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Research Article

Repeated measurements and quality of estimates in the analysis of NPP pipeline erosion-corrosion wear*

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Abstract

The article presents a study carried out on carbon steel pipe components subjected to erosion-corrosion wear (ECW). Based on the repeated control data, the authors present the calculated ECW characteristics, i.e., the wall-thinning and rate. It is shown that such estimates contain great uncertainty due to corrosion products deposited on the pipeline inner surface and their migration during operation. In addition, with an increase in the operating time, for example, when the lifetime is extended, the difference between the forecast and the results of control becomes larger. This means that the error in the estimates of the residual lifetime also increases. The study is based on the data of wall thickness measurements of the feedwater pipeline (273×16 mm) and steam pipeline (465×16mm) of nuclear power plants with the VVER-440 reactors, for which a sufficient number of repeated measurements were performed over a large time interval. An analysis is made of the error in estimating the pipeline wall-thinning and ECW rate using Chexal-Horowitz Flow-Accelerated Corrosion (FAC) Model (EKI-02 and EKI-03 software tools). The estimate of the ECW rate according to the above forecast model differs from the estimate according to the current control data by no more than 12.5%, since the corrosion products deposited on the pipeline inner surface wall are leveled at a large time base. When calculating the wall-thinning, due to the obvious filtering of the control data, it is possible to achieve an acceptable accuracy of estimates, i.e., about 16% without upgrading the model.

Keywords

Erosion-corrosion wear (ECW), lifetime forecasting, Keller coefficient, data filtering, repeated measurements, ECW (Erosion-Corrosion Wear) rate, Chexal-Horowitz Flow-Accelerated Corrosion (FAC) Model

Introduction

The results of the metal condition monitoring show a significant unevenness of erosion-corrosive wear (ECW) of the equipment and pipelines due to a large number of factors. Knowing the ECW mechanism, its dependence on the metal properties, geometric characteristics or operating conditions, it is possible to make the most effective design decisions at the stage of designing technological systems of the NPP secondary circuit, optimize the scope

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of operational control and reduce the number of incidents due to ECW and unscheduled shutdowns of power units as well as control costs.

The ECW rate of a component of equipment or a pipeline, calculated from the results of one-time control of wall thicknesses, contains many uncertainties (Baranenko et al. 2016) that reduce the accuracy of estimates (Bridgeman and Shankar 1991; Lee et al. 2003; Moolayil 2007, 2008; Baranenko et al. 2010). These factors include as follows:

- lack of input control data on wall thicknesses, while the wall thickness tolerance for manufacturing pipelines from carbon steel varies in the range from –5 to + 20% (TU 14-3-460-75 1976, NSAC-202L-R4 2013);
- fixation of the joint thickness of undamaged metal and dense wet deposits of corrosion products during operational control (Baranenko et al. 2014), although the presence of deposits does not increase the bearing capacity of the component; and
- selection of a grid for wall thickness measurements in the circumferential and axial directions, the influence of the geometry of pipeline components, routing of pipeline systems, etc. (Chexal et al. 1998).

These factors contribute to the fact that it is very difficult to estimate the error in calculating the ECW rate based on the operational control data.

There is a wide variety of methods for estimating the ECW characteristics, taking into account the above factors (Baranenko et al. 2016, 2017), including the repeated control data (NSAC-202L-R4 2013).

The simplest model for estimating the ECW rate W_{ECW} (Ruscak et al. 1996, Gulina and Frolova 2012) is:

$$W_{ECW} = (S_{nom} - S_{min})/\Delta\tau, \quad (1)$$

where S_{nom} is the nominal thickness, mm; S_{min} is the minimum thickness according to the control data, mm; $\Delta\tau$ is the time interval from the date of putting the component into operation until the date of control, years; $(S_{nom} - S_{min})$ is the thinning.

The ECW rate is used to determine the pipeline remaining lifetime τ (or its operating period until the allowable wall thickness is reached), years,

$$\tau = (S_{min} - S_{allow})/W_{ECW}, \quad (2)$$

where S_{allow} is the the minimum allowable thickness (determined by (Guidance document RD EO 1.1.2.11.0571-2010 2012)), mm.

To refine the estimates of the ECW characteristics, various methods of processing repeated measurements (NSAC-202L-R4 2013) are used: Band Method, Area Method, Moving Blanket Method, and Point-to-Point Method. All these methods are based on the fact that the erosion caused by ECW is in the local area. However, ultrasonic testing measures the combined thickness of undamaged metal and deposited corrosion products and, during repeated measurements, the thickness can either increase or decrease at the same points. All this complicates the use of the above methods, since calculations give conflicting results.

