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German Nuclear Power Plants Utility Ageing Management – Long Term Fatigue Evaluation of Safety Relevant Components

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Integral Plant Life Management comprises the technological and administrative measures of relevant systems, structures and components during the lifetime of a Nuclear Power Plant (NPP) to safeguard the safety requirements.

This publication will give a brief introduction to the basics of Ageing Management (AM) in German NPPs while clarifying the delineation to Plant Life Management (PLIM). Surveillance measures on primary circuit piping components are essential for comprehensive analysis of thermal fatigue being one significant long-term degradation mechanism. This component specific data is the basis for further detailed analysis in order to determine a continuously updated data-based fatigue usage factor and finally to deduct required measures proactively.

1 INTRODUCTION

In USA Ageing Management activities have begun in the middle of the eighties motivated by the extension of the operating licence. In contrast to Germany the operating licence for USA NPP is temporary and thus, one has to decide whether to extend this operating licence and if to define specific conditions to keep. Meanwhile lifetime extension has been practiced for nearly half of the 104 US-American NPPs from 40 to 60 years.

In order to obtain comparable results of surveillance measures, new Ageing Management activities have to start up to accomplish safety precaution measures for future operating time. In German NPPs such surveillance measures exist nearly since commissioning of the plants and therefore Ageing Management activities are not motivated by this fact mainly.

In Switzerland the topic of Ageing Management was initiated in the beginning of the nineties due to regulatory requirements in order to restructure and complete documentation. Here detailed component specifications including long term integrity assessment of safety relevant components were basis for possible lifetime extension for the NPPs.

In other countries measures to control degradation mechanisms have been introduced also in order to meet ageing relevant individual problems as well as fundamental topics like long term integrity assessment of safety relevant systems structures and components (SSC) and plant life extension. Chosen approaches are prevalently based on available recommendations of the International Atomic Energy Agency (IAEA). The IAEA is concerned with ageing related topics since 1988, focused on areas of material / physical ageing of safety relevant SSC mainly. This comprises all mechanical components of the pressure boundary basically.

Generic AM activities were initiated by German Utilities in 1997. The intention was to frame the various activities under one headline in order to provide a conceptual and structural framework for plant specific AM application.

The German KTA standard no. 2301 “Ageing Management in Nuclear Power Plants” is being prepared currently to ensure a harmonized understanding of involved partners, utilities, authorities, and independent assessors like the German Technical Inspection Agency (TÜV). The existing draft standard proposal

accounts for recommendations of the German Reactor Safety Commission (RSK) stated in 2004 within the corresponding guideline to control of ageing processes in nuclear power plants.

2 PLANT LIFE MANAGEMENT AND AGEING MANAGEMENT

2.1 SSC lifetime

In order to classify occurring lifetime limiting mechanisms correctly, a detailed analysis of the failure rate over operating time is useful. This first step is basically necessary because the factor time plays the key role only in a small number of failures which defines the scope of physical / material ageing effects. Lifetime of a technical component can be classified into three different phases.

The first phase describes the commissioning of the SSC. It can be observed that after a relatively high failure rate in the beginning, the number of failures descents to a much lower level. During the second phase failures at random are feasible. Consequently, relatively low failure rates can be discovered. In the course of the operation and usage of the technical components the third phase can be reached. Within this phase increasing failure rates can be observed, possibly resulting in component unavailability (in the end complete unavailability of the whole plant within certain circumstances is conceivable). Additionally it should be mentioned that the time of application defines the significant life time limiting factor and not the real operating time compulsively. In any case the factor time plays the main role within all failures referring to the third phase. For example component failure resulting from a temporary high loading (e. g. misuse of measuring lines as step tread accidentally) has not to be classified into the third phase. Accordingly, operational ageing mechanisms like physical and material degradation (e. g. thermal fatigue) are effects appearing in the third phase mainly.

Consequently the main aim of an effective lifetime management for SSC is to keep the failure rate for components within the third phase as low as possible. This includes specific measures to preventively maintain all pertaining components before reaching the third phase.

2.2 Plant Life Management and Ageing Management

Basis for all considerations is always the state of design fabrication which is predefined by documentation. The proven quality by design and fabrication for SSC is founded in detailed drawings and system diagrams for example existing since construction time mainly but being updated by demand.

The essential distinction between AM and PLIM is defined by the extension of consideration (figure 1). In order to get a common understanding of the delimitation of areas, a detailed definition is helpful for clarifying the difference.

