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Probabilistic Safety Assessment of the Steam Generator Cover

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Abstract

The structural integrity of a steam generator cover is investigated in probabilistic terms. The goal is to make the inspection strategies for nuclear power plants (NPPs) more realistic and efficient. Mathematical description of the gradual damage of the stud bolt until its rupture is based on the three stages: origin of a surface defect such as a crack or pitting; growth of defect before conditions of stress corrosion cracking; growth of defect under stress corrosion cracking. The results of probabilistic safety assessment of the analyzed demountable connection of the 1st circuit collector of steam generator for two kinds of sealing and for different limit mechanism are presented.

Keywords: Probability, failure, fracture mechanics, limit loads, nuclear power plant, plasticity, uncertainty, random variable, probabilistic safety assessment, reliability, risk assessment, structural integrity, steam generator, stud bolt, demountable joint, collector, stress, bending, gasket, expanded graphite, stress corrosion cracking, tightening, torque moment, pre-stressing, hydraulic device

1. Introduction

In both the probabilistic safety assessment (PSA) and the risk analysis the calculation of the probability of failure is involved. Using the appropriate probabilistic techniques the answers to several questions may be gained, among others:

(1) how a system may fail and lead to hazardous scenarios;
(2) how likely are these scenarios to occur;
(3) what are the consequences of these scenarios;
(4) what risk is involved (a quantification).

This study is focused on the failure of the steam generator cover addressing issues (1) and (2). The item (3) is mainly a technological and economical issue; (4) may be simply solved by the formula (1.2). The loss of functionality of the demountable joint of the 1st circuit collector of the steam generator is investigated in probabilistic terms, concentrating on the stud bolt rupture and the loss of tightness probability. Two kinds of sealing and two different limit mechanism are taken into account. Thus the safety measures are assessed with a goal to make the inspection strategies for the nuclear power plant (NPP) more realistic, efficient and economic. In general, the structural integrity is defined as the probability of a system satisfactorily performing its specified function under all stated conditions.

In dealing with such problems the probability of failure assessment is utilized. It is generally defined [1] by using limit function g (.) of the relevant load and resistance parameters, called basic random variables X_i: $g(X_1, X_2, ..., X_N) = g(\mathbf{X})$. The failure surface of this limit state of interest can than be defined as $g(\mathbf{X}) = 0$. This is the boundary between the safe and unsafe regions in the design parameter space. The failure is supposed to occur when $g(\mathbf{X}) \leq 0$. Therefore, the probability of failure p_f is given by the integral:

$$p_f = P(g(\mathbf{X}) \leq 0) = \int_{D_f} f_X (x_1, x_2, ..., x_n)\, dx_1, dx_2, ..., dx_N \qquad (1.1)$$

in which f_x (x_1, x_2, ..., x_N) is the joint probability density function to x_1, x_2, ..., x_N and the integration is performed over the failure region D_f in which g (**X**, t) ≤ 0. Symbol t reflects the fact that limit state function depends on time t (due to material deterioration).

Numerical methods for evaluating necessary integral (1.1) achieved at present the level enabling routine applications and are well documented, see e.g. [2]. Taking the advantage of (1.1), the risk R may be quantified rather simply by [3]:

$$R = p_f C_f , \qquad (1.2)$$

where C_f is the consequence of an accident (event, limit state) given either by economical terms, number of fatalities or other appropriate measures.

Long-term experience has made it possible to identify many sources of errors in ordinary structures. However, there is only a limited experience with the structures in nuclear power plants concerning real failures and one cannot be confident that all likely sources of errors have been identified. But we should realize that gross (human) errors in design and construction are seldom apparent in NPP structures because of the enforcement of strict quality assurance programs. Errors arising from natural random physical variability of material, geometrical, loading, technological and environmental parameters are therefore in focus of the present case study, represented as random variables (components of vector **X**).

