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Fatigue of NPP Components and Piping under Service Conditions

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К оценке циклической прочности оборудования и трубопроводов АЭС с учетом эксплуатационных факторов

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Предложены эмпирические уравнения для описания кривых усталости (до 10^{12} цикл) сталей, используемых для оборудования и трубопроводов АЭС. Параметры представленных уравнений позволяют учитывать влияние асимметрии цикла, коррозионного и механического взаимодействия между охладителем и металлом трубопровода, а также снижения пластичности металла в процессе эксплуатации.

Ключевые слова: коррозионная усталость, кривая усталости, асимметрия цикла, легководный ядерный реактор.

The kinetics of fatigue damage suffered by components of nuclear power facilities with light-water reactors is governed by a number of simultaneous processes:

a) unsteady-state loading (mechanical and thermal stresses) during transients, alternating in a general case with steady-state conditions and giving rise to a series of loading half-cycles with various amplitudes and maximum stresses, which are separated by steady-state loading conditions with possible coincident vibrations;

b) in-service variations of metal condition (loss of ductility due to ageing, coolant effects and irradiation, hardening or softening under cyclic elastic-plastic loading, radiation hardening, formation of oxide films with properties dissimilar to those of the metal);

c) corrosive and mechanical interaction between coolant and metal (with possible deviation of water chemical composition from its nominal parameters during transients, faults in the water treatment system, local increase in the coolant corrosivity in stagnant zones, gaps and pockets with accumulation of sludge).

It appears unrealistic to produce integrated models based on empirical data for accumulation of fatigue and corrosion fatigue damage in the component metal, with allowance for all the above processes, operational factors and their interaction. The equations employed to assess the condition of components in terms of cumulative fatigue damage [1] are modified fatigue curve equations – of

Manson–Coffin–Langer type – in which the essential data on metal are confined to mechanical characteristics under static tension. These equations determine the durability at the time of crack initiation and make allowance for operating conditions [2–5].

The loading history calculated at the operation stage is based on monitoring data for pressure, temperature and coolant flow, component displacements, and vibrations. The calculated tensile (ascending) half-cycles of equivalent stresses, whose number is equal to the number of full cycles, are used in calculation with no regard for the chronological sequence of the combined half-cycles or their parts, in order to obtain the maximum ranges [1]. For cycles fund within the elasticity limits, it is often impossible to establish the true cycle asymmetry. This can be explained by the peculiarities of the strength theory in use (the maximum shear stresses), by the absence of reliable information on the constitutive equation of metal and its in-service variations (values of the yield stress $R_{p0.2}^T$, ultimate strength R_m^T, and area reduction Z^T). Moreover, establishment of the half-cycle asymmetry for incorporation in calculations is not justified when the actual loading history is not properly represented by half-cycles formed by the principle of the maximum range.

This is the reason why fatigue curves with regard to maximum cycle asymmetry effects are used in the national standards. In this case, it will suffice to know the stress amplitude to make the calculation.

This issue is also of considerable importance for determining the half-cycle parameters beyond the elasticity limits as the result of elastic-plastic stress analysis or rough correction of the elastic analysis result [1, 6], prior to forming half-cycles of stress ranges, depend on the cyclic proportionality limit, with the stresses exceeding it, as well as on the strain-hardening exponent. Normally, the half-cycle parameters are calculated with the use of simplified constitutive equation based on the specified mechanical properties [1], with the result that the stress range is underestimated and the strain range is overestimated in elastic-plastic half-cycles. The set of mechanical properties (the yield stress $R_{p0.2}^T$ and the ultimate strength R_m^T) specified in [1], is provided for use in the calculations to choose the basic dimensions (wall thickness of components) at the design stage and establishes the lower limits of these characteristics.

A higher real value of the initial yield strength or its increase due to, e.g., cyclic hardening or irradiation, will lead to a different value of stress range in the elastic-plastic half-cycle and to a different cycle asymmetry for elastic half-cycle as compared to the use of the specified parameters $R_{p0.2}^T$, R_m^T, and Z^T.