Plant Life Management (or Lifetime Management) is practiced within the area of accountability of the utility mainly and is done for the whole plant. It covers SSC relevant to availability and safety under the aspects of technological and conceptual further development and material / physical ageing. Respecting adequate measures PLIM is one major tool for increasing plant availability while reducing unscheduled outages, subsequently. Classification is done by demands on both availability and safety while each relevant degradation mechanism has to be identified.

The scope of AM is covered within the framework of PLIM. AM respects all effected measures being relevant for safe operation of the NPP in order to identify and control ageing related degradation mechanisms. Ageing Management is practiced under the supervision of the responsible safety authorities for assigned safety relevant SSC. The main aim of an effective AM is to identify each relevant ageing phenomenon and to effectively control all effects targeted in order to prevent harmful consequences for all assigned safety relevant SSC.

Within both aspects, PLIM as well as AM, check of efficiency of applied measures plays the key role to provide an efficient and comprehensive framework. By means of the PDCA (plan-do-check-act) circle measures have to be planned, realized, checked and respectively modified and adopted if necessary such that degradation mechanisms can be controlled comprehensively.

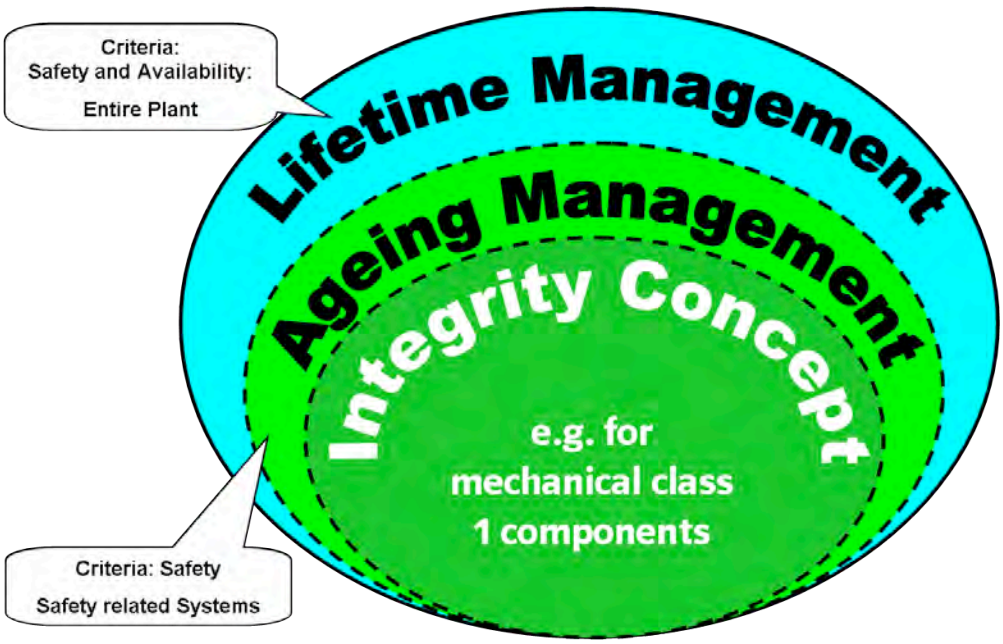

Figure 1. Plant Life Management (PLIM) and Ageing Management (AM).

2.3 Aspects of ageing

After providing a basic differentiation between the classification on AM and PLIM a more detailed view to ageing related degradation mechanisms is useful. AM deals with aspects of

- technological further development concerning operational degradation mechanisms and
- material / physical ageing.

A technological further development of safety relevant SSC emerges from changes in the state of know-how. Within the context of AM this accounts for additional gain in know-how and experience regarding potential operational degradation mechanisms in consideration of material component properties as well as testing-, analysis- and calculation methods.

Material / physical ageing respects all time dependent physical, biological and chemical processes which can result into a change of SSC's properties including material properties respectively. Physical ageing effects like fatigue, erosion or corrosion count to these degradation mechanisms. It has to be mentioned that not all events with the consequence of failure can be identified as ageing relevant. If and only if the factor time plays the essential role within the damage process an ageing relevant degradation mechanism is present contingently. All occurring and relevant damage mechanisms have to be covered in time and all their harmful results have to be prevented goal-oriented.

