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NPP EQUIPMENT LIFETIME MANAGEMENT UNDER AGEING

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Abstract

This paper deals with the problem of nuclear power plant (NPP) equipment lifetime prediction with the use of information about damage processes, operation conditions and preventive actions. The developed model is based on Kalman linear stochastic filter. For steam generator heat-exchanged tubes we use the martingale theory for predicting the number of suppressed heat-exchanged tubes to the next control. Finally, we formulate the principle of SG lifetime optimal management.

Key words: Steam generator, heat-exchanged tubes, Kalman filter, martingale, optimal management principle.

1. Introduction

Equipment lifetime management

Optimal management of nuclear power plant (NPP) equipment lifetime is based on an adequate mathematical model of damage process, the reliability estimation and lifetime prediction methods, performed prophylactic actions, their calculated efficiency and period.

The adequate model must be verified by control data at operation condition. The general principles are the individual approach to equipment and the usage of maximum information about equipment and analogs. The prediction accuracy is defined by the quality of damage process renewal from different kinds of data.

Equipment failure cannot be allowed. Thus, the equipment limited state is connected with leaving permissible boundaries by observed or calculated parameters. The equipment lifetime management is aimed at reduction of the rate of degradation processes by performing periodically some preventive actions such as wash cleaning, improving of water-chemical characteristics by different manner and so on. The rate of degradation processes is defined by the efficiency of these preventive actions that is different for each one. The most difficult one is the estimation of preventive actions efficiency including the economic factor.

The general techniques of lifetime management are equipment maintenance, repairs, replacement of elements and their parts, construction modernization, soften operation conditions, establishment of new permissible boundaries for parameters and so on.

The part of such equipment as the Steam Generator (SG) is large number of heat exchanged tubes (HET) – pencil of HET, or HET assembly – which are irreplaceable and define the work capacity of SG as a whole.

Damages of SG HET take place at different degrees at each unit of NPP and at each SG (see Tables 1 & 2).

Table 1. Plugged-out HET at one unit of NPP (1991-1999)

Year	1991	1992	1993	1994	1995	1996	1997	1998	1999	In all
SG-1	2	5	1	0	0	0	0	14	0	63
SG-2	1	1	4	0	1	3	0	14	0	81
SG-3	8	4	4	2	1	4	24	7	6	173
SG-4	7	0	1	0	0	3	23	9	2	96

The number of plugged-out heat-exchanged tubes is different in each year, because only a part of tubes assembly is controlled every year and performed preventive actions lead to reduction of the damage rate.

Table 2. HET damage dynamic on each of four steam generators of NPP unit (1984 – 2001) – MD: manufacture defects

SG	**MD**	**1987**	**1988**	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**In all**
1	1	1	20	4	15	2	5	1	0	0	0	0	14	0	25	2	90
2	1	1	25	20	10	1	1	4	0	1	1	0	14	0	0	14	93
3	1	9	62	23	18	8	4	4	2	1	4	24	7	8	0	0	175
4	2	3	17	6	23	7	0	1	0	0	3	23	2	0	0	4	91

Table 3 presents analogous data for another unit of NPP: in general, almost all damages are defects of manufacture, and only some ageing damages appeared during the 12-year period. Several factors including the quality of water in pond-coolant determine this fact. It may be said that HET assembly state at this unit is ideal.

Increase of the number of damaged tubes may depend on either the increase of corrosion activators in condenser coolant or the increase of the number of condenser leaks that leads to the intensification of degradation processes in the condenser and heaters and to entering of corrosion products to SG. HET damages depend also on heat loading: the increase of heat loading leads to the increase of soiling rate, steam content, admixtures concentrations and the decrease of the circulation number; all of which lead to the decrease of HET work capacity.

