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Research

Establishment and use of attention values in environmental fatigue assessments

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SSM perspective

Background

As Swedish NPPs reach their original technical design life, re-assessment of the fatigue life of structural components is needed for safe long term operation (LTO). In these re-assessments one must consider that new knowledge has shown that environmental effects on fatigue life must be considered.

One common method to verify the fatigue life of structural components subjected to an LWR coolant environment is to use so-called attention values. This simplistic method is beneficial as re-assessments can be based on existing fatigue analyses. The basic idea behind the method is that if the accumulated fatigue utilization factor in an existing fatigue analysis (not considering environmental effects) is lower than the attention value, the fatigue criterion is fulfilled also for environmental conditions. That is, the fatigue life margin is large enough to to deal with the negative effects of the LWR coolant environment.

The present study aims to investigate how attention values can be established and used. Furthermore, the study investigates the possibility to apply a general attention value for Swedish NPPs.

Results

The report presents fatigue evaluations of different locations in BWR systems and one location in a PWR system. Environmental conditions are included in the analyses with the purpose to get an enhanced understanding of how attention values could be established and used.

For austenitic stainless steel in BWR environments, an attention value of 0.4 is suggested. For carbon and low-alloy steel in BWR environments, an indicative value of 0.2 is presented. For PWRs, no attention values are suggested as data for only one component was available.

Relevance

The work has increased the understanding for how attention values can be established and used. Furthermore, attention values for BWRs and PWRs are presented. These attention values may be used in re-assessments of fatigue life when environmental effects must be considered.

Need for further research

The work is based upon a relatively few number of locations in class 1 piping components. Hence, more locations, especially for PWRs but also in the region of $0.2<U_{acc}<0.4$ for BWRs, would increase the significance of the attention values presented.

Project information

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Nomenclature

ASME	The American Society of Mechanical Engineers
ATT	Attention value
BWR	Boiling water reactor
EPRI	Electric Power Research Institute
F_{en}	Environmental fatigue correction factor
$F_{\mathrm{en}}^{\mathrm{eff}}$	Effective environmental fatigue correction factor
K_{e}	Factor used for simplified elastic-plastic analysis
LWR	Light water reactor
LTO	Long term operation
NPP	Nuclear power plant
O^*	Transformed oxygen level
PWR	Pressurised water reactor
RPV	Reactor pressure vessel
S^*	Transformed sulphur content
S_1, S_2, S_3	Principal stress 1, 2 and 3
S_{12}, S_{23}, S_{31}	$S_{12} = S_1 - S_2, S_{23} = S_2 - S_3, S_{31} = S_3 - S_1$
$\Delta S_{12}, \Delta S_{23}, \Delta S_{31}$	Range of $S_{12},$ S_{23} and S_{31} between sub-cycles
S_{m}	Design stress intensity value
T	Temperature
T^*	Transformed temperature
U_{acc}	Accumulated fatigue utilization factor not considering environmental conditions
$U_{\mathrm{acc}}^{F_{\mathrm{en}}}$	Accumulated fatigue utilization factor considering environmental conditions
$\dot{\varepsilon}$	Strain rate
$\dot{\varepsilon}^*$	Transformed strain rate
$\sigma_r, \sigma_\varphi, \sigma_{ax}$	Radial, circumferential and axial stress in a pipe

1. Summary

The technical design life of many of the Swedish NPPs has been or will soon be reached. This means, among other things, that a re-assessment of the fatigue life of structural components is needed for long term operation (LTO). For components subjected to an LWR coolant environment, new knowledge has shown that environmental effects on the fatigue life must be considered. In re-assessing these components, it would be beneficial if already existing fatigue analyses could be used.

One way to verify the fatigue life of a component subjected to an LWR coolant environment in a simplistic way, is to use a so-called attention value *ATT*. If the accumulated fatigue utilization factor U_{acc} in an existing fatigue analysis (not considering environmental effects) is lower than the attention value, the fatigue criterion is fulfilled also for environmental conditions. With $U_{\mathrm{acc}} \leq ATT$, a margin to cope with the effective environmental fatigue correction factor $F_{\mathrm{en}}^{\mathrm{eff}}$ (for the whole load collective) is established.

This report presents fatigue evaluations of different locations in BWR systems and one location in a PWR system. Environmental conditions are included in the analyses with the purpose to get an enhanced understanding of how attention values could be established and used. The possibility to apply a general attention value of 0.4 for Class 1 piping systems in Swedish BWRs and PWRs is also investigated.

The results show that determined attention values vary with U_{acc}. No obvious trends are seen except that carbon and low-alloy steels seem to require a lower attention value compared to austenitic stainless steels. For austenitic stainless steels in BWR environments, an attention value of 0.4 is suggested. For carbon and low-alloy steels in BWR environments, an indicative value of 0.2 is presented. For PWRs, no attention values are suggested as data for only one component was available.

2. Introduction

In design of Class 1 components in nuclear power plants (NPPs), the damage mechanism fatigue needs to be explicitly considered according to the ASME Section III, Division 1 – Subsection NB [1]. By use of fatigue design curves, the fatigue utilization is determined for respective components. A set of load combinations are considered in a fatigue analysis. According to the ASME Section III Code, only level A and Level B service limit loads need to be taken into account. Among these, the different pressure and thermal transients normally have largest impact on the accumulated fatigue utilization factor U_{acc}.

The fatigue design curves in the present ASME Code do not consider environmental conditions in light water reactor (LWR) coolant systems. According to NUREG/CR 6909 rev. 1 [2], fatigue lives in LWR water at operating temperature relative to those in air at room temperature can be a factor of approximately 12 lower for austenitic stainless steels, 3 lower for Ni-Cr-Fe alloys, and 17 lower for carbon and low-alloy steels. For some environmental and loading conditions, the factor can be even higher. Table 2-1 shows maximum values of the environmental fatigue correction factor F_{en} determined according to NUREG/CR 6909 rev. 1 and ASME Code Case N-792-1 [3] for a BWR operating at T=286°C.

Table 2-1 Maximum value of F_{en} determined according to NUREG/CR 6909 rev. 1 and ASME Code Case N-792-1 for a BWR operating at T = 286°C.

Material	Max F_{en} NUREG/CR 6909 rev.1	Max F_{en} ASME CC N-792-1
Carbon and low-alloy steels	65.5	41.1
Austenitic stainless steels	8.23	9.42
Ni-Cr-Fe alloys	3.11	3.77

The technical design life of many of the Swedish NPPs has been or will soon be reached. This means, among other things, that a re-assessment of the fatigue life of structural components is needed for long term operation (LTO). The possibility to use already existing fatigue analyses of mechanical systems in this re-assessment would be beneficial. In most fatigue analyses, however, environmental conditions are not considered.

As seen above, the environmental fatigue correction factor F_{en} for LWR coolant environments can be rather high. Worst case for carbon and low-allow steels in Table 2-1 gives $F_{\mathrm{en}} = 65.5$. With such a high value, the fatigue utilization factor without considering environmental conditions, U_{acc}, would need to be less than 1/65.5 = 0.0153 to fulfil the fatigue criterion in the ASME Section III Code. In a fatigue analysis of a carbon or low-alloy steel component, however, F_{en} varies with load pair and some other parameters so the effective F_{en} often becomes substantially lower than 65.5.

According to NUREG/CR 6909 rev. 1, F_{en} varies with the temperature of the coolant water, the strain rate in the steel component, the coolant water oxygen content and the sulphur content of the steel (only for carbon and low-alloy steels). This means that F_{en} also varies with the type of loading transient as the transient, among other things, controls the temperature and the strain rate in the steel component.

One way to verify the fatigue life of a component subjected to an LWR coolant environment in a simplistic way, is to use a so-called attention value *ATT*. If the accumulated fatigue utilization factor U_{acc} in an existing fatigue analysis (not considering environmental effects) is lower than the attention value, the fatigue criterion is fulfilled also for environmental conditions. With $U_{acc} \leq ATT$, a margin to cope with the effective environmental fatigue correction factor F_{en}^{eff} (for the whole load collective) is established.