Aspects concerning conceptual further development such as changes in the safety philosophy or the evaluation of new status and changes in the state of the art of technological processes are not covered within the scope of Ageing Management (see figure 2). These aspects are treated within the more comprehensive PLIM. Nevertheless an influence and feedback of experience to the corresponding process within AM activities is guaranteed anyhow by the scope of the underlying management process.

3 CLASSIFICATION OF SSC

Within the framework of AM all SSC are being classified into different groups based on the demand of a systematic procedure. Basic classification is done by SSC properties. Thus, relevant SSC are distinguished between mechanical components (class M), electrical components and I&C (class I), buildings and structures (class B) and auxiliary / operating materials, additionally.

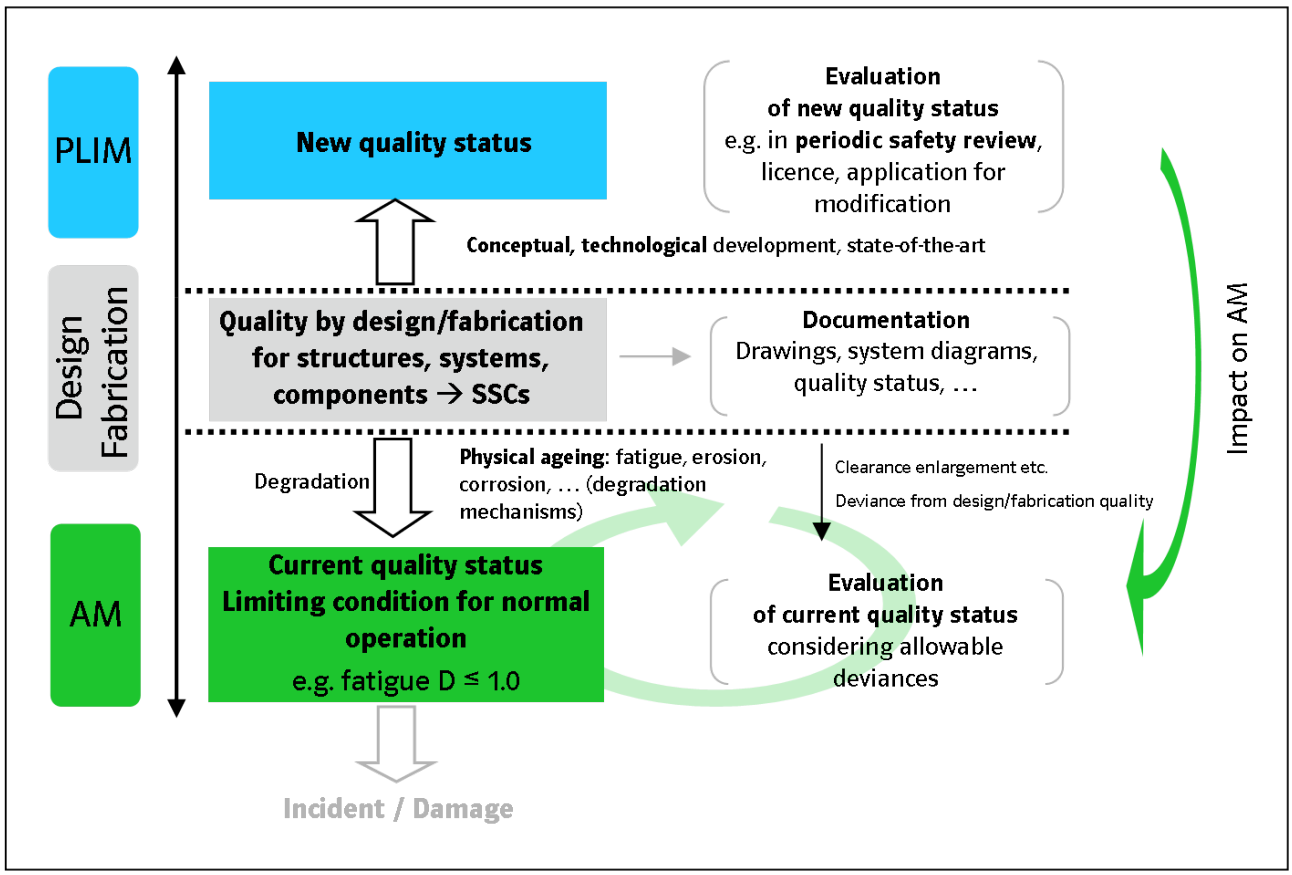

Figure 2. SSC status evaluation during lifetime.

