EUROPEAN
TECHNICAL SAFETY
ORGANISATIONS
NETWORK

TECHNICAL REPORT

COMPARISON OF RULE-MAKING AND PRACTICES

SPECIAL TOPICS OF INTEREST IN THE FATIGUE EVALUATION FOR NPP

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CONTENTS

1 INTRODUCTION

Fatigue is one of the major degradation mechanisms of pressurized components in NPPs that has to be taken into account in the design phase and pursued in the framework of ageing management during service. This includes monitoring, in-service inspections and eventually new, more refined analyses, mitigating actions, or replacements. Therefore, it is an important topic for plant safety in all countries with operating reactors and within the focus of any TSO.

As the total area of fatigue evaluation for components in NPP appears to be too vast and complex to be tackled in a short report, the EG2 decided to focus on special topics of common interest that may not yet be addressed or adequately included in the regulations of all the participating countries. These are the following ones:

1. Extension of the fatigue curves to high cycles
2. Environmentally assisted fatigue
3. Analysis of mixing zones
4. Analysis of stratification
5. Approach to fatigue for long-term operation (LTO) of plants

After a general introduction to fatigue of metallic components, the approaches to these five topics are addressed separately in the following chapters with subchapters for each country. Conclusions are drawn for each topic at the end of each chapter.

2 GENERAL INTRODUCTION TO FATIGUE

2.1
Short phenomenology of fatigue damage

In general, material fatigue is an irreversible process of progressive localized change of the microstructure, occurring in a material subject to fluctuating stresses and strains. This may culminate in cracks or complete fracture after a sufficient number of fluctuations. The following descriptions of the fatigue mechanisms and their analyses applies to metallic materials, where plastic deformation is realized by dislocation movements.

Fatigue mechanisms are relatively simple when viewed at a large scale but are more complex when viewed at smaller scales. We generally distinguish three phases in the fatigue damage mechanism, i.e. the crack initiation phase, the crack propagation (or crack growth) phase and finally the failure of the component.

The initiation phase involves dislocation creation, movement and local culmination, eventually forming persistent slip bands that nucleate short cracks at the surface. Under uniaxial tensile stress the plane of maximum shear stress is at 45° to the surface, so slip develops on favorably oriented planes at about this angle. Resistance to crack initiation depends strongly on surface roughness, residual stress and environment.

When the initial crack reaches a critical length, it changes direction and propagates normally to the maximum principal tensile stress. This initiates the crack propagation phase. The propagation mechanisms involve ductile deformation at the crack tip as it opens and closes under the fluctuating stresses and strains. At each cycle, the crack tip blunts, and fatigue propagation occurs because unloading re-sharpens the crack tip, leading to an increment of crack propagation. Fatigue crack propagation is in fact a consequence of irreversible plastic deformation at the crack tip. During this phase, the most striking feature of the fracture surface created during the crack propagation is the presence of distinct line markings (striations), parallel to each other, and normal to the local direction of crack propagation.

As the propagation of the fatigue crack continues, progressively reducing the load-bearing cross-section of the component, it eventually weakens it sufficiently that complete fracture can occur by only one more loading. This constitutes the last phase of fatigue damage.

2.2
Fatigue design curves in the codes

For the design analyses of components in NPP, only the first phase of fatigue before any crack might initiate will be considered for their operation. Therefore, this report focusses on this first phase. A fatigue crack growth analysis might be performed showing that a postulated flaw will not grow (significantly) during further service. This is seen as a flaw tolerance analysis. Such an analysis might also be performed for a detected flaw that was created by manufacturing or during service to justify further operation of the component until repair of the flaw or the end of life of the component.

The greater the applied stress or strain range for components under cyclic loading, the shorter the fatigue life, i.e.

the number of cycles until failure. As the damage is cumulative, the metal does not recover when rested, unless heat treated at elevated temperatures, where dislocations can annihilate each other, or, at even higher temperatures, recrystallization occurs. Yet, these temperatures are generally above operating temperatures of the structures or components. Therefore, in fatigue analysis, a cumulative us-age factor (CUF) of a location is defined, that sums up the damage created by different subsequent fluctuating stresses or strains of the structure at this location. In the simplest model, the Miner rule is applied, where the partial CUF calculated for different regimes of stress or strain range are just added up to the total CUF. Failure of the structure may happen only at a CUF ≥ 1. /GUT 14/

Material performance is commonly characterized by a stress range versus number of cycles curve, also known as a Wöhler curve. This is a graph of the amplitude of cyclic stress range (ΔS) against the number of cycles to failure (Nf) in logarithmic scale. Fatigue life is the number of stress or strain cycles of a specified amplitude that a specimen sustains before failure occurs. The design curves have been developed from the best–fit curves to the experimental cyclic strain vs. Nf data using reduction factors. In ASME III, the "old" design curve is composed of two overlapping curves, one created by reducing the experimental best-fit curve by a factor of 2 on strain (or stress) amplitude and the other by a factor of 20 on the number of cycles, whichever is more conservative at any point of the curve /ASM 69/, see figure 1 for illustration.

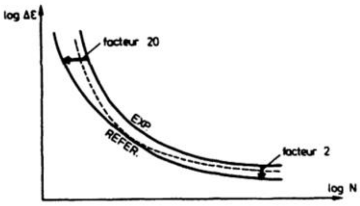


Figure 1 : Construction of the design curve "REFER" on the basis of the best fit to the experimental curve "EXP", see text above for explanations (illustration from /LAR 86/).

According to /ASM 69/ these reduction factors shall cover the stage between crack initiation and loss of specimen strength detected at Nf and should also consider different parameters influencing the transposition of the data from polished specimens to real components, e.g. data scatter (including material variability), surface finish, size and geometry, residual stresses, and to some extent also an effect of the environment that may reduce fatigue life being more aggressive than air /ASM 69/.

According to /NUR 18/ the factors of 2 and 20 are not safety margins but rather adjustment factors that should be applied to the small–specimen data to obtain reasonable estimates of the lives of actual reactor components. These factors were intended to account for data scatter (including material variability) and differences in surface condition and size between the test specimens and actual components.

According to /COO 92/ cited in /NUR 07/, the factor of 20 on life was regarded as the product of three subfactors:

- Scatter of data (minimum to mean) 2.0
- Size effect 2.5
- Surface finish, atmosphere, etc. 4.0

Although these factors were intended to cover such effects as environment, /COO 92/ further states that the term "atmosphere" was intended to reflect the effects of an industrial atmosphere in comparison with an air-conditioned laboratory, not the effects of a specific coolant environment.

During recent developments, on the one hand a lower reduction factor of 12 on the number of cycles was justified to achieve less conservative design curves, on the other hand environmental factors were introduced to explicitly account for the effect of an environment being much more "aggressive" than air thereby reducing fatigue life significantly /NUR 07/.

Fatigue design curves in the different codes, e.g. in ASME III /ASM 17/, Appendix I are generally based on strain–controlled tests of small polished specimens at room temperature in air. The fictitious stress is then obtained by multiplying the strain by Youngs modulus E. Strain–controlled tests are easier to perform than stress-controlled tests, yet failure as total rupture of the specimen appears to be ill defined in strain–controlled tests. Therefore, failure (Nf) is generally defined as a significant loss of strength of the specimen, e.g. by 25%, due to crack formation /NUR 18/. Per definition CUF = 1 at any point of the design curve ΔS(Nf).

The approach of /PNA 86/ to determine the stress range versus number of cycles curve is substantially different. This approach was adopted in Ukraine without modifications and also in the Czech standard /NTD 20/ with some modifications. It is not based on fatigue tests, but on theoretical considerations, yet validated by experimental tests.