The effective F_{en}^{eff} in a fatigue analysis varies with type of component, position in component, type of loads, characteristics of loads, type of load combinations and occurrence of load combinations. Application of an attention value approach requires that analysed type component shows a characteristic type of response for representative load collectives. This also means that the load collective, its loads and the occurrence of the different load combinations of the component type should be characteristic.

Pipe components in LWR coolant environment is judged to fulfil the requirements for application of an attention value approach in assessing environmental fatigue. The axisymmetric cross-section geometry facilitates a characteristic type of response and loads, load combinations and occurrence of load combinations are similar for the LWR coolant piping systems.

For components with few evaluation points and where no natural grouping of systems can be done, the use of an attention value approach is of less interest. Here, it is more convenient to perform an explicit re-assessment of the fatigue life considering environmental effects. Examples of components are those where lack of symmetry in geometry and load exist; i.e. parts of the internal structures, valve bodies, feed water nozzles, particle traps etc.

Different attention values have been suggested. In KTA [4], an attention value of 0.4 is suggested. In Switzerland a value of 0.1 is recommended [5]. IAEA SRS No 82 (TLAA 106) [6] mentions attention values of both 0.2 and 0.4. The spread shows that an enhanced understanding of how attention values should be established and used is needed.

2.1 Purpose with project

The purpose with this project is 1) to get an enhanced understanding of how attention values should be established and used and 2) to investigate if an attention value of 0.4 can be applied in environmental fatigue analyses of piping systems in Swedish BWRs and PWRs.

3. Effect of LWR coolant environments on the fatigue life

Initiation and growth of a fatigue crack are controlled by both physical and chemical mechanisms in the region close to the crack tip. The mechanisms affecting the initiation and growth rate act on different timescales depending on material, load levels and load rates, the temperature, concentration levels of substances in the environment, flow rates etc. Experimental data from small-scale laboratory fatigue tests indicate a significant decrease in fatigue life for specimens submerged in LWR environments, Figure 3-1. Key parameters shown to influence the fatigue life are the strain range above a threshold value, strain rate below a threshold value, service temperature above a threshold value, dissolved oxygen in the water above a minimum value, and for carbon- and low-alloy steels the sulfur content in the steel.

Explanations for the observed decrease in fatigue life are dependent on the material and generally attributed to corrosion fatigue mechanisms constituting of a slip oxidation/dissolution process and/or hydrogen-induced cracking and dynamic strain aging. It is hard to differentiate between the oxidation/dissolution process and/or hydrogen-induced cracking mechanisms since both depend on rates of oxide rupture, passivation and liquid diffusion. However, for some of the mechanisms to take place at the crack tip, the water needs to have contact with the fracture surfaces. According to the experimental data presented in [2], the environmental effect is much less pronounced at compressive parts of the load cycle. During that period, water does not have access to the crack tip due to crack closure. In this context, the word “compressive” means that compressive stresses prevail. The experimental results also show that the environmental effects on fatigue life occur primarily during the loading portion of the cycle (i.e., up ramp with increasing strain and stress).

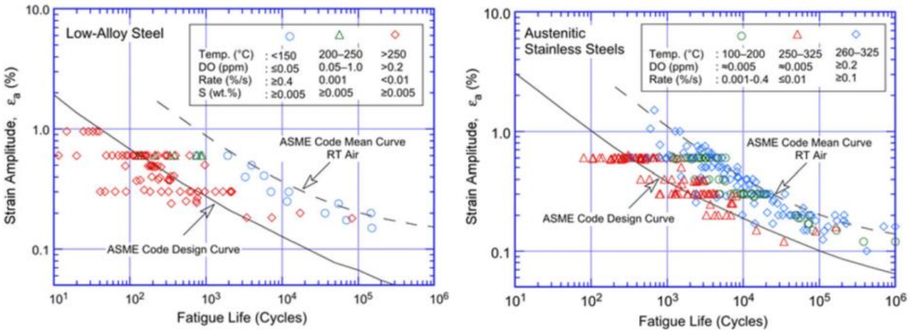

Figure 3-1 Strain amplitude vs number of cycles for low-alloy steel and austenitic stainless steels [2]. Comparison between the fatigue life in air and the corresponding life in LWR water.

4. Calculation of the environmental fatigue correction factor F_{en}

4.1 NUREG/CR-6909 rev. 1

The American Nuclear Regulatory Commission have published the report NUREG/CR-6909 rev. 1 [2] which provides guidance for how environmental effects caused by the presence of LWR coolant water can be considered in a fatigue analysis. In the report, a comprehensive review of the fatigue ε–N data for nuclear power plant piping and pressure vessel steels presented in the original version of NUREG/CR-6909 is re-evaluated using a much larger database.

Parameters controlling the environmental fatigue correction factor F_{en} are the temperature of the coolant water, the strain rate in the steel component, the coolant water dissolved oxygen content and the sulphur content of the steel (only for carbon and low-alloy steels).

For **carbon and low-alloy steels** the environmental correction factor is given as

$$F_{\text{en}} = \exp\left((0.003 - 0.31 \cdot \dot{\varepsilon}^{*}) \cdot S^{*} \cdot T^{*} \cdot O^{*}\right) \tag{4-1}$$

where

$$S^{*} = 2.0 + 98 \cdot S \qquad (S \le 0.015 \text{ wt. \%}) \tag{4-2}$$

$$S^{*} = 3.47 \qquad (S > 0.015 \text{ wt. \%}) \tag{4-3}$$

$$T^{*} = 0.395 \qquad (T < 150^{\circ} \text{ C}) \tag{4-4}$$

$$T^{*} = (T - 75)/190 \qquad (150 \le T \le 325^{\circ} \text{ C}) \tag{4-5}$$

$$O^{*} = 1.49 \qquad (DO < 0.04 \text{ ppm}) \tag{4-6}$$

$$O^{*} = \ln(DO/0.009) \qquad (0.04 \le DO \le 0.5 \text{ ppm}) \tag{4-7}$$

$$O^{*} = 4.02 \qquad (DO > 0.5 \text{ ppm}) \tag{4-8}$$

$$\dot{\varepsilon}^{*} = 0 \qquad (\dot{\varepsilon} > 2.2 \text{ \%/s}) \tag{4-9}$$

$$\dot{\varepsilon}^{*} = \ln(\dot{\varepsilon}/2.2) \qquad (0.0004 \le \dot{\varepsilon} \le 2.2 \text{ \%/s}) \tag{4-10}$$

$$\dot{\varepsilon}^{*} = \ln(0.0004/2.2) \qquad (\dot{\varepsilon} < 0.0004 \text{ \%/s}) \tag{4-11}$$

For **wrought and cast austenitic stainless steels** the environmental correction factor is given as

$$F_{\mathrm{en}} = \exp\left(-T^* \cdot \dot{\varepsilon}^* \cdot O^*\right) \tag{4-12}$$

where

$$T^* = 0 \qquad (T < 100^\circ \text{ C}) \tag{4-13}$$

$$T^* = (T - 100)/250 \qquad (100 \leq T < 325^\circ \text{ C}) \tag{4-14}$$

$$\dot{\varepsilon}^* = 0 \qquad (\dot{\varepsilon} > 7 \text{ \%/s}) \tag{4-15}$$

$$\dot{\varepsilon}^* = \ln\left(\dot{\varepsilon}/7\right) \qquad (0.0004 \leq \dot{\varepsilon} \leq 7 \text{ \%/s}) \tag{4-16}$$

$$\dot{\varepsilon}^* = \ln\left(0.0004/7\right) \qquad (\dot{\varepsilon} < 0.0004 \text{ \%/s}) \tag{4-17}$$

$$O^* = 0.29 \qquad (DO < 0.1 \text{ ppm, PWR or BWR and HWC}) \tag{4-18}$$

(all wrought and cast stainless steels and heat treatments and stainless-steel weld metals)

$$O^* = 0.29 \qquad (DO \geq 0.1 \text{ ppm, BWR and NWC}) \tag{4-19}$$

(sensitized high carbon wrought and cast stainless steels)

$$O^* = 0.14 \qquad (DO \geq 0.1 \text{ ppm, BWR and HWC}) \tag{4-20}$$

(all wrought stainless steels except sensitized high-carbon stainless steels)