3.1 Safety requirements

A more detailed differentiation depending on SSC's safety requirements is done accessorily, see figure 3. For components belonging to the first group premature ageing effects have to be avoid respectively minimized. Safety requirements for this group are highest while surveillance of root causes and consequences of degradation mechanisms are the corresponding applicable measures. The quality of SSC has to be guaranteed in order to exclude failure by all means. This group with highest safety requirements only exists for components belonging to the mechanical group such as the reactor pressure vessel (RPV), leak-before-break-systems and other classified fatigue significant components (group M1). Subsequently in this paper more detailed aspects on thermal fatigue for components belonging to group M1 will be mentioned in detail, later on.

The second group covers all SSC where degradation effects have to be minimized in order to maintain required component quality for redundant components. Safety requirements are high while preventative maintenance is the appropriate measure. A single case failure resulting in a SSC failure is no safety problem and is admitted due to system's redundancy design. But common cause failures within this group of SSC are not acceptable and have to be excluded by adequate measures. Components like safety relevant valves, pumps, vessels (group M2), components with functional requirement in emergency / faulted conditions (group I2.1) and building structures with specific requirements for emergency / faulted conditions (group B2.1) belong to this group. Other SSC can be classified into the second group also based on specific safety or availability relevant reasons (group I2.2, B2.2). In addition other components can be upgraded to the next higher class by means of increasing availability or safety reasons. The way of classification gears to the "integrity concept" within the framework of the German KTA standard no. 3201.4 and is according to the recommended classification by the German Reactor Safety Commission (RSK).

All other SSC belonging not to first or second group are classified into the third group accordingly. Here a component replacement after failure is one advisable measure. Hence, maintenance activities are condition and failure oriented. All SSC being classified into group 3 are not covered within the framework of AM and belong to the scope of PLIM as a matter of course.

Component Criteria	Safety Requirement / Measure	Objective
Group 1 → "avoid / minimize premature ageing"	**highest** surveillance of root causes and consequences of degradation mechanisms	„guarantee" required SSCs quality, SSC must not fail: RPV, LBB-Systems, others (specific safety or plant availability reasons?)
Group 2 →"minimized degradation effects"	**high** preventive maintenance	"maintain" required component quality, for redundant components -> single case failure no safety problem, no common cause acceptable: valves, pumps, E/I & C-components, building, others
Group 3 → "component replacement after failure"	**low (no)** condition/failure orientated maintenance	redundant SSCs (single case failure is no safety problem): valves and others

Figure 3. General classification of SSC.

3.2 SSC group M1

As mentioned previously for group M1 SSC premature ageing and life time limiting effects have to be avoided respectively reduced to a minimum level. SSC must not fail within operating time by means of highest safety requirements. For PWR type NPP passive mechanical components like the RPV, main coolant line, surge line and pressurizer are classified into this group for example. Additionally a limited number of other components belonging to the pressure boundary is counted among group M1.

In order to control each relevant degradation mechanism the application of comprehensive surveillance measures and proactive monitoring of root causes is necessary to guarantee the required component quality. Thermal fatigue is one significant long-term degradation mechanism which can not be avoided completely. Thus lifetime limiting effects and mechanisms have to be reduced to a minimum level. Within this context surveillance of thermal loading as a main root cause leads to an extensive understanding of operational loading. Detailed surveillance measures of mechanical group 1 components and corresponding analysis will provide reliable information regarding to a component specific fatigue rate.

4 SURVEILLANCE MEASURES OF MECHANICAL GROUP 1 COMPONENTS

4.1 Temperature measurement

A component based fatigue evaluation requires a detailed assessment of measured data. Fatigue of NPP components is driven by thermal loading mainly. Therefore, the fatigue monitoring system is predominantly based on temperature measurement. Piping systems are usually instrumented with permanent thermocouples at the outside of the pipe wall for the surveillance of thermal-cyclic loads such as plug type transients and thermal stratifications. During recent years of operation these measuring information has been reviewed and adapted, leading to comprehensive, representative and global information of existing thermal loadings.

To guarantee an adequate measurement of all relevant loads acting to the fatigue relevant regions of a piping system, e. g. nozzles, pipe bends or junctions, thermocouples have to be installed as close as possible to those locations. At local variations in wall thickness, for instance at nozzles, the thermocouples need to be installed in the pipe section with the smaller wall thickness to ensure that fast changes of temperature can be

measured with sufficient accuracy. On the other hand long horizontal pipe sections can require several measuring planes along the pipe run for detection of transient stratifications.