The fatigue curves are expressed as the sum of two curves: an elastic (high cycle) curve and a plastic (low cycle) curve. The plastic curve is based on parameters of the tensile test at fracture. The elastic curve is based on the endurance limit. Finally, the fatigue curves are expressed analytically, and they are dependent only on the common tensile properties (Young modulus, yield stress, ultimate strength and reduction of area) and on a coefficient of asymmetry of the loading cycle. Finally, it means, that the fatigue curve in the approach of /PNA 86/ is different for each material and depends on temperature. Similar to the ASME approach, safety factors on strain (or stress) amplitude and on the number of cycles are applied. The most common safety factors are 10 on the number of cycles and 2 on strain, but there are also different specific safety factors, e.g. for bolts. In additional to the above-mentioned formulae, some "generic" fatigue curves are included both in /PNA 86/ and in /NTD 20/ for simplified analyses. An example of such a "generic" fatigue curve for austenitic stainless steel from /PNA 86/ is shown in Fig. 2.

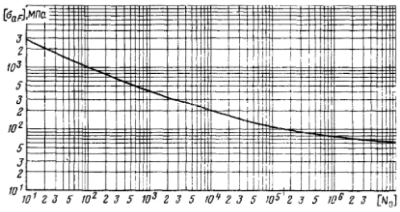


Рис. 5.6. Расчетная кривая усталости сталей аустенитного класса до $T=723$ K (450 C)

Figure 2: Fatigue curve (dependency of fictitious stress amplitude on number of cycles) for austenitic steel up to 450 °C according to /PNA 86/.

3

EXTENSION OF THE FATIGUE CURVES TO HIGH CYCLES

3.1

Introduction

Wöhler curves are traditionally limited to 106 or 107 cycles for practical reasons: tests are difficult and time consuming and such high numbers are rarely considered in technical applications. Furthermore, some materials exhibit a fatigue or endurance limit, i.e. a strain or stress amplitude below which continued cycling does not lead to structural failure whatever the number of cycles. These materials show a straight horizontal line of the ΔS(Nf) curve if extended to cycle numbers > 106. This is generally assumed for ferritic steels.

Other materials do not show such an endurance limit, e.g. austenitic stainless steels. For these materials the Wöhler curve continues to drop until very high numbers of cycles. For these materials the term “fatigue strength” indicates the stress range at which failure may occur after a given number of cycles, e.g. 106. If a larger number of cycles shall be analyzed for these materials, the traditional experimental Wöhler curves and the related design curves should be extended to this high cycle regime. Nevertheless, a kind of endurance limit might also exist for these materials, yet at a lower stress range than the fatigue strength at 106 cycles.

At some locations of NPP components, mostly made of austenitic stainless steel, up to 1011 cycles may occur due to vibrations or thermal fatigue. For the assessment of the resistance of these locations against high-cycle fatigue, extension of the fatigue curves to such a high number of cycles is necessary. In different countries different approaches are used for such an extension. Some approaches are based on an endurance limit, while other approaches use "extended" fatigue curves with decreasing allowable stress amplitude depending on the number of cycles.

The following questions were considered in the following subchapters:

- Who uses extended fatigue curves for which application?
- Is there any regulatory requirement?
- What is the need from a safety point of view?
- How do the curves look like?
- Where do the curves stem from (e.g. experimental basis, other codes)?
- How are they applied (margins, safety factors)?

3.2

Belgium

Extension of the fatigue curves to high cycles has not yet been considered in Belgium. Issues related to high cycles have been resolved otherwise (in particular through specific inspections).

3.3

France

France uses an extension of the fatigue curve from 106 to 1011 only for thermal fatigue of stainless steel and nickel alloys. For ferritic steels there is no need for an extension.

There is no specific regulatory requirement. But according to the French law, the utility must control all the risks of the NPP.

Areas “sensitive to thermal fatigue” are determined and included in inspection plans. These are areas where CUF > 1. CUF is the cumulative usage factor calculated according to a process close to the process developed for mechanical fatigue. The following curves are used in France. They stem from the ASME code 2003 /ASM 03/ and are not yet introduced in the French code RCC-M /RCC 18/. In case of welds without leveling, curve C is used divided by a stress concentration factor Kf = 1,5.

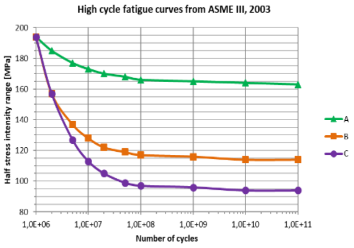


Figure 3: High cycle fatigue curves A, B, C from ASME III (2003) as used in France: Curve A applies for good surface finish (Ra ≤ 3,2 µm)

Curve B is not used in France

Curve C applies for raw surface finish (mixing zones of French auxiliary systems) or a high level of mean stress.

3.4
Germany

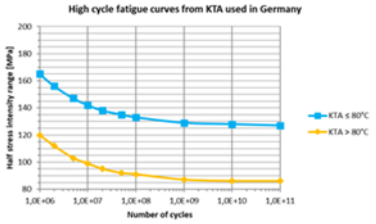
The design fatigue curve for ferritic steels still ends at 106 cycles. The curves for austenitic stainless steels were extended to 1011 cycles in KTA standards for the Reactor Coolant Pressure Boundary and associated systems as well as for RPV internals (i.e. in KTA 3201.2 /KTA 17a/, KTA 3211.2 /KTA 13/, and KTA 3204 /KTA 17b). They may be used for vibrations and thermal mixing zones in exceptional cases. They might also help to define the endurance limit for fatigue of austenitic steels.

The extended curves are not directly required by regulations but integrated in KTA standards that describe generally accepted approaches for licensing and supervising procedures.

Deviant from other data sets like those underlying the ASME curve, some temperature dependence was found. So, there are two curves for T ≤ 80°C and for T > 80°C applicable to the stabilized austenitic stainless steel types 1.4541 (X6 CrNiTi 18 10) and 1.4550 (X6 CrNiNb 18 10) predominantly used in German NPP. The data for the fatigue curves for the steels 1.4550 and 1.4541 shown in the figure below are taken from the table provided in the mentioned KTA standards.

The lower curve for T > 80°C is rather close to the curve in ASME Section III, Appen-dix I, edition 2009b and later. For other stainless steels than 1.4550 and 1.4541 the ASME curve shall be applied. As the ASME Code fatigue design curves given in Mandatory Appendix I to ASME Code Section III, are based on strain–controlled tests /NUR 18/, the stress ranges given in the figures and tables are "pseudo-stresses" calculated by multiplication of the strain range with the Young modulus E. The same procedure underlies the data given in KTA, yet unfortunately using a smaller value of E. Therefore, for a direct comparison of the different curves the stress ranges have to be normalized by the ratio of the Youngs moduli EASME/EKTA = 195/179 = 1,09 see Figure 4, bottom. In fact, for the stainless steels concerned, 195 GPa is a realistic value at room temperature, while 179 GPa is a value attained at about 240°C.

The curves for the German austenitic stainless steel types 1.4541 and 1.4550 are based on experimental tests performed mostly at room temperature and at elevated temperature (at 200 to 350°C). As only few data at elevated temperature and N > 2·106 were available, the curve was extrapolated to merge into the new ASME curve at high cycles.



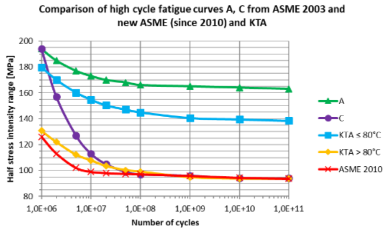


Figure 4:
Top: High cycle fatigue curves from KTA applicable to the austenitic stainless steel types X6 CrNiTi 18 10 and X6 CrNiNb 18 10 for the temperature ranges T ≤ 80°C and T > 80°C.
Above: Comparison of the old and new ASME curves with KTA curves normalized to the Young modulus used in ASME, E = 195 GPa.