One of the ways to adequately estimate the condition of a pipeline component, as well as to solve the problem of optimizing the scope and frequency of control, is to use predictive models. One of the most common models, embedded in various software tools, is Chexal-Horowitz Flow-Accelerated Corrosion (FAC) Model (Chexal and Horowitz 1995; Chexal et al. 1998). This model is the basis for the Russian software tools: EKI-02 (for a single-phase environment) and EKI-03 (for a two-phase environment) (Gulina and Frolova 2012).

The ECW rate in this model is determined by the following empirical dependence

$$W_{ECW} = C_0 \times F_1(T) \times F_2(XC) \times F_3(W) \times F_4(O_2) \times F_5(\mathrm{pH}) \times F_6(\mathrm{Ke}) \times F_7(\alpha) \times F_8(A), \quad (3)$$

where W_{ECW} is the ECW rate, mm/year; C_0 is the coefficient equal to 1 mm/year; $F_1(T)$ is the coefficient taking into account temperature; $F_2(XC)$ is the coefficient taking into account the composition of the metal (content of chromium, copper and molybdenum); $F_3(W)$ is the coefficient determined by the fluid vlocity; $F_4(O_2)$ is the coefficient taking into account the oxygen concentration; $F_5(\mathrm{pH})$ is the coefficient depending on pH; $F_6(\mathrm{Ke})$ is the coefficient taking into account the geometry of the pipeline (its standard size and Keller coefficient); $F_7(\alpha)$ is the coefficient taking into account the steam moisture (for a single-phase environment $F_7(\alpha) = 1$); $F_8(A)$ is the coefficient taking into account the amine used (ammonia, morpholine, ethanolamine).

Thus, Chexal-Horowitz model takes into account the main parameters affecting the ECW rate. Using the software tools, it is possible to carry out forecast calculations and rank pipelines according to the degree of ECW exposure.

However, it was noticed that, with long operating periods, for example, when the lifetime is extended, the difference between the forecast and the results of control becomes larger. This means that the error in the estimates of the residual lifetime also increases. This situation requires additional research and possible modernization of the forecast model, if necessary.

The work is focused on the analysis of the wall thickness control data, their interpretation and estimation of the discrepancy with the forecast results depending on the operating period.

The aim of the study is to reduce the conservatism of the ECW forecast based on estimates of the informativeness of repeated measurements. As part of this study, calculations were made for components of feedwater pipelines and steam pipelines of NPPs with the RBMK-1000 reactors and NPPs with the VVER-440 reactors.

Influence of deposits on control data interpretation

When analyzing the repeated control data, it is possible to reveal the influence of corrosion products deposited on the pipeline inner surface on the estimates of the ECW characteristics. The deposits of corrosion products lead to the fact that repeated measurements can show an increased or decreased wall thinning at a certain point, which contradicts the physical meaning of wear. However, the control data look exactly like this. Figures 1, 2 show the minimum and maximum wall thicknesses of the feedwater pipeline bend for NPPs with VVER-440 of a body size of 273×16 mm in 1996 and 2002 (Baranenko et al. 2014).

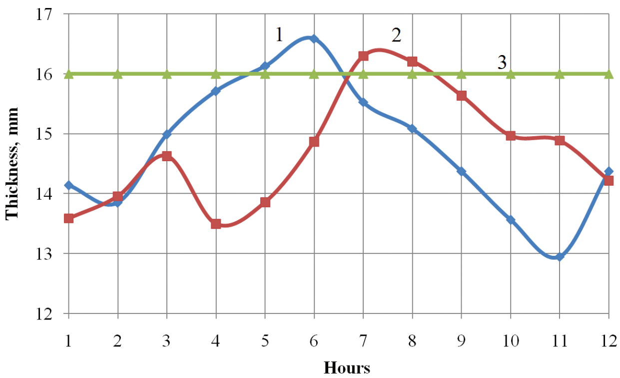

Figure 1. Minimum bend wall thicknesses (Baranenko et al. 2014): 1 – in 1996; 2 – in 2002; 3 – nominal thickness.