2. Deterministic model of a bolt rupture

2.1. Working conditions of demountable joint

The demountable connection of the 1st circuit collector of the steam generator (see Fig. 1) creates a barrier between the primary and secondary circuits. It is necessary to know what probability of the stud bolt rupture is and what the loss of tightness probability in case of different non-destructive examination interval is. Both probabilities as subjective measures of reliability can be called failure probabilities. Non-destructive tests of heat-exchange pipes require the cover dismantling. All stud bolts and the thread in the collector tapped holes are checked by the non-destructive testing. Stud bolts with defects detected on the surface are exchanged. In the repetitive manhole packing the new sealing ring is used.

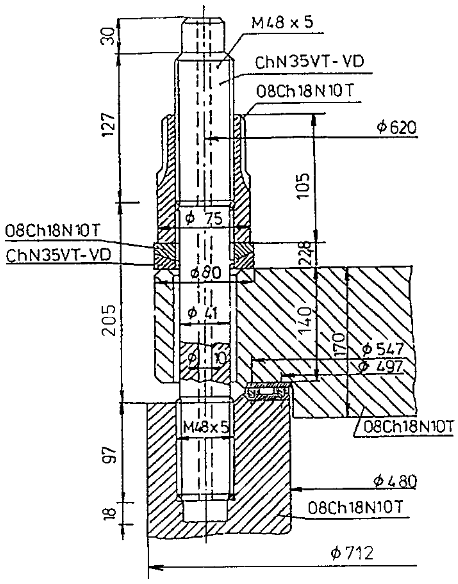

Figure 1 Scheme of the analyzed demountable joint

Experimental measurements of stud bolts strain using strain gauges under service conditions during four years endorsed theoretical assumption that the axial force in stud bolts does not significantly change. So, fatigue is not a decisive damage mechanism of the bolt material. However, in case of the non-favorable environment influence, conditions, which are suitable for stress corrosion cracking, may arise. The process of stress corrosion cracking occurs at a sufficient level of stress, material sensitivity to the corrosive environment and at a sufficient inherence of chemical ingredients in the environment. The stress corrosion process will not occur when one of these factors is absent. In the above case, all three factors can be present. It is necessary to determine the allowable level, and subsequently, to provide probability analysis of the bolt rupture and the loss of tightness for the reached level. For the structure in question, material characteristics are given. Stress levels in stud bolts may decrease using a sealing made of austenitic steel combed sealing with the 0,75 mm expanded graphite foils on its both surfaces instead of nickel gaskets and tightening of nuts by means of a hydraulic pre-stressed device instead of their tightening through the torque moment. In case of using the hydraulic pre-stressed device, a bending stress of bolts will significantly decrease. When using a pre-stressed stud bolt, two pads with spherical surfaces that may mutually take suitable positions at a small thrust force. This may not happen in case of tightening by torque moment. The nut is set into recess in the upper pad.

In the probabilistic analysis, mechanical material characteristics are used according to stud bolt testimonials, supplied for the whole power station. Time before the defect initiation on a stud bolt surface is taken according to the results based on the non-destructive bolts testing under operational conditions.

