favorable efficiency compared with the other available power plants. With increasing age, it will be deployed more and more in cycling duty or as a peaking plant.

This different operating mode compared with the design of course results in a different anticipated service life of the boiler – for which reason the boiler must be continuously monitored.

According to the service loading combination, which includes service time as well as starts and load changes, the actual fatigue is shown in percent and not in hours. This applies also for RUL.

5. Calculation Method

5.1. Creep Fatigue

Calculation of creep fatigue D_C is based on a comparison of the exposure time T_{op} of a component at specific levels of pressure and temperature with the theoretical service life T_{al} of the component at these conditions:

$$D_c = \sum_i \sum_k \frac{T_{op,i,k}}{T_{al,i,k}}$$

The theoretical service life is calculated from the creep resistance (material property), the operating temperature and the membrane stress (or pressure).

The procedure is as follows: From inside pressure the circumferential stress for the inner surface of the most loaded nozzle bore is calculated. This stress is compared with the temperature dependent stress-rupture strength given for 10,000, 100,000 and 200,000 h and taking into account a 20% safety margin. The result is the theoretical service life for the inside pressure and temperature value. (see EN 12952-4 for details of calculation).

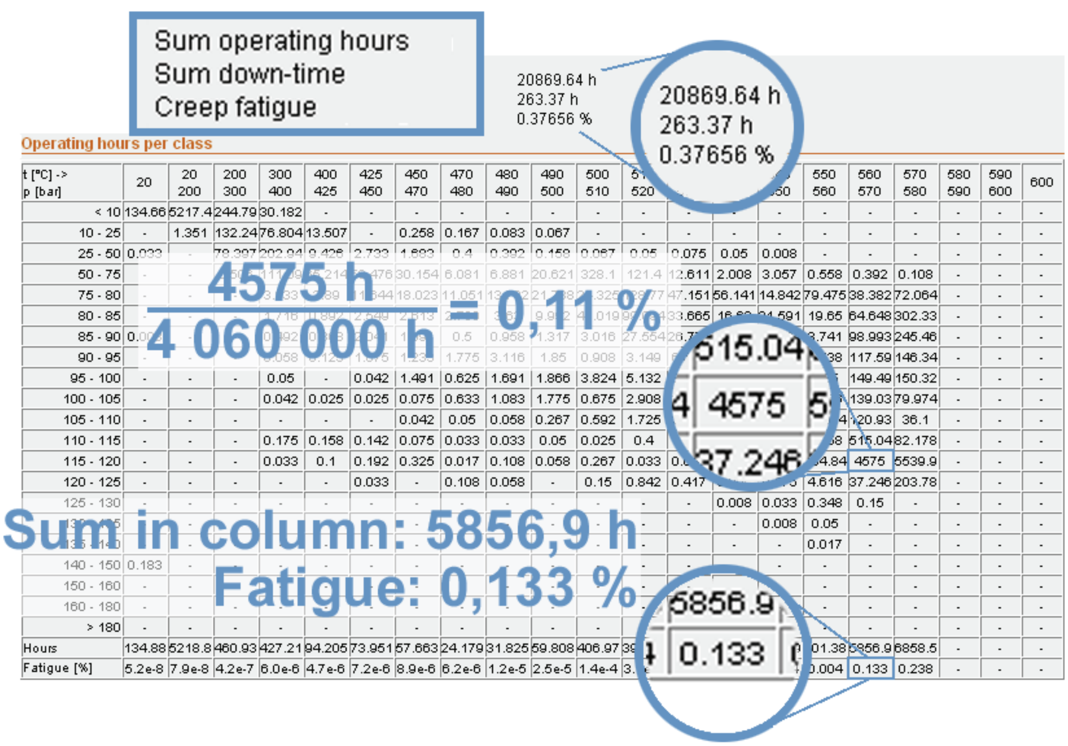

Fig. 2 Determination of creep fatigue from exposure time for example of class 560...570°C / 115...120 bar (theoretical service life in class: 4,060,000 h)

For a later quick overview of the operating mode of the power plant, it is expedient to categorize pressure and temperature in classes – to perform the fatigue calculation in classes. The classification is given by experts. The background is to define small intervals for normal operation values and wider intervals for low temperature and pressure values.