Experimental data concerning the effect of water coolant on the cyclic strength of carbon steels (CS), low-alloy steels (LAS) and austenitic stainless steels (SS) [3, 7–12] point to the possibility of a considerable decrease in the number of cycles to failure under certain combined conditions of cyclic loading. In a general case, these are characterized by coolant temperature T, sulfur content S (CS, LAS), strain rate $\dot{e}$, and oxygen concentration (OC) in the coolant. Static holds at maximum stresses will also reduce durability of the material in contact with the coolant [7].

Low-cycle fatigue in the range of up to 10^5 cycles is best covered by available data. Tests were conducted with a fully reversed strain-controlled cycle. In the region of strain amplitudes e_a allowable in nuclear plant components ($e_a < 0.3\%$), results were obtained only for a relatively high strain rate.

No tests have been performed under conditions of unsteady-state loading for strain amplitude and rate, oxygen concentration and temperature, with holds under compression and/or tension, during which a damaged oxide film could be restored on the surface of the stressed metal. The effect of stress asymmetry under exposure to water in various states (steam, steam-water mixture) has not been studied in the high-cycle region. This lack of information on corrosion fatigue dictates a priori some calculation provisions and is explained primarily by the complexity, high cost and long duration of the required tests.

In a fully reversed strain-controlled cycle, with the number of cycles exceeding 10^5, the cyclic strength of specimens is associated with the oxide film strength at the threshold strain amplitude e_{ath}. The strain is expected to cause the crack to open wide enough to let the fluid enter the crack cavity.

As reported in [7], the threshold value e_{ath}, below which no ambient effects are observed in a fully reversed cycle of the specimen loading, is equal to or is $\sim 20\%$ higher than the fatigue limit of metal (CS, LAS) exposed to air.

For SS, e_{ath} is estimated by various sources at 0.126 [12], 0.16 [7], and 0.18% [9], which is above the strain of the fatigue limit for SS. It is noteworthy that the film and metal often have different mean stresses of loading cycles, as restoration of the oxide film after its rupture in the preceding half-cycle may occur under conditions of stressed metal.

Initiation of fatigue cracks under the oxide film is not improbable in the high-cycle region, which is accounted for by the correlation between e_{ath} and the fatigue limit of metal in air under conditions of asymmetrical stress cycling.

The key parameters affecting corrosion-fatigue damage being invariant and dependant on the steel grade alone, it was deemed possible to use the data [7, 11] for setting up equations of corrosion fatigue.

In [3], the Langer equation was applied to derive the low-cycle corrosion fatigue curve for low-alloy steel with the use of ductility Z_w^T and rupture strain of the oxide film, which were determined for a low strain rate during tensile testing in water of specified parameters (temperature, OC).

Equations according to [1] for conditions of loading in the air environment at temperatures typical of light water reactors, were extended to the region of giga-cycle fatigue (up to 10^{12} cycles) with exponent m_e of power dependence of the number of cycles, N, on elastic cyclic strain, determined by the stress R_c^T with $N = 1/4$ (static tension to strain $e_c^T \le e_f^T$ – true fracture strain and fatigue limit ($N = 10^7$) in a fully reversed cycle $R_{-1}^T = \kappa R_m^T$, where $\kappa = 0.4$ at $R_m^T \le 700$ MPa and $\kappa = (0.54 - 2 \cdot 10^{-4} R_m^T) R_m^T$ with $700 < R_m^T \le 1200$ MPa.

This assumption certainly adds conservatism to the fatigue analysis with $N > 10^7$, but allows performing calculations aimed at minimization of vibration stresses.

The effect of stress ratio is determined by the modified Goodman diagram, with the maximum mean stress R_m^T replaced by R_c^T.

Inasmuch as the fatigue analysis method applies to components of light water reactors in which cyclic plastic strains are only allowed in limited areas making a small part of the component wall thickness (stress concentration zones), the maximum true stress, R_p^T, including a similar cycle with the ratio of similitude n_σ (safety margin on stresses), is determined roughly by R_m^T, R_m^T with regard to cyclic instability of material.