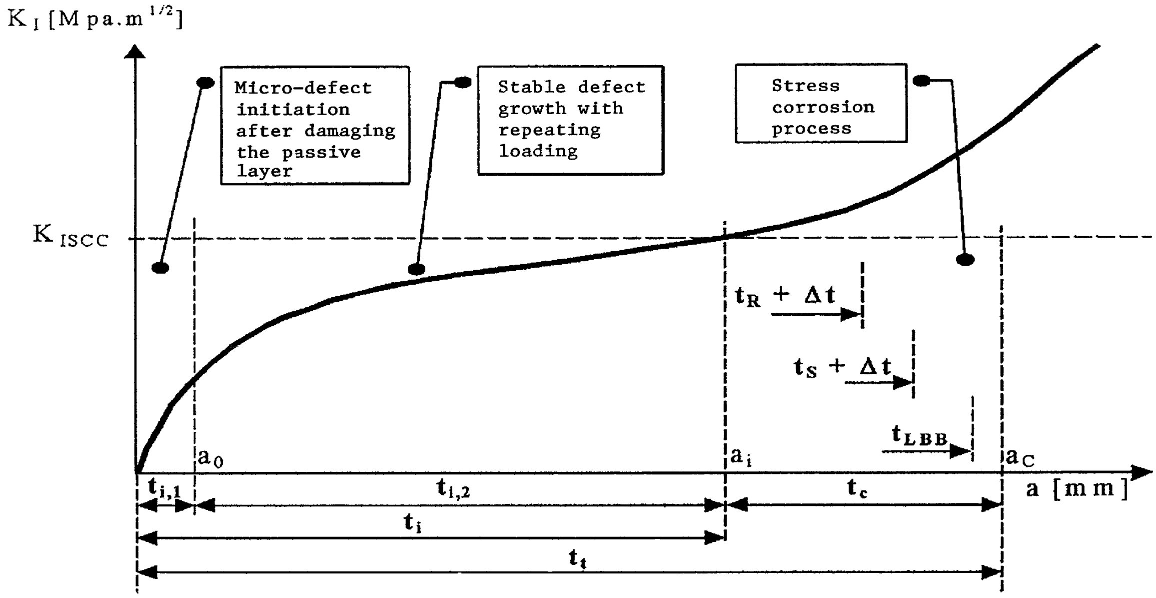

Figure 2 The process of material degradation under stress corrosion cracking

2.2. Stages of a stud defect origin and growth

Mathematical description of the gradual damage stud bolt until its rupture is based on the following stages [4, 5, 11], Fig. 2:

1) **Stage 1** represents the origin of a surface microdefect defect such as a crack or pitting. Time of the 1st stage duration is indicated as t_{i1}. At this time, the micro crack will reach value $a_o \sim 0{,}05$ mm.

2) **Stage 2** represents a defect growth caused by forces F, M_b in corrosion environment but excluding stress corrosion cracking conditions. The crack growth in comparison with the previous stage accelerated due to the cyclic loading. The bolt cross section is weakened, so the stress increased here. Time of stage 2 (duration) is indicated as t_{i2}, and at its end a defect depth will reach value a_i. These conditions may be describe by stress intensity factor:

$$K_I = \sigma Y \sqrt{\pi a} = f(\sigma, a, Y) \qquad (2.1)$$

3) **Stage 3** represents a defect growth under stress corrosion cracking when stress intensity factor K_I reaches value K_{ISCC}, representing threshold value K_I. The crack growth continues by a mechanism of stress corrosion cracking until limit value a_L is reached. The stud bolt cross-section is weakened by the defect and is not capable of carrying the load induced by an axial force and the bending moment. In the stud bolt cross section stressed in elastic-plastic state the value of stress $S_m = 0{,}5\ (S_y + S_u)$ is reached. The time of duration of stage 3 is indicated as t_c.

4) **Total time** t_t of the stud bolt operation its damage:

$$t_t = t_{i1} + t_{i2} + t_c \quad \geq (t_R \text{ or } t_s \text{ or } t_{LBB}) + \Delta t \tag{2.2}$$

In the probability analysis, time t_t is related to periods of non-destructive examination being 3, 4, 5, 6, 7 and 8 years. Where Δt is safety time reserve, t_{LBB}, t_R t_s are time to: LBB – leak before break; R - repair of a defect; s – end of service .

Mathematical descripton of the stud bolts manufectured from ChN35VT-VD matherial is not adequate experimental verified up to the present time, therefore the time t_{i1} was determined from data represents the time to exchange the stud bolts for corrosion damage in the NPP Dukovany, Fig. 3. Number of the stud bolts exchanged for their corrosion damage signifiyly decrease ufter 1996 year thanks measures taken in the NPP Dukovany. Following measures were used: decreasing of the tightening force of the stud bolts thanks using expanded graphite gasket (the type temporary used till 2002 year), decreasing of the bending stress thanks using of the hydraulic pre-stressed device, cleaning of the hole surface for stud bolts in the steam generator 1st collector flange during scheduled opening of the demountable joint for non-destructive examination.