The mean curve from experimental data was shifted by SN = 12 to lower cycles and by Sб = 1.79 to lower strain ranges. The two resulting curves were then joined by a lower envelope to these curves to form the design curve. Both factors are not considered as safety factors. They are rather factors covering the influence of different boundary conditions as surface roughness, size, mean stress and sequence of loads as well as data scatter.

3.5
Switzerland

In the context of the Ageing Management KATAM critical areas of components have to be evaluated and observed. A total usage factor CUF has to be calculated

$CUF_{U\ total} = CUF_{design} + \Delta CUF \cdot F_{en}$

where ΔCUF is the usage factor for those loadings not considered in the design. For those loadings already considered in the design, the effect of the environment is supposed to be covered sufficiently by the original analyses.

If CUF_U total is larger than 1 or if the usage factor increase within one year is larger than 0.1, some follow up has to occur. The options for this follow up are similar as already described in the sections for Belgium and Germany.

3.6
Czech Republic

The first fatigue analyses considering environmental effects were performed recently for the RPV of Dukovany NPP (VVER 440). In recent version of /NTD 20/ there are formulae for reducing fatigue lifetime due to environmental effects.

Based on international experience the environmental effects should be taken into account for LTO.

Fatigue tests in environment were performed for a limited number of materials and specimens until now. There are plans to extend the database by national projects and data from the European INCEFA project (Increasing Safety in NPPs by Covering gaps in Environmental Fatigue Assessment). International experience like /NUR 18/ is also taken into account.

Differently to the approach applied in PWRs, the environmental factor is applied by co-efficient multiplying the fictitious stress amplitude. It is in accordance to approach used for other reduction factors (e.g. effect of welding) used in /NTD 20/ and /PNA 86/.

Three different levels of reduction factors can be used according to /NTD 20/. The 1st level means reduction factor (on stress) equal to 1.3 for carbon and low alloy steels and 1.56 for austenitic steels. This level is usually conservative. In the 2nd level the reduction factor depends on the amplitude of the fictitious stress. In the 3rd level the reduction fac-tor depends also on the temperature, sulphur content in the steel, oxygen content in the environment and the strain rate.

3.7
Slovakia

The influence of the environment is not considered for general fatigue analyses, it is only used for crack growth assessment and in the evaluation of flaw acceptability in NPP components. The general fatigue analyses are performed regarding /PNA 86/ and crack growth assessment according to VERLIFE 2008 /VER 08/, Appendix XII, Evaluation of Flaw Acceptability in Components, Chapter 4: Crack Growth Calculation using environmental factors.

3.8
Ukraine

There are no requirements to consider environmentally assisted fatigue in Ukrainian regulations at present. Discussions about the development of new requirements about this subject are in progress.

3.9
Conclusions

The approach to environmental fatigue significantly differs between countries. For some countries, environmental effects are not requested to be taken into account (except for crack growth assessments) or the need to do so is still under discussion. For some other countries, assessing environmental fatigue is only requested for NPPs going for LTO. Finally, in one country, the need to assess environmental fatigue is conditioned to the value of the CUF in air: environmental effects should be considered only if the CUF value exceeds some threshold.

The way to assess environmental fatigue may also differ between countries. Environ-mental effects on fatigue are generally modelled by the consideration of an environ-mental correction factor (as a factor on the number of cycles or on stress range). This factor may be applied in different ways. As a general solution this factor may be applied to the result obtained for the usage factor of each cycle. In some countries, this correction factor is directly applied to the CUF instead of the number of individual cycles as a simplified approach.

Finally, it has to be noted that the calculation of the environmental factors for real transients is rather complex. Moreover, application of factors on old calculations is generally not possible as the necessary data are not available. Therefore, efforts to improve our knowledge on this topic are still ongoing, and some TSOs are actively participating to experimental projects.

One of the aims of the calculations is to update the inspection plan regarding the degradation by fatigue. The result of the inspections will give information about the conservatism of the calculation

4

ENVIRONMENTALLY ASSISTED FATIGUE CYCLES

4.1

Introduction

Environmentally assisted fatigue or corrosion (assisted) fatigue means an effective reduction of the time to fatigue crack initiation and also an acceleration of fatigue crack growth in the presence of a corrosive environment compared to the fatigue life in air under identical mechanical loading conditions. It is caused by the simultaneous and synergistic interaction of cyclic or fluctuating stress and corrosive attack of the material. Such a synergistic effect appears plausible, as fatigue cracking is initiated at the surfaces of a component, i.e. at locations that are also accessible to the environment. In fact, extensive experimental laboratory programs have shown that the fatigue life of steel components is reduced in LWR coolant environments. While there appears to be no clear evidence of such an effect in the LWR plants /EPR 01/, /EPR 14/, there is no consensual explanation for the different behavior in the laboratory and in the plants either. Different loading conditions, hold times, or surface conditions may play a role. /GUT 14/

Since the original fatigue design for NPPs that are currently in operation is based on laboratory data obtained by fatigue tests performed at room temperature in air a re-evaluation of the fatigue life of NPP components in hot water environments appears necessary. As the creation of new fatigue design curves for each pair material/environment is not practical, environmental influence correction factors or correction factors “Fen” were defined based on experimental fatigue tests in these environments.

Fatigue data in air and LWR environments were analyzed by researchers of the Argonne National Laboratory (ANL) for their dependence on different parameters. Four of them were identified as key parameters: strain rate ($\dot{\varepsilon}$), dissolved oxygen content (O), sulphur content in the steel (S), and temperature (T). These parameters are taken into account to evaluate the fatigue life correction factors “Fen” in the ANL model. In this model these correction factors are defined as the ratio of the fatigue life in air at room temperature to the life in the LWR environment, i.e.:

- Fen = Nf (air, RT) / Nf (LWR water).

Resulting from the data analyses in /NUR 07/ the following Fen for austenitic stainless steels and nickel alloys (SS), carbon steels (CS) and low alloy steels (LAS) were developed by ANL:

- Fen (SS) = exp ($0.734 - T'\dot{\varepsilon}'O'$)
- Fen (CS) = exp ($0.632 - 0.101\ S\ T'\dot{\varepsilon}'O'$)

and

- Fen (LAS) = exp ($0.702 - 0.101\ S\ T'\dot{\varepsilon}'O'$).

In these formulas transformed values of strain rate ($\dot{\varepsilon}'$), dissolved oxygen content (O’), sulphur content in the steel (S’), and temperature (T’) are defined, see /NUR 07/, Appendix A. Besides, it is noted in the US American Regulatory Guide 1.207 /RG 07/ that the Fen (SS) should be used in conjunction with the new stainless steel fatigue design curve also developed in /NUR 07/. An extension of the underlying data base and new analyses confirmed the validity of the principal model, only the parameters were adjusted /NUR 18/, /RG 18/.

The following questions may/should be answered:

- Who takes into account any influence of the environment for which application?
- Is there any regulatory requirement?
- What is the need from a safety point of view?
- How is the influence of the environment taken into account (e.g. additional curves, environmental factors, account of hold times)?
- Where do the data stem from (e.g. experimental basis, other codes)?
- How are they applied?

4.2
Belgium

The licensee has to take into account environmental fatigue for NPPs which go to LTO. Regulatory requirements are laid down in /FAN 09/ issued by FANC and Bel V.

The influence of the environment on fatigue is taken into account by using environmental factors (as explained in /NUR 98/, /NUR 99/, and /NUR 07/, /NUR 18/).

In Belgium, the evaluation of the LWR environmental effects for the LTO of Doel 1/2 and Tihange 1 were not limited to the primary components, as done in the USA, but did also encompass components of the secondary circuits that may be sensitive to environmental fatigue. Typical component locations selected for fatigue assessment were the following:

- RPV outlet nozzle,
- Several nozzles of the pressurizer,
- Pressurizer lower head to heater sleeve junction,
- Hot leg surge nozzle,
- Some parts of the reactor coolant pump (such as outlet nozzle);
- Some parts of the charging and let-down lines (chemical and volume control system (CVCS)),
- The regenerative heat exchanger (CVCS),
- Some parts of the feedwater lines,
- Some unit specific locations.