For **Ni-Cr-Fe alloys** the environmental correction factor is given as

$$F_{\mathrm{en}} = \exp\left(-T^* \cdot \dot{\varepsilon}^* \cdot O^*\right) \tag{4-21}$$

where

$$T^* = 0 \qquad (T < 50^\circ \text{ C}) \tag{4-22}$$

$$T^* = (T - 50)/275 \qquad (50 \leq T \leq 325^\circ \text{ C}) \tag{4-23}$$

$$\dot{\varepsilon}^* = 0 \qquad (\dot{\varepsilon} > 5.0 \text{ \%/s}) \tag{4-24}$$

$$\dot{\varepsilon}^* = \ln\left(\dot{\varepsilon}/5.0\right) \qquad (0.0004 \leq \dot{\varepsilon} \leq 5.0 \text{ \%/s}) \tag{4-25}$$

$$\dot{\varepsilon}^* = \ln\left(0.0004/5.0\right) \qquad (\dot{\varepsilon} < 0.0004 \text{ \%/s}) \tag{4-26}$$

$$O^* = 0.06 \qquad (\text{NWC BWR water, i.e. } \geq 0.1 \text{ ppm } DO) \tag{4-27}$$

$$O^* = 0.14 \qquad (\text{PWR or HWC BWR water, i.e. } < 0.1 \text{ ppm } DO) \tag{4-28}$$

4.2 ASME Code Case N-792-1

The overall approach in the ASME Code Case N-792-1 [3] to calculate the environmental correction factor F_{en} corresponds to that of NUREG/CR-6909 rev. 1 [2], compare sections 4.1 and 4.2. The equations presented in ASME Code Case N-792-1 origins from NUREG/CR-6909 rev. 0 [7].

For **carbon and low-alloy steels** the environmental correction factor is given as

$$F_{en} = \exp\left(0.121 - 0.101 \cdot S^* \cdot T^* \cdot O^* \cdot \dot{\varepsilon}^*\right) \tag{4-29}$$

where

$$S^* = 0.015 \qquad (DO > 1.0 \text{ ppm}) \tag{4-30}$$

$$S^* = 0.001 \qquad (DO \leq 1.0 \text{ ppm and } S \leq 0.001 \text{ wt. \%}) \tag{4-31}$$

$$S^* = S \qquad (DO \leq 1.0 \text{ ppm and } 0.001 < S \leq 0.015 \text{ wt. \%}) \tag{4-32}$$

$$S^* = 0.015 \qquad (DO \leq 1.0 \text{ ppm and } S > 0.015 \text{ wt. \%}) \tag{4-33}$$

$$T^* = 0.0 \qquad (T < 150° \text{ C}) \tag{4-34}$$

$$T^* = T - 150 \qquad (150 \leq T < 350° \text{ C}) \tag{4-35}$$

$$O^* = 0 \qquad (DO \leq 0.04 \text{ ppm}) \tag{4-36}$$

$$O^* = \ln\left(DO/0.04\right) \qquad (0.04 < DO \leq 0.5 \text{ ppm}) \tag{4-37}$$

$$O^* = \ln\left(12.5\right) \qquad (DO > 0.5 \text{ ppm}) \tag{4-38}$$

$$\dot{\varepsilon}^* = 0 \qquad (\dot{\varepsilon} > 1 \text{ \%/s}) \tag{4-39}$$

$$\dot{\varepsilon}^* = \ln\left(\dot{\varepsilon}\right) \qquad (0.001 \leq \dot{\varepsilon} \leq 1 \text{ \%/s}) \tag{4-40}$$

$$\dot{\varepsilon}^* = \ln\left(0.001\right) \qquad (\dot{\varepsilon} < 0.001 \text{ \%/s}) \tag{4-41}$$

For **wrought and cast austenitic stainless steels** the environmental correction factor is given as

$$F_{en} = \exp\left(0.734 - T^* \cdot \dot{\varepsilon}^* \cdot O^*\right) \tag{4-42}$$

where

$$T^* = 0 \qquad (T < 150° \text{ C}) \tag{4-43}$$

$$T^* = (T - 150)/175 \qquad (150 \leq T < 325° \text{ C}) \tag{4-44}$$

$$T^* = 1 \qquad (T \geq 325° \text{ C}) \tag{4-45}$$

$$\dot{\varepsilon}^* = 0 \qquad (\dot{\varepsilon} > 0.4 \text{ \%/s}) \tag{4-46}$$

$$\dot{\varepsilon}^* = \ln(\dot{\varepsilon}/0.4) \qquad (0.0004 \le \dot{\varepsilon} \le 0.4\ \%/\mathrm{s}) \tag{4-47}$$

$$\dot{\varepsilon}^* = \ln(0.0004/0.4) \qquad (\dot{\varepsilon} < 0.0004\ \%/\mathrm{s}) \tag{4-48}$$

$$O^* = 0.281 \qquad (\text{all } DO \text{ levels}) \tag{4-49}$$

For **Ni-Cr-Fe alloys** the environmental correction factor is given as

$$F_{\mathrm{en}} = \exp(-T^* \cdot \dot{\varepsilon}^* \cdot O^*) \tag{4-50}$$

where

$$T^* = T/325 \qquad (T < 325^\circ\ \mathrm{C}) \tag{4-51}$$

$$T^* = 1 \qquad (T \ge 325^\circ\ \mathrm{C}) \tag{4-52}$$

$$\dot{\varepsilon}^* = 0 \qquad (\dot{\varepsilon} > 5.0\ \%/\mathrm{s}) \tag{4-53}$$

$$\dot{\varepsilon}^* = \ln(\dot{\varepsilon}/5.0) \qquad (0.0004 \le \dot{\varepsilon} \le 5.0\ \%/\mathrm{s}) \tag{4-54}$$

$$\dot{\varepsilon}^* = \ln(0.0004/5.0) \qquad (\dot{\varepsilon} < 0.0004\ \%/\mathrm{s}) \tag{4-55}$$

$$O^* = 0.09 \qquad (\text{for BWR normal water chemistry}) \tag{4-56}$$

$$O^* = 0.16 \qquad (\text{for PWR and BWR hydrogen water chemistry}) \tag{4-57}$$

4.3 Comparison of NUREG/CR 6909 rev. 1 and ASME Code Case N-792-1

A comparison of NUREG/CR 6909 rev. 1 and ASME Code Case N-792-1 shows that the physical basis used in determination of an environmental fatigue correction factor F_{en} is the same. Both procedures consider the temperature of the coolant water, the strain rate in the steel component, the coolant water oxygen content and the sulphur content of the steel (only for carbon and low-alloy steels). The highest value of F_{en} for the different materials differs between the procedures, see Table 2-1.

The way to calculate the environmental correction factor F_{en} differs somewhat between NUREG/CR-6909 rev. 1 and ASME Code Case N-792-1. Particularly for carbon and low alloy steels, F_{en} and the transformation values S^*, T^*, O^* and $\dot{\varepsilon}^*$ are differently defined, compare equations (4-1) to (4-11) with (4-29) to (4-41). Also, for the other two material groups there are some differences.

As NUREG/CR 6909 rev. 1 is based on the latest knowledge and generally accepted in the nuclear industry, this procedure is used in the following analyses.

5. Effect of the K_e factor

According to ASME Section III, Division 1 – NB, the $3S_m$ limit on the range of primary plus secondary stress intensity may be exceeded provided some specified requirements in NB-3228.5 (Simplified Elastic-Plastic Analysis) are met. One of these requirements is that the stress range amplitude S_a of the alternating stress intensity component (one-half of the alternating stress intensity range) is multiplied by a factor $K_e > 1$ before entering the design fatigue curve. The K_e factor approach gives the possibility to consider an elastic-plastic response in a simplified way. The increase of the elastically calculated S_a results in a shorter fatigue life.