It can then be easily seen during the analysis how long the component has been operated within specific temperature/pressure ranges (see Fig. 2).

5.2. Low-Cycle Fatigue

Low-cycle fatigue D_F is determined by counting the number of load cycles *n* and comparing these with the number of cycles to crack initiation *N* of the component for specific values of the stress range *2f* and temperature *t* on which the load cycle is based:

$$D_F = \sum_i \sum_k \frac{n_{i,k}}{N_{i,k}}$$

A load cycle is defined by EN 12952-4 as a closed hysteresis loop in the stress/strain diagram. The stress in the material is calculated from the pressure and temperature gradient, while the numbers of cycles to crack initiation are material properties.

To simplify future analysis, it is expedient to categorize the stress range and temperature in classes. This makes it easy to assign load cycles to specific operating modes.

Stresses (including extremes) which cannot yet be combined in load cycles are maintained on the "list of residual extremes" until a "partner" is found for them.

5.3. Total Fatigue

The total fatigue of a component is determined as the sum of:

- Creep fatigue,
- Low-cycle fatigue,
- Fatigue from the current list of remaining extremes,
- Fatigue from prior history of the component and
- Correction of fatigue.

Fatigue from the current list of remaining extremes is an estimate of the fatigue component of the stress values which do not yet represent load cycles.

6. Continuous Fatigue Monitoring

Continuous fatigue monitoring yields information on the actual service life utilization based on the actual (measured) design of the boiler components and the current operating mode. In practical terms, this constitutes verification of the design analysis.

Continuous fatigue monitoring is the responsibility of the power plant operator (not the manufacturer) and shall be performed for the most highly loaded components.

The manufacturer, the subsequent power plant operators and the licensing authority define jointly, which components of the boiler should be continuously monitored, usually in the construction phase of the power plant.

6.1. Monitored Components

Heavily loaded components which are continuously monitored with regard to creep fatigue and low-cycle fatigue are as follows:

- Headers
- Drums
- Separators
- Spray attemperators
- Piping (pipe bends)

Drums and separators are generally only monitored for low-cycle fatigue (not creep fatigue), as these components are operated in temperature ranges for which no creep of the material occurs (below the grain recovery temperature).

6.2. Requisite Measuring Points

Operating parameters (measured values) are required for each component to be monitored for calculation of the service life:

- Creep fatigue:
  - Mean wall temperature t_{mw} and
  - Internal pressure p
- Low-cycle fatigue:
  - Inner wall temperature t_{im}
  - Mean wall temperature t_{mw}
  - Internal pressure p

As a general rule, the drums and headers to be monitored are already equipped with temperature measurements in the component wall by the manufacturer.

If measurement of the inner wall temperature and the mean wall temperature is not possible, these temperatures can be calculated from the time behavior of the medium temperature.

6.3. Preparatory Calculations

Before the start of the on-line calculation, all of the parameters to be determined once are specified or determined. These are as follows:

- Specification of classification for creep and low-cycle fatigue calculation
- Calculation of theoretical service life for each pressure/temperature class
- Calculation of numbers of cycles to crack initiation for each stress range/temperature class

6.4. On-Line Calculations

Continuous fatigue calculation is performed online. The following steps are processed sequentially:

- Acquisition of the requisite values (a typical acquisition interval is 30 s)
- Calculation of inner wall temperature and mean wall temperature from the fluid temperature if these are not directly measurable
- Determination of exposure times and calculation of current creep fatigue
- Calculation of component stress, check if new load cycles have taken place, assignment of the load cycles to the defined classes and determination of current low-cycle fatigue and fatigue component of the list of residual extremes.
- Calculation of total fatigue

The creep, low-cycle or resulting total fatigue are always recalculated for each data acquisition interval, so that the residual service life of a component is always up to date.

7. Internal Structure of Continuous Fatigue Monitoring

The boiler fatigue monitoring module FMS (fatigue monitoring system) was developed for calculation of the creep fatigue and low-cycle fatigue.

FMS requires a standard PC.

The FMS software is implemented as a Web application. This system concept enables operation and calling up of information both directly in the system as well as from any PC in the office network (providing that a connection to the office network is implemented).

All data (measurement, configuration and results data) are stored in a database.