The allowable amplitude of stress $[\sigma_{aF}]$, which is quasi-elastic stress in the elastic-plastic area, or the allowable number of cycles $[N]$ for steels with $[N] \le 10^{12}$ are equal to the least of the two values found from Eqs. (1) and (2), in which the stress cycle asymmetry factor (stress ratio) is absent in an explicit form, as distinct from [1]:

$$[\sigma_{aF}] = E^T e_c^T (4n_N[N])^{-m} + (R_c^T - [\sigma_{F\max}] i_\sigma)[(4n_N[N])^{m_e} - i_\sigma]^{-1}, \tag{1}$$

where

$$[\sigma_{F\max}] = R_p^T \quad \text{with} \quad [\sigma_{F\max}] \ge R_p^T,$$

$$i_\sigma = 0 \quad \text{with} \quad [\sigma_{aF}] \ge [\sigma_{F\max}] \quad \text{or} \quad [\sigma_{aF}] \ge R_p^T,$$

$$i_\sigma = 1 \quad \text{with} \quad [\sigma_{aF}] < [\sigma_{F\max}] < R_p^T,$$

$$[\sigma_{aF}] = \{E^T e_c^T (4[N])^{-m} + (R_c^T - n_\sigma[\sigma_{F\max}] i_\sigma)[(4[N])^{m_e} - i_\sigma]^{-1}\} n_\sigma^{-1}, \tag{2}$$

where

$$n_\sigma[\sigma_{F\max}] = R_p^T \quad \text{with} \quad n_\sigma[\sigma_{F\max}] \ge R_p^T,$$

$$i_\sigma = 0 \quad \text{with} \quad [\sigma_{aF}] \ge [\sigma_{F\max}] \quad \text{or} \quad n_\sigma[\sigma_{aF}] \ge R_p^T,$$

$$i_\sigma = 1 \quad \text{with} \quad n_\sigma[\sigma_{aF}] < n_\sigma[\sigma_{F\max}] \le R_p^T,$$

n_σ and n_N are safety margins on stresses and on the number of cycles, m, m_e, and R_c^T are the material characteristics, and e_c^T is the ductility characteristic dependant on Z_c^T and determined as

$$e_c^T = \ln[100/(100 - Z_c^T)] - \{|(\sigma_F^*)_{\max}| - R_{p0.2}^T\}(2E^T)^{-1}, \tag{3}$$

or with $(\sigma_F^*)_{\max} < R_{p0.2}^T$, by the formula

$$e_c^T = \ln[100/(100 - Z_c^T)], \tag{4}$$

where $(\sigma_F^*)_{\max}$ is the stress of maximum magnitude throughout the loading history.

Calculation of $[\sigma_{aF}]$ or $[N]$ with regard to the maximum effect of mean stress in the cycle relies on formulas (1) and (2) with $[\sigma_{F\max}] = R_p^T$ and satisfaction of the condition for i_σ.

When using the data from the national standards, material specifications or regulations (e.g., [1]), which specify the mechanical characteristics, $Z_c^T = Z^T$ should be set for $Z^T \le 50\%$. In case of $Z^T > 50\%$, we take $Z_c^T = 50\%$.

If the ductility characteristic e_c^T is determined according to Z^T found from static tensile tests, the following formulas are to be used:

$$e_c^T = 0.005Z^T - \{|(\sigma_F^*)_{\max}| - R_{p0.2}^T\}(2E^T)^{-1}, \tag{5}$$

and

$$e_c^T = 0.005Z^T \quad \text{with} \quad |(\sigma_F^*)_{\max}| < R_{p0.2}^T. \tag{6}$$

The characteristics E^T, Z^T, and R_m^T are taken as equal to the minimum values in the interval of operating temperatures with allowance for ageing. The safety margin for stress n_σ is set equal to 2, and $n_N = 10$ for the number of cycles.