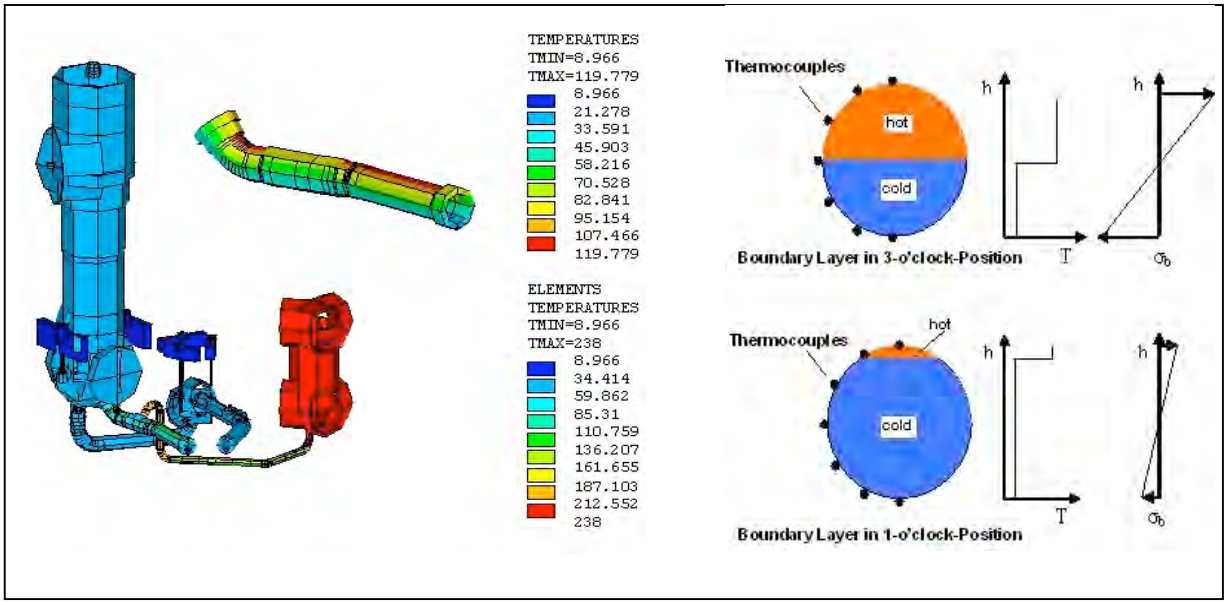

Figure 4. Temperature measurement for adequate detection of thermal stratification.

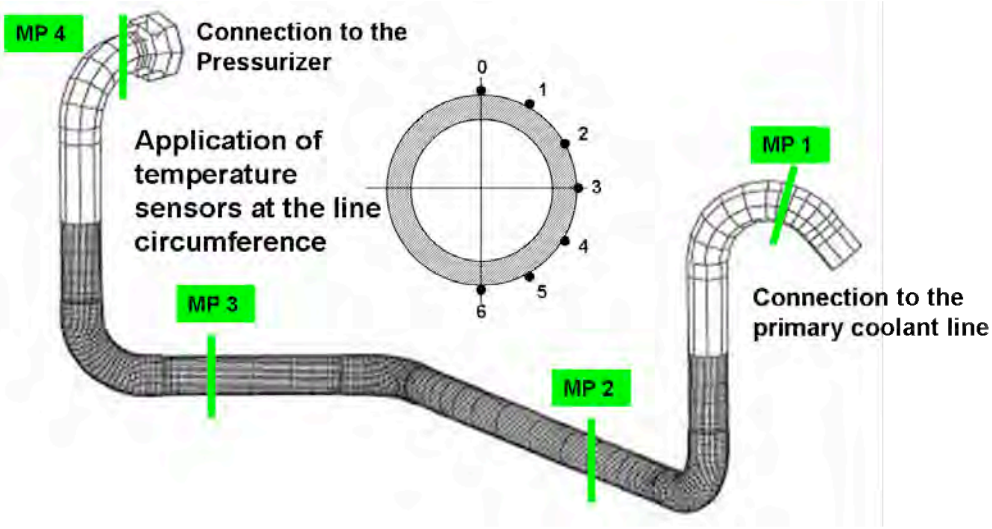

Figure 5. Position of measuring planes at the surge line.

