Parameters influencing the low-cycle fatigue life of materials in pressure water reactor nuclear power plants

Parametry ovlivňující únavové chování materiálů pro tlakovodní jaderné reaktory v režimu nízkocyklové únavy

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In this literature review we identify and quantify the parameters influencing the low-cycle fatigue life of materials commonly used in nuclear power plants. The parameters are divided into several groups and individually described. The main groups are material properties, mode of cycling and environment parameters. The groups are further divided by the material type - some parameters influence only certain kind of material, e.g. sulfur content may decreases fatigue life of carbon steel, but is not relevant for austenitic stainless steel; austenitic stainless steel is more sensitive to concentration of dissolved oxygen in the environment compared to the carbon steel. The combination of parameters i.e. conjoint action of several detrimental parameters is discussed. It is also noted that for certain parameters to decrease fatigue life, it is necessary for other parameter to reach certain threshold value. Two different approaches have been suggested in literature to describe this complex problem - the Fen factor and development of new design fatigue curves. The threshold values and examples of commonly used relationships for calculation of fatigue lives are included. This work is valuable because it provides the reader with long-term literature review with focus on real effect of environmental parameters on fatigue life of nuclear power plant materials.

Tento literární přehled identifikuje a kvantifikuje parametrů ovlivňující odolnost materiálů používaných v jaderné energetice proti nízkocyklové únavě. Parametry jsou rozděleny do několika skupina jednotlivě diskutovány. Hlavními skupinami jsou: typ materiálu – některé typy materiálu nejsou citlivé na změny určitých podmínek – např.: síra v prostředí může snižovat únavovou životnost uhlíkových ocelí, na austenitické korozivzdorné oceli nemá vliv; austenitické oceli jsou naopak mnohem citlivější na obsah rozpuštěného kyslíku. Dále je diskutován kombinovaný efekt jednotlivých parametrů. Je důležité zmínit, že vliv určitých veličin začíná být patrný až po překročení určité úrovně jiné veličiny. Pro řešení tohoto komplexního problému byly navrženy dva různé postupy – kalkulace pomocí environmentálního faktoru Fen a navržení nových návrhových křivek (design curves). V textu jsou dále zmíněny výše zmíněné hraniční hodnoty veličin a příklady metod pro odhad únavových životností. Tato práce je přínosná především proto, že čitateli předkládá dlouhodobý literární přehled se zaměřením na skutečný vliv prostředí na únavovou životnost materiálů používaných v jaderné energetice.

INTRODUCTION

The first documented catastrophic fatigue failure was railway accident in 1842 in Versailles, France. During the accident, the engine of a steam locomotive fell to the ground, causing all the following carriages to derail which resulted in major loss of life. This and many other railway fatigue failures, usually axle related, lead to extensive investigation of the nature of fatigue.

Fatigue is generally cyclic loading of material, which eventually forms a crack at the surface. Growing crack reduces the thickness of a body which bears the load, the crack thusly works as a stress concentrator. In final stage, the remaining thickness of the component is not strong enough to support the load and fails completely (separates, ruptures etc.).

Fatigue damage is generally divided in two groups - high-cycle and low-cycle. Most fatigue failures in transportation industry are "high-cycle", that is, the failure will occur after more than 10^4-10^5 cycles. High-cycle fatigue is somewhat easier to monitor – after the crack is formed on the surface, it continues growing – this step is called crack propagation and it takes about 90% of the time until the component fails. In comparison, low-cycle fatigue is quite different – 90% of the time is the crack initiation and after the crack is formed, it grows fast. This means that the low-cycle fatigue damage can be long-term ongoing without any visible deterioration and then fail very quickly. This is caused by higher applied stresses – Yao [1] defines low-cycle fatigue as a loading where: "the test loads are usually sufficiently large to cause plastic deformation in the material and a corresponding hysteresis in its stress-strain behavior, which may change from one cycle to the next." This statement also addresses another difference – loads large enough to cause plastic deformation are above the yield strength of the material, sometimes even close to the ultimate strength. Materials subjected to loads this high cannot exhibit an endurance limit – level of stress below which the material can theoretically withstand infinite amount of cycles – behavior typical for steels in high-cycle mode.