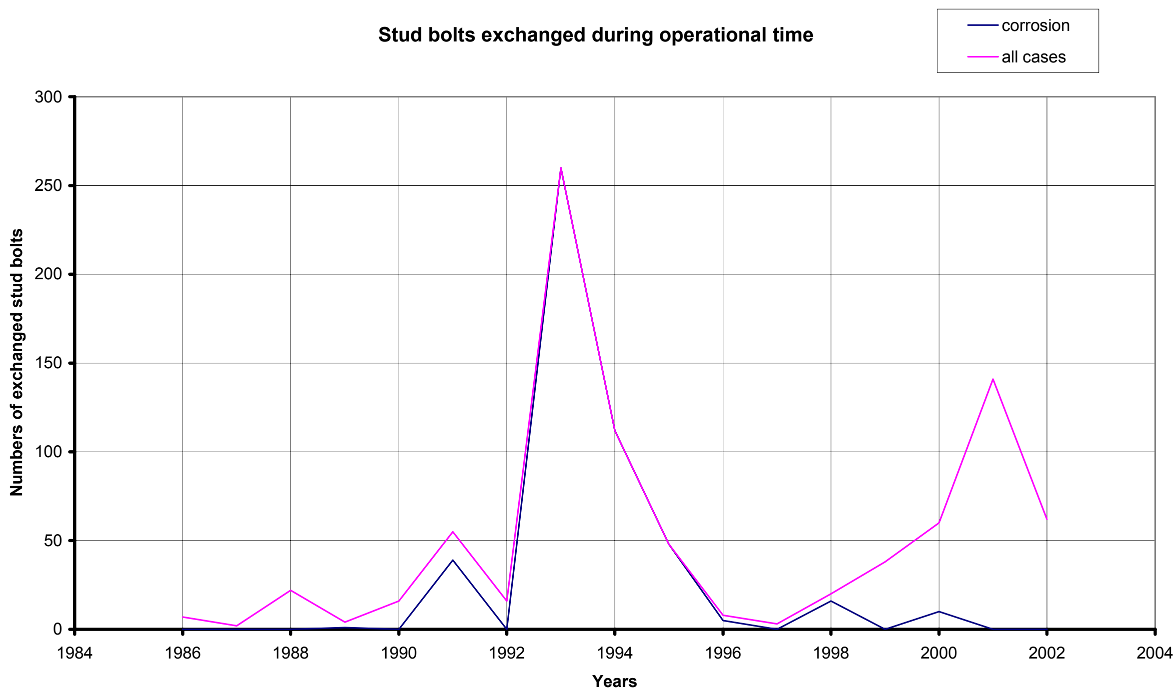

Figure 3 Influence of used measures on decreasing number of stud bolts exchanged for corrosion damage

3. Reliability analysis

3.1. General remarks

As mentioned in the introduction of this paper, the deterministic analysis of computational model described above cannot provide realistic results concerning the assessment of reliability and risk. There are many uncertainties related to the input parameters of the problem and they have to be modeled as random variables. Then the reliability of the cover can be expressed in probabilistic way: The probability that an event (failure) occurs (or does not occur) is assessed. In case of the steam generator cover, such an event represents e.g. the breaking of a stud bolt, the loss of the functionality of the cover (leakage from the primary to the secondary system of the circuit) or the break off of the complete cover. Generally, an event is described by an appropriate limit state function constructed using the computational model. Within the framework of reliability analysis based on Monte Carlo type simulation technique, the limit state function should be evaluated many times with different realizations of random variables, and consequently the statistical, sensitivity and probability information may be gained. The present study concentrates on the probability analysis providing its time profile.

