NUMERICAL REDUCTION OF CUMULATIVE FATIGUE USAGE FACTORS – ONE MEASURE TAKING ENVIRONMENTALLY ASSISTED FATIGUE INTO ACCOUNT IN THE FRAMEWORK OF GERMAN KTA

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ABSTRACT

During design of NPP (nuclear power plant) predicted cumulative fatigue usage factors (CUF) were defined based on specified transients. In German NPPs various temperature measurement planes are applied at fatigue relevant positions among others to calculate actual CUF based on real temperature loads.

The range of methods to calculate component specific CUF goes from conservative approaches based on the evaluation of the specific events up to numerical Finite Element simulations. Based on the level of detail the conservatism decreases while the complexity of the model increases.

German KTA consider the intensively discussed topic of environmentally assisted fatigue (EAF) by introducing so called attention thresholds for the CUF. One way to take this into account is to apply sophisticated procedures and to show that the numerically calculated CUF is below the defined attention thresholds. The article presents an overview of the whole framework taking into account operational temperature measurements, sophisticated fatigue evaluations and EAF.

INTRODUCTION

Thermal transients are one of the most lifetime limiting events for primary piping components in NPP. During design phase the fatigue assessment provides CUF based on conservatively specified loads. Specified events have to cover the whole life time of the systems, structures and components (SSC) considering changes in pressure and thermal loading including very rare service load events. Taking sophisticated methods into account, re-evaluation of CUF is one appropriate method to precise the CUF. This requirement could be motivated by different reasons. For example respecting new operational transients like stratifications is one possibility. On the other hand, in German KTA (e.g. No. 3201.4), the EAF is under consideration in terms of the introduction of so called attention thresholds for the CUF. It is defined that, if the CUF, calculated without consideration of EAF, exceeds the threshold, further measures like for example non-destructive in-service inspections including fracture mechanical analysis or detailed assessment procedures (e.g. as described within NUREG/CR-6909) have to be taken into account.

Hence, application of sophisticated methods is one appropriate measure to evaluate the cumulative fatigue usage factor on a detailed level.

TEMPERATURE MEASUREMENTS

Since beginning of operation of German NPP, various temperature measurement planes were initially applied or have been installed at fatigue relevant positions of primary circuit components, allowing an evaluation of real operating temperature transients. Figure 1 on the left shows an example of the measurement plane setup at the surge line of a PWR schematically. A picture of the corresponding measurement plane 2 is shown on the right side of Figure 1.
At PWRs operated by E.ON Kernkraft GmbH all fatigue relevant locations of the primary circuit are observed by temperature measurement installations. Additionally various temporary operation accompanying measurements are evaluated. Hence, components like the main coolant line, the surge line, the pressurizer including the spray-nozzles, spray lines, components of the volume control system, nozzle areas of the emergency core cooling system, components of the residual heat removal system and feedwater nozzles at the steam generator are monitored and analyzed comprehensively according to the regulatory requirements of the German KTA. While the general philosophy of the KTA, especially with respect to calculation procedures for primary circuit components, is based on the ASME Code, the mentioned requirements in terms of operation monitoring exceed the American standard.

During recent years of operation this measuring information has been reviewed and adapted, leading to comprehensive, representative and global information of existing thermal loadings. Based on measurement planes, detailed surveillance of thermal-cyclic loading such as plug-flow transients and thermal stratification is accomplished on the one hand. On the other hand the information is used to optimize the plant’s behavior in general e.g. in terms of minimizing fatigue events by operational measures. Based on temperature measurements for example the point in time at which the main coolant pumps stop during shut-down of the plants has been optimized. Thus, significant stratifications in the surge line could be reduced. More details about applied temperature measurement can be found in PVP2013 – 97395.

Figure 2 shows the temperature measurements in the surge line for measurement plane 3 during a year. It can be easily seen, that fatigue relevant stratification events only occur during start-up and shut-
down of the plant. The most relevant loadings of PWR surge lines are caused by in-surge and out-surge events of coolant medium from the pressurizer into the main coolant line or vice versa. These events occur when the main coolant pumps are turned off. Initiated by the mass transfer events, temperature stratifications take shape in the surge line and decline later on. So, the relevant loading parameters are the maximum temperature difference in pipe cross section (stratification), the detailed distribution of temperatures in pipe circumference as well as the temperature gradient.