In power plant engineering, the high-cycle fatigue is a well-known problem, which is thoroughly monitored and can be prevented/repaired. Most of the high-cycle fatigue damage is vibration or flow induced (cavitation).

Low-cycle fatigue is, as it has been mentioned before, more difficult to assess – until the crack is formed on the surface there is no evidence of component being damaged. Low-cycle fatigue damage is largely caused by rapid thermal changes ("thermal fatigue") other causes can be pressure changes, water/steam hammer and others, unknown [2]. All of these occur mainly during the start-ups and shutdowns of a power-plant. It has been shown that each start up (or shutdown) can present a single (or multiple) cycle. EPRI report which sums up fatigue-related failures in PWR and BWR NPPs states that most of the low-cycle fatigue failures are attributed to design configuration and aging [2, 3]

The failures in power plants due to low-cycle fatigue is somewhat periodical - the failures occur after similar number of start-ups/shutdowns. The total number of low-cycle fatigue failures over the operation life sometimes spikes and then drops (Figure 1). The spike can be due to ocurrence of the same problem in plants in operation for similar time and after the failure occurs, the power plant usually shares the information with other power plants, causing the drop in number of failures. Authors of the report also attribute part of the failures to staff rotation - when new staff comes in, certain problems, which had been identified and prevented, can re-occur. It is also visible that the overall number of fatigue-related failures in the US nuclear power plants is increasing.

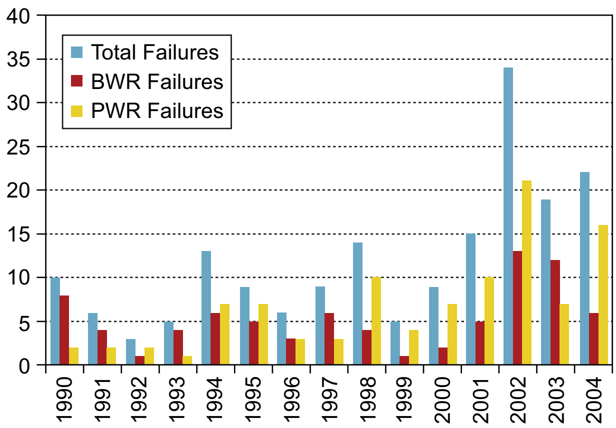

Fig. 1. Fatigue failures in 1990-2004 [2]
Obr. 1. Únavou vyvolané poruchy v letech 1990-2004 [2]

Certain components are more prone to failure. According to the cited EPRI report, the component most-frequently damaged by low-cycle fatigue in PWR plants is the small bore pipe, which was about one third of all failures in 2002. Correspondingly, the system typically damaged by low-cycle fatigue is the recirculation system.

Low-cycle fatigue life parameters

Low-cycle fatigue life is the relation between the load level and corresponding number of cycles the material can withstand at given load. Generally, fatigue life is affected by:

- material
  - – material type
  - – chemical composition
  - – mechanical properties
  - – corrosion resistance
  - – surface roughness
  - – metallurgical state
  - – bulk material/welded joint
  - – thermal stability
  - – deformation present in the structure before cycling
  - – response to cycling

- cycling parameters
  - – R ratio
  - – strain rate
  - – strain range
  - – shape of the load curve
  - – variability of loading (periodical with same amplitude/non-periodical with varying load levels)

- environment (medium)
  - – water composition (this review focuses on medium used in PWR NPPs; other media are not considered)
  - – temperature
  - – water conductivity
  - – dissolved species (hydrogen/oxygen)

It is also useful to note that in literature fatigue life is defined in several ways:

- total failure – defined as a number of cycles to achieve complete fracture of a sample;
- stress drop – most of the low-cycle fatigue experiments are strain controlled – stress drop is defined as, for

example, 25% drop of stress at constant strain amplitude cycling, e.g. number of cycles to cause stress drop (compared to the initial stress value): N_{25}, N_{50} for 50% drop;

- number of cycles to achieve "mechanically-small cracks" (cracks longer than 3 mm).

Material

Material type has strong effect on fatigue behavior – in this work, we focus on metallic materials with emphasis on steel. Steel, unlike aluminum alloys can have an endurance limit, however, this is not the case for low-cycle fatigue, since there always will be plastic deformation and hysteresis during cycling due to higher stresses. Material typical for most of the PWR designs are austenitic stainless, carbon steel and also, to lesser extent, low-alloyed steel. Authors of most of the reviewed literature experimented with austenitic (AISI 304, 316 and 321) and carbon steel with very similar chemical composition – carbon steel types are usually differentiated by their mechanical properties.