Background processes activated by time control ensure that the data acquisition and on-line fatigue calculation are performed continuously and independently of the user interface.

Display of the information in the form of logs, tables or trend plots is updated and compiled based on the latest database values each time the user interface is called up. (cf. Fig. 3).

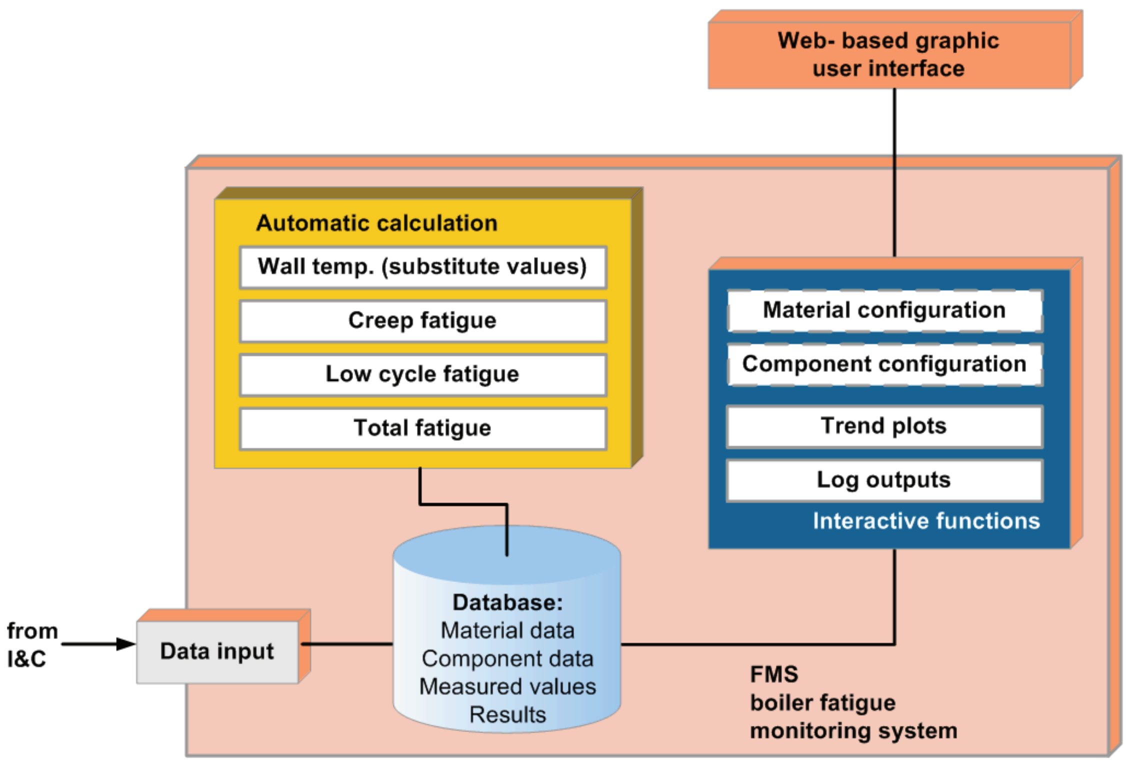

Fig. 3 Structure of FMS

8. INTEGRATION OF FMS IN THE SPPA-T3000 PROCESS I&C SYSTEM

Although FMS obtains data from the process I&C as an independent module, the results obtained are not written back again.

The configuration of the module is more complex – for FMS this includes the entry of material and component data. Previously, this had to be performed completely separately from configuration of the process I&C system with separate tools. Measuring points and their designations in the process I&C had to be coordinated through parameter lists and entered in the FMS.

Many diagnostics modules which do not yet provide integrated functions in the I&C are in a similar situation.

It is therefore often desirable – as was also the case for the FMS – to be able to perform the configuration with the tools of the process I&C and to display the results from the diagnostic module in the I&C and to be able to use the infrastructure available there (display in process displays, trend plots, automatic report generation).

The solution lies in embedding the modules in a runtime container (see Fig. 4).

A runtime container is a component of the SPPA-T3000 process I&C system with strictly defined interfaces and functions. In addition to simple measurement and calculation results, further, more complex structured data can be exchanged with other SPPA-T3000 components through these interfaces. In addition, SPPA-T3000 can control and diagnose the module through these interfaces.