The selection of those components was based on the CUF determined in air for 50-year operation, on the level of conservatism of the last fatigue analyses and on the estimated value of the environmental correction factor corresponding to the most severe thermal transients.

For components whose fatigue analysis led to a CUF > 1, the following actions had to be considered:

- Reduce where possible any excess of conservatism in the fatigue analysis,
- Provide a better estimation of the number of transients expected for 50-year operation from the current knowledge of the number of transients occurring.

In case the CUF remained larger than 1 for some component after having applied both previous actions, additional actions had to be envisaged, such as

- Modify operating procedures to have less penalizing transients.
- Provide the component with a fatigue monitoring to determine the thermal loading during the transients more realistically.
- Perform a fatigue crack tolerance evaluation where the crack growth calculation includes the environmental effects.
- Propose inspections of the component with an adequate frequency.
- Repair or replace the component, if required.

4.3
France

The French safety authority demanded in 2012 that the utility EDF takes into account the environmental effect for plants going for LTO. There is no regulatory requirement, but the demands of the French safety authority, being an independent body, have a le-gal status and have to be fulfilled. The French utility has proposed to introduce environ-mental effect factors Fen following /NUR 07/ with 2 added modifications:

1. The new design fatigue curve is created in less conservative manner by reducing the factors between the experimental mean curve and the design curve on the stress range and the number of cycles from 2 and 20 to 1,4 and 10.
2. An intrinsic value of 3 for the environmental factor is assumed to be integrated in the design curves. So to say, if Fen ⍰ 3 no additional environmental effect has to be considered; only if Fen > 3, the calculated CUF value will be multiplied by Fen divided by 3.

These modifications have been submitted as modification requests in the French code RCC-M /RCC 18/. The modifications are based on 169 fatigue tests performed in the period 2012-2017 to confirm the intrinsic value of 3 and to justify the application to some materials (austenitic and duplex steels, Nickel alloys). Results from an international EU funded project, a collaboration of TSOs and industry named INCEFA (Increasing safety in NPPs by Covering gaps in Environmental Fatigue Assessment) are also included.

In France hold times are not considered, i.e. transients are separated by infinite periods of time. As for the application, EDF defines an environmental factor for each transient that is in fact a mean value for the transient period under tensile stress.

4.4
Germany

A simplified approach is proposed in standards KTA 3201.2 /KTA 17a/ and 3211.2 /KTA 13/: The effect of the environment has to be considered for any location with CUF > 0.4. If an effect of the environment cannot be excluded for these locations, then at least one of the following measures shall be taken at CUF > 0.4:

a) the components shall be included in a monitoring program according to KTA 3201.4 /KTA 16/, or
b) experiments simulating operating conditions shall be performed, or
c) verifications by calculation shall be made in due consideration of environmental reduction factors and realistic boundary conditions.

Environmental factors according to /NUR 07/ or /NUR 18/ may be used. No account is taken of hold times so far. The threshold value CUF = 0.4 = 1/2.5 was derived from the analyses of transients in German PWR and BWR that have shown that the maximum environmental reduction factors during these transients are in the range of 2.5

4.5
Switzerland

In the context of the Ageing Management KATAM critical areas of components have to be evaluated and observed. A total usage factor CUF has to be calculated

$CUF_{U\ total} = CUF_{design} + \Delta CUF\ .\ F_{en}$

where ΔCUF is the usage factor for those loadings not considered in the design. For those loadings already considered in the design, the effect of the environment is supposed to be covered sufficiently by the original analyses.

If CUF_U total is larger than 1 or if the usage factor increase within one year is larger than 0.1, some follow up has to occur. The options for this follow up are similar as already described in the sections for Belgium and Germany.

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In recent version of /NTD 20/ there are formulae for reducing fatigue lifetime due to environmental effects.

Based on international experience the environmental effects should be taken into account for LTO.

Fatigue tests in environment were performed for a limited number of materials and specimens until now. There are plans to extend the database by national projects and data from the European INCEFA project (Increasing Safety in NPPs by Covering gaps in Environmental Fatigue Assessment). International experience like /NUR 18/ is also taken into account.

Differently to the approach applied in PWRs, the environmental factor is applied by co-efficient multiplying the fictitious stress amplitude. It is in accordance to approach used for other reduction factors (e.g. effect of welding) used in /NTD 20/ and /PNA 86/.

Three different levels of reduction factors can be used according to /NTD 20/. The 1st level means reduction factor (on stress) equal to 1.3 for carbon and low alloy steels and 1.56 for austenitic steels. This level is usually conservative. In the 2nd level the reduction factor depends on the amplitude of the fictitious stress. In the 3rd level the reduction fac-tor depends also on the temperature, sulphur content in the steel, oxygen content in the environment and the strain rate.

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Finally, it has to be noted that the calculation of the environmental factors for real transients is rather complex. Moreover, application of factors on old calculations is generally not possible as the necessary data are not available. Therefore, efforts to improve our knowledge on this topic are still ongoing, and some TSOs are actively participating to experimental projects.

One of the aims of the calculations is to update the inspection plan regarding the degradation by fatigue. The result of the inspections will give information about the conservatism of the calculation.

5 ANALYSIS OF MIXING ZONES

5.1 Introduction

Nuclear power plant piping may be submitted to a high cycle thermal fatigue phenome-non in mixing zones. It may happen in pipes where flows of different temperatures mix together in a turbulent manner. Temperature fields resulting from this turbulent mixing lead to variable local stresses on the pipe, namely at the inner surface, that may cause fatigue damages. In May 1998, a significant leak occurred in the Residual Heat Removal System (RHRS) at the French power plant Civaux 1 (PWR type N4, 1400 MWe) where a 180 mm through-wall crack was found in a 304L austenitic stainless steel el-bow.

Following this incident, some countries consider that the precautions taken at the design stage and the absence of detection of cracks in their NPPs have proven that they are not concerned. Other countries have reinforced their inspection plans of specific areas selected on an operation experience basis. The treatment of the phenomenon appears to vary between countries and is detailed below.

An analysis of this phenomenon needs a complex multi-disciplinary approach involving thermal-hydraulics, mechanics and material science. In a first screening the potentially concerned locations can be selected based on the temperature difference (ΔT) be-tween the hot and cold mixed fluids. Then, a more detailed analysis of this area may be performed, e.g. using F.E. or CFD calculations or results of mock-ups. Yet, the results may not be precise enough to predict the appearance of cracks. It should be emphasized that many parameters such as the surface finish, the type of material (base metal or weld metal) etc. have a great influence and have to be taken into account in the analysis. Enforcements of inspection plans (NDE) or changes in reactor operation may have to be envisaged. Some periodic replacement may also have to be planned.

The ingress of cold water into dead ends by turbulence may also lead to similar effects, however, these cases are not addressed in this report.

5.2 Belgium

There is no specific regulatory requirement regarding the effect of thermal fatigue in mixing zones. However, in the frame of the last Periodic Safety Reviews, the licensee had to investigate thermal fatigue, amongst others in mixing zones. More particularly, the piping systems that are connected to the primary coolant loop have been screened for their susceptibility to thermal fatigue phenomena. Four levels of susceptibility were defined: no susceptibility, low, medium and high susceptibility. A level of susceptibility was determined for all parts of the considered piping on the basis of the possible fatigue mechanisms that could affect them, and taking into account applicable operating experience as well as the EDF criteria related to the mixing zones: thermal fatigue in mixing zones would only be significant when the temperature difference between hot and cold water exceeds 80°C for stainless steels and 50°C for carbon steels. No calculations were carried out in this process.

