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Research Article

Flow-accelerated corrosion rate and residual life time estimation for the components of pipeline systems at nuclear power plants based on control data*

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Abstract

As of today, large volumes of data related to non-destructive operational control are accumulated on NPPs. For ensuring safe operation of power units, optimization of scope and scheduling operational control it is necessary to continue development of guidance documents, software products, methodological guidance and operational documentation (Baranenko et al. 1998, Gulina et al. 2013, Recommendation (NSAC-202L-R4) 2013).

Approaches are examined to assessment of the rate of erosion-corrosion wear (flow-accelerated corrosion - FAC) according to the data of operational control. The present study was performed based on the data of thickness gauging of different elements of pipelines of NPPs with different types of reactor. Further development of ideas exposed in (Baranenko et al. 2016) allowed revealing specific features of ECW processes on straight sections, bends and in the zones adjacent to weld joints of pipelines of NPPs equipped with VVER and RBMK reactors. Presence of the process of deposition of corrosion products on internal surfaces of pipeline walls results in the fact that residual lifetime of elements nominally increases due to deposition. However, real wall thickness under the layer of deposits is unknown just as the initial wall thickness is unknown as well. Investigation implemented in the present study is aimed at the substantiation of the methodology of calculation of FAC rate according to the data of operational control for the purpose of drawing calculation results closer to the reality keeping conservatism. Uniform approach to the assessment of FAC rate in the examined elements of pipelines was developed. Methodologies for evaluation of correction coefficients taking into account dimensional technological tolerances, special features of geometry of the element, as well as effect of deposits on the results of thickness measurements were suggested based on the data of operational control and industry standards.

The implemented studies demonstrated efficiency of the developed procedures for pipeline welding zones. Analysis of known and newly developed procedures was performed for bends and ranking of these procedures according to the criterion of “conservatism of evaluation of residual lifetime” was executed.

Introduction of correction coefficients allows enhancing conservatism of calculations of lifetime characteristics as compared with calculations performed on the basis of nominal values of thicknesses; the result depends on the type and dimensions of the element, its geometry, as well as on the type of reactor.

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Keywords

Flow-accelerated corrosion (FAC), thickness gauging, evaluation of FAC rate, bends, welding, residual lifetime.

Introduction

Substantiation of the methodology for calculation of FAC rate for NPP piping elements manufactured of carbon steel requires high-quality analysis of data of operational control and taking into account significant number of factors (Baranenko et al. 2010. Introduction of additional correction coefficients taking into account the technology used in manufacturing the pipelines and effects of deposits on the values of initial and minimal permissible thicknesses (Baranenko et al. 2016) results in the significant change of estimated FAC rate and the residual lifetime which ensures certain conservatism of calculations and provides certain time margin for implementation of the next control.

Methodology for estimation of FAC rate presented in (Baranenko et al. 2016) is applicable for calculating straight pipeline sections:

$$W_{FAC1} = [(S_{nom} \times K_{11} \times K_{12} - S_{min} \times K_2)]\, K_{safe} / \Delta\tau_0, \quad (1)$$

where S_{nom} is the nominal wall thickness; K_{11} is the coefficient taking into account positive tolerance for wall thickness during manufacturing the pipeline; K_{12} is the coefficient taking into account contribution of corrosion products depositions in the nominal wall thickness; K_2 is the coefficient taking into account corrosion products depositions to value of measured minimal wall thickness (S_{min}); K_{safe} is the safety factor; $\Delta\tau_0$ is the duration of operation of the element before the date of control. Geometrical features of such elements as bends and welding zones (Baranenko et al. 2010, Baranenko et al. 2009) will probably require correction of the methodology in question and accounting of real thicknesses of these elements.

The purpose of the present study is the development of methodologies for evaluation of FAC rate taking into account geometrical features of such element as bends and welding zones.

Taking into account specific features of geometry of pipeline elements in the calculation of FAC rate

Determination of correction coefficient for bends. Value of thickness measured during pre-start control must be substituted in formula (1) in the calculations of FAC rates for extended elbow bends as the nominal thickness S_{nom}, otherwise the following dependence (Nakhalov 1983, OST 24.321.26-74 1975) must be applied for calculation of thickness of extended elbow bend sections S_{bend}:

$$S_{bend} = S_{nom}\, (R - 0.2\, D) / (R + 0.3\, D), \quad (2)$$

where R is the radius of pipeline bend, mm; D is the pipeline outer diameter, mm; S_{bend} is the thickness of extended part of the bend, mm.