The program code of FMS is not changed by embedding. It is the original code of the independent module, which ensures that errors within the module can be ruled out on integration and that existing certifications remain effective.

Embedding enables reuse of the results from the module in the process I&C. For example, they can be

- Displayed together with measured values in process and curve displays
- Stored in the process data archive and used together with stored measured values for later evaluations
- Input in controls or other automatic control functions
- Used for generating alarms which are annunciated together with process alarms in the alarm display.

However, some results (the classified fatigue data) must be expected in very specific displays in the boiler fatigue monitoring module which exceed the possibilities of the standard tools in SPPA-T3000.

It proved to be an advantage here that both the SPPA-T3000 process I&C system as well as the FMS module use Web technology for the graphical user interface. It was thus possible to insert special logs and displays from FMS as a separate (browser) window in the user interface of the process I&C. The authorizations and thus also the access restrictions of the T3000 operator be inherited here from SPPA-T3000 to FMS.

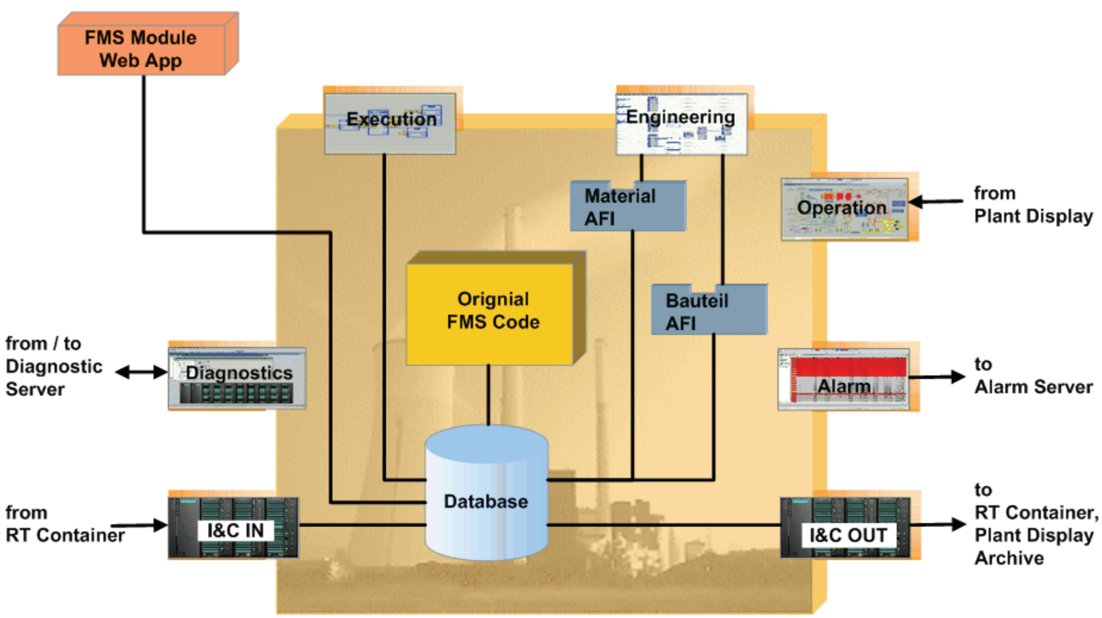

Fig. 4 Embedding the FMS module (code and data) in an SPPA-T3000 runtime container

9. EXAMPLES

The relevant information for continuous fatigue monitoring is provided in the form of logs on the user interface (and also in parallel as a PDF file for downloading):

- Overview (summarizing tabular presentation of fatigue values for all monitored components, cf. Fig. 5)
- Theoretical service life (component-specific) for each defined pressure/temperature class
- Exposure time log (component-specific) – operating time for each defined pressure/temperature class including the resulting creep fatigue
- Numbers of cycles to crack initiation (component-specific) for each defined stress range/temperature class
- Load cycles (component-specific) for each defined stress range/temperature class including the resulting low-cycle fatigue (cf. Fig. 6)
- Configuration data for the components to be monitored
- Configuration data for materials (material database)

In addition to the output of logs, the results can also be displayed graphically – fatigue values together with operating parameters – this enabling direct comparison of the operating mode of the plant with the resulting utilization values (cf. Fig. 7).