CUMULATIVE FATIGUE USAGE FACTORS

The existence of real temperature measurements allows a detailed view of real temperature transients at fatigue relevant locations. This set of data provides a much more precise view on real SSC loading scenarios in comparison to conservatively determined reference transients during design phase. In terms of comprehensive temperature measurement data, re-evaluating of cumulative fatigue calculation provides a detailed component and location specific knowledge of the cumulative usage factor.

Basis for fatigue evaluations are in general loading transients which where specified during design stage. This end of life (EOL) related CUF are calculated based on load cases specified for NPP operation, considering numbers of load cycles which are conservatively specified for the whole lifetime. Additionally, also load cases with a very low probability of occurrence (abnormal operation or emergency cases) are included in the fatigue analysis, Thus, CUF calculated this way contain portions from load cases that will occur with significantly fewer cycles than considered or even never. Furthermore, in general specified temperature transients conservatively cover real transients with respect to their amplitude and their temperature gradient. The goal of fatigue analyses based on specified loads is to show at design stage, that the CUF calculated with conservative assumptions for EOL is less than 1.0, and not to calculate a most accurate CUF by means of a sophisticated analysis procedure.

Regulatory framework in Germany requires a continuous operational accompanying long term fatigue evaluation. Thus, a periodical determination of actual CUF is performed for fatigue relevant components continuously. Basis for the evaluation are measured transients. Therefore, the actual component and location specific CUF is calculated under consideration of both real loads and real numbers of cycles. On the basis of these data, it is a widely used conservative estimation method to calculate actual CUF by means of the so called “rough fatigue analysis”. Using this method, any variation of temperature in time is conservatively assumed to be a thermal shock (for every temperature gradient). In addition, the stresses caused by any measured thermal stratification are calculated for a pipe with fixed support on both sides (independent on the actual flexibility of the pipe work).
The most effective way to calculate more realistic CUF is the definition of component specific reference transients (CSRT) on the basis of measured loads together with well-defined counting conditions. Their use in place of specified transients or even of the rough fatigue analysis leads to a significantly reduced level of conservatism in the fatigue analyses, while keeping the computational effort on an acceptable level. Hence, in contrast to the rough fatigue analysis, taking into consideration actual loads defining CSRT (Figure 3) for calculating stresses, much more realistic CUF will be calculated. Nevertheless, because of the increasing complexity of the evaluation and calculation procedure and to reduce the computational effort, it is necessary to make conservative assumptions also with this more precise procedure. Furthermore, the procedures to calculate the fatigue relevant strain amplitudes contain conservative approaches, too, since most fatigue calculations are performed as simplified elastic-plastic analyses.

ENVIRONMENTALLY ASSISTED FATIGUE

Environmentally assisted fatigue (EAF) is internationally being discussed since several years, as for example in a comprehensive format in NUREG/CR-6909 in by Chopra et. al. in 2007. The empirically derived correction factor $F_{en}$ as defined there summarizes observed influencing factors of limiting fatigue lifetime. Thus, the plain cumulative fatigue usage factor $CUF$ being defined without the consideration of EAF has to be multiplied by the empirically derived $F_{en}$ correction factor. The result is a fatigue usage factor which takes EAF into account

$$CUF_{Fen} = F_{en} \cdot CUF.$$ (1)

It can be easily seen, that the $F_{en}$ correction factor has a large influence on the numerically determined cumulative fatigue usage factor due to the multiplicative influence. Thus, the calculation of the $F_{en}$ correction is as important as the plain cumulative usage factor itself. The quantification of the correction factor and subsequently the impact on the component specific fatigue assessment highly depends e.g. on the geometry of the SSC, the loading scenario etc.

![Figure 4: Comparison of Fen Formulas.](image)

Currently the whole procedure itself as well as the set of numerical correction factors are being revised. Various publications dealing with the influence of LWR coolant environment have been
published and partially controversial discussed. Anyhow, the possibility to quantify EAF is accepted in general, while final answers on the real amount of the effect and transferability of laboratory data to plant conditions are still pending. Existing numerical calculation procedures have a similar approach and set of formulas in common. But different basic parameters lead to significant differences when numerically deriving the $F_{\text{en}}$. Figure 4 shows for example different approaches for the determination of the numerical correction factor. Due to the fact that e.g. NUREG/CR-6909 defines the phenomena itself, but states no clear guidance for evaluating the $F_{\text{en}}$ in application, EPRI recently published a technical report (No. 1025823) in order to fill this gap.