Table 3. HET damage dynamic on each of four steam generators of NPP unit (1989 – 2001)

SG	MD	1993	1996	1997	1998	1999	2000	2001	In all
1	2	-	1	-	-	-	-	2	5
2	13	-	-	-	-	-	2	-	15
3	4	1	-	-	-	-	-	-	5
4	3	-	-	-	-	3	-	-	6

Deposits on the surface of SG HET are the result of entering corrosion products to SG. These are small particles (less then 10 µm): products of corrosion of carbon steel and copper alloys (Fe_2O_3, Fe_3O_4, CuO, Cu_2O, etc.). In addition there are under-dissoluble salts: sulphates, silicates, hydrates of calcium and magnesium. Soiling of HET surface promotes the origin and development of HET damages (fig. 1). Also the soiling of the surface reduces the heat exchange between the first and the second outlines and decreases steam production.

Damage Processes

The damage intensity rate depends on many factors: the technical state of condenser, the quality of feed water (including concentrations of iron and copper), the soiling of tube surface, the tube location in lattice and so on. These factors lead to deposits formation on HET surface, intensification corrosion processes under deposits and to different damages of HET (Table 4, fig. 1): there are sore, crack, pitting and chloride and sulphate stress corrosion cracking, - in fig. 1 their location and relative size are shown.

Table 4. Damage processes at HET and measures of lifetime management

Damage processes at HET	Reasons	Measures of lifetime management
Pitting and sore formation	High concentration of O_2, Cu Soiling Soiling	Reduction of condenser leaks Replacement of equipment rich in copper
Stress corrosion cracking (SCC)	Concentration of corrosion activators (O_2, Cl^-) on soiling surface	Decrease of corrosion products on tube surface
Sulphate corrosion cracking	High concentration of O_2, Cu	Decrease of corrosion rate

For the case of sore, its diameter is approximately equal to its depth and for pitting, a special case of sore, the diameter is by far smaller than the depth. Finally, the surface crack is usually orientated along the tube axis.

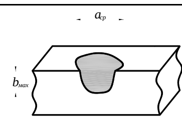	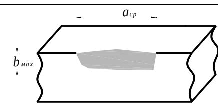	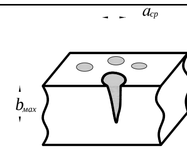	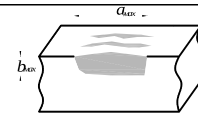
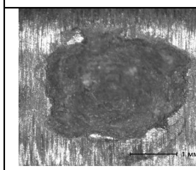	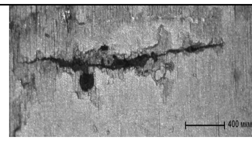	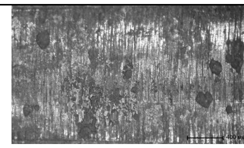	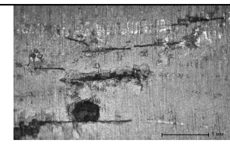
sore	Crack	pitting	cracking

Figure 1: General types of defects

To increase HET lifetime certain actions are recommended: exclude copper alloys at second outline; clean feed water from copper compounds; decrease concentration of chloride-ion in water of SG blowing off; decrease the rate of copper-ammoniac complexes carrying-out.

As a result of these actions, pH is increased from 8.5 to 8.9 leading to two times reduction of iron concentration in feed water and analogous reduction of the deposits rate. The use of ethanol instead of hydrazine-ammoniac regime at the second outline of PWR leads to five times reduction of erosion-corrosion wear, increase of pH in feed water to 9.2, and two times reduction of iron concentration without replacement of construction materials.

Factors Influencing the HET Reliability

Condenser leaks lead to entering of water from the environment (pond-coolant) to the secondary outline. The concentration of corrosion activators in pond-coolant dynamically arises due to unfavorable ecological conditions and leads to intensification of corrosion rate and intensity of damage processes. Corrosion products located on the HET surface (soiling) (fig. 2) cause the concentration of corrosion activators under deposition.

Chemical wash cleaning is the effective measure to reduce the rate of local corrosion and quantity of corrosion products (Tables 5-6). This is yet another way of lifetime management.