Several medium susceptibility zones were identified, but no high susceptibility zone was found. Medium susceptibility zones had then to be inspected to confirm that these locations are crack free. In this analysis, the Upper Plenum Injection (UPI) lines of Doel-1 and -2 were considered in scope, but as dead ends only. And as such, the utility justified that they did not need to be inspected. However, in April 2018 a leak occurred on the UPI-A line of Doel-1, initiated by a low stress high-cycle fatigue degradation mechanism. In reality, due to a design change modifying the downcomer configuration to-wards an upper plenum injection configuration at both plants, an unexpected small gap appeared between the downcomer and the UPI lines. This gap allowed for mixing of water at cold and hot leg temperatures, leading to high cycle temperature fluctuations in the UPI lines.

5.3
France

As a consequence of the Civaux incident France has decided to implement a special process for the treatment of this complex topic. A specific analysis for all mixing zones of PWR is performed. Mixing zones are areas where cold and hot fluids mix together. The ΔT should be at least > 50°C for ferritic systems and > 80°C for austenitic systems, in order to be taken into account. These screening criteria are based on the endurance limits of these materials. A specific diagram is used for each area investigated (see figure 5) which gives the time limit for each ΔT above the screening criteria. This leads to a cumulative factor CUF = $t_{recorded}$ / t_{limit} for all the transients. If CUF > 1 the area is “sensitive to thermal fatigue”. In that case, each ΔT is associated with a time limit. In case of excess use, an inspection must be planned. The utility follows up the operating of the equipment and tries to maintain it as low as possible.

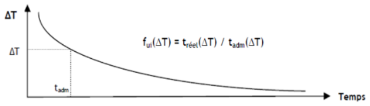

Figure 5: Diagram illustrating the dependence of the admissible time t_{adm} as a function of the temperature difference ΔT in a mixing zone, f_{ui} is the partial usage factor for the time $t_{réel}$ at ΔT.

The diagrams were established on the basis of simplified F.E. calculations: a pipe with a sinusoidal thermal solicitation at the most detrimental frequency.

Regarding mixing zones, there are 9 areas in France on primary, secondary and auxiliary systems. It should be kept in mind that, due to some design specificities, not all the French NPP are concerned. There are 4 areas on the primary circuit, mainly nozzles. There is only one area on the secondary circuit (connection between the main feedwater (MFWS) and the emergency feedwater system (EFWS). There are four zones on the residual heat removal system (RHR), all of them being tee areas. On the whole, the main areas concerned are:

- The RHR nozzle on the cold branch of the primary circuit,
- The connexion between the MFWS and the EFWS (1400 MWe NPP not concerned),
- The main tee connexion on the RHR. That area is where the Civaux incident happened in 1998. This area is controlled every 450 h at ΔT > 90°C.

As for the replacements, all main tee connexions on the RHR were replaced following the Civaux incident between 1999 and 2001. Tees at other locations where indications have also been detected were also replaced. One nozzle of the chemical and volume control system (CVCS) into the main coolant line was replaced at Fessenheim-1 in the year 2000.

Although CUF was >> 1 no indication was discovered. In the 2010s indications were detected after 800 h for example at Dampierre-4 and Cruas-1. Tees have been replaced once again.

5.4
Germany

According to the safety standards KTA 3201.2 /KTA 17a/ and KTA 3211.2 /KTA 13/ all loadings caused by the fluid, including temperature and pressure transients have to be considered in the design. During operation temporal and local temperature changes relevant to fatigue shall be monitored by a sufficiently dense net of measuring points. Yet, these requirements aim at locations suspect of thermal transients or stratification, they do not target mixing zones. In fact, operating experience from German plants does not show any damage due to turbulent mixing of coolant of different temperatures. There-fore, no special requirements for mixing zones appear to be necessary.

5.5
Switzerland

A level of susceptibility was determined for all parts of the considered piping on the basis of the possible fatigue mechanisms that could affect them, and taking into account applicable operating experience as well as the criteria related to the mixing zones: thermal fatigue in mixing zones would only be significant when the temperature difference between hot and cold water exceeds 80°C for austenitic steels and nickel alloys, and 50°C for other materials. These are the same criteria also used by EDF and the Belgian utility. Components classified as fatigue relevant have to be systematically monitored, the data need to be permanently stored and interpreted. The usage factor of these components has to be evaluated according to state-of-the-art and annually reported.

Since there is no information about problems with mixing zones in Swiss plants, there are no further specific regulatory requirements for mixing zones.

5.6
Czech Republic

There is a limited number of locations in Temelin VVER 1000 units (T-pieces in different systems: T-piece of low pressure ECCS to passive ECCS, T-piece in the residual heat removal system) with potential mixing of hot and cold water during some specific operating modes like shut down. Therefore, the effective time of fatigue loading by mixing is rather limited. Some thermocouples were installed at the outer surface of the piping up-stream the T-pieces to measure the temperature differences. The systems were modified to prevent high fatigue loads, e.g. by preheating the spray system by a bypass of hot water. In VVER 440 no mixing zones were identified. There are no regulatory requirements to consider the special analysis of mixing zones in fatigue calculations.

5.7
Slovakia

In VVER 440 no mixing zones were identified. There are no regulatory requirements to consider the special analysis of mixing zones in fatigue calculations.

5.8
Ukraine

There are no regulatory requirements to consider the special analysis of mixing zones in fatigue calculations. At the same time, the operating experience of VVER-1000 and 440 does not show any failures due to turbulent mixing of coolant at different temperatures.

5.9
Conclusions

At the design stage, the detrimental effect of mixing zones which create turbulence and therefore local thermal fatigue has not been anticipated properly. Amongst the participating countries, the only known cases with through wall cracking were in France and Belgium, in Civaux-1 (1998) and Doel-1 (2018). In both cases, the cracking is considered a systematic effect, as more surface cracks were found in similar locations of other plants. Following this incident, all the utilities settled a specific approach to tackle this problem.

A first group of countries consider that in the absence of operating experience, they are not concerned. In some countries, inspections of some areas were performed: these areas were determined by means of screening criteria or by operation experience. In other countries at least periodic inspection plans have been settled in accordance with the results of complex fatigue calculations. In that case, similar screening criteria are used for thermal mixing as for the susceptibility for HCF cracking. Some utilities introduced modifications of the installation for instance in order to reduce the thermal transient by pre-heating.

On the one hand the incident at Doel indicates that some of the locations with severe loading due to mixing might not have been identified. On the other hand, more than 20 years after the Civaux incident, the absence of another through-wall crack tend to prove that the follow-up of mixing zones is adequate in most cases. In France this follow-up included some replacements of the piping concerned.

6 ANALYSIS OF STRATIFICATION

6.1 Introduction

Thermal fatigue in general was considered in the original design of all NPP as one of the major ageing mechanisms of NPP components and pipelines that are subjected to thermal transients during plant operation. Yet fatigue due to thermal stratification was not considered in the original fatigue design analyses of most NPP as this phenomenon was discovered later, mainly during real plant operation. Therefore, it was considered only in some NPP designs of more recent vintage.

Thermal stratification means that the coolant flow inside the pipeline is separated into a “cold” and a “hot” layer. Usually stratification develops in nearly horizontal pipelines when streams with different temperatures flow slowly, i.e. as laminar flow. Then the colder stream with its higher density will flow at the bottom of the pipe and the hotter stream at the top, leading to a strong gradient in thermal expansion of the pipeline be-tween the bottom and the top. This leads to a “banana” bow of the piping resulting in in-creased overall bending stresses and localized thermal gradient stresses at the boundary between hot and cold. Furthermore, the bow may be partly restrained by piping supports and connections leading to local deformation. Cyclic loads due to different transients with different temperatures and flow rates involve the accumulation of material damage due to low to medium cycle thermal fatigue and can cause the initiation and accelerated growth of defects. Therefore, NPP components and pipelines subjected to stratified flow should be evaluated for thermal stresses due to vertical temperature gradients. The fatigue assessment should be based on the results of continuous measurements of mechanical and thermo-mechanical loads. The latter can be achieved by thermocouples around the outer surface of selected piping sections and effective application of the measured data to a computational model analyzing the 3D temperature and stress field in the components.