Record type 1: Overview (Components)

Tag	Starttime	Endtime ZSE	Endtime DWE	ZSE [%]	DWE [%]	DWE-R [%]	E0 [%]	Ecorr [%]	**Eges [%]**	tZSE [h]	taZSE [h]
10HAD10BB001D|	11/05/2011 09:12:30	-	23/02/2012 00:59:41	-	0.0903	0.0655	0.000	0.000	**0.1558**	-	-
10HAD10BB001W|	11/05/2011 09:16:05	-	23/02/2012 00:59:41	-	0.1634	0.0757	0.000	0.000	**0.2391**	-	-
10HAH20AC001|	11/05/2011 09:57:24	23/02/2012 00:59:41	23/02/2012 00:59:41	0.3292	0.0190	0.0000	0.000	0.000	**0.3482**	5899.87	1004.17
10HAJ60AC002B|	11/05/2011 10:39:36	23/02/2012 00:59:41	23/02/2012 00:59:41	0.0599	0.0061	0.0000	0.000	0.000	**0.0659**	4632.49	2270.85
10LBA10BR002|	11/05/2011 09:35:55	23/02/2012 00:59:41	23/02/2012 00:59:41	0.2346	0.0023	0.0000	0.000	0.000	**0.2369**	5474.10	1430.29
10LBA21BR001|	11/05/2011 09:46:53	23/02/2012 00:59:41	23/02/2012 00:59:41	0.1137	0.0023	0.0000	0.000	0.000	**0.1161**	5108.40	1795.82
10LBA22BR001|	11/05/2011 09:52:13	23/02/2012 00:59:41	23/02/2012 00:59:41	0.1155	0.0024	0.0000	0.000	0.000	**0.1178**	5108.31	1795.82
10LBB40BR002|	11/05/2011 09:40:47	23/02/2012 00:59:41	23/02/2012 00:59:41	0.0841	0.0036	0.0001	0.000	0.000	**0.0878**	4633.56	2270.75
10LBB51BR001|	11/05/2011 09:26:20	23/02/2012 00:59:41	22/02/2012 23:33:39	0.0320	0.0030	0.0000	0.000	0.000	**0.0350**	6711.64	192.92
10LBB52BR001|	11/05/2011 09:21:39	23/02/2012 00:59:41	22/02/2012 00:59:50	0.0297	0.0026	0.0000	0.000	0.000	**0.0323**	6147.72	756.91

Fig. 5 FMS overview display (all monitored components and the current results of the fatigue calculation)

Low-cycle fatigue 0.16338 %
Uncomplete cycles list 0.07572 %

Cycles per class

t [°C] -> σ [N/mm²]	20	20 120	120 140	140 160	160 180	180 200	200 220	220 240	240 260	260 280	280 290	290 300	300 310	310 320	320 330	330 340	340 350	350 360	360 370	370 380	380
< 200	-	14	4	3	10	25	8	10	22	34	138	124	167	191	111	4	-	-	-	-	-
200 - 225	-	1	-	-	1	-	-	-	-	1	-	-	-	6	-	-	-	-	-	-	-
225 - 275	-	-	-	-	-	-	-	-	-	-	-	-	-	3	-	-	-	-	-	-	-
275 - 325	-	-	-	-	-	-	-	-	-	-	-	-	1	5	1	-	-	-	-	-	-
325 - 375	-	-	-	-	-	-	-	-	-	-	-	1	30	1	-	-	-	-	-	-	-
375 - 425	-	-	-	-	-	-	-	-	-	-	-	1	4	-	-	-	-	-	-	-	-
425 - 450	-	-	-	-	-	-	-	-	-	-	2	1	-	-	-	-	-	-	-	-	-
450 - 500	-	-	-	-	-	-	-	-	-	-	4	2	-	-	-	-	-	-	-	-	-
500 - 530	-	-	-	-	-	-	-	-	1	1	4	-	-	-	-	-	-	-	-	-	-
530 - 570	-	-	-	-	-	-	-	-	-	2	1	-	-	-	-	-	-	-	-	-	-
570 - 600	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
600 - 650	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-
650 - 700	-	-	-	-	-	-	-	-	-	2	-	-	-	-	-	-	-	-	-	-	-
700 - 750	-	-	-	-	-	-	-	-	-	2	-	-	-	-	-	-	-	-	-	-	-
750 - 800	-	-	-	-	-	-	-	-	1	1	-	-	-	-	-	-	-	-	-	-	-
800 - 900	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-
900 - 1000	-	-	-	-	-	-	-	-	-	2	-	-	-	-	-	-	-	-	-	-	-
1000 - 1500	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1500 - 2000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2000 - 2500	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
> 2500	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Cycles	-	15	4	3	11	25	8	10	24	47	149	129	202	206	112	4	-	-	-	-	-
Fatigue [%]	-	1.5e-4	4.0e-5	3.0e-5	1.1e-4	2.5e-4	8.0e-5	1.0e-4	0.014	0.126	0.013	0.004	0.002	0.002	0.001	4.0e-5	-	-	-	-	-