The number of thermocouples required at the circumference of the pipe depends on the expected type of thermal loading: If only plug type transients can occur, one thermocouple would be enough to detect the relevant parameters. Nevertheless, in practice it is usual to attach two sensors at minimum. But if stratifications have to be characterised a larger number of sensors is needed, usually seven at the circumference, see figure 4.

4.2 Example: Surge line of PWR designed NPP

The surge line of PWR designed NPP is known to be sensitive to thermal stratifications due to in-surge and out-surge events coming from water level variations in the pressurizer. To detect these loads four

thermocouple sections (measuring planes - MP) are positioned at the line each consisting of seven sensors, see figure 5.

As an example, figure 6 gives the plot of temperatures measured within the period of one year in 12-o'clock- and 6-o'clock-position captured at one of the thermocouple sections. Additionally, the corresponding stratification is plotted. Since the threshold value of fatigue relevant temperature stratifications at the surge line was identified to be 70 K, there are no fatigue relevant loads during plant operation. Fatigue relevant loads only occur during start up and shut down process of the NPP, basically.

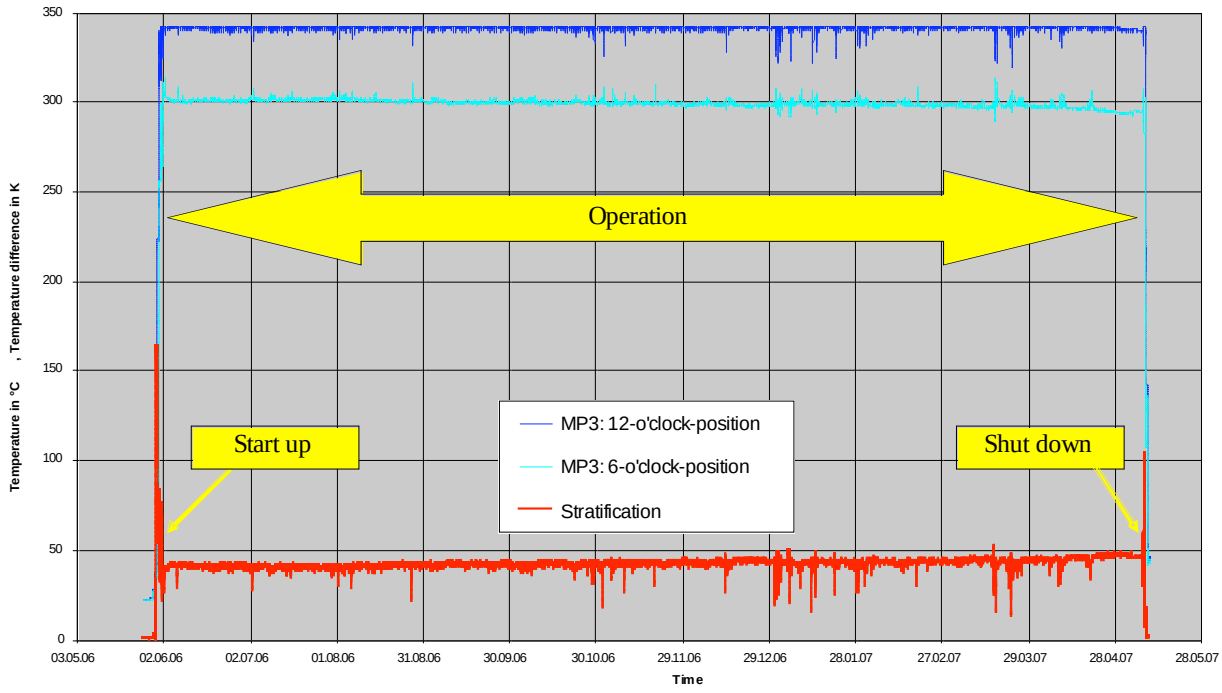

Figure 6. Temperature and thermal stratification at the surge line.

4.3 Detailed analysis

At NPP construction time predicted fatigue usage factors were defined based on calculations of specified transients. So various uncertainties, resulting due to the fact that precise operation conditions were not known in detail at plant design time, are part of this predicted end-of-life fatigue usage factors. In comparison to detailed analysis being based on real measured values, it is obvious that predictions adapted on specified loads will lead to more conservative results mostly. But nevertheless, in a small number of cases the registered events show new effects, not accounted for at design state, so that analyzing these data leads to substantial progress in knowledge about component integrity assessment. Additionally these technical experiences on measured thermal loading will give a direct input in optimizing operation mode of relevant SSC and subsequently minimizing fatigue relevant stresses.