Symbol	$R_m^T \le 700$ MPa	$700 < R_m^T \le 1200$ MPa
R_{-1}^T	$0.4R_m^T$	$(0.54 - 2\cdot 10^{-4}R_m^T)R_m^T$
m	0.5	$0.36 + 2\cdot 10^{-4}R_m^T$
m_e	$0.132\log[R_m^T(R_{-1}^T)^{-1}(1+1.4\cdot 10^{-2}Z_c^T)]$	
R_c^T	$R_m^T(1+1.4\cdot 10^{-2}Z_c^T)$	

The values of R_p^T for steels are adopted according to the properties at the minimum temperature of the cycle:

$$R_p^T = 0.5[R_{p0.2}^{(T_{\min})} + R_m^{(T_{\min})}]. \tag{7}$$

It is acceptable to take $T_{\min} = 20°\mathrm{C}$.

Assessment of the cycle asymmetry effect with the use of R_p^T offsets application of the specified $R_{p0.2}^T$ and R_m^T which may be lower than the actual values, but may prove to be too conservative. Whenever justified (in the absence of residual stresses after manufacture and of elastic-plastic strain during operation), the R_p^T value may be reduced according to the stress analysis results.

The regulations [1] contain recommendations for fatigue analysis for cyclic high-frequency loading, e.g., vibration stresses, coinciding with low-frequency cycles.

The fatigue curves according to [1], Eqs. (1), (2) and ASME Code [13], adopted in French, German, UK and Japanese standards, are compared in [4, 5].

The recommendations for analyses of cases involving exposure to the coolant of light water reactors apply to steels with $R_m^{20} \leq 700$ MPa.

The factors affecting the cyclic strength of CS and LAS and their welds are S, T, and $\dot{e}$ in the tensile half-cycle as well as OC, while those affecting the cyclic strength are T, $\dot{e}$, and OC.

The recommended analysis involves fatigue equations including the coefficient of cyclic strength reduction in water environment F_{en} $(F_{en} \geq 1)$.

The amplitude $[\sigma_{aF}]$ or number of cycles $[N]$ for steels with $[N] \leq 10^{12}$ are equal to the least of their values found from Eqs. (8), (9) and (1), (2):

$$[\sigma_{aF}] = E^T e_c^{20} (4n_N F_{en}[N])^{-m} + R_{cF}^T (4n_N [N])^{-m_{eF}}, \tag{8}$$

where e_c^{20} is determined from formulas (3), (4) with the use of specified values of $Z^T = Z^{20}$ or by formulas (5), (6) when the calculation involves the actual properties $R_{p0.2}^T$, R_m^T, and Z^T

$$[\sigma_{aF}] = [E^T e_c^{20} (4F_{en}[N])^{-m} + R_{cF}^T (4[N])^{-m_{eF}}] n_\sigma^{-1}. \tag{9}$$

The values of R_{cF}^T and m_{eF} in Eqs. (8) and (9) are determined with regard to the influence of water environment by the formulas:

$$R_{cF}^T = R_m^T (1 + 0.014 Z_F),$$

$$m_{eF} = 0.132 \log(2.5 + 0.035 Z_F),$$

where Z_F is calculated with the use of specified values:

$$Z_F = 100[1 - \exp(-2e_c^{20} F_{en}^{-m})],$$

or with the use of actual Z^{20} values:

$$Z_F = Z^{20} F_{en}^{-m}.$$

The coefficient F_{en} is found from formulas involving the data from [7, 11]:
for CS

$$F_{en} = 2.49 / \exp(0.101 S^* T^* O^* \dot{e}^*),$$

for LAS

$$F_{en} = 2.8 / \exp(0.101 S^* T^* O^* \dot{e}^*),$$

where

$$S^* = 0.015 \quad \text{with} \quad OC > 1.0 \text{ ppm},$$

$$T^* = 0 \quad \text{with} \quad T < 150°\text{C},$$

$$S^* = S\% \quad \text{with} \quad OC \le 1.0 \text{ ppm} \quad \text{and} \quad 0 < S \le 0.015\%,$$