Both nuclear power plants in Czech Republic (NPP Temelín – ETE; NPP Dukovany – EDU) are equipped with russian-design based WWER 440 and WWER 1000 reactors. Both reactors are of PWR type and the design material choice were predominantly austenitic stainless steel 08Ch18N10T (GOST standard 9941) and carbon steel 22K (GOST 5520). Former steel is comparable with the AISI 316. Chemical composition of mentioned steels is given in Table 1.

Obvious difference between carbon and stainless steel is their structure. The structure defines material's bulk mechanical properties such as yield strength, ultimate strength, ductility etc. It has been shown that in some cases the fatigue life can be calculated from tensile strength of the material. Structure also affects the response of material to cyclic stress/strain, e.g.: in some cases, the material exhibits increase in stress level (in strain controlled experiments) after several cycles - strain hardening. The cyclic hardening and softening greatly affects material fatigue behavior [4].

The structure itself depends on thermal treatment and chemical composition. Chemical composition also defines the corrosion resistance of the material. In the presence of corrosive medium, even demineralized water, this can't be ignored. Another important factor is the stability of the structure. Instable structure is prone to new phases formation/phase transformation (new grains, precipitates etc.). These can significantly affect fatigue performance as precipitates can work as a stress concentrator, while grain coarsening can significantly change the mechanical properties [5, 6]. Fortunately, most of these effects can be neglected since common nuclear power plant reaches maximum of ≈ 320 °C – the rate of coarsening/precipitation at these temperatures is very slow. This problem will need to be considered in next-generation nuclear reactors as the medium temperature will likely be increased to increase efficiency.

Production inherent grain size is also important factor, however this property is controlled precisely since its effects on material behavior is well defined and understood.

Surface quality is very similar – detrimental effect of rough-surface on fatigue is well-known, however unlike the grain size, the surface can be altered during assembly, operation or repair of the power plant. The quality of surface finish is one of the most important factors for fatigue performance [7]. When comparing the fine ground and rough surface specimen, the latter yielded fatigue lives lower by a factor up to 5. Author also concludes that not only scratches but also other particles (MnS), closed pores and inclusions can present a crack initiation sites. In other work, it has been found that effect of surface finish is much stronger for high-strength steel [8].

Material related effects get even more complex when combining two materials. Welded zone has different distribution of alloying elements compared to the base materials, heat used to produce the weld results in grain coarsening, precipitation of other phases. Uneven heat distribution and different thermal expansion coefficients result in tensile stresses being induced into the weld which can lead to cracking unless correct post-weld heat treatment is applied. Weld is often the weakest part of a component in NPP [9].

Tab. 1. Chemical composition of steel commonly used in NPPs / *Složení ocelí běžně používaných v jaderných elektrárnách*

	C	Cr	Ni	Mo	Si	Mn	S	P	Cu	N	Ti
22K	0,19-0,26	<0.4	<0.3	–	0.2-0.4	0.75-1	<0.025	< 0.025	< 0,03	–	–
AISI 304	<0.08	18-20	8-10,5	–	< 0,75	<2	<0.03	< 0.045	–	< 0.1	–
AISI 316	<0.08	16-18	10-14	2-3	< 0,75	<2	<0.03	< 0.045	–	< 0.1	–
AISI 321	<0.08	17-19	9-12	–	< 0.75	<2	<0.03	< 0.045	–	–	Ti 5(C+N) min, 0.7 max.
08Ch18N10T	<0.08	17-19	9-11	–	< 0.8	<2	<0.02	< 0.035	–	< 0.1	< 0.7

Presence of tensile stresses or deformation in the structure of the metal was studied by Coffin et. al. [10] – Figure 2 shows the example of sample used in the experiment - the sample was produced as on the figure and then twisted, inducing torgue plastic deformation into the thinner part of the test section. The middle, thicker part was then machined down to the same dimensions as the thinner part producing standard tensile specimen. The author tested samples with different length of the middle part while inducing same torque plastic deformation – this changes the distribution and degree of the deformation on the thinner part. The chart shows the fatigue results – X axis shows the ratio between undeformed central section and the deformed, thinner, part. For α=0 which is uniformly twisted specimen, the fatigue life is about ten times higher compared to extrapolated line. Coffin explained this discrepancy by presence of small region of inhomogeneity at the boundary between the two sections. This shows the significance of non-uniformity of deformation on low-cycle fatigue life.