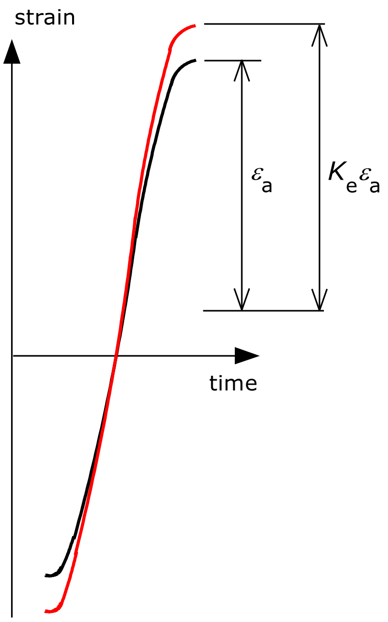

Figure 5-1 Half strain cycle as a function of time, with and without consideration of the K_e factor.

Figure 5-1 shows a half strain cycle with and without consideration of the K_e factor. The strain amplitude ε_a corresponding to S_a is smaller than that corresponding to $K_e \cdot S_a$. With the same time scale, this means that the strain rate $(\Delta\varepsilon/\Delta t)$ is higher when K_e is considered. A consequence of an increased strain rate is that F_{en} decreases. This in turn means that it is conservative not to consider K_e when determining the attention value *ATT*.

In this report, the K_e factor is not considered in the determination of *ATT*. For positions where the load collective includes loads that result in an elastic-plastic response, omitting K_e means that a slightly lower *ATT* is determined.

6. Dynamic loadings

In NUREG/CR 6909 rev. 1 no distinction is made between different types of loads based on their origin when to consider the effect of strain rate on the environmental correction factor. The stain rate thresholds in the eqns. 4-1 to 4-28 are based on data sets including all types of loads possible in a nuclear piping system.

However, from a computational point of view simplifications giving a small additional conservatism may be motivated. For instance, in EPRI guidelines [8], distinction is made between load pairs involving only dynamic loads and those pairs including other loads e.g. temperature variations.

For load pairs derived exclusively from dynamic loads, reversing or non-reversing, the threshold for high strain rate is assumed to be satisfied and therefore the environmental factor could be set to unity for those load pairs. This is stated clearly in ASME Code Case N-792-1.

For stress cycles involving combinations of dynamic loads and other loads, ASME Code Case N-792-1 states that the strain rate threshold is satisfied for the dynamic load portion of the cycle. For application of the modified strain rate approach this means that the incremental portion of the environmental factor of the load pair due to the dynamic perturbation will be set to unity. If the transformed strain rate is based on the complete load cycle range, incorporating the dynamic portion leads to an increased mean strain rate. For both approaches, the effect of adding dynamic loads to other varying loads in a combination will lead to a reduced environmental factor. The conclusion is that for estimation of attention values it is conservative to estimate environmental factors by omitting dynamic loads from the load combinations.

In this report, dynamic loadings are not considered in the determination of *ATT*. For positions where the load collective includes dynamic loadings, omitting these loads means that a slightly lower *ATT* is determined.

7. Establishment and use of an attention value

7.1 General

The idea with an attention value *ATT* is to assess environmental fatigue in a simplistic way by use of existing fatigue analyses where environmental conditions have not been considered. If an existing fatigue evaluation shows that the analysed system fulfils the ASME fatigue criterion, also the case where environmental conditions are considered fulfils the criterion if

$$U_{\mathrm{acc}} \leq ATT \qquad (7\text{-}1)$$

where U_{acc} is the accumulated fatigue utilization factor not considering environmental conditions.

An attention value *ATT* can be determined as follows. Define the effective environmental fatigue correction factor as

$$F_{\mathrm{en}}^{\mathrm{eff}} = \frac{U_{\mathrm{acc}}^{F_{\mathrm{en}}}}{U_{\mathrm{acc}}} \qquad (7\text{-}2)$$

where $U_{\mathrm{acc}}^{F_{\mathrm{en}}}$ is the fatigue utilization factor considering environmental conditions. Cases where $U_{\mathrm{acc}}^{F_{\mathrm{en}}} = 1$ give the limit for the attention value. With this assumption the attention value is given as

$$ATT = \frac{1}{F_{\mathrm{en}}^{\mathrm{eff}}} \qquad (7\text{-}3)$$

For systems where the characteristics of the components and the loadings are similar, it should be possible to establish an attention value that can be used for an environmental fatigue evaluation in a simplistic way. Grouping of systems that can use the same attention value is thus part of the approach.

7.2 Determination of attention value

An overview of how an attention value is determined is given below. A pipe component is used for which the principal stresses equal the component stresses in the radial, circumferential and axial direction. The steps are as follows:

1. Determine principal stresses as a function of time for all transients.
   $S_1(=\sigma_r)$, $S_2(=\sigma_\varphi)$, $S_3(=\sigma_{ax})$
2. Determine differences between principal stresses (~ shear stresses).
   $S_{12} = S_1 - S_2$, $S_{23} = S_2 - S_3$, $S_{31} = S_3 - S_1$

3. Divide S_{12}, S_{23} and S_{31} curves in sub-cycles.

4. Determine ranges for the respective “shear stress” $\Delta S_{12} = S_{12}^{i} - S_{12}^{j}$, $\Delta S_{23} = S_{23}^{i} - S_{23}^{j}$, $\Delta S_{31} = S_{31}^{i} - S_{31}^{j}$ (i and j are different sub-cycles).
   - Ranges are determined between sub-cycles and the sub-cycle itself.

5. Highest range for the respective sub-cycle combination (ΔS_{12}, ΔS_{23}, ΔS_{31}) gives the fatigue utilization factor for the sub-cycle combination.

6. Calculate accumulated fatigue utilization factor U_{acc} for the whole load collective without considering environmental effects.
   - A sub-cycle is removed from the analysis as its number of occasions in related transient is reached.

7. Calculate environmental fatigue correction factor F_{en}^{i} for each load range pair.
   - Calculation is based on the sub-cycle combinations used in step 6.

8. Re-assess accumulated fatigue utilization factor $U_{\mathrm{acc}}^{F_{\mathrm{en}}}$ for the whole load collective considering the environmental effect.

9. Determine effective environmental fatigue correction factor.

   $$F_{\mathrm{en}}^{\mathrm{eff}} = \frac{U_{\mathrm{acc}}^{F_{\mathrm{en}}}}{U_{\mathrm{acc}}}$$

10. Determine attention value.

    $$ATT = \frac{1}{F_{\mathrm{en}}^{\mathrm{eff}}}$$

7.3 Piping components

Fatigue life assessment of piping systems normally requires evaluation of several locations. The possibility to use existing fatigue analyses for consideration of LWR coolant environmental effects is therefore of interest.

Principal stresses in a pipe essentially coincide with the component stresses $\sigma_{r}, \sigma_{\varphi}$ and σ_{ax} for all loadings of interest. This condition simplifies the fatigue analysis as component stresses can be used directly in the assessment. According to stress classification for piping in the ASME Section III Code, stresses caused by internal pressure and thermal expansion are classified as primary, secondary or peak stresses. Stresses caused by radial thermal gradients are classified as peak stresses. The stress category is of importance when determining the K_{e} factor.

7.4 Components other than piping components

In environmental fatigue assessment of components other than piping components, the benefit with an attention value approach is limited. The reasons are:

- It is difficult to generalise the loading characteristics.
- The number of locations to evaluate are relatively few why the benefit with an attention value approach is minor.
- Validation of used attention value is often needed.

7.5 Attention value 0.4

The possibility to use an attention value of 0.4 requires that the effective environmental fatigue correction factor $F_{\mathrm{en}}^{\mathrm{eff}}$ does not exceed 1/0.4 = 2.5. Even though F_{en}^{i} for individual load pairs exceeds 2.5, $F_{\mathrm{en}}^{\mathrm{eff}}$ can remain below 2.5 if F_{en}^{i} for load pairs that contribute most to U_{acc} is smaller than 2.5. In the following chapter this is investigated for some cases.