3.2. Limit state functions

The general form of the limit state function used in reliability engineering was already shown see formula (1.1). Limit state condition requires (safe state):

$$g(\mathbf{X}) > 0 \quad (3.1)$$

A case of negative limit state function represents failure condition, the unreliability of the system can be expressed by a theoretical failure probability:

$$p_f = P\,(g(\mathbf{X}) \leq 0) \quad (3.2)$$

Such a failure probability is the quantitative measure of unreliability resulting from uncertainties involved in the problem. The measure of reliability simply is:

$$p_s = 1 - p_f \quad (3.3)$$

The basic task of our study is to assess the possible loss of functionality of the cover – a leakage occurrence. The aim of reliability analysis is to estimate the probability of such a loss of functionality. Limit state function of such a situation can be expressed in the form:

$$g(\mathbf{X}, t) = q_{min}\,(\mathbf{X}, t) - q_{lim} \quad (3.4)$$

where q_{min} is the minimum actual pressure on the seal between bolts, and q_{lim} is the limit (allowable) minimum pressure. The function is defined for a specific time – deterministic parameter t.

Alternatively, for the comparison purposes, the probability of one (first) bolt has been assessed, the limit state function being defined in the form:

$$g(\mathbf{X}, t) = \sigma_m\,(\mathbf{X}, t) + \sigma_b\,(\mathbf{X}, t) - 0{,}5\,(S_y + S_u) \quad (3.5)$$

where σ_m represents the middle stress and σ_b bending stress in the cross-section of the stud bolt in the actual simulation.

Together four different limit state functions are introduced (3.4), (3.5) – see Par. 4.1. Note that q_{min} in (3.4) and σ_m, σ_b in (3.5) are functions of many geometrical and material parameters, as described in section 2. The majority of them are of random nature. They have to be considered as random variables when assessing the safety of the constructional member in different operational situation of the NPP and when making the decision of the inspection or repair strategies.

3.3. Random variables

In probabilistic calculations, the definition of the set of random variables is the primary task. It consists of two steps: Firstly, the choices of the parameters, which will be considered stochastic and will be simulated as random variables, thus forming vector **X**. Secondly, every random variable X should be described by the theoretical model of probability distribution function. Such a function is in many cases (two-parametric distributions) characterized by a particular type of distribution simply described by mean value $\mu(X)$ and standard deviation $\sigma(X)$.

If statistical data are available for all the variables, the statistical characteristics can be estimated, and a theoretical model of probability distribution function can be assigned by well-known procedures of mathematical statistics. In most cases, there is scanty data available. The statistical properties will then have to be estimated based on different assumptions. The following sources for the estimation (also for deterministic parameters involved) were used: In site measurements, information published in literature, experience and opinions of experts, engineering judgment and intuition. The choice between the normal, log-normal and other distribution depends on the physical nature of the random variable. Log-normal distribution is to be preferred for variables possessing a low coefficient of variation (COV ≤ 0.10), the difference between normal and log-normal probability distribution function being for practical purposes negligible.

The above assumptions resulted in a choice of the type of distribution, the mean value and the standard deviation of the random variables involved in (3.4) or (3.5). Together 77 random variables X_1, X_2, …, X_{77} considered here are listed in Table 1. The mean values and standard deviations adopted are those values, which were rated as providing the best estimates of the type indicated above. The normal probability distribution was considered to model the majority of parameters. The statistical correlation among random variables was not considered here due to the lack of sufficient information.

For the purpose of this pilot study, a rather high number of input parameters were considered as random. Let us note that some of them will influence the scatter of limit state functions in a dominant way. It could be a task of the sensitivity analysis (see e.g. [9]) to distinguish such parameters with the aim to make future reliability computations more simple by considering variables exhibiting low sensitivity as deterministic. This is in the focus of authors ongoing research.