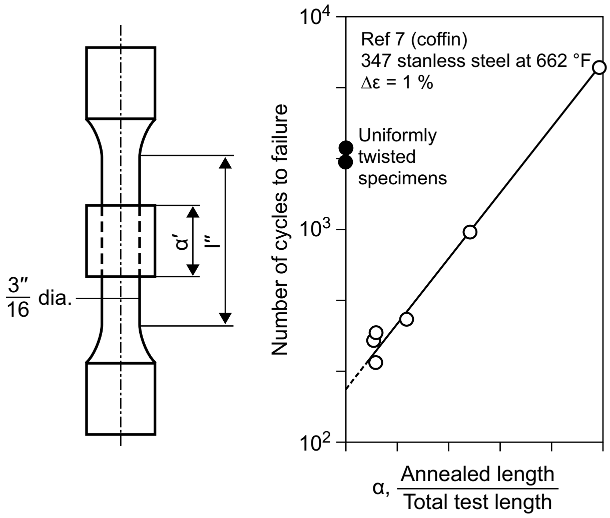

Fig. 2. Sample design and results from non-uniform plastic deformation effect on fatigue behavior [10]
Obr. 2. Nákres vzorku a výsledky měření vlivu nerovnoměrné plastické deformace na únavové chování [10]

Another material parameter is the sulfur content. Effect of sulfur as a precipitate has been shown before. Other authors showed the effect of sulfur on fatigue life in presence of oxygen containing medium. If DO ≤ 1 ppm, fatigue life decreases with increasing S content. Iida concluded that this effects saturates at S ≈ 0,015 wt. %, however, further verification of this value is required [11]. For higher DO level, fatigue life is insensitive to *S* content in the range of 0,002-0,015 wt. % [12]. This synergistic effect have not been observed for austenitic stainless steel.

Cycling parameters

Cycling parameters define the stresses and their variations in time during the experiment. Definition of some of the parameters overlap, i.e. one can be calculated from the other and vice versa. The parameters cover the maximum and minimum stress (strain) levels, whether is the cycling done in tensile/tensile-compressive/compressive regime, loading frequency/rate of loading, shape of loading curve and others. For the sake of completeness, the parameters are listed, however, their effect on fatigue life is not discussed thoroughly, as most experiments are carried out in similar manner.

Cyclic loading parameters can be described by:

- R – ratio between minimum and maximum stress level; for complete reversal (tensile to compression of same level) loading the R= -1
- σ_a – mean stress, the average value of stress
- σ_{max} – maximum stress
- σ_{min} – minimum stress
- strain rate
- strain range – Δ (σ_{max}-σ_{min})
- the shape of loading curve (wave like, triangular...)
- loading periodicity – defines if the maximum and minimum stress are periodical or vary in time

Most of the low-cycle experiments are conducted in with wave-like loading curve, in strain-control regime i.e. the experiment is controlled via sample displacement to ensure plastic deformation - the term “plastic straining” is sometimes used. The R ratio can vary, however for most of the low-cycle experiments it is set to R = -1. Other parameters and their effect on fatigue life are studied more extensively.

Strain rate defines how fast the load is applied to the sample and how fast it is unloaded. It has been stated in multiple papers, that strain rate within certain range affects fatigue life - below certain threshold value (1 %/s), reduction of strain rate reduces the fatigue life logarithmically; this effect saturates at about 0,001 %/s for carbon and low-alloy steel [13-15], the threshold values for austenitic stainless steel were found to be 0,4 and 0,0004 %/s [16-20]. It has also been shown that certain parameters such as temperature, DO content and others need to be met, otherwise the strain rate effect is negligible.

Strain range effect on fatigue life is somewhat similar to the strain rate – its effect is notable only in concurrence with other parameters. This was verified for both carbon [13, 15-16, 21] and austenitic steel [22].

Shape of the loading curve has been suggested to have significant effect on fatigue life [23], especially at higher mean stress [24].