The following questions may/should be answered:

- Who uses them for which application (e.g. surge line, feed water line, leaking valves)?
- Is there any regulatory requirement?
- What is the need from a safety point of view?
- How do the analyses look like?
- Where do the data for temperature variations in the component stem from (e.g. experimental basis, computer simulation of fluid and heat transfer, other codes)?

6.2 Belgium

There is no specific regulatory requirement regarding the effect of thermal fatigue due to stratification. However, in the frame of the last Periodic Safety Reviews, the licensee had to investigate thermal fatigue, amongst others due to stratification.

Analyses for thermal stratification issues have been performed, especially for the feed water piping (up to the feed water nozzle), the spray nozzle, and the surge line. The analysis is based on specific measurements of the stratification in the concerned piping and with typical CUF calculations.

6.3
France

In France a specific instrumentation has been installed for two years at several units of the 900 MW series for validation of the assumptions made:

- Surge line (stratification area) on 2 NPP (one operates in load following mode, the other in base load mode)
- EFWS nozzle on main feed water line (stratification area) on 2 NPP
- RHR suction nozzle (dead leg area) on 2 NPP (one in base load, one in load following mode)
- RHR discharge nozzle (dead leg area) on 2 NPP
- Safety injection nozzle on the cold leg 1 NPP

The results of these instrumentations - which are less conservative than the results of design calculations in most cases – shall be integrated in the stress analyses starting from the 4th periodic re-evaluation of the 900 MWe NPP (2019). The other plant series will be treated later.

6.4
Germany

At the Reactor Coolant Pressure Boundary temperature measuring points shall be in-stalled, where thermal stratification is expected to occur. According to safety standard KTA 3201.4 /KTA 16/ they shall be located such that all relevant loading variables across the pipe cross-section and axially to the pipe run can be measured.

For systems outside of the reactor coolant pressure boundary, there is only a general requirement that all operating parameters that are important regarding the integrity of pressure and radioactivity retaining components shall be monitored /KTA 16/. Stratification is not directly addressed for these systems. Yet, operating conditions occurring that are not covered by the specified load regime, shall be determined and evaluated with special regard to their safety-relevant effects.

At the locations suspect to stratifications typically 7 thermocouples are clamped to the outside surface around half the circumference of the piping. These allow a realistic analysis of the fatigue loading of the piping. This instrumentation is permanently installed in all German plants. In the German PWR plants locations suspect to stratifications are e.g. at the surge line and the pressurizer spray line, in German BWR plants e.g. at the residual heat removal system.

6.5
Switzerland

Switzerland has an Ageing surveillance program (KATAM) including temperature monitoring of components. As part of KATAM special measuring systems are installed in Swiss NPPs in order to observe stratification in piping. The components concerned will be classified as relevant for fatigue usage if the stratification shows temperature differences larger than $\Delta T = 100$ K for austenitic steels and Ni-based materials or if $\Delta T > 60$ K for all other materials /ENS 11/. For such piping the ASME code can be applied to assess stratification.

6.6
Czech Republic

In some cases, effect of thermal stratification was identified and assessed (e.g. surge line, cold spray to pressurizer, feed water line, high pressure ECCS piping, passive ECCS piping). At these locations, temperature instrumentations at the outside surface are installed. The hydrogen outflow pipe is currently under investigation.

There is no specific requirement for thermal stratification assessment. Standard procedure for fatigue assessment is used also for loading due to thermal stratification. In /NTD 20/, Sect. IV, there is Appendix VIII "General recommendations for piping and components temperature measurement", which is applicable to measurement of thermal stratification effects.

The measured temperature profile is assessed, resulting in boundary conditions for FEM model. Subsequently the temperature and stress fields are calculated in FEM model containing appropriate part of piping and attached components. Number of individual types of stratifications during the lifetime is estimated. Finally, the standard fatigue assessment is performed.

6.7
Slovakia

Stratification was continually measured and periodically assessed in the surge lines and feed water lines. Temperature is measured by 5 or 7 thermocouples on the outer sur-face of the surge line in several cross-sections mainly in horizontal part of pipelines according to the recommendations in /VER 08/, APPENDIX VIII. The FEM model of the surge line is analyzed on the basis of these measured data. Fatigue assessments were performed according to /PNA 86/.

The cumulative usage factor in the pressurizer surge line caused by the stratification is higher than in the main primary circuit components.

6.8
Ukraine

According to the Methodology /MT-T/ the following aspects should be taken into account performing fatigue calculations:

- loading due to operational modes of the system not considered in the design (in case such modes took place in operation);
- additional loads that are specific for a component (i.e. consideration of stratification in the surge line).

Stratification effects were not considered at the design stage, concomitant additional loads should be considered in new calculations.

From safety point of view stratification effects have been considered in safety justifications of LBB concept implementation for primary loop and reassignment of load cycles for Ukrainian NPPs.

Analyses of existing data show a possibility of stratification on horizontal parts of surge line in several operating modes.

For instance, some surge line measurements have been performed for the latest plants Khmelnitskiy NPP Unit 2 and Rivne NPP Unit 4 at the stage of testing before commercial operation. Depending on the operational mode, the temperature range was 25-50°C. Even in this case the re-fined calculation shows that there is no significant impact on the fatigue usage factor. These results are considered representative for the other units of type VVER 1000/320.

At present the measurements of stratification effect are in progress on South Ukrainian NPP Unit 1 but final results are not available yet.

6.9
Conclusions

The approach to stratification appears to be rather similar in all participating countries. While fatigue due to thermal stratification was not considered in the original fatigue de-sign analyses of most NPPs, it is currently addressed by screening and monitoring the temperature from the outer surface of susceptible parts of the pipeline, e.g.:

- Surge Line
- Feed Water Lines (SG feed water nozzle)
- Cold Spray to Pressurizer
- Emergency Core Cooling Systems (ECCS) piping
- Residual heat removal (RHR) systems

In most countries, there are no specific regulatory requirements regarding the effect of thermal fatigue due to stratification, but only a general requirement to monitor all operating parameters that are important for the integrity of pressure-retaining components. At the locations suspect to stratifications typically 5 or 7 thermocouples are clamped to the outside surface around half the circumference of the piping. During operation, these thermocouples continuously measure the temperature of the metal on the outer surface of the pipeline to be analyzed. Based on the measured data, it is possible to define boundary conditions (i.e. the time dependent temperature field) for stress-strain analyses, which are usually done using FEM models. Finally, the assessment of the cumulative usage factor (CUF) caused by stratification is performed. In some cases, the CUF due to stratification in the pipeline may be higher than the CUF due to thermal transients during plant operation.

7 APPROACH TO FATIGUE FOR LTO OF PLANTS

7.1
Introduction

Long-term operation ("LTO") in this report means the operation of a plant beyond its originally foreseen lifetime.

Fatigue assessment of equipment and pipelines is an essential and important issue especially in the framework of LTO in order to prevent and avoid failures due to fatigue cracks. Therefore, when preparing the NPP for LTO, a comprehensive fatigue reassessment is required. Mitigative and corrective actions also should be addressed in the Ageing Management Program. This may also include an adaptation of the in-service inspection program for LTO. Fatigue assessment is usually considered as one part of the Time Limited Ageing Analyses (TLAA).

In order to confirm safe operation of equipment and pipelines during design lifetime the corresponding usage factor shall be calculated for design number of loading cycles. The number of operational modes is limited by plant design and presented in operating documentation. When the actual number of modes reaches its design value or the cumulated usage factor CUF becomes higher than accepted before the end of operation, mitigative or corrective actions have to be implemented. These actions can be more realistic fatigue analysis or changes in operational modes. This will lead to an updated value of the cumulated usage factor. If the value is still higher than accepted, dedicated periodic inspection of the area concerned may be performed or the equipment shall be replaced as a last option.