Fig. 6 FMS display output (detail protocol for HP drum 10HAD10BB001W – matrix of completed cycles in dependence of temperature and stress)

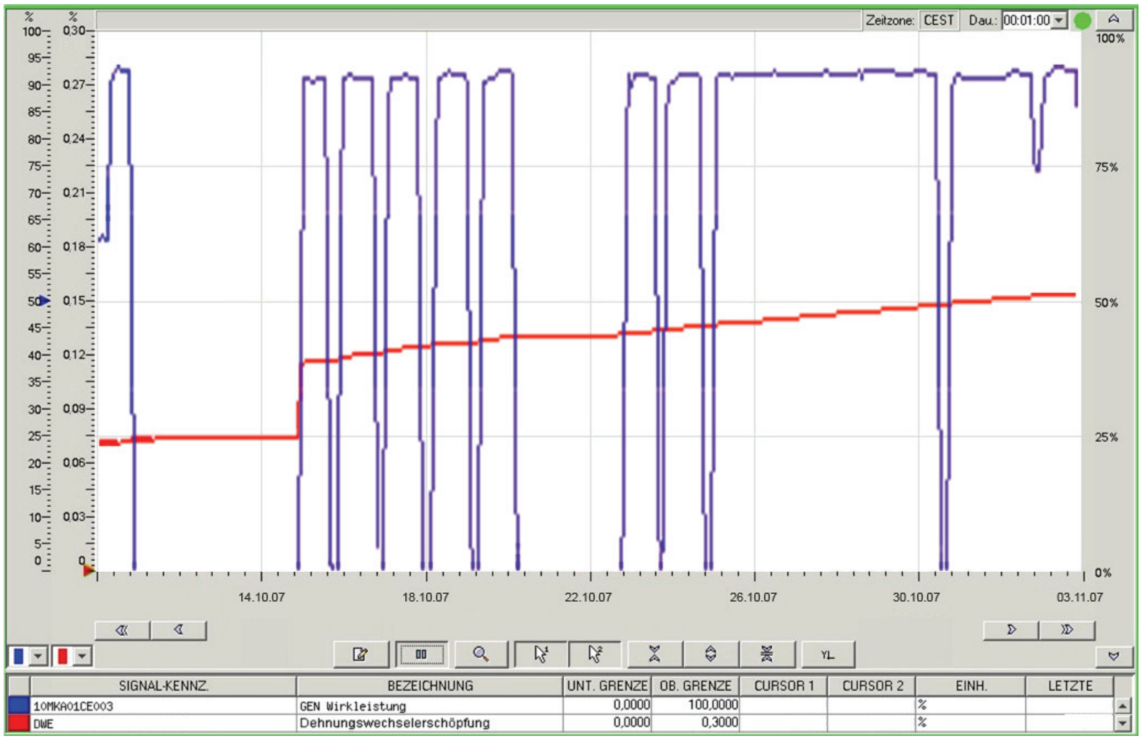

Fig. 7 Trend of active power (blue) and low cycle fatigue (red) over time from Oct. 10 to Nov. 03 with a noticeable start-up at Oct. 15

Low cycle fatigue (DWE) depicts the influence of load cycles – in particular start-up and shut-down. Fig. 6 shows the detail protocol of low cycle fatigue with cycles in dependence of temperature and stress. Start-up and shut-down operations that contribute particularly to the lifetime consumption can easily detected by a simple representation of the trend. An example for this purpose is Fig. 7 with active power of the power plant and low cycle fatigue in dependence of time.

