Structural health monitoring of power plant components based on a local temperature measurement concept

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Abstract
The fatigue assessment of power plant components based on fatigue monitoring approaches is an essential part of the integrity concept and modern lifetime management. It is comparable to structural health monitoring approaches in other engineering fields. The methods of fatigue evaluation of nuclear power plant components based on realistic thermal load data measured on the plant are addressed. In this context the fast fatigue evaluation (FFE) and detailed fatigue calculation (DFC) of nuclear power plant components are parts of the three staged approach to lifetime assessment and lifetime management of the AREVA Fatigue Concept (AFC). The three stages simplified fatigue estimation (SFE), FFE and DFC are characterized by increasing calculation effort and decreasing degree of conservatism. Their application is case dependent. The quality of the fatigue lifetime assessment essentially depends on one hand on the fatigue model assumptions and on the other hand on the load data as the basic input. In the case of nuclear power plant components thermal transient loading is most fatigue relevant.

Usual global fatigue monitoring approaches rely on measured data from plant instrumentation. As an extension, the application of a local fatigue monitoring strategy (to be described in detail within the scope of this paper) paves the way of delivering continuously (nowadays at a frequency of 1 Hz) realistic load data at the fatigue relevant locations. Methods of qualified processing of these data are discussed in detail. Particularly, the processing of arbitrary operational load sequences and the derivation of representative model transients is discussed. This approach related to realistic load-time histories is principally applicable for all fatigue relevant components and ensures a realistic fatigue evaluation.

Keywords: Local fatigue monitoring approach, Operational load sequences, Model transients, Fast Fatigue Evaluation (FFE), Detailed Fatigue Calculation (DFC)

1. Introduction
The safety check against cyclic operational loads, i.e. the fatigue check, takes a central position within the aging management of nuclear power plants (NPPs). This design check is applied in order to show that the fatigue aging mechanism, which is normally due to cold and hot feed operations, does not result in an increased incipient crack probability. It is important to note that in the context of extended operational times (nowadays 60 years) of new power plants the monitoring of operational loads as well as the storage of the acquired data should start right at the beginning, i.e. the commissioning phase. A later evaluation of these loads can be based on the available data. In consequence of the long operational times conceptually elaborate and mature solutions as normally offered by the vendors are preferable.

For this purpose, AREVA provides the fatigue monitoring system FAMOS. It is embedded in the AREVA Fatigue Concept (AFC) as the data provider that acquires the operational load data and ensures by way of different evaluation processes that the analysis effort complies with the real damage potential. In this sense, three harmonized evaluation processes SFE (simplified fatigue estimation), FFE (fast fatigue evaluation) and DFC (detailed fatigue calculation) are available within this graded approach.

SFE and FFE constitute highly automated evaluation processes and deliver a fatigue assessment in the framework of an easy to use software environment. More detailed evaluations are possible if required due to increased operational loads. In this context, the DFC comprehends
a detailed load case counting and the possible application of realistic material models within the finite element analysis (FEA). The design code requirements are met and lower usage factors U may be calculated this way. Compared to other vendors AREVA recommends a local acquisition of load data for the follow-up of fatigue trends. This way it is ensured, that the local loads at the locations of interest with regard to fatigue (e.g. thick walled nozzles) are captured. The operational measurement instrumentation – generally measurements based on thermal (immersion) wells – is usually neither positioned appropriately for local fatigue follow-up nor disposes of the required measurement dynamics in order to deliver the loading data. This means, appropriate measurement systems should be applied in order to ensure a realistic follow-up of operational loads. Particularly, the measuring tolerance should be known and as small as possible.

The key aspects mentioned in the introduction are explained now in detail - to show the whole purpose of a conceptually harmonized approach of fatigue follow-up and compare local fatigue monitoring to the application of operational measurement points.