Table 5. Results of chemical wash cleaning on one unit of NPP

SG	Mass of corrosion products wash off, kg		
	In all	Fe compounds	Cu compounds
SG-1	800	479	288
SG-2	1200	728	380
SG-3	800	500	252
SG-4	800	436	276

Washed off from SG corrosion products consists of approximately 36% of copper compounds and 64% of iron compounds.

Table 6. Results of chemical wash cleaning on some NPP with PWR-1000

NPP	Mass of corrosion products wash off, kg		
	In all	Fe compounds	Cu compounds
NPP 1	17181	10718	6463
NPP 2	17610	11777	5833
NPP 3	17476	14528	2948
NPP 4	2449	1985	464
NPP 5	863	798	65

Thus, the analysis of HET work capacity shows that SG HET damages, in general, are at zone of corrosion products deposits. The main components of deposits are copper and iron compounds. The intensity of damage process increases as Cu compounds concentration is more than 20% which gives rise to pitting development on HET surface. Increase of Cu compounds content to 30% leads to thorough sores (fig. 1). In this case the development of stress corrosion cracking is also quite possible. Thus, the replacement of equipment rich in copper with an analogous one from corrosion-stable materials leads to reduction of corrosion products and, consequently, to reduction of the number of plugged-out HET.

Criterion of HET Limited State

The technical state of SG is defined by the steam production and depends on the quantity of working HET. Thus, the HET limit state is a criterion of HET plugging-out, namely the achievement of a damage level or «metal shortage» denoted by d (% to wall thickness). This criterion is different in different countries (Table 7). The damage level d is controlled by vortex-current method. Achievement of the level d by a tube implies that this tube must be suppressed (plugged-out).

The main problem of optimal management of nuclear power plant equipment lifetime is the development of an adequate mathematical model of damage process and the estimation of equipment lifetime as moment of leaving permissible boundaries (in our case – level d) by observed or calculated parameter (for example, depth of corrosion crack). The procedure of lifetime prediction must take into account prediction methods, performed prophylactic actions and their calculated efficiency.

Table 7. Criterion of HET plugging-out

Country, type of NPP reactor	Criterion of HET plugging-out – damage level *d* (% to wall thickness)
USA, PWR	>40
France, PWR	>40
Germany, PWR	>60
Canada, CANDU	>40
Bulgaria, PWR	>40
Brasilia, PWR	>40
Czech, PWR	>80
Slovenia, PWR	>45

2. Kalman Filter Model

Research Results

For the prediction of SG HET lifetime there is the mathematical model of linear stochastic filter for growing corrosion crack on the HET surface, since about 80% material defects are caused by corrosion crack growth.

The development of the mathematical model takes also into consideration some research results. For instance, the empirical appropriateness of plugged-out HET $f(h)$ from the height *h* of tube lattice may be presented as (fig. 2)

$$f(h) = C_0 \cdot e^{C_1 \cdot h} + C_2 \tag{1}$$

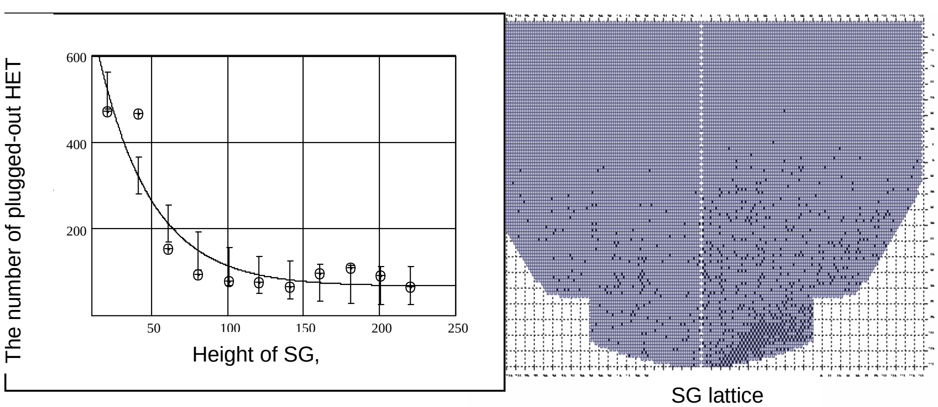

Figure 2. Empirical appropriateness of plugged-out HET from the height of tube lattice (with tolerance intervals)