Analysing measurement data of a sufficient time period, typical reference transients are determined representing the component specific loadings during operation conservatively. Based on these reference transients temperature classes are defined for load cycle counting. A detailed Finite Element analysis is performed for this set of load transients to find the corresponding fatigue usage factors and the above mentioned threshold value of fatigue relevance. Table 1 gives the temperature classes and corresponding fatigue usage factors for the surge line of a German NPP on the basis of the design fatigue curve according to the German KTA standard no. 3201.2 as an example. This way, it is possible to find a conservative value of the contribution of every individual measured event to the overall fatigue usage factor based on the maximum recorded temperature stratification during the event.

Table 1. Temperature classes and corresponding fatigue usage factors for the surge line.

Temperature class	Admissible load cycles	Fatigue usage factor per load cycle
70 K < ΔT ≤ 100 K	177400	$0{,}0564 \cdot 10^{-4}$
100 K < ΔT ≤ 130 K	40810	$0{,}245 \cdot 10^{-4}$
130 K < ΔT ≤ 160 K	5130	$1{,}95 \cdot 10^{-4}$
160 K < ΔT ≤ 180 K	1140	$8{,}77 \cdot 10^{-4}$
180 K < ΔT ≤ 200 K	425	$23{,}5 \cdot 10^{-4}$

4.4 Lifetime prediction

With the aid of the measured value based load cycle counting and fatigue usage contribution of each load cycle (see Table 1) the fatigue usage factor for the time period covered by the in-service measurement is determined. The time without installed measurement is considered by linear extrapolation in conjunction with an allowance for uncertainties, if any. This way a conservative current fatigue usage factor is calculated covering the whole service time since commissioning. For the surge line this leads to a fatigue usage factor of $U_{2007} = 0{,}077$ by the end of the year 2007. This current fatigue usage factor, based on measurement data, is being updated every year as a matter of course.

In addition, the expected fatigue usage factor for end-of-life (EOL) is determined in an analogical manner. For the above mentioned surge line one gets $U_{EOL} \approx 0{,}1 < U_{admissible} = 1{,}0$. Therefore, it is predicted that the admissible lifetime of the surge line would be ten times the planned service life of the power plant.

5 CONCLUSION

The presented paper points out main aspects on Ageing Management (AM) covering all safety relevant systems structures and components (SSC). In more detail, within the German understanding a clear differentiation between Plant Life Management (PLIM) and Ageing Management is done. PLIM refers to the entire NPP (primarily under utility responsibility) in order to guarantee safe operation and additionally to increase plant availability while minimizing unscheduled outages and planned downtimes. In contrast to this, AM refers to safety relevant SSC only and is done under the supervision of the responsible safety authority. Within AM operational ageing degradation mechanisms like physical and material ageing phenomena are covered due to the fact that a sufficient knowledge of stresses and strains are indispensable for a precise prediction of the lifetime and subsequently for safe and reliable operation. Suitable and applicable assessment tools like comprehensive temperature surveillance measures are indispensable, especially for group M1 components comprising highest safety requirements and highest operational standards to surveillance measures.

Measured values are evaluated on a per-component-basis with regard to relevant temperature loads and their corresponding number of occurrences. This way bookkeeping of load cycles is performed to determine current fatigue usage factors. In the presented paper measurement values of the surge line of PWR designed NPP are shown due to the fact that this component is known to be sensitive to thermal stratifications. In load cycle counting lists for each registered event a partial fatigue usage factor is stored. Those load cycle counting lists are also prepared on a per-component-basis by analyzing the temperature and stress distributions for reference transients. This procedure guarantees both adequate realism and necessary conservatism.

The presented approach shows the framework of operational applied surveillance, measuring, and analysing methods in order to obtain a detailed, reliable and exact knowledge of the system’s status. Herein

the surveillance of thermal loading as one important root cause for ageing relevant material degradation mechanisms is the basis for further actions. A detailed knowledge of the loading history based on measured values will lead to the reduction of conservative results. Additionally, the assessment of new and possibly unspecified loading events including a statement of the influence to a SSC specific fatigue usage factor is feasible.

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