2. Local Fatigue Monitoring Strategy

During the early operation of NPPs in the 1970s and 1980s local loads occurred at different locations causing fatigue cracks. These were either due to new loading conditions which were not considered in the design phase (e.g. temperature stratification) or insufficient manufacturing quality (e.g. welded joints). These problems constituted the starting signal for the development of fatigue monitoring systems. Simultaneously, the compliance with authority demands was assured. In Germany, FAMOS was for instance developed by then Siemens KWU (now AREVA NP GmbH) at the end of the 1980s and installed in German NPPs. At that time, this was a very progressive data logging system. Henceforth, it was possible to measure the local loading effects.

The installation is carried out as a clamped measurement strap on the outer wall surface of the pipe nearby the fatigue relevant location as it is shown in figure 1.

![Figure 1: Exemplary local measurement section](image)

Nowadays, the measurement system is based on a modern data management approach (data bus structured; SQL database; live network data stream) and is very flexible in installation and application. The modern system design ensures an easy system installation and relatively low costs.
The fatigue relevance of those effects was analyzed by simple assessment methods. These experiences gave rise to a better understanding of the ongoing loading phenomena. The fatigue assessment induced the necessity of retrofitting of components or the modification of the operating mode. For instance, the feedwater sparger of the steam generator was subsequently designed in a way that the stresses of cyclically occurring stratification transients were minimized. Nevertheless, the technology of the data logging system at that time still had certain limits with respect of the frequency of data logging and the recording and storage. A data logging frequency of 10 s (0.1 Hz) constituted the upper limit (nowadays, 1 s respectively 1 Hz is usual). Furthermore, the capacitive effect of the applied measurement sections was underestimated in their transient behavior. Nowadays, this effect is appropriately considered by correction factors specific to the respective measurement section.

The calculation of realistic local stresses and strain rates is even more important within the fatigue calculation including environmentally assisted fatigue (EAF) effects. The knowledge of actual local loads and strain rates is a prerequisite for the consideration of the NUREG/CR 6909 EAF rules [1] as a “new” requirement of fatigue analyses. Opposite effects between high stresses due to fast transients (high strain rate) and high \( F_{en} \) factors (low strain rate) have to be considered.

Global fatigue monitoring strategies have to rely on operational signals and some transfer functions. The operational instrumentation was not originally intended for fatigue monitoring. Usually, it is neither located near the fatigue relevant positions nor it is able to resolve highly transient phenomena due to its own measuring dynamics characteristics. Hence, while addressing fatigue monitoring requirements, a clear distinction has to be made between global and local approaches [2].

The global monitoring is based on existing operational measurement. The corresponding operational signals could be fluid pressure, fluid temperature, the position of valves etc. measured at different parts of the systems. Local fatigue monitoring is located at fatigue relevant locations at the outer surface of pipes in the proximity of fatigue relevant components and is based on additional temperature measurement by means of thermocouples. The thermocouples are manufactured as measurement sections.

The complex fluid flow events occurring during the operation of NPPs are influenced by the automatic operational control processes. Nevertheless, as a consequence of the manifold manual intervention opportunities equal technological processes may induce different local loading sequences for the components. In other words, an assessment of components exclusively based on operational measuring instrumentation in connection with transfer functions does not guarantee the detection of local load phenomena. Thus, local data acquisition and monitoring of local loads at the fatigue relevant components is the appropriate solution. Local effects such as the swapping flow after feeding interruption can only be recorded in the load data set this way. It is to be pointed out that the safety check against cyclic loads of the components has to be a permanent operation accompanying procedure. The German KTA rules regulate this issue as part of the rule for operational monitoring (KTA 3201.4) [3].

### 3. The Three Staged AFC Model

#### 3.1 Modules of the AFC

AREVA develops its own integrated fatigue concept AFC [4]. This concept provides for a multiple step and multidisciplinary process (process engineering, fatigue monitoring, fatigue analyses etc.) against fatigue before and during the entire operation of NPPs. The structure and the modules of the AFC are shown in figure 2.
The modules are described in more detail in [4] and [5]. Figure 2 underlines the central position of the fatigue monitoring module. AREVA now offers FAMOSi (“i” = integrated) as a modern central data logging system (for further description and explanation see [5] and [6]).