8. Determination of attention values for BWR systems

8.1 General

In the following sections, dynamic loadings and the K_e factor are disregarded in establishing attention values. Such an approach is conservative. A consideration of these factors might slightly increase the attention value. Furthermore, if not otherwise stated, the evaluations are made on as-welded girth butt welded straight pipes with nominally identical wall thicknesses, i.e. stress indices from table NB-3681(a)-1 are used $K_p = 1.2, K_M = 1.8 \text{ and } K_T = 1.7$. Compared to a straight pipe remote from welds or other discontinuities this will lead to a slightly higher attention value, i.e. an approach in the non-conservative direction.

8.2 Main feed water line

8.2.1 Positions close to the containment

A main feed water line is investigated. A position close to the containment is chosen, see Figure 8-1. Pressure and thermal transients control the fatigue utilization factor. These transients and their respective occurrence during 60 years are considered in the analysis. F_{en} is determined according to NUREG/CR 6909 rev. 1. The material is a carbon steel.

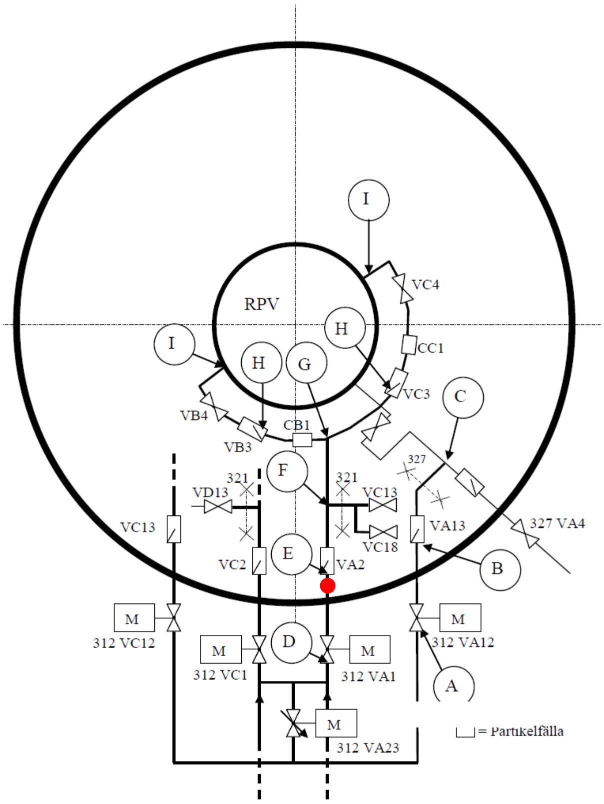

Figure 8-1 Part of main feed water system in a BWR. Position of evaluation is marked with red point.

The highest environmental fatigue correction factor among the cycle pairs is $F_{\mathrm{en}} = 13.39$. The contribution of this cycle pair to the fatigue utilization factor is however negligible. F_{en} for those load pairs that contribute to 94% of $U_{\mathrm{acc}}^{F_{\mathrm{en}}}$ vary between 3.80 and 4.65.

The fatigue utilization factor at the inside of the pipe, not considering environmental conditions, is $U_{\mathrm{acc}} = 0.047$. Consideration of the environmental conditions results in a fatigue utilization factor $U_{\mathrm{acc}}^{F_{\mathrm{en}}} = 0.195$. The effective environmental fatigue correction factor then becomes $F_{\mathrm{en}}^{\mathrm{eff}} = 0.195/0.047 = 4.12$ which gives an attention value of $ATT = 0.24$.

The parallel main feed water line close to the containment gives similar values. The fatigue utilization factor at the inside of the pipe, not considering environmental conditions, is $U_{\mathrm{acc}} = 0.040$. Consideration of the environmental conditions results in a fatigue utilization factor $U_{\mathrm{acc}}^{F_{\mathrm{en}}} = 0.161$. The effective environmental fatigue correction factor then becomes $F_{\mathrm{en}}^{\mathrm{eff}} = 0.161/0.040 = 4.06$ which gives an attention value of $ATT = 0.25$.

8.2.2 Position between containment an RPV

A main feed water line is investigated. A position between the containment and the reactor pressure vessel is chosen, see Figure 8-2. Pressure and thermal transients control the fatigue utilization factor. These transients and their respective occurrence during 60 years are considered in the analysis. F_{en} is determined according to NUREG/CR 6909 rev. 1. The material is an austenitic stainless steel.

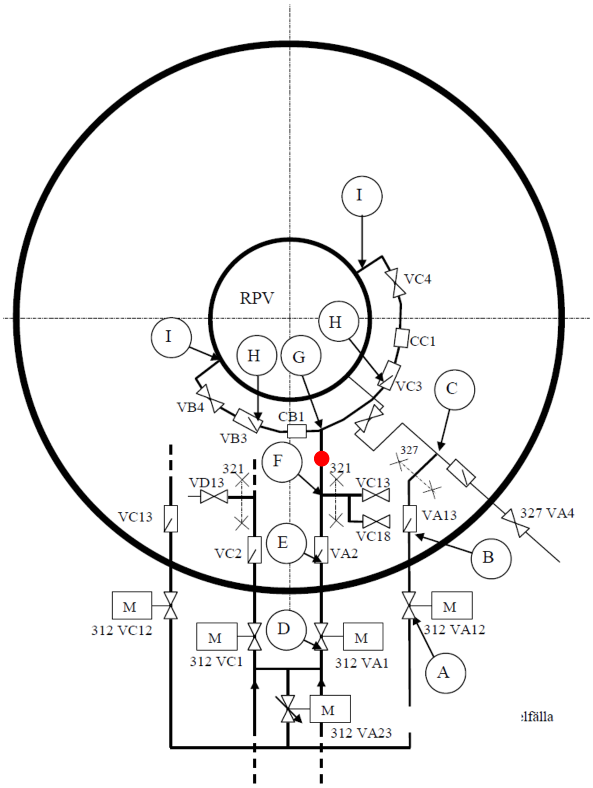

Figure 8-2 Part of main feed water system in a BWR. Position of evaluation is marked with red point.

The highest environmental fatigue correction factor among the cycle pairs is $F_{\mathrm{en}} = 1.74$. The contribution of this cycle pair to the fatigue utilization factor is however negligible. For this position, low feed water flow via the outer valve dominates the fatigue utilization.

The fatigue utilization factor at the inside of the pipe, not considering environmental conditions, is $U_{\mathrm{acc}} = 1.533$. Consideration of the environmental conditions results in a fatigue utilization factor $U_{\mathrm{acc}}^{F_{\mathrm{en}}} = 1.853$. The effective environmental fatigue correction factor then becomes $F_{\mathrm{en}}^{\mathrm{eff}} = 1.853/1.533 = 1.209$ which gives an attention value of $ATT = 0.83$.

The parallel main feed water line between the containment and the reactor pressure vessel gives similar values. The fatigue utilization factor at the inside of the pipe, not considering environmental conditions, is $U_{\mathrm{acc}} = 1.525$. Consideration of the environmental conditions results in a fatigue utilization factor $U_{\mathrm{acc}}^{F_{\mathrm{en}}} = 1.846$. The effective environmental fatigue correction factor then becomes $F_{\mathrm{en}}^{\mathrm{eff}} = 1.846/1.525 = 1.21$ which gives an attention value of $ATT = 0.83$.

8.2.3 Position close to RPV

A main feed water line is investigated. A position close to the reactor pressure vessel is chosen, see Figure 8-3. Pressure and thermal transients control the fatigue utilization factor. These transients and their respective occurrence during 60 years are considered in the analysis. F_{en} is determined according to NUREG/CR 6909 rev. 1. The material is an austenitic stainless steel.