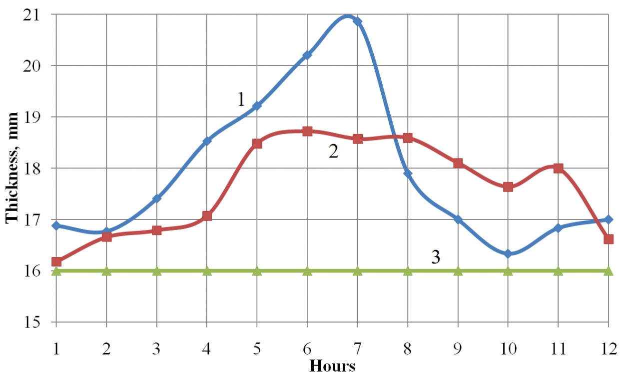

Figure 2. Maximum bend wall thicknesses (Baranenko et al. 2014): 1 – in 1996; 2 – in 2002; 3 – nominal thickness.

It can be seen that, at practically the same average thickness, there was a significant migration of the deposited corrosion products. Estimating the ECW rate according to the usual formula (1) will lead to the fact that over time the estimated residual life will increase. To obtain adequate estimates of the ECW characteristics, it is necessary to use forecast models or refine the estimates using the methods for processing repeated measurements (NS-AC-202L-R4 2013).

To make calculations using the forecast model (3), it is required to know the chromium content in the metal. Since this indicator is not known a priori, it was taken as a variable to adapt the model to the control data.

To ensure the conservatism and additional reliability, when calculating according to the EKI-02 software tool, we take three thinning values that are slightly higher than the actual value obtained in 2011, namely, 2.5 mm. Thus, the chromium values 0.0752, 0.0741 and 0.073% correspond to the thinning values 2.5248, 2.5545 and 2.585 mm, which are close to the control values (Tab. 1). Here, the initial data for the calculation are temperature $T = 170$ °C, steam humidity 0.2%, pH = 7, oxygen concentration O_2 15 μg/kg, inner diameter $D = 378$ mm; amine – ammonia; Keller's coefficient Ke = 0,04; and contents of both Mo and Cu = 0.03%.

Table 1. Calculations based on EKI-02 (2011).

Cr, %	T_{start}, years	T_{end}, years	ECW_{start}, mm/yr	ECW_{fin}, mm/yr	ECW_{av}, mm/yr	Thinning, mm
0.0674	0	30	0.4700	0.0535	0.0916	2.7489
0.0685	0	30	0.4641	0.0528	0.0905	2.7145
0.0696	0	30	0.4583	0.0521	0.0893	2.6809
0.0708	0	30	0.4528	0.0515	0.0883	2.6482
0.0719	0	30	0.4473	0.0509	0.0872	2.6162
0.073	0	30	0.4419	0.0503	0.0861	2.585
0.0741	0	30	0.4367	0.0497	0.0852	2.5545
0.0752	0	30	0.4317	0.0491	0.0842	2.5248
0.0764	0	30	0.4267	0.0485	0.0832	2.4957
0.0775	0	30	0.4218	0.0480	0.0822	2.4673
0.0786	0	30	0.4171	0.0474	0.0813	2.4395

The obtained values of the chromium content are used as parameters to forecast the ECW process for 2013 and 2014. The result of comparing the forecast and control data is shown in Fig. 3. As can be seen, the forecast results differ from the actual thinning values as the duration of operation increases, even in such a short time interval. It must be said that in this case there were already considerable deposits of corrosion products on the pipeline inner surface, since most of the measurements exceed the nominal value. However, the discrepancy in the results up to 60% should be considered significant. To make more sound conclusions, more repeated measurements are needed.

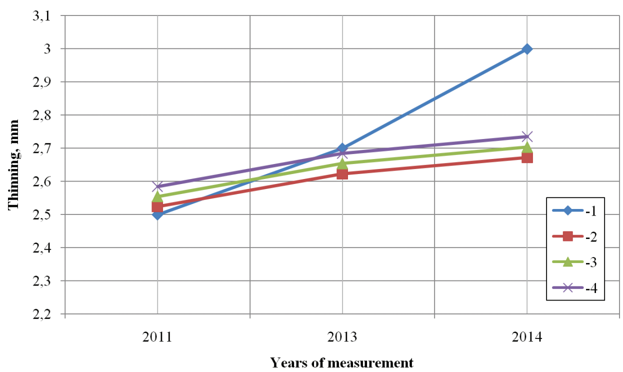

Figure 3. Predictive estimates obtained using EKI-02 at close values of the Cr concentration in the metal: 1 – measurements; 2 – Cr = 0.0752; 3 – Cr = 0.0741; 4 – Cr = 0.073.