### 3.2 Fatigue assessment methods SFE, FFE and DFC

The subsequent fatigue evaluation methods can principally be split up in three steps:

**Step 1: Simplified fatigue estimation (SFE)**

Simple estimations of fatigue relevance of real loads for components are based on thermal mechanical considerations using the equation of ideal thermally constrained strains. A basic decision about fatigue relevance (yes/no) for the monitored position is made. In case of fatigue relevance a further evaluation is proposed according to step 2.

**Step 2: Fast fatigue evaluation (FFE)**

A code conforming (cumulative) usage factor $U$ is calculated in a highly automated way based on the simplified elasto-plastic fatigue analysis route of relevant design codes such as [7]. If $U \leq U_{\text{admissible}}$ the fatigue check is successfully finished. If $U > U_{\text{admissible}}$ further analyses should be based on step 3.

As described above the measuring location of FAMOS is chosen in the proximity of a fatigue relevant component and the measurement sections installed at the outer surface of the pipe. Nevertheless, the points of interest are at the inner surface of the component. Therefore, the calculated temperature at the inner surface of the pipe will be transferred to the inner surface of the component. The thermal load cycles are well known after that step and the stress time history is calculated with the Green’s function approach. This approach deals with two unit (elementary) transients of $\pm 100$ K, which are used to scan the original temperature time history at each time step. By means of elementary transients, stresses are calculated at all fatigue relevant locations which are monitored. Pressure cycles as well as section forces and moments will also be evaluated based on the Green’s function approach.

**Step 3: Detailed fatigue calculation (DFC)**

Fatigue analysis is based on a detailed catalogue of transients. This catalogue of transients results from the evaluation of the real loads for the monitored component.
In this context loading data of the operational period as well as anticipated loads of future operation are used as essential input parameters. Hence, usage factors are calculated for the current state of the plant and until the end of life (e.g. 40 or 60 years). The fatigue analysis for primary circuit components is based on design codes such as the ASME code [7], the German KTA rules [8] or the French RCC-M code [9]. Fatigue calculations are usually carried out as simplified elasto-plastic or elasto-plastic analyses. The simplified elasto-plastic fatigue analysis based on elastic FEA and plasticity correction (fatigue penalty or strain concentration factors $K_e$) e.g. according to paragraph 7.8.4 of [8] or equally NB 3228.5 of [7] is known to yield often overly conservative results [10].

3.3 Cycle Counting

The determination of cumulative usage factors requires the application of appropriate cycle counting procedures. The peaks and valleys approach of the ASME code [7] NB-3222.4 is often applied for the determination of the required stress ranges. The largest stress ranges are usually determined from “outer combinations” (e.g. load steps across different transients respectively events). The associated frequency of occurrence results from the actual number of cycles of the participating two events with the smaller number of cycles. This event provides the associated contribution to the partial usage factor $U_i$. The summing up of all partial usage factors according to Miner’s rule delivers the (cumulated) usage factor.

As soon as the load history is directly considered (e.g. within the FFE) the code conforming peaks and valleys method can be combined with or replaced by a rain flow algorithm, e.g. the hysteresis counting method – HCM - according to Clormann and Seeger [11]. In the framework of DFC based on a catalogue of transients the rain flow counting algorithm may be conservatively combined with the peaks and valleys method in the sense of a sub-cycle counting procedure.