The following coefficient is introduced using dependence (2):

$$K_{bend} = 1 - [0.5\, (1 - S_{bend} / S_{nom})]. \quad (3)$$

Dependence (3) takes into account that maximum thinning can be found on the section located beyond the extended part of the bend.

Determination of correction coefficient for welding zones. Large numbers of welding zones – WZ – are present on NPP power units. Quantities of fittings installed on power units of NPPs with VVER-440, VVER-1000, RBMK-1000 and RBMK-1500 reactors are presented in Table 1. There are two weld joints (WJ) made on each element and, correspondingly, there are two zones adjacent to weld joints on each of them. Besides fitting elements significant number of WZ is found on pipeline systems. Cases of washing out of WZ of NPP pipelines because of FAC were registered in the practice of operation of NPP power units (Korhonen and Hietanen 1994).

Table 1. Quantities of fittings installed on power units of NPPs with VVER-440, VVER-1000, RBMK-1000 and RBMK-1500 reactors.

Name of the element	VVER-440	VVER-1000	RBMK-1000		RBMK-1500	
			Odd power unit	Even power unit	Odd power unit	Even power unit
Gate valves	74	246	1820	1145	886	886
Shutoff valves	5448	6519	8715	8714	8135	7849
Control valves	80	126	352	265	789	788
Safety valves	65	172	135	135	119	119
Check valves	338	421	609	429	896	896
Total	6005	7484	11631	10688	10825	10538

On straight sections of pipelines and on WZ with outer diameter less than 108 mm initial thickness is similar to nominal thickness. Technological boreholes creating conditions for high-quality mating of joints during welding are drilled on WZ with outer diameter over 108 mm in accordance with industry standard OST 24.125.31-89. Drilling bores is performed on the input and output WZ on the section with length equal to 50 mm (OST 24.125.30-89 1989).

Thickness S_k determining the wall thickness in the zone of weld joint along the length of 50 mm has on the average the value smaller than the thickness of the bore S_r^* by approximately 1.3 times. In the process of operational control thickness S_k can be taken as the minimum permissible value.

Values of S_k in the zone of boreholes for WZ of different types and dimensions, nominal thicknesses and boreholes S_r^* calculated according to diameters of boreholes (OST 24.125.30-89 1989) are presented in Table 2**.** Thickness of the borehole S_r^* must be accepted as the initial value for WZ with outer diameters ≥ 108 mm. Measurements of wall thicknesses of WZ are performed on the cross-sections located at the distance of less than 50 mm from the weld joint. For pressure equal to 3.92, 5.89, 8.44, 11.77 MPa average value of the ratio S_r/S_{nom} is equal to 0.9. Thus, the value equal to $0.9S_{nom}$ can be used as the nominal or initial thickness. For determining coefficients K_{12} and K_2 it is necessary to know average values of wall thicknesses of pipelines which can be calculated on the basis of data of operational control. Calculations of average thicknesses are performed for pipelines minimum thicknesses of which are smaller than the initial values. Average wall thicknesses are determined according to the following dependence:

$$S_{av} = \Sigma S_i / n_{meas}, \tag{4}$$

where S_i is the wall thickness in the i-th measurement point; n_{meas} is the number of measurement points. The following is determined in the calculation of coefficients K_{12} and K_2:

– Difference between the average and initial (nominal) thicknesses:

$$\Delta S_{init} = S_{av} - S_{init}, \tag{5}$$

Table 2. Thicknesses of boreholes and nominal thicknesses, ratios of thicknesses S_r^*/S_{nom} and S_k/S_r^* for control pressure and temperature.