Analysis of control data at NPP with VVER-440

According to the operational control data (Guidance document RD 27.28.05.061-2009 2010) given in the conclusions about NPPs with VVER-440, the rates of corrosion and thinning of the pipeline walls with single-phase and two-phase media were calculated in different operating periods. The values of the operating time τ_{oper}, the minimum measured wall thickness S_{min}, the thinning ΔS_{thin} and the ECW rate W_{ECW} are given in Tab. 2 for the feedwater pipeline and steam pipeline. The wall thickness measurements were carried out from 1984 to 2008.

Table 2. Values of thinning and ECW rate of the feedwater pipeline and steam pipeline at NPPs with VVER-440 in different operating periods.

Feedwater, 273×16 mm					Steam pipelines, 465×16 mm				
Year	T_{oper}, years	S_{min}, mm	ΔS_{thin}, mm	W_{ECW}, mm/yr	Year	T_{oper}, years	S_{min}, mm	ΔS_{thin}, mm	W_{ECW}, mm/yr
1984	3	13.3	2.7	0.9	1985	4	13.2	2.8	0.7
1988	7	13.2	2.8	0.4	1985	4	13.7	2.3	0.575
1989	8	14.1	1.9	0.238	1995	14	13.2	2.8	0.2
1995	14	12.0	4.0	0.286	1995	14	13.2	2.8	0.2
2001	20	12.3	3.7	0.185	2000	19	13.0	3.0	0.158
2005	24	12.2	3.8	0.158	2005	24	13.7	2.3	0.096
2006	25	12.6	3.4	0.136	2005	24	13.7	2.3	0.096
2007	26	13.1	2.9	0.112	2006	25	13.7	2.3	0.092
2008	27	12.0	4.0	0.148	2006	25	13.7	2.3	0.092
2009	28	11.7	4.3	0.154					

A decreased thinning at a certain point in time is associated with the deposited corrosion products, due to which the monotony of the wear process is visually disturbed. To adequately predict the ECW process, it is necessary to either modify (upgrade) the model or take to data filtering.

To adapt the EKI-02 and EKI-03 software tools, the chromium concentration in the pipeline metal and the Keller coefficient reflecting the component geometry, including, possibly, the condition of the inner surface, were selected as the most significant but unknown parameters. Since the chromium content in the pipeline metal is not known a priori, this indicator was taken as a variable. The adaptation of these tools is carried out by forecasting the thinning on the components under consideration and comparing the results obtained with the actual values. The chromium concentration is selected with the smallest discrepancy between the calculated and measured thinning for the feedwater pipeline section for 1984 and the steam pipeline section for 1985, respectively.

The ECW rate and thinning take the maximum values at a chromium content of 0.037%, and decrease at its higher values. Further, the chromium content equal to 0.037% is used, since the thinning according to the control data is significant.

The results of the thinning forecast at a chromium content of 0.037% for the feedwater pipeline section in the range from 3 to 28 years and the steam pipeline section in the range from 4 to 25 years are shown in Fig. 4.

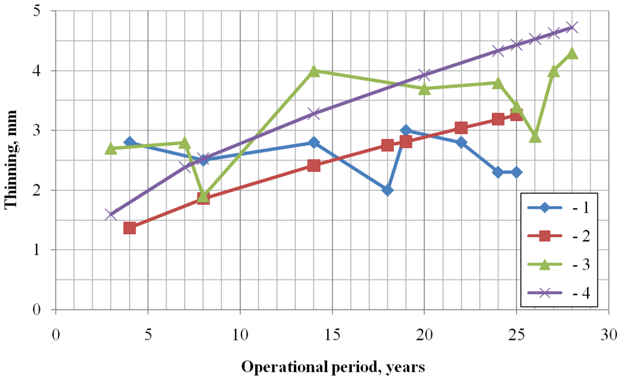

Figure 4. Control data and forecast results for the steam line: 1 – protocol (SL); 2 – forecast (SL); 3 – protocol (FL); 4 – forecast (FL).

It can be seen from the graphs that the forecast results do not agree well with the control data. One of the reasons for this may be the Keller coefficient, which, during long-term operation, may turn out to be time-dependent.