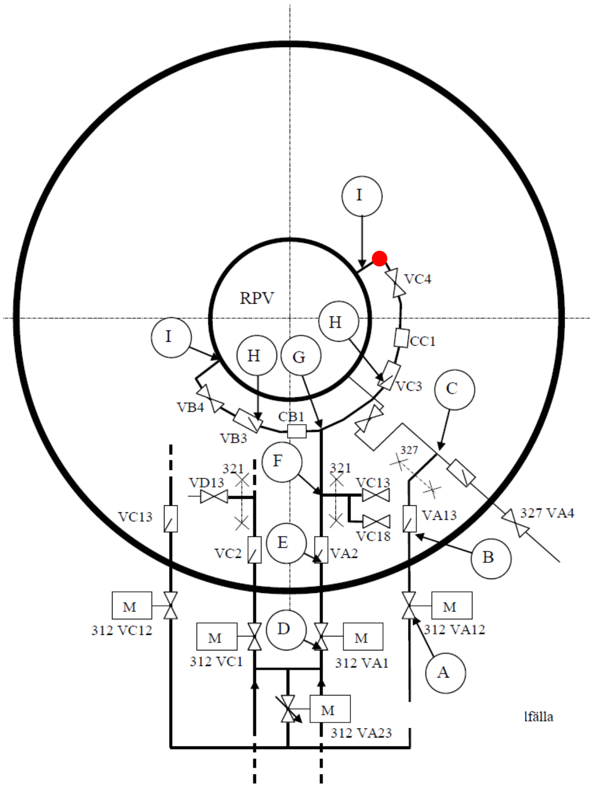

Figure 8-3 Part of main feed water system in a BWR. Position of evaluation is marked with red point.

The highest environmental fatigue correction factor among the cycle pairs is $F_{en} = 1.98$. The contribution of this cycle pair to the fatigue utilization factor is however negligible.

The fatigue utilization factor at the inside of the pipe, not considering environmental conditions, is $U_{acc} = 0.063$. Consideration of the environmental conditions results in a fatigue utilization factor $U_{acc}^{F_{en}} = 0.088$. The effective environmental fatigue correction factor then becomes $F_{en}^{eff} = 0.088/0.063 = 1.40$ which gives an attention value of $ATT = 0.71$.

The parallel main feed water line close to the reactor pressure vessel gives similar values. The fatigue utilization factor at the inside of the pipe, not considering environmental conditions, is $U_{acc} = 0.059$. Consideration of the environmental conditions results in a fatigue utilization factor $U_{acc}^{F_{en}} = 0.084$. The effective environmental fatigue correction factor then becomes $F_{\mathrm{en}}^{\mathrm{eff}} = 0.084/0.059 = 1.43$ which gives an attention value of $ATT = 0.70$.

8.3 Main steam line

Only for systems in contact with LWR coolant water should environmental fatigue be considered. Thus, for the main steam line in a BWR, environmental fatigue is not an active damage mechanism.

8.4 Sprinkler system for reactor tank flange

The sprinkler system for cooling of the reactor tank flange is investigated, see Figure 8-4. The main contributing loads to the fatigue utilization factor are the dynamic SRV-loads. The system has several locations with a fatigue utilization factor excluding the environmental factor but including dynamic loads in the range $0.2 < U_{\mathrm{acc}} < 0.4$. Pressure and thermal transients only contribute with a minor part to the fatigue utilization factor. However, only pressure and thermal transients and their respective occurrence during 60 years are considered in the evaluation of the environmental factor. F_{en} is determined according to NUREG/CR 6909 rev. 1. The materials in system parts B-C-D are different types of austenitic stainless steels.

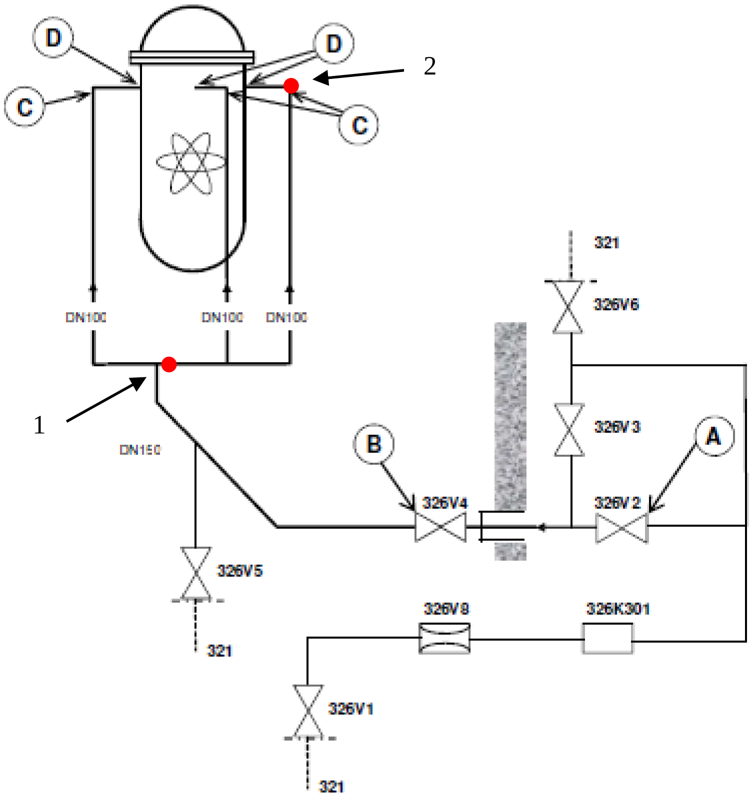

Figure 8-4 Part of sprinkler system in a BWR. Positions of evaluation are marked with red points.

Position 1: The highest environmental fatigue correction factor among the cycle pairs is $F_{\mathrm{en}} = 2.10$. The contribution of this cycle pair to the fatigue utilization factor is however small.

The fatigue utilization factor at the inside of the pipe, not considering environmental conditions, is $U_{\mathrm{acc}} = 0.048$. Consideration of the environmental conditions results in a fatigue utilization factor $U_{\mathrm{acc}}^{F_{\mathrm{en}}} = 0.100$. The effective environmental fatigue correction factor then becomes $F_{\mathrm{en}}^{\mathrm{eff}} = 0.100/0.048 = 2.08$ which gives an attention value of $ATT = 0.48$.

Position 2: The highest environmental fatigue correction factor among the cycle pairs is $F_{\mathrm{en}} = 2.77$. The contribution of this cycle pair to the fatigue utilization factor is however negligible.

The fatigue utilization factor at the inside of the pipe, not considering environmental conditions, is $U_{\mathrm{acc}} = 0.015$. Consideration of the environmental conditions results in a fatigue utilization factor $U_{\mathrm{acc}}^{F_{\mathrm{en}}} = 0.023$. The effective environmental fatigue correction factor then becomes $F_{\mathrm{en}}^{\mathrm{eff}} = 0.023/0.015 = 1.45$ which gives an attention value of $ATT = 0.69$.

8.5 Reactor core sprinkler system

8.5.1 Position close to containment

The sprinkler system for reactor core cooling is investigated. Two positions close to the containment are chosen, see Figure 8-5. The dominating loads contributing to the fatigue utilization factor are the dynamic SRV-loads. However, only pressure and thermal transients and their respective occurrence during 60 years are considered in the evaluation of the environmental factor. F_{en} is determined according to NUREG/CR 6909 rev. 1. The material is a carbon steel.

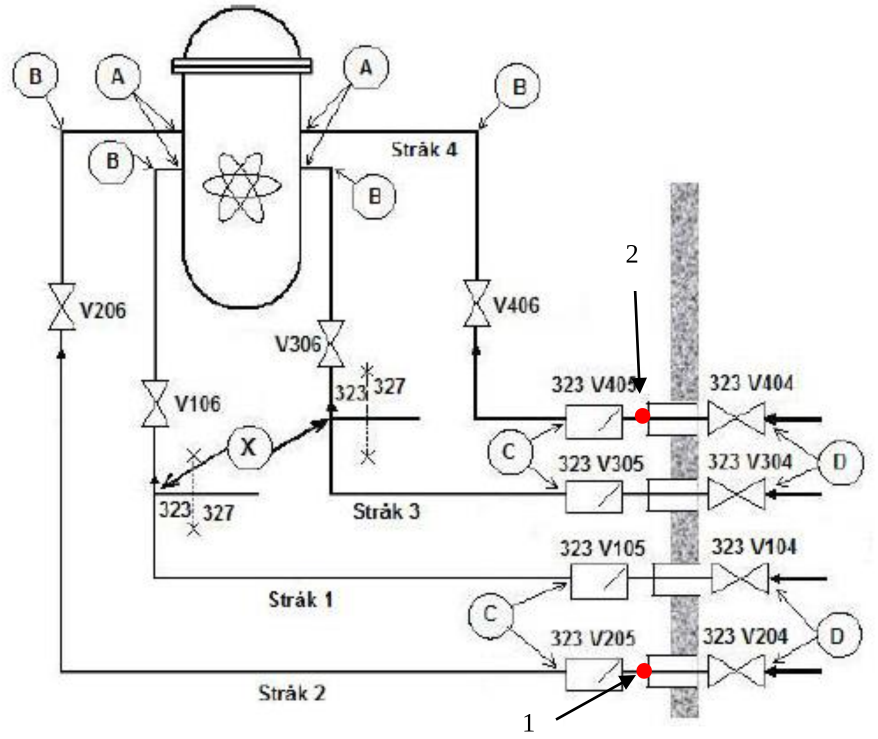

Figure 8-5 Reactor core sprinkler system in a BWR. Positions of evaluation are marked with red points.