4. Application Examples

4.1 Example 1: Pressurizer spray line

Figure 3 gives an example of operational and local measurement configuration in the primary circuit of a pressurized water reactor (PWR) as a principle scheme. The pressurizer spray lines are known to be fatigue relevant sections and one pipeline of interest is pointed out in red color in figure 3. One exemplary fatigue relevant location is the component (nozzle). The next operational measurement location is marked as a light blue rectangle and pointed out by a circle. The temperature $T_{sl}$ (index “sl” for “spray line”) is measured at this location. As it can be seen in the scheme this operational measurement is located behind the valve and considerably away from the component of interest. In fact, this operational measurement was not originally intended for the fatigue monitoring of the component (nozzle). The next operational measurement delivers the pressurizer temperature $T_{pr}$. Any global fatigue monitoring approach has to rely on the operational measurements $T_{sl}$ (spray line), $T_{pr}$ (pressurizer) and $T_{mcl}$ (main coolant line) as input and some transfer considerations for the fatigue load assessment of the component (nozzle).

In terms of specifications from the design phase (see figure 2) temperature transients $T_{des}$ are given for the spray line between the valve and the pressurizer. These data are based on plant models and experiences related to similar operating plants.
In contrast, the additional local measurement section is located at a U-bend close to the component (nozzle). Continuous transient temperature measurement at 1Hz frequency is carried out and yields the local temperature transients $T_{loc,i}$ and $T_{loc,e}$ at the intrados (index “i”) and extrados (index “e”) positions of the U-bend for the operational cycles of interest. Note, that local temperature measurement refers to the outer wall as it is shown in figure 1. The proximity of the local temperature measurement to the component of interest (nozzle) is clearly visible in figure 4.

The measured temperature transients for an exemplary shut-down process are shown in figure 5. The time period from 01:00 a.m. to 06:00 a.m. (Universal Time Coordinated, UTC) is depicted. As it can be expected the range of temperatures is limited by the measurement results of the pressurizer $T_{pr}$ and the spray line $T_{sl}$. Both are operational measurements. The measured spray line temperature $T_{sl}$ does not differ very much from the measured main coolant line temperature $T_{mcl}$. This information is available from the global operational measurement. Detailed information about the temperature transient at the location of the component (nozzle) is available thanks to the local temperature measurement $T_{loc,e}$ and $T_{loc,i}$. Differences between $T_{loc,e}$ and $T_{loc,i}$ at a certain time are indicators of stratification flows. These are visible near the 06:00 a.m. measurements.

In the following stress analysis example the spraying processes indicated by the local measurement results between 01:20 a.m. and 02:10 a.m. (pointed out by the blue box in figure 4) are considered in more detail. As there is no indication of significant stratification flows ($T_{loc,e}$ and $T_{loc,i}$ are nearly identical) the exemplary analyses are exclusively based on the measured intrados temperatures $T_{loc,i}$ at the local measurement section $T_{loc}$. 
Figure 4: Measured temperature transients

Figure 5 shows the meshed component model (nozzle) for the structural finite element analyses following the thermal transient analyses. A 2D axially symmetric model is used. Temperature dependent material data for the austenitic nozzle and cladding (stabilized austenitic stainless steel X6CrNiNb18-10, e.g. 1.4550 respectively ANSI 347) and the ferritic body material (20 MnMoNi 5 5, e.g. 1.6310 respectively ASTM A 533) are taken from KTA rule 3201.1 [12]. More details on finite element FE modelling and FEA can be taken from [13].

Figure 5: Meshed finite element model for the structural analysis
The example refers to the spray events pointed out in figure 4. The associated design and model transients are shown in figure 6 (bulk temperatures) compared to the locally measured temperature transient. Note that direct comparison refers to the outer wall position.

In a subsequent step, FEAs are carried out for the design and model temperature transients (see bulk temperatures in figure 6) as well as the locally measured temperature transients (see figure 4). Exemplary linearly elastic stress responses ($\sigma_z$) and the corresponding local temperature transients $T_{loc,i}$ are plotted in figure 7. The purely elastic stress responses – particularly for the locally measured temperature transients – are advantageously obtained by the FFE approach. Of course, an individual FEA is applicable as well. The stress responses reveal
that both the design and the model temperature transients cover conservatively the stress response to the locally measured temperature transients. Note that the local temperature measurements deliver data at a frequency of 1Hz. The amount of incurring data and the handling of data processing are further arguments in favor of the application of the elementary transients approach as implemented in the FFE module of the AFC.