Precise definition of parameters' values is somewhat troublesome, as loading caused by start-ups and shutdowns is hardly periodical – Figure 3. Precise description of parameters is necessary for data from different sources to be comparable, but the correlation between lab results and real-power plant fatigue is complicated. Some factors, namely the shape of the fatigue curve therefore seem negligible for the real application. There was only a limited number of research focusing on this problem [25] – in their work, authors used a programmable tensile machine for low-cycle experiments. A pre-programmed series of 50 cycles with different stress amplitude was used, this so called "spectrum" was repeated and statistically evaluated. Eventually, authors concluded that life is mostly affected by the cycles with the highest stress levels.

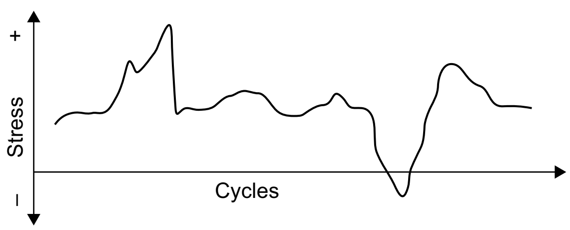

Fig. 3. Example of real operation loading
Obr. 3. Příklad reálného (cyklického) zatěžování v provozu

The gap between lab results and real application were implemented in ASME code safety margins. Safety margins reduce allowable stresses by a factor to account for these. Further elaboration is in the Chapter 2.

Effect of environment (medium)

It has been shown by many researchers that medium (high-purity water of 280-320 °C and 12-15 MPa) can significantly reduce fatigue life of a component. The effect of environment is similar to the effect of environment in corrosion fatigue or environmental assisted stress-corrosion cracking experiments. Several mechanisms of the interaction between a cycled component and an environment have been suggested:

- hydrogen embrittlement – hydrogen from various sources enter the lattice deforming it; deformed (strained) lattice is more prone to brittle fracture
- film rupture – the oxide layer has different mechanical properties than the bulk material; during cycling, the layer can rupture and the underlying material is exposed
- dissolution and repassivation – during passivation, the material dissolutes and oxidizes via corrosion reactions, the passive layer (topotactic) also dissolutes, however at much slower rate; these dissolved species can again precipitate on the surface - properties of this precipitated layer (epitactic) is different compared to the original passive layer
- enhanced localized plasticity
- interactions of dislocations with surface dissolution, film or adsorbed atoms

and complex combination of these processes [26].

Environment parameters can be divided in several groups:

- temperature - temperature as such has limited effect on fatigue life, however, temperature affects fatigue life in concurrence with other parameters [27]; effect of temperature is negligible up to the 150 °C for both carbon and austenitic stainless steel [28-30]
- dissolved oxygen (DO) content – if other parameters meet their corresponding threshold values, the fatigue life of carbon and low-alloyed steel decreases logarithmically with increasing DO content in water above 0,04 ppm; the effect saturates at 0,5 ppm. Only moderate decrease of fatigue life was observed when the DO level was reduced below 0,04 ppm [27]. However, some authors reported increase in crack growth rate in low-DO environments [31]. For austenitic stainless steel, the effect is more distinct - significant decrease of fatigue lives was observed even in low-DO water (< 0.01 ppm). The decrease was even greater at low strain rates and high temperatures [17-20, 22, 32-33]
- water conductivity – water conductivity is a measurement of amount of dissolved species in the water - these can be aggressive anions like clorides and fluorides, however, the water conductivity is held low. Nevertheless, unintentional increase of conductivity can reduce the fatigue life of a component; for example, increase from 0,07 uS/cm to 0,4 uS/cm while keeping the DO level high can decrease the fatigue life by a factor of 2 [13]
- hydrogen – hydrogen is known to propagate fatigue damage in steel, however, its effect above 150 °C is only marginal. Nevertheless, this can pose a problem during start up and shutdown.