Position 1: The highest environmental fatigue correction factor among the cycle pairs is $F_{\mathrm{en}} = 35.6$. The contribution of this cycle pair to the fatigue utilization factor is however negligible. F_{en} for those load pairs that contribute to 94% of $U_{\mathrm{acc}}^{F_{\mathrm{en}}}$ vary between 1.75 and 1.91.

The fatigue utilization factor at the inside of the pipe, not considering environmental conditions, is $U_{\mathrm{acc}} = 0.00196$. Consideration of the environmental conditions results in a fatigue utilization factor $U_{\mathrm{acc}}^{F_{\mathrm{en}}} = 0.00383$. The effective environmental fatigue correction factor then becomes $F_{\mathrm{en}}^{\mathrm{eff}} = 0.00383/0.00196 = 1.95$ which gives an attention value of $ATT = 0.51$.

Only considering the dynamic GV/SRV(1) and GV/SRV(12) loads gives a fatigue utilization factor of 0.3974. Hence the contribution from the environmental factor is negligible in this position.

Position 2: The parallel sprinkler water line, “Stråk 4” in Figure 8-5, close to the containment has the same fatigue utilization factor since the pipe section geometry, material, pressure and thermal transient loads are the same as in position 1.

Only considering the dynamic GV/SRV(1) and GV/SRV(12) loads gives a fatigue utilization factor of 0.7763. Hence the contribution from the environmental factor is negligible in this position.

8.5.2 Position between RPV and containment

The sprinkler system for reactor core cooling is investigated. Two positions between the containment and RPV are chosen, see Figure 8-6. The dominating loads contributing to the fatigue utilization factor are the dynamic SRV-loads. However, only pressure and thermal transients and their respective occurrence during 60 years are considered in the evaluation of the environmental factor. F_{en} is determined according to NUREG/CR 6909 rev. 1. The material is a stainless steel.

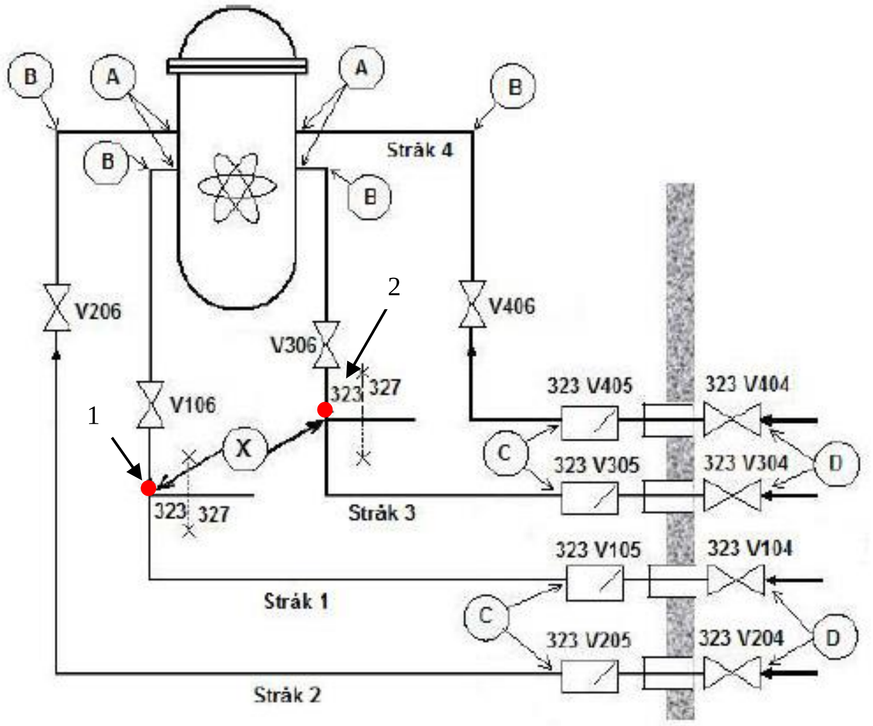

Figure 8-6 Reactor core sprinkler system in a BWR. Positions of evaluation are marked with red points.

Position 1 and 2: The highest environmental fatigue correction factor among the cycle pairs is $F_{en} = 2.76$. The contribution of this cycle pair to the fatigue utilization factor is however negligible. F_{en} for those load pairs that contribute to 100% of $U_{acc}^{F_{en}}$ vary between 1.00 and 1.24.

The fatigue utilization factor at the inside of the pipe, not considering environmental conditions, is $U_{acc} = 0.00679$. Consideration of the environmental conditions results in a fatigue utilization factor $U_{acc}^{F_{en}} = 0.00691$. The effective environmental fatigue correction factor then becomes $F_{en}^{eff} = 0.00691/0.00679 = 1.02$ which gives an attention value of $ATT = 0.98$.

Only considering the dynamic GV/SRV(1) and GV/SRV(12) loads gives a fatigue utilization factor of max 0.21. Hence the contribution from the environmental factor is negligible in this position.

8.5.3 Position close to RPV

The sprinkler system for reactor core cooling is investigated. Two positions close to the RPV are chosen, see Figure 8-7. The dominating loads contributing to the fatigue utilization factor are the pressure and thermal transient loads. The pressure and thermal transients and their respective occurrence during 60 years are considered in the evaluation of the environmental factor. F_{en} is determined according to NUREG/CR 6909 rev. 1. The material is a stainless steel.

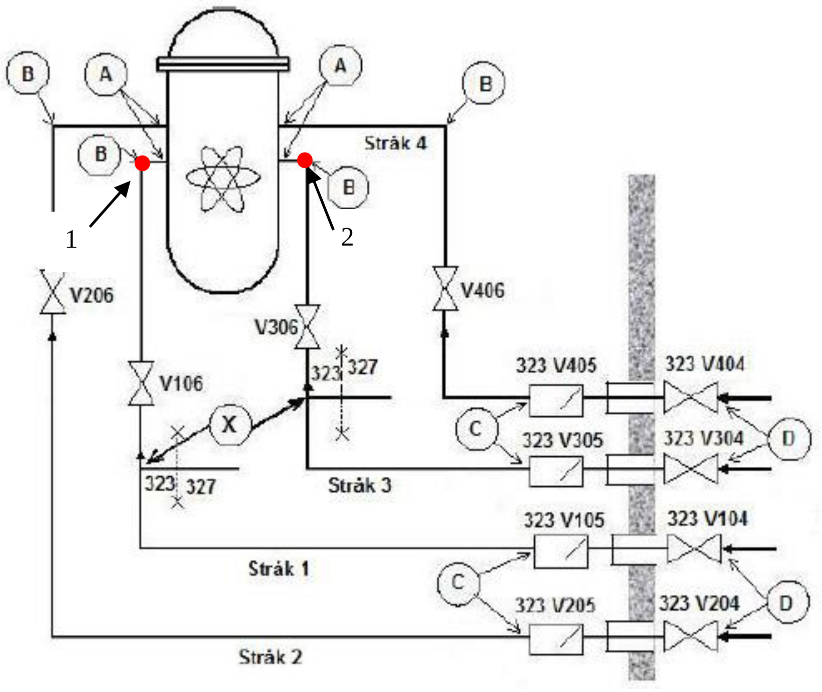

Figure 8-7 Reactor core sprinkler system in a BWR. Positions of evaluation are marked with red points.