	p = 3.92 MPa, T = 200°C					**p = 5.89 MPa, T = 275°C**				
Item no.	$D_o \times S_{nom}$, mm	S_r^*, mm	S_k, mm	S_k/S_r^*	S_r^*/S_{nom}	$D_o \times S_{nom}$	S_r^*, mm	S_k, mm	S_k/S_r^*	S_r^*/S_{nom}
1	108×6	5.5	3.6	0.655	0.917	108×6	5.5	3.7	0.673	0.917
2	133×6.5	5.5	3.7	0.673	0.846	133×6.5	5.5	3.7	0.673	0.846
3	159×7	5.5	4.0	0.727	1.071	159×7	5.5	4.0	0.727	0.786
4	219×9	7.5	5.5	0.733	0.944	219×9	7.5	5.5	0.733	0.833
5	273×10	8.5	6.5	0.765	1.100	273×10	8.5	6.5	0.765	0.850
6	325×13	11	8.5	0.773	0.885	325×13	11.5	9.0	0.783	0.885
7	377×13	11.5	9.0	0.783	0.962	426×14	12.5	9.0	0.720	0.893
8	426×14	12.5	9.8	0.784	0.893	465×16	14.0	10.8	0.771	0.875
9	465×16	14	10.8	0.771	0.875					
10	630×17	16	14.0	0.875	0.941					
11	Min			0.655	0.846	Min			0.673	0.786
12	Average			**0.754**	**0.943**	Average			**0.731**	**0.861**
13	Max			0.875	1.100	Max			0.783	0.917
	p = 8.44 MPa, T = 300°C					**p = 11.77 MPa, T = 250°C**				
Item no.	$D_o \times S_{nom}$, mm	S_r^*, mm	S_k, mm	S_k/S_r^*	S_r^*/S_{nom}	$D_o \times S_{nom}$	S_r^*, mm	S_k, mm	S_k/S_r^*	S_r^*/S_{nom}
1	108×6	5.5	3.7	0.673	0.917	108×8	6.5	4.7	0.723	0.813
2	133×8	7	5.8	0.829	0.875	133×8	7	5.8	0.829	0.875
3	159×9	8.5	6.9	0.812	0.944	159×9	8.5	6.9	0.812	0.944
4	219×13	12	9.5	0.792	0.923	219×13	12	9.5	0.792	0.923
5	273×16	14.5	11.8	0.814	0.906	273×16	14.5	11.8	0.814	0.906
6	325×19	17.5	14.2	0.811	0.921	325×19	17.5	14.2	0.811	0.921
7	426×24	22	18.5	0.841	0.917	530×28	25	19.0	0.76	0.893
8	530×28	25	19.0	0.760	0.893					
9	630×25	24	22.0	0.917	0.960					
10	Min			0.673	0.875	Min			0.723	0.813
11	Average			**0.805**	**0.917**	Average			**0.791**	**0.896**
12	Max			0.917	0.960	Max			0.829	0.944

– coefficient K_{12}:

$$K_{12} = (S_{init} - \Delta S_{init}) / S_{init}, \tag{6}$$

(if $S_{av} < S_{init}$, difference between the values will be negative and value of K_{12} will be larger than unity);

– coefficient K_2

$$K_2 = (S_{min} - \Delta S_{init}) / S_{min}. \tag{7}$$

Calculation of FAC rate and residual lifetime. Corrosion rate aggravated by the flow W_{FAC} is calculated according to equation (1), nominal thicknesses are replaced with corresponding values of S_{bend} for bends and $0.9S_{nom}$ for welding zones. Residual lifetime of pipeline element is calculated according to the following equation:

$$\tau = (S_{min} - S_{perm})/W_{FAC}, \tag{8}$$

where S_{perm} is the minimum permissible wall thickness of the element (RD EO 1.1.2.11.0571-2015 2012, Case of ASME Requirements 2003).

Calculation of corrosion rate and residual lifetime of welding zones according to the data of operational control and taking into account correction coefficients

Values of wall thicknesses in circular points (Fig. 1) for 16 inlet and outlet WZ of pressure pipelines of feed electric pump and emergency feed pumps, minimum, average and maximum thicknesses, number of measurements with less than nominal thicknesses and thicknesses of boreholes of WZ on the pipeline with standard size equal to 426×24 mm are presented in Tables 3 and 4. Measurements of thicknesses were performed in eight points along the WZ circumference.

Measurements in axial direction were performed in one cross-section with step equal to 45° (corresponding to 12:00, 1:30, 3:00, 4:30, 6:00, 7:30, 9:00 и 10:30 “on a clock dial”). In accordance with Fig. 1 measurements are performed in the zones with wall thicknesses determined by the diameter of the borehole. In the present case thickness of the borehole must be equal to 21.6 mm. Results of measurements on inlet sections of WZ are presented in Table 3, those for outlet sections are presented in Table 4.

It follows from Tables 3 and 4 that the number of measurements with values of thicknesses less than 24 mm amounts on the WZ inlet and outlet sections to 78.1 and 73.4%, respectively. Number of measurements (on the borehole section) with values of thicknesses less than 21.6 mm amounts for the WZ inlet and outlet sections to 18.8 and 17.2%, respectively.