Concurrent effect of parameter

We mentioned several times that the complex effect of medium on fatigue life is much greater than effect of a single parameter e.g. temperature, DO, strain rate etc. Exceeding the so-called threshold value of a parametr of a medium significantly reduces fatigue life of a component only if other factors' threshold values are also met. To account for this complex behavior, complex approaches have been implemented [27]:

- first approach, suggested by Higuchi, introduced the F_{en} factor, which directly compares the fatigue life of material tested in air and in environment - this allows the designers to project components based on air fatigue curves. This environmental factor is described by the equation: $F_{en} = N_{air}/N_{en}$ that is, if the environment causes zero decrease in fatigue life, the $F_{en}= 1$;
- second approach suggests measurement of new design fatigue curves - this approach is much more precise, however, the number of possible material – environment combinations is very large and the data gathering is extensively time consuming.

Example of complex behavior in medium is shown in Table 2. First four columns describe the experiment setup, last three actual results – $N_{f,25}$ is the number of strain controlled cycles causing either total failure or 25 % of stress drop. Last two columns compare F_{en} factors. Predicted F_{en} factor (last column) in first four rows shows that the effect of environment parameters should be zero – the predicted F en = 1. However, comparing this with the F_{en} factor calculated from the number of cycles ("measured") shows that even small change of environment parameters have some impact on fatigue behavior (next-to-the-last column).

Further, the table shows the effect of other parameters, namely strain rate in PWR environment – rows 5 and 7. Reduction of strain rate (≈10 times) reduces number of cycles to failure from 15600 to 1400. Other

Tab. 2. Summary of fatigue data from PWR environment [25] / *Shrnutí výsledků z měření únavového chování v VVER prostředí [25]*

Environment	**Frequency**	**Strain rate**	**ε_a**	**$N_{f,25}$**	**Mean curve/N_f (F_{en})**	
	Hz	% s^{-1}	%	cycles	measured	predicted
air 25 °C	0,5	1,02	0,51	6 120	1,41	1,0
air 25 °C	0,5	0,62	0,31	47 000	0,99	1,0
air 100 °C	0,1	0,168	0,42	15 600	1,03	1,0
air 25 °C	spectrum	0,8	0,2..0,8	9 650	2,3	1,0
PWR 320 °C	0,1	0,1	0,25	15 600	8,65	3,65
PWR 320 °C	0,01	0,16	0,4	2 650	7,08	5,88
PWR 320 °C	0,01	0,02	0,508	1 400	6,29	5,53
PWR 320 °C	0,01	0,013	0,315	6 660	6,61	6,26
PWR 320 °C	0,01	0,013	0,315	7 800	5,64	6,26
PWR 320 °C	spectrum	0,039	0,11..0,48	4 600	30,58	4,67
PWR 320 °C	spectrum	0,065	0,19..0,78	1 250	20,31	4,09

Tab. 3. Japanese proposal on F_{en} calculation equations [34] / *Rovnice používané pro výpočet F_{en} faktoru v Japonsku [34]*

Carbon and low alloy steel		**Stainless steels**	
$\ln(F_{en}) = -(0.199T^*O^* + 0,112\ )S^*\varepsilon\`$		**$\ln(F_{en}) = (C - \varepsilon\`^*)T^*$**	
ε`* = 0	(ε > 1.0 %/d)	C = 1.182	(BWR)
ε`* = ln(ε`)	(1,0 ≥ ε`≥ 0.0004 %/s)	C = 3.91	(PWR)
ε`* =0	(ε` < 0.0004 %/s)	ε`* = ln(3.26)	(BWR: ε` >3.26%/s)
T* = 0.00531T-0.7396	(T ≥ 180 °C)	ε`* = ln(49.9)	(PWR: ε` >49.9%/s)
T* = 0,216	(T < 180 °C)	ε`* = ln(ε`)	(BWR: 0.0004) ε` ≤ 3.26 %/s)
O* = ln(DO/0.03)	(0,03 ≤ DO ≤ 0.5 ppm)		(PWR: 0.0004) ε` ≤ 49.9 %/s)
O* = 0	(DO < 0.03 ppm)	ε`* = ln(0.0004)	(ε` < 0.0004 %/s)
O* = ln(0.5/0.003)	(DO < 0.5 ppm)	T*=0.000813T	(BWR)
S* = 17.23S + 0.777		T*=0.000782T	(PWR: T ≤ 325 °C)
F_{en}=1,0	(ε_a ≤ 0.042 %)	T*=0.254	(PWR: T > 325 °C)
	(ε_a of 0,042 % is the same strain amp. at 10^6 cycles in the design fatigue curve)	F_{en} = 1.0	(ε_a ≤ 0,11 % or in case of an earthquake)
The same as MITI guideline		Revised MITI guideline	

significant changes of fatigue life are also visible but it is apparent, that the effects of parameters are very complex.