Data as presented in Tables 1-2 and the location of each suppressed tube in tube lattice allow the determination of coefficients C_0, C_1, C_2. For example, for one unit of PWR we have

$$f(h) = 811.3 \cdot e^{-0.03 \cdot h} + 67$$

while for another PWR this function takes the form

$$f(h) = 82.3 \cdot e^{-0.017 \cdot h} + 19.6.$$

Hence, the coefficients are specific and should be calculated for each SG separately. Because more than 85% of defects are cracks, the mathematical model of filter is developed for growing corrosion crack on the HET surface. The rate of crack growth is described by Paris equation for materials actually used for SG HET

$$\frac{dl}{dt} = C \cdot K_I{}^m, \tag{2}$$

where l is the crack depth (m), K_I is the stress intensity coefficient (MPa $\sqrt{m}$), t is the time and C & m are material constants.

In order to use information about the distribution of suppressed tubes at tube lattice as mentioned above let us designate the dimensionless coefficient

$$K_h = \frac{f(h)}{\max f(h)}.$$

For surface semielliptical crack after linearization and variables substitution the next equation for abstract z is obtained

$$\begin{aligned} &\frac{d}{dt} z(t) = C \cdot \sigma^m \cdot \pi^{m/2} \cdot K_h{}^{m/2} \\ &z(0) = 0,\ z(\tau) = z_{cr}, \end{aligned} \tag{3}$$

where z_{cr} is the value of z being equivalent to crack depth limit and σ is the mechanical stress (MPa). The ageing appropriateness received from operation and special experiments allows the reduction of the model dimension essentially and therefore the improvement the quality of prediction. In general, z(t) is the stochastic process depending on a large number of weak defined factors.

Let $z_p(t, x)$ be a p-component vector, p the number of HETs, n the number of controls, x the coordinate along the tube, t the discrete time: $t_n = \sum_{i=1}^{n} \Delta_i$ and Δ_i the time intervals between controls. Then, the difference equation is given by

$$z_{n+1} = z_n + \Delta_n \cdot C \cdot \sigma^m \cdot \pi^{m/2} \cdot K_h{}^{m/2},$$

and the observation model as a stochastic recurrent process $\eta_n = \left(z, \Delta_n\right)$ [1,3] by

$$\eta_{n+1} = \eta_n + A_n + F_n \cdot N_n . \tag{4}$$

The process of measurement is

$$\xi_n = C_n \cdot \eta_n , \tag{5}$$

and then the observed vector v_n is

$$v_n = \xi_n + G_n N_n , \tag{6}$$

where $F_n N_n$ is the reaction on stochastic fluctuation of operation parameters and it should be simulated as a Gaussian process and $G_n N_n$ is the measurement noise.

The Kalman linear stochastic filter is built in both the general and the special cases for the model of crack growth by using the Balakrishnan model [Balakrishnan, 1984]. For the general case, as shown in Gulina et. al [2006], the observation model may be presented as

$$\eta_{n+1} = A_n \eta_n + B_n + F_n \cdot N_n .$$

For special cases (2) and (3), the model is simpler and the one step predictor is developed in Gulina, et. al [2008]:

$$\bar{x}_n = \left(E - K_{n-1} \cdot C_{n-1}\right)\bar{x}_{n-1} + B_{n-1} + K_{n-1} \nu_{n-1},$$

$$\hat{x}_n = \bar{x}_n + K_n (\nu_n - C_n \bar{x}_n), \qquad \bar{x}_0 = M[\eta_0] .$$

This equation predicts the next value of crack depth (through abstract z) under given control data. Therefore, the problem is to choose the optimal preventive action for this moment to increase residual time to limited level d achievement by each HET.