3.4. Failure probability estimation by importance sampling

The utilization of classical Monte Carlo simulation (simple random sampling) is impossible due to very low failure probabilities expected and computationally intensive limit state function. Our problem belongs to this category – the step-by-step breaking of bolts and the calculation of crack lengths due to the stress corrosion represent iteration algorithms ([4, 11]) used in every simulation. This is the reason why the so-called advanced simulation techniques (e.g. importance sampling, adaptive sampling, directional sampling, etc.) have to be applied [1, 7, 8]. These techniques concentrate simulation in the failure region around the surface $g(\mathbf{X}) = 0$. They enable us to estimate also very low probabilities quite efficiently using only e.g. a few thousands of simulations. For our limit state functions, we have utilized importance sampling around mean values, which represents a rather conservative and stable method for the problem with many random variables involved [1].

Studying the tightness functionality of the generator cover, then, during the simulation process, the bolts have to be broken one by one so that the limit state surface $g(\mathbf{X}) = 0$ according to (3.4) may be reached. The number of broken bolts necessary to reach this stage varied approximately from 1 to 6.

Table 1. Input random variables

	Variable	Unit	Symbol	Mean	COV	PDF	Note
1	Force in stud bolt	kN	F_s	280.75 226.31	0.101 0.101	log-normal log-normal	Nickel Graphite
2–21	Correction of force in stud bolt	–	F_{sc}	1.0 1.0	0.038 0.030	normal normal	Torque moment Hydraulic device
22	Bending stress	MPa	σ_b	163.83 95.39	0.358 0.358	log-normal log-normal	Torque moment Hydraulic device

23–42	Correction of bending stress	–	σ_{bc}	0.96	0.047	normal	
43	Ultimate stress	MPa	S_u	860.90	0.039	normal	Set of data
44	Yield strength	MPa	S_y	502.58	0.071	normal	Set of data
45	Radius of shank	mm	R	20.5	0.001	normal	
46	Radius of shank axis hole	mm	r	5.0	0.005	normal	
47	Radius of bolt circle	mm	R_w	310.0	0.001	normal	
48	Pressure in primary circuit	MPa	p_I	13.65	0.09	log-normal	
49	Pressure in secondary circuit	MPa	p_{II}	3.36	0.26	log-normal	
50	Testing pressure	MPa	p_h	16.33	0.002	log-normal	Control
51	Diameter of inside sealing ring	mm	$D_{tm,1}$	497.0 494.5	0.0002 0.0002	normal	Nickel Graphite
52	Diameter of outside sealing ring	mm	$D_{tm,2}$	547.0 548.0	0.0002 0.0002	normal	Nickel Graphite
53	Proportion of seal yielding	–	k_t	0.315 0.507	0.008 0.008	normal	Nickel Graphite
54	Characteristics of sealing	–	m	2.56 1.73	0.012 0.029	normal	Nickel Graphite
55	Effective width of sealing	mm	b_{eff}	7.2 9.0	0.014 0.014	normal	Nickel Graphite
56	Model uncertainty factor	–	Φ	1.0	0.15	normal	
57	Fracture toughness	$MPa.m^{1/2}$	K_{ISCC}	93.204	0.122	log-normal	
58–77	Correction of fracture toughness	–	K_{ISCCc}	1.0	0.025	normal	

3.5. Summary of basic steps of probabilistic analysis

The deterministic computational model described in section 2 is an iterative one. In addition, the simulation used for the failure probability assessment requires repetitive calculation.

The algorithm for the calculation of the limit state function in focus can be briefly summarized as follows:

- Simulation of realizations of vector **X**.
- Calculation of actual and limit forces in bolts. The influence of corrosion under stress is taken into account here.
- Conditions for corrosion fracture of bolts are checked individually for every bolt (based on comparison of stress intensity factor and fracture toughness).
- If above stated conditions are satisfied (as suitable for fracture corrosion initiation) two values are calculated: Maximum length of crack and actual crack length for time given.
- Determination of the bolt (out of the 20 existing ones), which will be broken first. It will be controlled by crack length and forces in bolt calculated in previous steps.
- Calculation of limit state function selected ((3.4) or (3.5)). In case that $g(\mathbf{X}) < 0$, there is a contribution to failure probability, and next simulation is performed.
- In opposite case, i.e. $g(\mathbf{X}) > 0$, the redistribution of forces should be calculated; then the process of step-by-step breaking off bolts continues as well as the tightness condition (3.4).