It is the opinion of the authors, that the latest approach described at the ASME Code Meeting in Nashville in 2012 by Chopra et.al is the most feasible one. Describing all approaches and calculation procedures in detail would be out of the scope of this paper. More details are described e.g. in publications like PVP2012-78107 or PVP2013 – 97397.

Nowadays the consideration of EAF is applied in Codes and Standards like ASME and the German KTA (e.g. No. 3201.4), although the lifetime of German NPPs is limited to less than 40 years of operation based on political reasons. In fact the average operating years of the German fleet are below the design lifetime of 32 full load operating years. Internationally, the consideration of EAF is taken into account for new builds and license renewal processes only. However, in the framework of the German KTA, so called attention thresholds are used to allow for EAF in general. In terms of this procedure, attention threshold values for ferritic materials and for austenitic materials were defined in the KTA. When exceeding these values, additional measures like non-destructive testing (NDT) including fracture mechanical calculations, analytical evaluation of the influence of EAF by means of the mentioned reduction factor ($F_{\text{en}}$) or alternative methods should be applied.

**SOPHISTICATED METHODS TO RE-EVALUATE CUF NUMERICALLY**

Sophisticated methods to evaluate the CUF based on operational measurement, as described in the previous chapters, are one possibility to precise, and possibly reduce, the CUF. Therefore, any CUF both for EOL and “actual CUF” include a certain level of conservatism, which can be reduced by a detailed analysis. In some cases, the additional effort for this more detailed evaluation can be considerable. On the other hand: If the resulting CUF are less than the attention thresholds according to German KTA, it is possible to avoid the above mentioned measures such as non-destructive testing or detailed calculative assessment of EAF. Going below the CUF threshold values is one approach in order to take the topic of environmentally assisted fatigue into account. Therefore, detailed evaluation of temperature measurements is carried out, providing a comprehensive set of input data for Finite Element calculations. Following examples show, that this could result into a significant reduction of CUF below the above mentioned threshold value. Existing measurement data allows the re-evaluation of CUF taking into account state-of-the-art methods like elastic-plastic determination of plasticity correction factors and consideration of the inertia of thermocouple installations.

For instance, the “actual CUF” of a surge line was calculated using a conservative assessment procedure to be 0.61. A detailed and more sophisticated evaluation of the monitored load data leads to a covering reference transient based on measurements. In combination with a sophisticated FE-based stress and fatigue analysis a reduction of the “actual CUF” to 0.19 was achieved (Figure 5). For this case it should be mentioned that this value consists of two portions. The first one being the CUF representing the time before installation of the long term fatigue monitoring (LTM) including a couple of conservative assumptions: $\text{CUF}_{\text{before LTM}} \approx 0.18$. The second one is based on the above mentioned detailed evaluation considering actual measurements: $\text{CUF}_{\text{LTM}} \approx 0.01$. Both portions of CUF represent time periods of almost the same duration indicating the potential to further reduce this actual CUF (by reducing the first portion of CUF).
An additional example for possible reduction of fatigue usage factors is the pressurizer nozzle of an auxiliary spray line. Since about 10 years, “actual CUF” have been determined based on conservative component specific reference transients. This way the “actual CUF” results in \( CUF_{\text{conservative}} = 0.3 \). Taking more reference transients into account and performing a fully detailed fatigue analysis the actual CUF can be reduced by a factor 10 to \( CUF_{\text{detailed}} \approx 0.03 \) (Figure 6).

Both examples state, that sophisticated methods are a feasible procedure to assess the CUF on a detailed level. In both cases the described approach is based on the evaluation of measured temperature transients while taking additional conservative assumptions, like e.g. the application of actual loads defining CSRT into account. Summarized, sophisticated state-of-the art approaches are giving a much
more precise picture of the component and location specific CUF while still incorporating significant conservatism.

CONCLUSION

In contrast to international practice, German KTA require an continuous evaluation of fatigue assessment considering environmental effects in the framework of operational accompanying long term fatigue evaluation. In order to do this it has to be shown that CUF in fatigue relevant areas do not exceed certain threshold values. In this context it is necessary to determine realistic CUF instead of using overly conservative values. Therefore in this publication the determination of the CUF based on state-of-the-art methods and procedures is shown. By means of two examples it is demonstrated, that detailed evaluation of temperature measurement data yields to significant reduction of component specific CUF.

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