After lengthy review and discussion of features of both approaches, the F_{en} factor has been implemented into the ASME Code Part III: Boiler and Pressure Vessel Component. Verification of F_{en} equation is ongoing and there is an effort to extend its range of applicability. Examples of F_{en} calculation models are shown in Table 3.

CONCLUSION

This literature review sums up the effects of different parameters of environment on fatigue life in low-cycle regime of carbon, low-alloyed and austenitic stainless steel with focus on PWR environment. Environmental parameters often affect the fatigue life in some kind of concurrence, i.e. certain value of other parameters is necessary for another parameter to cause redution of fatigue life. This complex problem can be simplified by material selection and consideration of common PWR NPP parameters, thusly reducing the number of combinations. However this is not applicable for future power plants which are designed with focus on higher efficiency (higher temperature and pressure) and are also expected to use different media (liquid metals, helium, supercritical water).

Models for fatigue life calculations accounting for these complex effects are shortly described in the text. Multiple equations for the same environment are available - their applicability and preciseness is being discussed in the research community. Current research focuses on quantifying fatigue damage during transient states.

LITERATURE

1. Yao, J.; Munse, W. *Low-cycle Fatigue of Metals*. Literature Review; Defense Technical Information Center, 1961.
2. Deardorf, K. K. C. J., Fujikawa A.F. *A survey of current US nuclear plant fatigue issues*. 3rd International Conference on Fatigue of Reactor Componentss. 2004.
3. Materials Reliability Program: *Operating Experience Regarding Thermal Fatigue of Piping Connected To PWR Reactor Coolant Systems* (MRP-85).
4. Ehrnsten, U.; Ivanchenko, M.; Nevdacha, N.; Yagozinskyy, Y.; Toivonen, A.; Hänninen, H. *Dynamic Strain Ageing of Deformed Nitrogen-alloyed AISI 316 Stainless Steels*. 3rd International Conference on Fatigue of Reactor Conference. 2004.
5. Baldwin, E.; Sokol, G.; Coffin, L. *Cyclic Strain Fatigue on AISI Type 347 Stainless Steel*. Proceedings ASTM. 1957.
6. Coffin, L.; Read, J. *A Steel of the Strain Cycling and Fatigue Behavior of a Cold-Worked Metal*. International Conference on Fatigue. 1957.
7. Suhr, R. The effect of surface finish on high cycle fatigue of a low alloy steel. EGF1. 2013.
8. Hanley, B. C.; Dolant, T. J. *Metals Engineering - Design*; Soc. Mech. Engrs., 1953.
9. Narayanan, R.; Kalyanaraman, V.; Sathakumar, A.; Seetharaman, S.; Satish Kumar, S.; Arul Jayachandran, S.; Senthil, R. *Teaching Material on Structural Steel Design for Civil/Structural Engineering*; 2001.
10. Coffin, L. *The Problem of Thermal Stress Fatigue in Austenitic Steels at Elevated Temperatures*. Symposium on Effect of Cyclic Heating and Stressing on Metals at Elevated Temperatures. 1954.
11. Iida, K.; Bannai, T.; Higuchi, M.; Tsutsumi, K.; Iida, K.; Bannai, T.; Sakaguchi, K. *Comparison of Japanese MITI Guideline and Other Methods for Evaluation of Environmental Fatigue Life Reduction*. Pressure Vessel and Piping Codes and Standards. 2001; pp 73-81.
12. Mehta, H. S.; Gosselin, S. R. *An Environmental Factor Approach to Account for Reactor Water Effects in Light Water Reactor Pressure Vessel and Piping Fatigue Evaluations*. Fatigue and Fracture. 1996; pp 171-185.
13. Chopra, O.; Shack, W. J. *Evaluation of Effects of LWR Coolant Environments on Fatigue Life of Carbon and Low-Alloy Steels*. Evaluation of Effects of LWR Coolant Environments on Fatigue Life of Carbon and Low-Alloy Steels, in Effects of the Environment on the Initiation of Crack Growth, ASTM STP 1298. 1997; pp 247-266.
14. Chopra, O. K.; Shack, W. J.; *Nuclear Engineering and Design* **1998**,184, 49-76.
15. Chopra, O.; Shack, W. J. *Effects of LWR Coolant Environments on Fatigue Design Curves of Carbon and Low-Alloy Steels*; 1998.
16. Chopra, O.; Shack, W. *Journal of Pressure Vessel Technology* **1999**, 121, 49-60.
17. Chopra, O.; Shack, W. *Environmental Effects on Fatigue Crack Initiation in Piping and Pressure Vessel Steels*; 2001.
18. Fujiwara, M.; Endo, T.; Kanasaki, H. *Strain Rate Effects on the Low-Cycle Fatigue Strength of 304 Stainless Steel in High-Temperature Water Environment*; Fatigue Life: Analysis and Prediction. Proc. Intl. Conf. and Exposition on Fatigue, Corrosion Cracking, Fracture Mechanics, and Failure Analysis. 1986; pp 309-313.
19. Higuchi, M.; Iida, K. *Reduction in Low-Cycle Fatigue Life of Austenitic Stainless Steels in High-Temperature Water*. Pressure Vessel and Piping Codes and Standards. 1997; pp 79-86.
20. Kanasaki, H.; Umehara, R.; Mizuta, H.; Suyama, T. *Effect of Strain Rate and Temperature Change on the Fatigue Life of Stainless Steel in PWR Primary Water*. Trans. 14th Intl. Conf. on Structural Mechanics in Reactor Technology (SMiRT 14). 1997; pp 485-493.
21. Chopra, O.; Muscara, J. *Effects of Light Water Reactor Coolant Environments on Fatigue Crack Initiation in Piping and Pressure Vessel Steels*. Proc. 8th Intl. Conference on Nuclear Engineering, 2.08 LWR Materials Issue. 2000.
22. Tsutsumi, K.; Dodo, T.; Kanasaki, H.; Nomoto, S.; Minami, Y.; Nakamura, T. *Fatigue Behavior of Stainless Steel under Conditions of Changing Strain Rate in PWR Primary Water*. Pressure Vessel and Piping Codes and Standards. 2001; pp 135-141.
23. Benham, P. *Metallurgical Reviews* **1958**, 3, 203-234.
24. Johansson, A. *Fatigue of steels at constant strain amplitude and elevated temperature*. Colloquium on Fatigue. 1956; pp 112-122.