Note that the stress response to the real operational load sequence (Sz_FFE_loc,i) covers the whole time history from 0s to 3000s while the stress responses to the design and model transients (Sz_DesignTr and Sz_ModelTr) refer to half cycles according to figure 7. Thus, the comparison of the stress peaks or amplitudes is most significant. The complete cycle for the determination of stress ranges would have to mirror the stress peak responses to the design and model transients. Figure 7 shows that the linearly elastic stress peak response to the design transient is about 45% higher (more conservative) than the response to the real operational load sequence.

![Figure 8: Exemplary partial fatigue usage](image)

Figure 8 depicts the normalized partial usage factors $U_i$ with the design transient taken as reference for the extract from the operational history pointed out in figure 4 (blue box). Application of the design transient as input yields the most conservative (covering) results as it can be expected by comparison of design and model transient (see figure 6) as well as the stress amplitudes respectively stress ranges (see figure 7). The model transient as load data input yields more conservative results than the FFE approach for the contribution of this particular partial operational history. This is due to the conservatism of model transient specification with respect of temperature range and temperature change rate (see figure 6). Note that the temperature transients of the considered part of the load history do not induce significant plasticity effects ($K_e=1.0$ in the simplified elasto-plastic fatigue analysis according to [7]). Plasticity effects may be more significant in more severe parts of the operational load history. In these cases, the conservatism of the plasticity correction by code conforming $K_e$-factors compared to the results of detailed elasto-plastic finite element analyses [10] are likely to overcompensate the differences in the temperature load description. Then, the trend for partial
fatigue usage (see figure 8) is likely to become reversed. Finally, the fatigue relevant parameter is the overall cumulative usage factor for the whole completed period of plant operation and for end of life considerations (prognosis of future model transients and their number of occurrence).

In a final exemplary step $F_{en}$-factors according to [1] for consideration of EAF were calculated. Details are given in [13]. Note that $F_{en}$ factors significantly depend on the strain rate and thus the time variable.

### 4.2 Example 2: Feedwater nozzle

The second example addresses an exemplary fatigue calculation for a steam generator feedwater nozzle of a nuclear power plant. Fatigue assessment for the period of one operating cycle is based on the FFE approach described above. The several steps which are necessary for the calculation are described and the resulting fatigue usage factors are documented.

An adequate FE model has to be created containing all the relevant geometry and material properties. In this particular case it is a part of the steam generator (SG) shell, the feedwater nozzle and a part of the connected piping of the feedwater system (LAB) (Figure 9). One 3D model of the nozzle is needed to calculate the stresses occurring in the nozzle, one 3D model of the pipe is needed to calculate the piping loads applied to the nozzle and one 2D model of the measurement section on the LAB pipe near the nozzle is needed to calculate the inner wall temperature.

After these necessary preparations the evaluation is done in the following steps:

- Reviewing the measured data
- Calculation of the inner wall temperature
- Calculation of the stress caused by thermal transients within the nozzle
- Calculation of the stress caused by internal pressure
- Calculation of the stress caused by piping loads due to stratification and thermal expansion of the pipe
- Superposition of the stresses
- Fatigue evaluation.
The evaluation is done for several locations at the 12 o’clock position and at the 6 o’clock position of the nozzle due to possible stratification effects to be considered.

Concerning materials the feedwater nozzle and the cylindrical shell of the steam generator are made of the ferritic steel 20 MnMoNi 5 5 (material no. 1.6310). The piping of the feedwater system and the transition piece are made of 15 NiCuMoNb 5 (material no. 1.6368).