Tables 3, 4 show various combinations of the Keller coefficient and the chromium content, at which the forecast for the first measurement coincides as closely as possible with the measurements for the feedwater pipeline and steam pipeline, respectively.

Table 3. Combinations of Cr content and Keller coefficient for steam pipelines.

Cr content,%	Ke	Thinning, mm
0.03	0.4699	2.801
0.04	0.5617	2.8021
0.05	0.6535	2.8029
0.06	0.7444	2.8001
0.07	0.8362	2.801
0.08	0.928	2.8017

Table 4. Combinations of Cr content and Keller coefficient for feedwater pipelines.

Cr content,%	Ke	Thinning, mm
0.03	0.271	2.701
0.04	0.325	2.7109
0.05	0.379	2.718
0.06	0.433	2.7234
0.07	0.487	2.7276
0.08	0.541	2.7309

Despite the variety of combinations of the Keller coefficient and Cr content, general trends in the development of the ECW process can be observed. The graph in Figure 5 shows the relationship between the control indicators and forecast results for the steam pipeline.

Based on the analysis performed, it is possible to state the discrepancy with the time of the predicted and control values. At the same time, the forecast model gives a more conservative estimation. To reduce the conservatism, it is necessary to test two possible hypotheses for improving the forecast model:

- change in the Keller coefficient over time as a reflection of changes in the inner surface; and
- control data filtering.

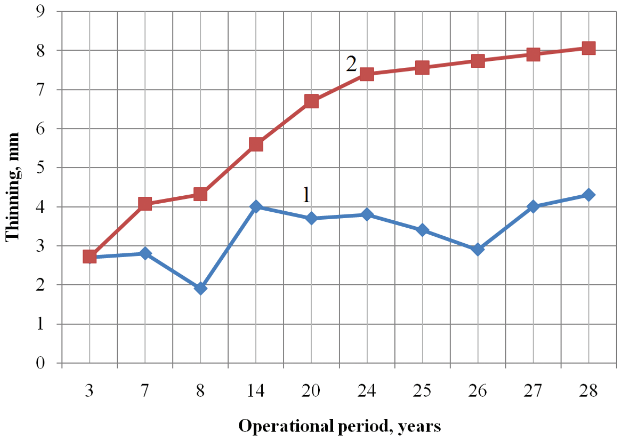

Figure 5. Control data and forecast results for the steam pipeline: 1 – protocol; 2 – forecast.

The Keller coefficient time dependence

It should be expected that the intensity of the ECW process is influenced by a change in the roughness of the inner surface of the pipeline walls, caused by the deposition and washout of corrosion products with an increase in the operating life due to a change in the flow regime near the walls. However, the height roughness is an order of magnitude less than the height of the deposited corrosion products; therefore, it has a significantly smaller effect on the change in the geometry of the pipeline inner surface. Let us assume that the influence of deposits is represented by the change over time of the Keller coefficient as the only metric responsible for the pipeline geometry in the Chexal-Horowitz model (3).

The use of a statistical approach to assessing the thinning trend did not lead to the desired result, since the trend, for example, in the case of the steam pipeline generally tended to decrease with time; for the feedwater pipeline, the regression shape also changed to decrease with time. This suggests that the processes of deposition of corrosion products significantly noise the real picture. In this case, the forecast results exceeded the control data, and the regulation by the Keller coefficient was reduced to a decrease in this coefficient with time.

For the regression of the latter, the confidence interval was calculated by the formula

$$\Delta_{s,t} = t_{n,\beta} \cdot \sqrt{S^2} \,/\, \sqrt{n},$$

where $\Delta_{s,t}$ is the confidence interval; β is the confidence probability (β = 0.95); n is the number of measurements (sample size, in our case: 10 and 8); $t_{n,\beta}$ is the quantile of Student's t-distribution (for n = 10 and β = 0.95 $t_{n,\beta}$ = 2.262 and for n = 8 and β = 0.95 $t_{n,\beta}$ = 2.365); S^2 is the sample variance:

$$S = \sqrt{\sum_{i=1}^{n} (f(t_i) - y_i)^2 \Big/ (n-1)},$$

where $f(t_i)$ are the values of the Keller coefficient by regression at time t_i; y_i are the values of the Keller coefficient obtained from the forecast at time t_i; t_i is the operating life of the component at the time of measurement.

Figure 6 shows a graph of the correspondence between the control data and the obtained forecast values for the approximated Keller coefficient.