4. Numerical results

4.1. Probability of the loss of cover tightness

In order to calculate failure probability, a higher number of simulations had to be used to achieve acceptable error of estimation (250000 ÷ 500000 simulations). All random variables summarized in Table 1 have been used. Probabilities were determined for two technological/constructional alternatives considering the condition (3.4):

- Tightening of bolts by torque moment and the sealing made of nickel gaskets, the results marked in following as KNN
- Tightening by a hydraulic pre-stressed device, seal made of austetinic steel combed gasket with the 0,75 mm expanded graphite foils on its both surfaces, marked as H2G.

The results of reliability analysis are shown in Fig. 4.

4.2. Probability of stud bolt fracture

The probabilities of first stud bolt fracture were calculated too (without paying attention on the tightness loss of the whole cover, considering the condition (3.5)), merely for comparative purposes. Achieved results are presented in Fig. 5. One can see that the alternative KNN resulted in the highest failure probabilities then the alternative H2G during the whole specified operational time.

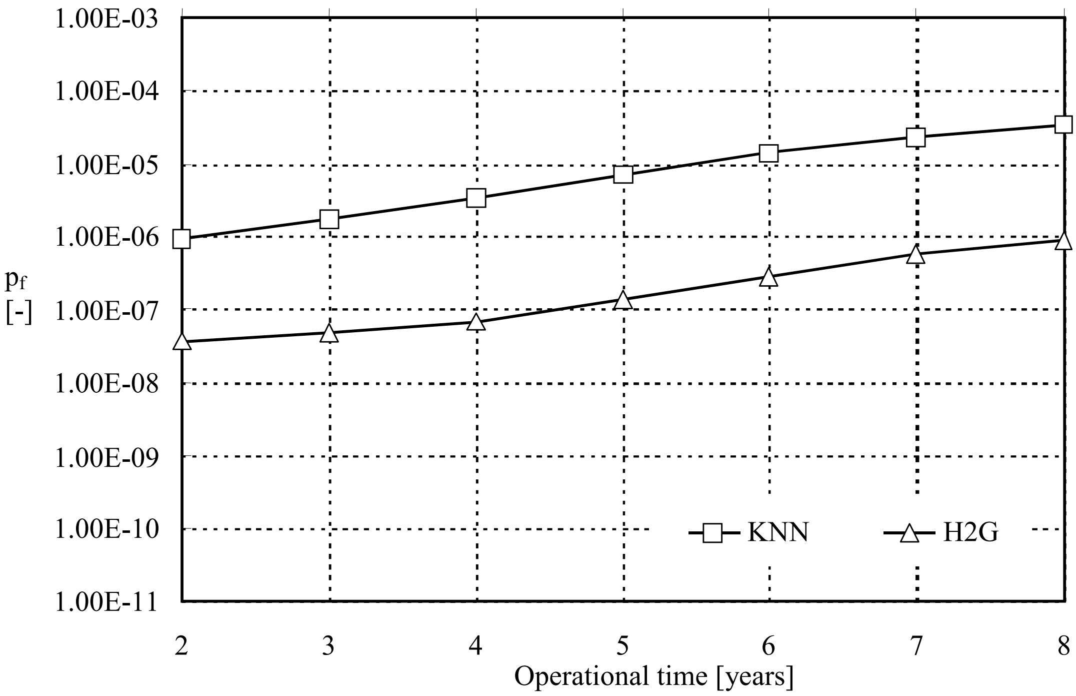

Figure 4 Probability of the loss of cover functionality vs. service time

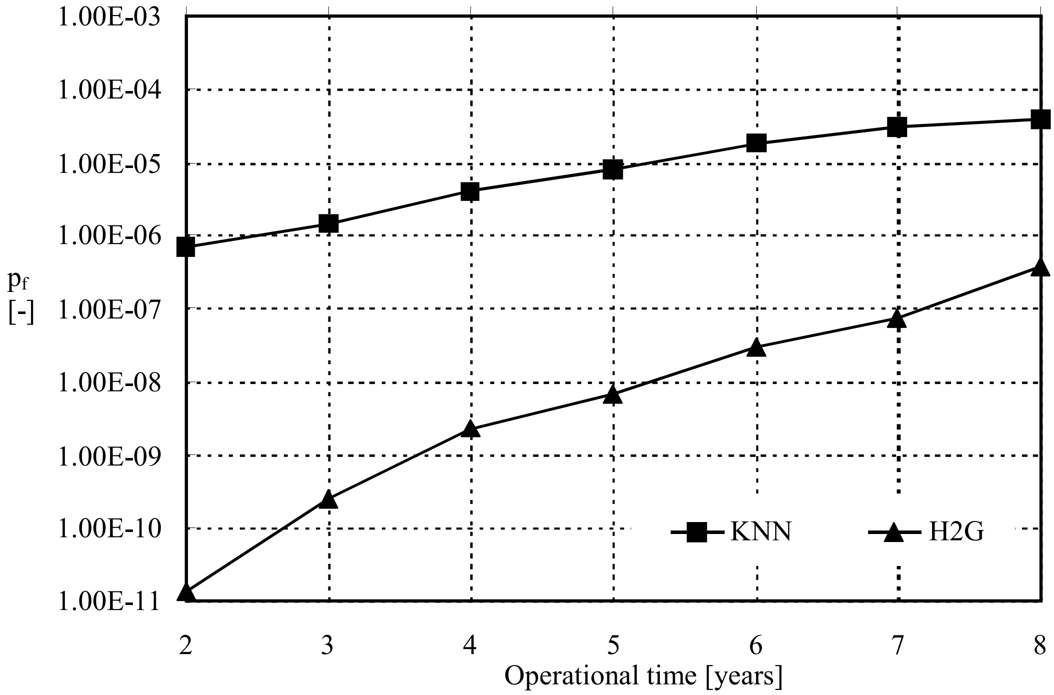

Figure 5 Probability of first stud bolt breaking vs. service time

Note: Other types of sealing were investigated by the authors in the same manner previously – see [11].

5. Conclusions