25. Solin, J.; Karjalainen-Roikonen, P.; Arilahti, E.; Moilanen, P. *Low cycle behaivor of 316 NG alloy in PWR environment*. 2004.
26. Gangloff, R. P.; Ives, M. B. *Environment Induced Cracking of Metals*.1990.
27. Chopra, O.; Shack, W. J. *Review of the Margins for ASME Code Fatigue Design Curve - Effects of Surface Roughness and Material Variability*; 2003.
28. Higuchi, M.; Iida, K. *Nuclear Engineering and Design* **1991**, 129, 293-306.
29. Katada, Y.; Nagata, N.; Sato, S. *ISIJ Intl.* **1993**, 31, 877-883.
30. Nakao, G.; Kanasaki, H.; Higuchi, M.; Iida, K.; Asada, Y. *Effects of temperature and dissolved oxygen content on fatigue life of carbon and low alloy steels in LWR water environment*; 1995.
31. Wire, G.; Li, Y. Initiation of environmentally-assisted cracking in low-alloy steels; 1996.
32. Kanasaki, H.; Umehara, R.; Mizuta, H.; Suyama, T. *Fatigue Lives of Stainless Steels in PWR Primary Water*. Trans. 14th Intl. Conf. on Structural Mechanics in Reactor Technology (SMiRT 14). 1997; pp 473-483.
33. Tsutsumi, K.; Kanasaki, H.; Umakoshi, T.; Nakamura, T.; Urata, S.; Mizuta, H.; Nomoto, S.; *Fatigue Life Reduction in PWR Water Environment for Stainless Steels*. Assessment Methodologies for Preventing Failure: Service Experience and Environmental Considerations. 2000; pp 23-24.
34. Higuchi, M. *Development of Evaluation Method of Fatigue Damage on Operating Plant Components in Considering Environmental Effect of LWR Coolant*. 3rd International Conference on Fatigue of Reactor Components. 2004.