$$T^* = T - 150 \quad \text{with} \quad 150 \le T \le 350°\text{C},$$

$$S^* = 0.015 \quad \text{with} \quad OC < 1.0 \text{ ppm} \quad \text{and} \quad S > 0.015\%,$$

$$O^* = 0 \quad \text{with} \quad OC \le 0.05 \text{ ppm},$$

$$\dot{e}^* = 0 \quad \text{with} \quad \dot{e} \ge 1\% \text{ s}^{-1},$$

$$O^* = \ln(OC/0.04) \quad \text{with} \quad 0.05 < OC \le 0.5 \text{ ppm},$$

$$\dot{e}^* = \ln \dot{e} \quad \text{with} \quad 10^{-3} < \dot{e} < 1\% \text{ s}^{-1},$$

$$O^* = \ln 12.5 \quad \text{with} \quad OC > 0.5 \text{ ppm},$$

$$\dot{e}^* = \ln 0.001 \quad \text{with} \quad \dot{e} \le 0.001\% \text{ s}^{-1},$$

for annealed SS steels

$$F_{en} = 2.55 / \exp(T^* O^* \dot{e}^*),$$

where

$$T^* = 0 \quad \text{with} \quad T < 150°\text{C},$$

$$\dot{e}^* = 0 \quad \text{with} \quad \dot{e} > 0.4\% \text{ s}^{-1},$$

$$T^* = (T - 150)/175 \quad \text{with} \quad 150 \le T \le 325°\text{C},$$

$$\dot{e}^* = \ln \dot{e}/0.4 \quad \text{with} \quad 4 \cdot 10^{-4} \le \dot{e} \le 0.4\% \text{ s}^{-1},$$

$$O^* = 0.26 \quad \text{at all } OC \text{ levels},$$

$$\dot{e}^* = \ln 0.001 \quad \text{with} \quad \dot{e} < 4 \cdot 10^{-4}\% \text{ s}^{-1}.$$

Sulfur content (S) in CS and LAS steels is taken in accordance with the respective certificates or specifications.

When the component loading half-cycles are formed according to the maximum stress (strain) range criterion, stress (strain) variation areas associated with different conditions are combined within one half-cycle, which is why this half-cycle may show loss of continuity in T, $\dot{e}$, and OC.

Temperature T is set equal to the maximum temperature in the half-cycle of tension in the region of the equivalent stress variation $[\sigma_{F\max}] - R_{-1}^{T}$; the strain rate $\dot{e}$ is taken equal to the minimum value in the tensile half-cycle in the same region as in determining T; oxygen concentration OC is set equal to its maximum value in regimes governing the tensile half-cycle for carbon and low-alloy steels.

The coefficients F_{en} for CS and LAS steels are taken higher than their values in [7], where they are determined for the moment of specimen ($D \sim 10$ mm) damage by the so-called engineering-size crack (3 mm in depth and ~ 10 mm in length on the surface), which is admissible for thick-walled components. These higher values of the coefficients are explained by the fact that the low-cycle test procedure [1] requires allowance for smaller cracks (0.5–2 mm in length and ~ 0.1 mm deep) in plotting the fatigue curves.

The effect of water environment as reported in [7], when at least one of the T^*, O^*, and $\dot{e}^*$ values leads to the minimum integral effect of the water environment, is determined for CS, LAS, and SS steels by coefficients $F_{en} = 1.74$; 2.45 and 2.55, respectively. The correction caused an increase in the coefficient values to $F_{en} = 2.49$ and 2.8 for CS and LAS, respectively. For SS, F_{en} was left unchanged in the absence of empirical data for its adjustment.

Equations (8) and (9) correspond to the fatigue curve in water environment and for a fully reversed cycle with exposure to water; the effect of loading asymmetry is allowed for by equations (1) and (2).