The following questions may/should be answered in this chapter:

- What kind of additional fatigue evaluations are performed for LTO (e.g. reinforced inspections, additional monitoring, new fatigue analyses for components)?
- Is there any regulatory requirement?
- When and how are fatigue evaluations for LTO applied?

7.2
Belgium

For LTO, new fatigue calculations had to be performed before LTO, taking into account the extended service life and also the environmental effects. These analyses are not limited to the primary components, but also encompass components of the secondary circuits that may be sensitive to environmental fatigue, see chapter 4.2. In this frame, additional monitoring has been used to measure more realistic transients for some specific components and thus to reduce the conservatism of the calculations. Reinforced inspections had to be carried out when these calculations led to unsatisfactory results.

Regulatory requirements for LTO were defined in /FAN 09/ issued by FANC and Bel V.

7.3
France

There are no specific studies of fatigue for ageing plants/LTO. Fatigue is included in a more global project called “ageing management” which addresses all possible degradations due to ageing in a NPP. About 500 “ageing sheets” have been produced. All the ageing sheets are updated on a yearly period. Besides, the counting of transients is reviewed every year. No overpassing of the limit of whatsoever transient hitherto has been identified for 40 years of operation. Even for 60 years of operation the extrapolations based on the last years of operation tend to prove that the limits defined on a supposed 40 years exploitation period will not be reached.

Leading areas where the CUF values have become close to 1 due to the environmental factor shall benefit from a dedicated inspection plan.

A complementary inspection program called “PIC” shall also be executed for NPP once after 40 years of operation of the 900 MW units. As required by the French authority this program is mainly axed on “concerned areas”, i.e. those areas with 0.5 < CUF < 1, that are normally not inspected during periodic inspections.

For example, in the framework of this program the following inspections shall be per-formed on the primary circuit:

- The lateral face of the flange of the vessel head of the RPV close to the closure bolts shall be inspected by PT at two representative units. (The horizontal face of the flange and the threads are already inspected during each outage of the unit as part of the periodic inspection program.)
- The nozzle ring of the RPV shall be inspected by UT for potential fabrication defects under the cladding at another 5 units (8 units were already inspected with no indications).
- Some instrumentation nozzles on the lower part of the pressurizer shall be inspected by UT at 2 representative units. These are areas with stress concentrations.
- The U-bend part of the relief line of the pressurizer to the safety/relief valve shall be inspected by internal VT at 2 representative units. In this U-bend condensation of the steam will lead to a diphasic area.
- At one drain line at the bottom of a U-bend of the main coolant line the inspection by UT shall be performed at the first bend of the drain line in one representative unit. These lines are dead ends that were affected by cracking in some cases according to international operating experience.

7.4
Germany

LTO is not foreseen for German plants. So, there is no national approach to LTO.

7.5
Switzerland

Since 1991 all the Swiss NPPs are running an ageing management program based on the catalogue of ageing mechanisms KATAM, which was defined by the group of Swiss NPP leaders GSKL. The annual ageing management reports are controlled by the authority ENSI. KATAM is evolving continuously and updated to fulfil the state-of-the-art.

The requirements and actions addressed to the licensee concerning ageing management are defined in the ENSI guideline /ENS 11/; these are:

- Components prone to ageing must be under systematical surveillance, their status must be updated regularly and documented in the annual ageing report.

- Data required to evaluate the usage factor must be recorded quality assured, permanently saved and interpreted.
- The local thermal and mechanical loading at the critical locations must be evaluated, the time-load function for an integrity assessment classified and the usage fac-tor evaluated according the state-of-the-art in science and technics.
- Appropriate countermeasures have to be taken if the total usage factor approaches 1.0 or if its annual increase exceeds 0.1.

7.6
Czech Republic

LTO beyond the original design lifetime of 30 years was approved for all 4 units of the Dukovany NPP. General regulatory requirements (given by the Czech regulatory body - SUJB) are given in a guideline /SUJ 15/. Detailed requirements for the lifetime assessment during operation are given in /NTD 20/, Section IV. Nevertheless, the details of fatigue assessments are referenced to Section III in /NTD 20/.

Fatigue re-evaluations were applied for selected components during preparation for ap-plication for license renewal. New fatigue assessments for the whole RPV were per-formed. For other components, existing fatigue analyses were checked and in cases with a potential for reaching fatigue limits during LTO, fatigue re-assessment was per-formed (TLAA re-evaluation). Modernization of the Program of temperature measurements was performed for selected systems based on operating experience with a focus on stratification. The software program DIALIFE for low cycle fatigue monitoring and evaluation was updated. Selected components are assessed by this program after each campaign.

A new project for NPP Dukovany was recently started based on requirement of the regulatory body as part of the LTO license. In a systematic approach, all NPP systems contained in the aging management review scope are reviewed from the point of view of potential to thermal fatigue. If there is such potential, the existing temperature measurement system is reviewed, if it is able to give sufficient information for thermal fatigue assessment. If there is no temperature measurement or its results are not sufficient for fatigue assessment, some modification is proposed, e.g. the installation of new sensors on piping outer surface (either temporal or permanent) or a change of current sensors locations, etc. In case of significant fatigue loading, new fatigue analyses have to be performed.

7.7
Slovakia

LTO beyond the original design lifetime of 30 years was approved for units 3 and 4 of the NPP Bohunice. For LTO, their monitoring system of the stratification was completely modernized (MONEZ). New cross sections with thermocouples were added on the surge line (augmentation from previous 6 to 31 cross sections) and feed water lines. Pressurizer cold injection (i.e. spray) line, pipelines of low and high pressure ECCS, and emergency feed water lines were now integrated in the monitoring system. More de-tailed FEM calculation models were generated, and the stratification is continually measured. Data are analyzed after each fuel cycle and the influence of the stratification is periodically assessed in the above-mentioned pipelines.

The Safety Guide of the Nuclear Regulatory Authority of the Slovak Republic for LTO /BN 14/ deals with the requirements for the implementation of activities necessary to guarantee safe long-term operation of nuclear facilities. This guide is based on the documents elaborated in the frame of the IAEA SALTO EBP /IAE 07/. The formulation of main principles, the sequence and the content of individual steps were derived, considering the most important experience with preparation and realization of long-term operation existing in the USA, not only from SALTO documents, but from US NRC documents too (/NRC 01a/, /NRC 01b/, /NRC 05/).

New FEM calculation models were created for selected components for the calculation of the fatigue usage during all design transients. For these components described below fatigue is assessed after each fuel campaign (once a year). Fatigue damage is assessed off-line on the basis of the real history of operational transients. The following components are periodically assessed:

- Primary main circuit pipeline components: pipeline double branch (i.e. nozzle) of two surge lines from the main coolant line DN 500/200, branches of emergency core cooling systems, branch of pressurizer cold injection (i.e. spray) line, hot elbow under steam generator
- Primary circuit components: reactor pressure vessel and its primary nozzles, main coolant pump, main isolating valve
- Pressurizer: injection nozzle, surge line nozzle, safety valve
- Steam generator - feed water nozzle, primary collector, steam generator shell and bottoms, steam collector nozzles.

Furthermore, stratification in the surge line and the feed water nozzle is evaluated based on actual measurements by thermocouples at external surfaces.

7.8
Ukraine

Fatigue assessment of equipment and pipes is an essential and important issue especially in the framework of LTO in order to prevent and avoid failures due to fatigue cracks. It is needed to identify the number of operational modes which are limited by initial design and presented in operating documentation.

In some units close to the end of the design lifetime actual numbers of some operational modes are approaching their allowable design values. In this case a reassessment of the fatigue usage factor according to /PNA 86/ has to be performed for the new in-creased number of modes for the extended period of operation.