Optimal Management Principle

For the estimation of the reliability of pencil of tubes it is necessary to formulate its state limit. For pencil of tubes the state limit may be the relative number of plugged-out tubes χ, suppressed according to the criterion «crack depth more than *d %* from tube thickness» with $0 < d < 1$. If the level d is equal to 40-80% (Table 7), then part of tubes assembly χ may be 5-25%. After this limit SG must be replaced. The main goal of lifetime management is reduction of degradation processes rates. This could be done by different methods: by influencing the operation factors (water-chemical regime parameters, admixture concentration and so on) or by using new constructive and technological decisions (chemical wash cleaning, quality of feed water and so on).

Let us assume that all factors influencing the degradation process are designated as a vector-parameter ***U***, let ***W*** be the field of their values, and $t_{n+1,k}(d)$ the k^{th} track that reached the level *d* at the (*n*+1) time moment. Since the subsequence η_n is monotonous, then the subsequence $t_{n+1,k}(d)$ received as decision of the system (4)-(6) is also monotonous (due to the fact that the reverse operator is linear and positively defined) and Normally distributed. Proof of this fact is simple but very cumbrous. The optimal management principle to define the most effective preventive action is given by the formula [Gulina et. al, 2008],

$$T(U) = M\left(t_n(d,x), t_n^*(d,x)\right),$$

where $M(t_n,t_n^*)$ is the expectation of scalar product and the sum includes only tubes that reached the level d and t_n^* is the conjugate vector.

Let us define an action as optimal, if

$$T(U_n^0) = \sup_{U \in W} T(U)$$

$$E(U) \leq E_{\lim}$$

where the last inequality defines the limited cost of any measure. This algorithm may be considered simple by exhaustion of every *U* at all points of ***W***, but it requires large computational resources. The goal of the proposed optimal management principle is to reduce the number of plugged-out tubes between controls and thus to extend the SG lifetime. Therefore, we must observe each tube taking into account prediction results. One way is by fixing some levels d_1, d_2, … d_k, …, $d_{\lim}$ and calculate the expectation of the number of level d intersection upwards by HET. For the last level – $d_{\lim}$ – it will be the number of HET to control and whether it is necessary to suppress.

Prediction of the Plugged-out Tubes Number

For the estimation of the number of tubes that will reach the level d to the next control point we use the fact that the subsequence after filtering is a submartingale. Moments of allowed level d achievement $t_{n,k}(d)$ are also submartingales. This allows the implementation of the martingale theory for the prediction of the number of plugged–out tubes. Since not every tube is measured at each control point, this issue is one of the problems of management by martingales with incomplete data.

Since sequence $x_{n,k}$ (k-component of vector $\hat{x}_n$) is a nonnegative submartingale, we designate $\beta_n(d)$ as the stochastic variable of the number of level d intersection upwards. According to Doob's inequality [Shiryaev, 1995], the expectation of level d_k intersection upwards satisfies the following

$$M(\beta_{n,k}) \le \frac{M(\hat{x}_{n,k})}{d_k},$$
$$\hat{x}_{n,k} = \bar{x}_{n,k} + K_{n,k}(\nu_{n,k} - C_{n,k}\bar{x}_{n,k}).$$

Only these HETS will be measured at the next control. At the level d_{lim} after crack depth measure the decision must be made about suppressing the considered HET. Thus, the proposed model allows the planning of the content of the next control to achieve the longevity of the SG operation.

3. Conclusions

The main conclusions of the present work are summarized below:

1. There are research principal factors influencing the work capacity of HET: types of defects in material of HET; the distribution of plugged-out HET on the height of tube lattice, preventive actions and their efficiency.

2. The mathematical model of Kalman filter for SG HET lifetime prediction is developed by taking into account received results.

3. The optimal management principle to increase SG lifetime is formulated.

4. It is shown that moments of achieving the allowed level are submartingales. This allows the implementation of the martingale theory for the prediction of the number of plugged-out tubes and the choice of optimal actions for this moment to reduce the rate of damage process.

4. The proposed model allows the planning of the content of the next control to achieve longevity of the SG operation.

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