The FFE method is applied for an operating period of about 16 months. All relevant transient data are available based on local measurements. The following seven relevant operational events (see figure 10) were identified based on the measured temperature data (one measurement section with five thermocouples around the circumference):

1) 1st cooldown event
2) 1st heatup event outage
3) Operational event
4) 2nd cooldown event
5) 2nd heatup event
6) 3rd cooldown event
7) 3rd heatup event

Figure 10: Temperature over time for one operating period

In a first step the inner wall temperatures at the location of the measurement section are calculated based on the outer wall measurements (solution of the inverse heat transfer equation). For the calculation of the inner wall temperature it is necessary to determine the thermal behavior of the complete structure at the measuring section including the thermocouple configu-
ration (see figure 1) and its related capacity. Therefore 2D FE model (see figure 11) is generated for that purpose. The elementary transient was applied on the inner wall of the structure. This transient describes a temperature increase from 0°C to 100°C within one second. The calculated answer at the location of the thermocouple is used for the scaling of the complete temperature response.

![2D finite element model for determination of inner wall temperatures](Image)

Figure 11: 2D finite element model for determination of inner wall temperatures

In the following step the stresses induced in the feedwater nozzle were calculated as a function of time based on the calculated inner wall temperature sequences. The inner wall temperatures of the measurement section at a distance of 500 mm from the nozzle were transferred to the inner wall of the nozzle. The calculation of the stress tensors of total and lin-
earized stresses was carried out by application of the elementary transient method. This required an FE calculation with an elementary transient as thermal load in order to determine the stress responses at the locations of interest.

Figure 12 shows the FE model used for the calculation of the elementary transient. Since the same FE model is used to calculate the stresses out of all kind of loads the nozzle is represented as a 3D model. For reasons of symmetry the geometry could be reduced to one half. The commercial FE program ANSYS® was used.

For the calculation of the elementary transient first a thermal transient calculation was done to determine the temperature distribution in the nozzle for every calculated time step. The thermal properties of the steam in the gap between sleeve and nozzle were considered in this (thermal) calculation. The associated “steam” elements (see figure 12) were eliminated in the subsequent structural mechanical analyses. As an elementary transient a temperature decrease from 290°C to 190°C within one second was chosen as loading on the inner wall of the nozzle. On the inner side of the steam generator a constant value of 290°C was applied.

![Figure 13: Locations of interest](image)

In a subsequent step the thermally induced stresses in the nozzle were calculated using the calculated temperature distribution as body loads. As a result of this analysis the stress tensor at the locations of interest is calculated as the response to the thermal elementary transient. The locations of interest with an exemplary stress response (contour plot) at a discrete time step is shown in figure 13. Nodes 555896 (inner wall of the thick walled component) and 546214 (notch of thermal sleeve connection) represent the locations of the structure where the highest usage due to thermal transients is expected. Node 332452 is located on the outside of the nozzle where the highest stresses caused by piping loads are expected.

Since the response of the structure to the elementary transient is known the scaling function can be built in order to determine the time dependent stress tensors (total and linearized) as a result of the measured temperature sequences.

The calculation of the stresses caused by internal pressure was done using a scaling procedure associated to an elementary pressure load of 1 MPa. Note that the pressure loading is static.
The calculation of the additional stresses caused by piping loads requires two steps. In a first step the forces and moments have to be calculated which are caused by the thermal expansion of the pipeline including the phenomenon of stratification. In a second step the stresses have to be calculated at the locations of interest caused by the piping loads.

In a horizontal pipe different forms of stratification can occur. It can be a hot layer over a cold layer with a strict partition in between. The partition can also be a more or less wide transition zone (linear or nonlinear transition). Another possibility is a temperature profile (linear or nonlinear) over the whole cross section of the pipe. On pipes where stratification is expected several thermocouples are located in circumferential direction of the cross section. To be able to handle with all this different kind of stratification a method was developed to reduce all the stratification data to two variables. The stratification can be described as an equivalent by a mean temperature $T_m$ and a linear distribution $\Delta T$ over the altitude of the cross section ($T_{\text{hot}} = T_m + \Delta T/2$; $T_{\text{cold}} = T_m - \Delta T/2$). This equivalent linearized stratification produces the same piping loads at the feedwater nozzle as the measured stratification profile.