In order to justify an increased number of allowable operating modes during LTO, the /MT-T/ was developed by the Utility and approved by the Ukrainian Regulatory Authority. This Methodology describes the general approach to reassignment of allowable number of modes by linear extrapolation of the numbers from the last 20 cycles of operation. For the fatigue calculations it refers to chapter 5.6 of /PNA 86/.

7.9
Conclusions

Fatigue reassessment for selected components is an important part of preparation of the NPPs for LTO in all countries (except of Germany where LTO is not foreseen). These analyses are performed mostly in the framework of ageing management pro-gram or time limited aging analyses re-evaluation. Some actions concerning fatigue re-assessment for LTO are performed only once (when preparing for license renewal) while others are repeated periodically.

Reasons for fatigue reassessment can be as follows:

- the number of some operational transients may approach or exceed its design value during LTO,
- a consideration of environmental effect on fatigue is required for LTO,
- new issues potentially affecting fatigue were identified during NPP operation that were not considered in the fatigue assessment during design (components or their locations not considered in design assessment, new transients or new parameters of transients, thermal stratification, etc.).

Fatigue reassessment in the participating countries includes the following specific features:

- considering an environmental effect,
- using results of additional or modified temperature monitoring to obtain more realistic time variations of transients or thermal stratification,
- using the state-of-the-art fatigue assessment methods,
- using more detailed FEM models.

Moreover, in many countries, for fatigue-sensitive areas specific in-service inspections shall be performed (either as a complementary inspection program for entry to LTO or by including these areas in the program for periodic inspections).

8

SUMMARY AND GENERAL CONCLUSIONS

Fatigue is one of the major degradation mechanisms of pressurized components in NPPs like in other industrial facilities. Therefore, monitoring and analyzing fatigue has a long tradition and was already taken into account in the design phase of the plants in operation today. Nevertheless, new issues arose in the last decades based on new in-sights from operating experience or laboratory results. Furthermore, more sophisticated monitoring and analyses are necessary to support the safe operation during longer operating times namely LTO. This situation led the ETSON Expert Group on Mechanical Systems (“EG2”) to address five of these issues by introducing them and comparing the approaches in the countries of the members of the group, i.e. Belgium, France, Germany, Switzerland, the Czech Republic, Slovakia, and Ukraine. The following conclusions can be drawn on these five topics:

- **Extension of the fatigue curves to high cycles:** In some special cases as fluid-induced vibrations or thermal fluctuations the number of loading cycles may exceed the number of N = 106 covered by traditional Wöhler curves. While ferritic steels reach their endurance limit at this number of cycles, i.e. they will withstand any stress range below this limit for an infinite number of cycles, the fatigue strength of austenitic steels and nickel alloys still decreases. In order to evaluate the eventual degradation of parts made of austenitic steels and nickel alloys by such high cycle fatigue, some countries extended the fatigue curves for these materials up to N = 1011 or even N = 1012 based on experimental tests or on formulas with material specific parameters. Apparently, these curves differ considerably from each other. This may also have a significant impact on the result. In other countries potential damage by high cycle fatigue is checked by monitoring and in-service inspections.

- **Environmentally assisted fatigue:** If the fatigue degradation mechanism has been considered at the design stage of all NPPs, the effects of the environment were generally not taken into account. Fatigue life seems however to be affected by temperature, dissolved oxygen in water, sulfur content in steel, and strain rate, in a generally detrimental way. This influence is taken into account by environmental factors based on laboratory results. If such effects were not detected in the plants up to now, this could change in the long term. Consequently, several countries re-quested to consider environmental effects while performing fatigue analyses, especially for NPPs going for LTO. The global approach to assess such effects is quite similar among countries, however its application presents significant differences.

- **Analysis of mixing zones:** At the design stage, the detrimental effect of mixing zones which create turbulence and therefore local thermal fatigue has not been anticipated properly. Following the Civaux-1 leakage event in 1998, all the utilities settled a specific approach to tackle this problem. The approach varies greatly between utilities going from specific inspections to complex thermohydraulic calculations and even to modifications of the installation. The most important point, as the recent leakage event at Doel-1 in 2018 reminds us, is to identify correctly the locations where mixing may occur and to plan a periodic inspection of these zones. The feasibility of replacements should also be investigated.

- **Analysis of stratification:** For most nuclear power plants currently in operation, thermal fatigue due to stratification was not considered in the original design analyses of fatigue lifetime of components and pipelines. This phenomenon was found only during operation and previous experience has shown that it may have a significant effect on fatigue damage, especially for some horizontal sections of pipes. De-spite the fact that in many countries there are no special regulatory requirements for the assessment of stratification, in most countries the effect of stratification is subject to monitoring by continuous temperature measurements. Thermocouples are attached on the outer surface of critical pipes allowing a subsequent assessment of fatigue damage due to stratification.

- **Approach to fatigue for LTO of plants:** Fatigue assessment of equipment and pipelines is an essential issue especially in the framework of LTO for preventing failures due to fatigue cracks. For countries where LTO is foreseen or practiced (i.e. all countries represented by the group members except Germany) these analyses are performed mostly in the framework of the ageing management program or time limited aging analyses (TLAA) re-evaluation. Corresponding national regulations for fatigue analyses exist and comprise general regulatory requirements and detailed ones regarding the methodology. While the overall approach for the fatigue assessment and reassessment is almost the same in all countries, the methodologies differ in detail. In most countries, based on the results of fatigue analyses performed, corresponding additional measures for fatigue-sensitive locations are fore-seen within the in-service inspection and ageing management programs.

In general, it is regarded as good practice to minimize significant cyclic stresses and strains by suitable design and operating conditions. The fatigue analyses generally imply large uncertainties regarding the initiation of cracking and results heavily depend on the methods used and the knowledge of the real loading of the component. Therefore, fatigue analyses may rather be used for screening the locations most susceptible to degradation than for predicting incipient damage and should be supported by monitoring and inspections of the relevant locations. As final solutions, repair and replacement should also be envisaged

9 ABBREVATIONS

ANL	Argonne National Laboratory
ASME	American Society of Mechanical Engineers
BWR	Boiling water reactor
CFD	Computational fluid dynamics
CS	Carbon steel
CUF	Cumulative usage factor
CVCS	Chemical and volume control system
ECCS	Emergency core cooling system
EDF	French utility
EFWS	Emergency feedwater system
EG	Expert group
ENSI	Swiss regulatory body
FANC	Belgian regulatory body
FE	Finite element
FEM	Finite element method
HCF	High cycle fatigue
IAEA	International Atomic Energy Agency
KATAM	Swiss catalogue of ageing mechanisms
KTA	German Nuclear Safety Standards Commission
LAS	Low alloy steel
LBB	Leak before break
LTO	Long term operation
LWR	Light water reactor
MFWS	Main feedwater system
NDE	Non-destructive examination
NPP	Nuclear power plant
PT	Penetration tests
PWR	Pressurized water reactor
RHR	Residual heat removal
RPV	Reactor pressure vessel
SALTO	Safety aspects of long-term operation
SG	Steam generator
SS	Stainless steel
SUJB	Czech regulatory body
TLAA	Time limited ageing analysis
TSO	Technical safety organization
US NRC	USA regulatory body
UT	Ultrasonic tests
VT	Visual tests
VVER	Water cooled water moderated energy reactor

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CONTRIBUTORS TO THE REPORT

The following members of the Expert Group EG2 “Mechanical Systems” contributed to this report:

François BALESTRERI	IRSN / France
Vincent DELEDICQUE	Bel V / Belgium
Peter HERMANSKY	VUJE / Slovakia
Uwe JENDRICH	GRS / Germany
Markus NIFFENEGGER	PSI / Switzerland
Vladislav PISTORA	UJV / Czech Republic
Oleksiy SHUGAYLO	SSTC NRS / Ukraine