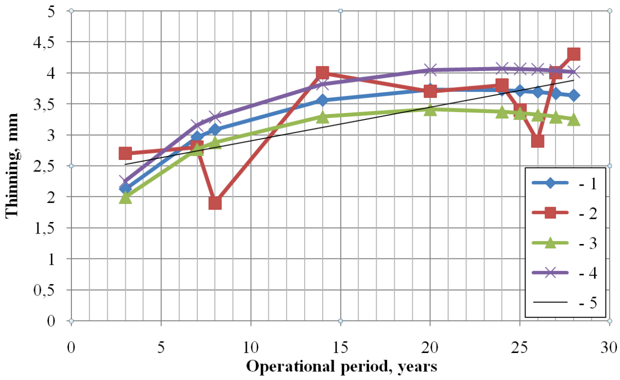

Figure 6. Correspondence between the control and forecast values for the approximated Keller coefficient (feedwater pipeline): 1 – forecast; 2 – control; 3 – –Δ; 4 – +Δ; 5 – regression (y = 0.054x + 2.361; R^2 = 0.459).

In this case, the constructed approximations describe satisfactorily the ECW process of the component under consideration, especially the lower limit of the confidence interval (less than 35%). However, a large number of repeated measurements are required to ensure the accuracy of the estimates.

For the steam pipeline, the situation is similar, only the thinning decrease rate over time is higher for the steam pipeline than for the feedwater pipeline, which corresponds to the control trends, i.e., the deposits of corrosion products are more intensive.

Data filtering

The graph of changes in the wall thickness (thinning), for example, for the feedwater pipeline is described above (see Fig. 4); however, approximately the same picture with measurements is observed on any other component. Simple logic says that wear is a monotonous process, and the thinning is decreased due to the deposited corrosion products but not due to the actual condition of the metal. In other words, at point 8 (years of operation), the actual thinning should be 2.8 (as at point 7) or more. Therefore, to eliminate the noise caused by the deposits, it is proposed to filter the control data so that the underlying next point will go to the level of the previous one. Then, the physical meaning of wear will remain, and dubious conclusions about an increase in the residual life over time will disappear.

Thus, the thinning value for this area should be taken equal to the largest previous value. Any subsequent thinning values, greater than the previous ones, should be left unchanged.

For the feedwater pipeline, screened values and the corresponding regression were found. According to this regression equation, graphs were plotted of the correspondence of the thinning values obtained during the control, the forecast data for the values of the Keller coefficient in the range from 0.16 (the value according to the Keller table for a given component) to 0.3 (assuming that over time the Keller coefficient will only increase) and the thinning by regression of the screened values (Fig. 7).

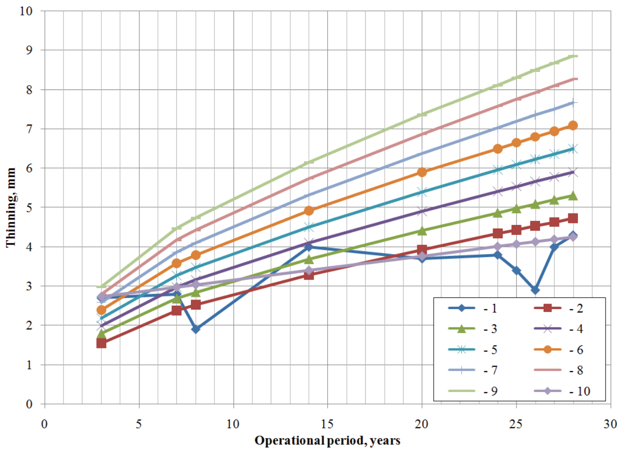

Figure 7. Correlation of thinning values obtained in different ways: 1 – control; 2 – Ke = 0.16; 3 – Ke = 0.18; 4 – Ke = 0.20; 5 – Ke = 0.22; 6 – Ke = 0.24; 7 – Ke = 0.26; 8 – Ke = 0.28; 9 – Ke = 0.30; 10 – screened values.

To select the best Keller coefficient, the sum of the squared forecast deviations (for different values of the Keller coefficient) were calculated depending on the regression of the screened control data:

$$\sum_{i=1}^{n}(f(t_i)-y_i)^2,$$

where $f(t_i)$ is the screened thinning at time t_i; y_i is the thinning at a fixed value of the Keller coefficient at time t_i; n is the number of measurements (sample size $n = 10$); t_i is the operating life of the component at the time of measurement.