In the period under review several start-up and shut-down operations happened. While for most operations the low cycle only slightly increased, it rose significantly at the 15th October start-up.

The analysis of the start-up showed that cold fluid was injected into the boiler, which resulted in high stresses in the boiler component wall. It was recommended to prevent such operation in the future.

10. Summary

Assessment of fatigue and remaining useful life for boilers according to the 2001 issued EN 12952 uses simplified methods for the evaluation of creep and low cycle fatigue. The consequence of this simplification is some conservatism for the estimated damage fraction.

The remaining useful life is expressed in parts of 100% taking into account the different approaches of creep fatigue and low cycle fatigue, especially that cycling operation of power plants results in low cycle fatigue and is not related to hours.

The main advantage of the assessment procedures from the standard is that they are easy to apply. Particularly they are qualified for temperatures up to more than 600 °C and 200,000 h and more service time of boiler components.

The boiler fatigue monitoring module FMS is based on EN 12952. FMS has been in use in power plants since mid-2004. It has been included in the scope of supply for many new combined-cycle power plants from Siemens Energy or backfit in existing plants.

The FMS module is certified by the German technical inspectorate TÜV Süd.

For the power plant operator, the implementation of FMS provides a continuous overview of the service life utilization of his boiler, so that

- The time for a necessary inspection can be selected optimally and thus the operating time between two inspections maximized
- Power plant safety can be increased
- Operating modes causing heavy wear can be detected and if possible prevented

- Components can be operated close to the material limits, so that the operating time of the plant can be maximized and operating costs minimized

The assessment of fatigue and remaining useful life for boilers according to EN 12952 is accepted as a standardized industrial application.

The Fatigue Monitoring System (FMS) is a standard industrial application for both, new built power plants and retrofits of existing units of any kind. The system is not limited to Siemens I&C systems, it is possible to integrate FMS also into power plants with I&C systems of other suppliers. FMS is also capable for calculating the remaining lifetime for boilers designed according to the American standard ASME VIII-2. Since 2004 it has been successfully implemented for more than 50 boilers.

REFERENCES

European Committee for Standardization (CEN) (2001). EN 12952-3, *Water-tube boilers and auxiliary installations - Part 3: Design and calculation for pressure parts*, Brussels, Belgium

European Committee for Standardization (CEN) (2001). EN 12952-4, *Water-tube boilers and auxiliary installations - Part 4: In-service boiler life expectancy calculations*, Brussels, Belgium

The American Society of Mechanical Engineers (ASME) (2001), ASME Boiler and Pressure Vessel Code Section VIII Division 2 (ASME VIII-2), *Rules of Construction of Pressure Vessels – Alternative Rules*, New York

American Boiler Manufacturers Association (ABMA), Task Group On Cyclic Service (2003), *Comparison of fatigue assessment techniques for heat recovery steam generators*, Version 1-1

Kunze, U., Walz, H. (2007), Integration of Web based Diagnostic Systems into Power Plant I&C with Boiler Fatigue Monitoring as an Example (in German), Proceedings of International ETG Congress, October 23/24, Karlsruhe, Germany

Kunze, U., Pels Leusden, C., Spinner, R., Hackstein, H., Walz, H., (2008), Integration der Lebensdauerüberwachung von Dampferzeugern in die Kraftwerksleittechnik, *40. Kraftwerkstechnisches Kolloquium 2008, October* 14/15, Dresden, Germany

BIOGRAPHIES

Ulrich Kunze is physicist and received a doctorate (Dr.-Ing. habil.) in mechanical engineering. He works as a senior expert for diagnostics of fossil fired power plants at Siemens AG in Erlangen (Germany). Previous he was head of the diagnostics department in a German nuclear power plant and then project manager at Siemens responsible for installation of diagnostic systems in nuclear power plants world wide. Currently he is member of the DIN and ISO specialist groups for Condition Monitoring and Diagnostics of Machines (TC 108 SỌ 5).

Stefan Raab received a doctorate (Dr.-Ing.) in mechanical engineering. Currently he is leading the diagnostics group for plant performance at Siemens AG in Erlangen (Germany). He is member of a VGB PowerTech specialists group for power plant performance diagnostics.