- The probabilistic safety assessment approach described above represents a suitable tool for the prediction of reliability decrease in the course of time, thus making it possible to gain more effective inspection and repair strategies. The minimum protection system integrity required to reduce the risk to a tolerable level may be assessed in this way.
- The presented probabilistic integrity study has shown the better alternative of the tightening process and used kind of the seal while respecting both the cover functionality and breaking of a stud bolt.
- Due to measures taken in the NPP Dukovany (decreasing of the tightening force of the stud bolts thanks using of austenitic steel combed sealing with the 0,75 mm expanded graphite foils on its both surfaces, decreasing of the bending stress thanks using of the hydraulic pre-stressed device for stud bolt tightening, cleaning of the hole surface for stud bolts in the steam generator 1st collector flange during scheduled opening of the demountable joint for non-destructive examination) the reliability level does not exceeds the usually required value 1.10^{-6} within interval of 8 years. It means, that the non-destructive examination interval can be prolonged from 4 years to 8 years.
- It has been shown that also the PSA problems leading to an extremely high number of basic random variables (77 in this case!) are feasible.
- A rather serious task is to reliably determine the set of basic random variables and their statistical parameters. A more detailed experimental study is generally needed in this context, providing more realistic statistical information. The stochastic sensitivity analysis may be an useful tool in this respect and it is in the focus of authors ongoing research.

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