Table 5 shows the results of calculating the sum of the squared deviations for the shielded thinning and thinning at fixed values of the Keller coefficient from 0.16 to 0.3, a fragment of the calculations is also given.

For the steam line, similar results were obtained, only the Keller coefficient changes from 0.23 (the value of the coefficient according to the table for a given component) to 0.5 (under the assumption that the Keller coefficient will only increase over time), and the regression equation has the form $y = 0{,}011t + 2{,}708$, where t is the operating time.

The residual sum of the squared deviations is also minimal for the original geometry of the component. Thus, the control data filtering makes it possible, without upgrading the model, to achieve an acceptable accuracy of the estimated thinning and residual life (16%).

A comparison of the ECW rates calculated using the software tools and those determined from the operational control data on feed water pipelines of NPPs with the VVER-440 reactors showed (Fig. 8) that the forecast estimate of the ECW rate differs from the estimate based on the control data by no more than 12.5%.

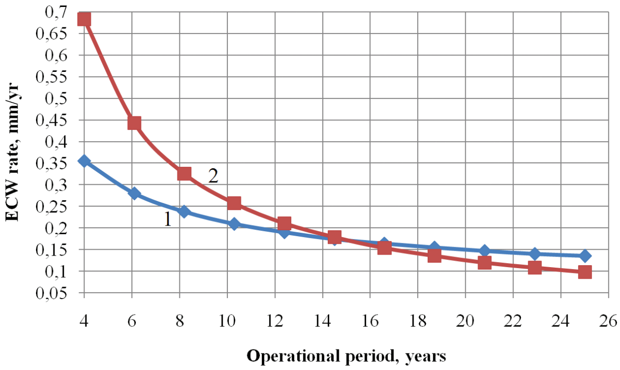

Figure 8. Values of the ECW rate in the steam line according to measurements and calculations using EKI-03: 1 – software-based calculations; 2 – operating control data

On a long time base, the values of deposits are leveled in both directions.

Conclusion

The control data were analyzed for components of feed water pipelines and steam pipelines of NPPs with the RBMK-1000 reactors and NPPs with the VVER-440 reactors. Based on the data of operational control, it was shown that the estimates of the ECW characteristics contained great uncertainty due to the corrosion products deposited on the

Table 5. Sums of the squared deviations for the shielded thinning and thinning at fixed values of the Keller coefficient.

Operating life, years	Screened thinning mm	Thinning, mm (Ke = 0.16)	Thinning, mm (Ke = 0.18)	Thinning, mm (Ke = 0.2)	Thinning, mm (Ke = 0.22)	Thinning, mm (Ke = 0.24)
3	2.7357	1.5497	1.794	1.9933	2.1927	2.392
7	2.9789	2.3844	2.6825	2.9805	3.2786	3.5767
8	3.0397	2.529	2.8452	3.1613	3.4774	3.7936
14	3.4045	3.2798	3.6898	4.0998	4.5098	4.9198
20	3.7693	3.928	4.419	4.9101	5.4011	5.8921
24	4.0125	4.3309	4.8723	5.4136	5.955	6.4964
25	4.0733	4.4313	4.9852	5.5391	6.093	6.6469
26	4.1341	4.5298	5.096	5.6622	6.2284	6.7946
27	4.1949	4.6263	5.2046	5.7829	6.3612	6.9395
28	4.2557	4.7235	5.3139	5.9043	6.4948	7.0852
Sum of squared deviations		2.85	6.15	14.04	26.41	43.26

pipeline inner surface and their migration during operation. At the same time, the forecast thinning data differed significantly from the control data for long operating lives, which was caused by the influence of deposited corrosion products recorded during control together with the base metal.

To adapt the forecast models, EKI-02 and EKI-03, to control data under uncertainty, two approaches were considered: (1) upgrading the forecast model by changing the Keller coefficient and (2) filtering control data with the model remaining unchanged.

It was shown that data filtering made it possible to improve the quality of the thinning forecast according to the model under consideration without its modernization with a discrepancy between the forecast and control data of no more than 16%.

It was also shown that calculating the ECW rate based on the control data adequately reflected reality and, with an increase in the operating time, the forecast accuracy increased (the error was no more than 13%).

The results obtained make it possible to confidently recommend the use of the forecast models, EKI-02.1 and EKI-03.1, both at the design stage of NPPs and in the process of operation to make decisions on the timing and scope of control.

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