Position 1 and 2: The highest environmental fatigue correction factor among the cycle pairs is $F_{\mathrm{en}} = 2.77$. The contribution of this cycle pair to the fatigue utilization factor is however negligible. F_{en} for those load pairs that contribute to 94% of $U_{\mathrm{acc}}^{F_{\mathrm{en}}}$ vary between 1.35 and 1.38.

The fatigue utilization factor at the inside of the pipe, not considering environmental conditions, is $U_{\mathrm{acc}} = 0.333$. Consideration of the environmental conditions results in a fatigue utilization factor $U_{\mathrm{acc}}^{F_{\mathrm{en}}} = 0.450$. The effective environmental fatigue correction factor then becomes $F_{\mathrm{en}}^{\mathrm{eff}} = 0.450/0.333 = 1.35$ which gives an attention value of $ATT = 0.74$.

9. Determination of attention values for PWR systems

9.1 General

In the following section, dynamic loadings and the K_e factor are disregarded in establishing attention values. Such an approach is conservative. A consideration of these factors might slightly increase the attention value.

9.2 Cold leg in primary coolant loop

A cold leg in a primary coolant loop of a PWR is investigated. Pressure and thermal transients control the fatigue utilization factor. These transients and their respective occurrence during 60 years are considered in the analysis. F_{en} is determined according to NUREG/CR 6909 rev. 1. The material is a stainless steel.

The highest environmental fatigue correction factor among the load pairs is $F_{en} = 2.89$. The contribution of this load pair to the fatigue utilization factor is however negligible.

The fatigue utilization factor at the inside of the pipe, not considering environmental conditions, is $U_{acc} = 0.00080$. Consideration of the environmental conditions results in a fatigue utilization factor $U_{acc}^{F_{en}} = 0.00176$. The effective environmental fatigue correction factor then becomes $F_{en}^{eff} = 0.00176/0.00080 = 2.205$ which gives an attention value of $ATT = 0.45$.

10. Evaluation of attention values

All evaluations are made on as-welded girth butt welded straight pipes with nominally identical wall thicknesses, i.e. stress indices from table NB-3681(a)-1 are used $K_\mathrm{p} = 1.2, K_\mathrm{M} = 1.8$ and $K_\mathrm{T} = 1.7$. Analyses on other geometries with both higher and smaller stress indices have been made for the same load collective. The anticipated behaviour when analysing positions with higher stress concentration factors would be a decrease of the environmental factor $F_\mathrm{en}^\mathrm{eff}$ due to the increase in strain rate, given the same load collective. However, the outcome is also dependent on if the loading is proportional or not. By use of stress indices a non-proportional loading situation applies resulting in switches of maximum stress range component, i.e. the largest range of $\Delta S_{12},\ \Delta S_{23},\ \Delta S_{31}$ for the different load- and subcycles combinations. Hence, the environmental factor may instead increase with increasing stress indices. However, for the proportional loading case a decrease of the environmental factor is expected.

The stress state due to thermal loads in a pipe component (i.e. a point in a pipe component) is determined by the both the global constraint from the pipe system and the local temperature distribution through the pipe wall. The functional form of the global constraint is dependent on the global system geometry. Hence, the only way to find the resulting internal loads at a specific location is to conduct a full analysis of a sufficiently large part of the pipe system.

As seen in the previous chapter, the attention value varies with U_acc. However, no obvious trend is seen except that carbon and low-alloy steels seems to require a lower attention value compared to austenitic stainless steels, see Figure 10-1. Arguments exists that a low attention value might be a result of smaller strain amplitudes which, for the same time scale, results in lower strain rate (compare effect of K_e factor). A consequence of lower strain rate is that the environmental fatigue correction factor F_en increases which in turn results in a reduction of the attention value.

Based on the results presented in Figure 10-1, a suggested attention value for austenitic stainless steels in BWR environment would be in the region 0.40-0.45. Since the current results are based on girth butt weld (as welded) stress indices, which gives a small increase in obtained *ATT*-value, the recommended attention value is chosen as the lower value, 0.4.

Due to the somewhat limited number of the evaluated locations for carbon and low-alloy steels in BWR environments, the attention value obtained in the present investigation should be considered more as indicative. The results indicate a lower attention value around 0.2, compared to 0.4 for austenitic stainless steels.

Since only one location is evaluated in connection to PWR environments and austenitic stainless steels it is difficult to suggest an appropriate attention value for Class 1 piping components.

The horizontal arrows pointing towards the limit line $U_\mathrm{acc}^{F_\mathrm{en}} = 1$, is chosen horizontal since this corresponds to a certain weighted environmental condition for the load collective. An inclined arrow would represent a change of the weighted environmental condition. However, both a positive and a negative slope of the arrow can be motivated based on specific conditions at different NPPs. Here a reasonable approach is to choose a horizontal line.

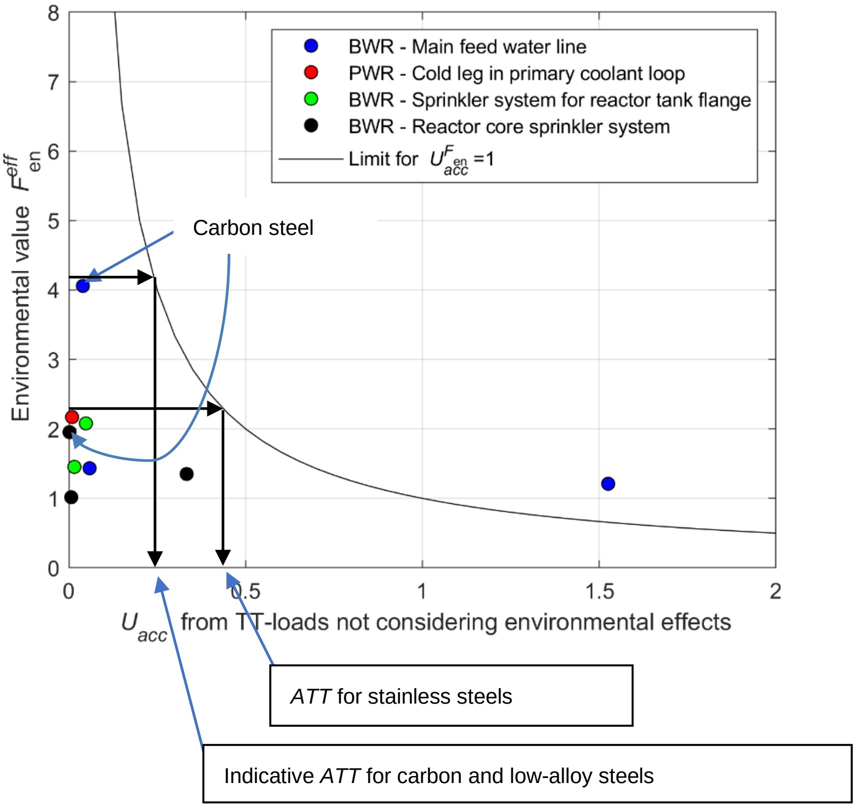

Figure 10-1 The effective environmental factor vs the fatigue utilization factor, U_{acc}, based on TT-loads excluding environmental effects. The black line describes the limit $U_{acc}^{F_{en}} = 1$, i.e. the product of $F_{en}^{eff} \cdot U_{acc}$. The attention value, *ATT*, is read of the abscissa. All evaluated points in the figure are stainless steels except the two points pointed out.

11. Further work

Difficulty was experienced in finding locations in Class 1 piping components with $U_{\mathrm{acc}}^{F_{\mathrm{en}}} \approx 1$ (or $0.2 < U_{\mathrm{acc}} < 0.4$) where the dominating contribution to U_{acc} origins from the thermal and pressure transients. Hence, the information base presented in this region is limited. More points would of course increase the significance of the estimated attention value for all materials in both BWR and PWR environment.

12. Acknowledgement

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