After this linearization process the piping loads have to be calculated. For this calculation a scaling method is equally applied within the FFE approach which determines the forces and moments in dependence of the linearized stratification and a calculated reference. The determination of the forces and moments is carried out as a function of time. The linearized stratification was applied on the inner surface of the reference model as unit load. With the resulting forces and moments (evaluated in the local coordinate system) at the connection to the nozzle the scaling function was created for the calculation of the piping loads in dependence of the measured data. Figure 14 shows the FE model of the pipe with an example of a linear stratification.

![Figure 14: Finite element model of the pipe with visualization of stratification effect](image)

The calculation of the stresses caused by the piping loads was equally based on a scaling procedure based on the determination of the stress tensor at the locations of interest resulting from elementary loads. The determination of the time dependent stresses was done using a linear scaling function between the piping loads and the reference elementary load. Because of the non-symmetrical loads the stresses were determined at the bottom of the nozzle and
also at the top of the nozzle. The locations of interest at the top of the nozzle correspond to those at the bottom in Figure 13.

As preparation for the fatigue evaluation the total stresses were calculated for all locations of interest by combination of the stresses caused by thermal transients, internal pressure and piping loads. The superposition was done for three locations at the bottom of the nozzle (see Figure 13) and the top of the nozzle.

Finally, the fatigue evaluation for the period of the operating was based on KTA3201.2 [8], chapter 7.8. Cycle counting was based on the rain flow algorithm as described above. The appropriate fatigue curve of [8] was used to determine the partial fatigue usage factors based on Miner’s linear damage accumulation rule. The resulting usage factors are shown in figure 15. The thermal sleeve connection results to be the most fatigue relevant location.

![Diagram with nodes and coordinates](image)

Figure 15: Resulting partial fatigue usage factors

5. Summary and Conclusions

The processing of fatigue monitoring data in NPPs has been discussed in detail with particular emphasis on the fundamental differences between global and local approaches. The availability of continuous local temperature data pave the way to graded fatigue evaluation methods such as those proposed within the AFC. Model transients derived from locally measured temperature data and used as input data for detailed fatigue checks usually differ significantly from specified design transients. In other words, model transients (see green path in figure 2) – although idealized with respect of temperature difference and gradient (temperature change rate) – reflect the locally measured data and allow for a realistic estimation of the number of occurrences. This ensures a qualitative difference compared to the design transient (see blue path in figure 2) which is usually specified before the commissioning of the plant and which is based on plant models, comparisons and conservative estimations. Exceptionally, design transients may be non-conservative when certain operational loads are not considered in the design phase. The most accurate load input is ensured by direct processing of the locally measured temperature data. In this case, the application of the elementary transients approach
(Green’s functions) as implemented e.g. in the FFE module of the AFC is an appropriate way of obtaining the linearly elastic stress response. Although limited to the calculation of the linearly elastic tensor of total and linearized stresses (used for plasticity corrections according to the design code [7],[8]) the FFE method ensures a fast online calculation of (cumulative) usage factors U for fatigue relevant locations. It proves to be an efficient and applicable method. Plasticity effects can be considered in a less conservative way by application of advanced correction factors Ke, application of direct methods or elasto-plastic FEA within the framework of the DFC [14]. In this context, model transients are used for capacity reasons. The direct processing of measured temperature data within long time series (e.g. one year) in connection with complicated 3D structures and non-linear FEA is still impracticable. It is an option to apply more advanced and more realistic correction factors Ke.

This described approach is equally applicable in other engineering disciplines such as conventional power plants, chemical plants, wind energy plants etc.

References