The fully reversed loading cycle in transition from the low-cycle to the high-cycle region is provisionally adopted for conditions of loading in water environment as the more damaging to the oxide film formed on the stressed metal as a result of its restoration during the previous loading. No significant difference in resistance to corrosion fatigue has been found for SS in cast and deformed states [7, 11], where coefficient F_{en} was assumed to be identical in both cases.

Conclusions. The procedure for cyclic strength analysis of nuclear plant components and pipelines performed during design and operation with the aim of assessing their condition, is based on the empirical equations of fatigue curves. The analysis takes into account the instability of mechanical properties of materials, the stress cycle asymmetry, and the influence of the water environment.

The effect of complicated conditions of the actual loading on the fatigue damage accumulation being still inadequately understood, the evaluation techniques have to be conservative, especially with allowance made for the environmental effect, when these techniques are recommended for identifying the component areas of potentially highest susceptibility to corrosion fatigue damage and for prescribing periodic inspection of such areas.

Резюме

Запропоновано емпіричні рівняння для опису кривих утоми (до 10^{12} цикл) сталей, що використовуються для обладнання та трубопроводів АЕС. Параметри представлених рівнянь дозволяють враховувати вплив асиметрії циклу, корозійної та механічної взаємодії між охолодником і металом трубопроводу, а також зниження пластичності металу в процесі експлуатації.

1. *PNAE G-7-002-86. Regulations for Strength Analysis of NPP Equipment and Pipelines* [in Russian], Énergoatomizdat, Moscow (1989).
2. V. M. Filatov, “Limits to initiation of fatigue macrocracks,” *Voprosy Atomnoi Nauki i Tekhniki. Ser. Nuclear Reactor Physics and Design*, **11** (**21**), P. 2, 114–123 (1978).
3. V. M. Filatov, “Computational and experimental assessment of cyclic corrosion resistance,” *Zavod. Lab.*, **9**, 66–68 (1991).
4. V. M. Filatov, “Permissible stresses and cyclic strength analysis according to Russian Regulations and ASME Code,” in: RF-US Workshop “Safety-Life Extension,” ASME–RAS-Minatom (19–22 May 1997), Moscow (1997).

5. V. M. Filatov, “Allowable stresses and design fatigue curves for NPP components in Russian Strength Standards and ASME Code,” in: 4th Int. Conf. on *Material Behavior Problems of NPP Equipment. Manufacture and Operation* (16–23 June), St. Petersburg, Russia (1996).
6. V. Yu. Zubov and V. M. Filatov, “Elastic-plastic strain concentration,” *Voprosy Sudostroeniya. Research in Metals*, **36**, 50–55 (1983).
7. O. K. Chopra and J. Muskara, “Effect of light water reactor coolant environments on fatigue crack initiation in piping and pressure vessel steels,” in: Proc. of ICONE 8 (April 2–6, 2000, Baltimore, MD USA) (2000).
8. M. Higuchi and K. Iida, “Evaluations strength correction factors for carbon and low-allow steels in oxygen-containing high-temperature water,” *NED*, **129**, 293–306 (1991).
9. H. Kanasaki, R. Umehara, H. Mizuta, and T. Suyama, “Fatigue lives of stainless steels in PWR primary water,” Proc. 14th Int. Conf. on *Structural Mechanics in Reactor Technology* (SMIRT 14), v. DO7/1, Aug. 1997, Lyon, France (1997), p. 473–483.
10. H. Kanasaki, R. Umehara, H. Mizuta, and T. Suyama, “Effects of strain rate and temperature change on the fatigue lives of stainless steels in PWR primary water,” Ibid., p. 485–493.
11. O. K. Chopra, “Mechanism and Estimation of Fatigue Crack Initiation in Austenitic Stainless Steels in LWR Environments,” in: NUREG/CR-6787, ANL-01/25 (2002).
12. H. S. Mehta and S. R. Gosselin, “Environmental factor approach to account for reactor water effects in pressure vessel and piping fatigue evaluations,” *NED*, **181**, 175–197 (1998).
13. *ASME BPVC*, Sec. III, Appendices (1992).

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