Results of calculations performed using formulas (5) – (8) are presented in Tables 5 and 6. Calculations of corrosion rates are given for welding zones for which the values of minimal thicknesses have values less than the initial value of the borehole thickness equal to 21.6 mm. Factor K_{11} was taken in the calculations to be equal to 1.075, time of operation before measurements – 24 years, minimum permissible wall thickness S_{perm} = 18.5 mm.

Estimated value of residual lifetime obtained using the formula for the nominal thickness S_{nom} (W_{FAC1} and T_1) is by 1.8 times less than the value obtained taking into account the borehole (W_{FAC2} and T_2).

Use of borehole thickness instead of S_{nom} results in the estimated value of residual lifetime larger by approximately 1.9 times, i.e. similarly to the picture for WZ inlet. Values of FAC rate and residual lifetime for WZ inlet without correction coefficients are presented in Table 7; borehole thickness equal to 21.6 mm was taken as the value of initial thickness.

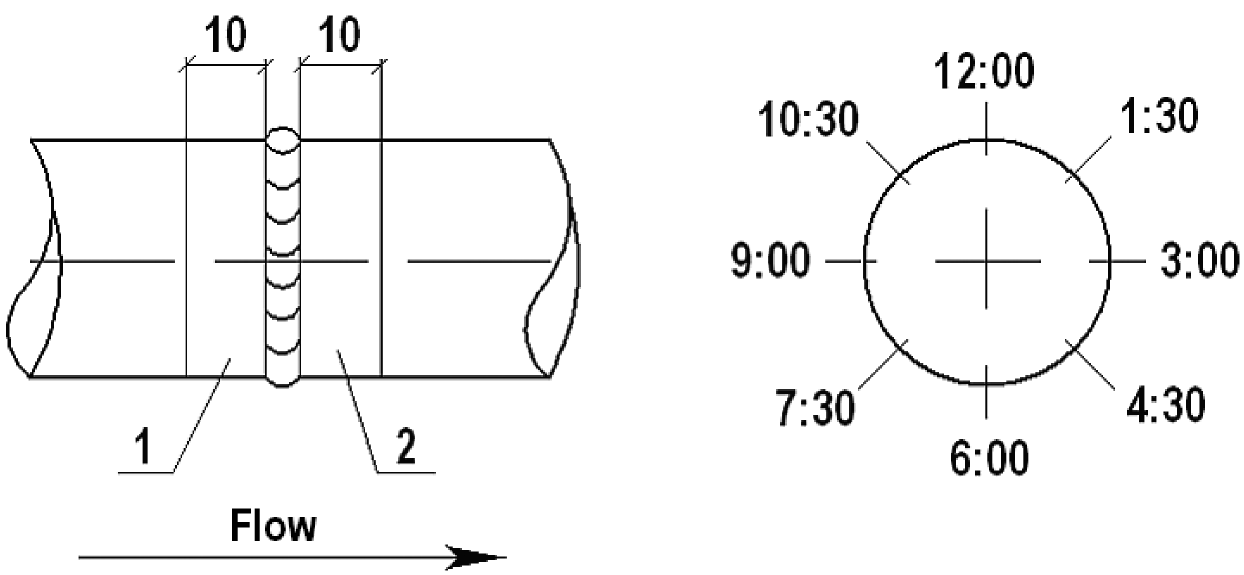

Figure 1. Layout of measurements of wall thicknesses of ZAWJ in eight points along the circumference: 1 – inlet zone; 2 – outlet zone.

Table 3. Wall thicknesses in circular points of WZ inlet , minimum, average and maximum thicknesses, number of measurements with values of thickness less than S_{nom} and S_r^*.

Item no.	Values of thicknesses in circular points, mm								Values of thicknesses			Number of measurements	
	12:00	1:30	3:00	4:30	6:00	7:30	9:00	10:30	Min	Average	Max	< 24 mm	< 21.6 mm
1	22.9	23.7	.30	22.6	22.7	22.6	22.4	24.2	**22.4**	**23.1**	**24.2**	7	0
3	22.1	23.4	22.4	21.5	21.9	23.8	24.9	24.4	21.5	23.1	24.9	6	1
5	22.2	24.5	24.2	22.7	22.2	22.8	20.4	21	20.4	22.5	24.5	6	2
7	22.9	24.2	23.9	24.8	23.2	24.7	24.6	24.7	**22.9**	**24.1**	**24.8**	3	0
9	22.3	24	25.2	23.6	21.8	23.5	23.2	21.9	**21.8**	**23.2**	**25.2**	6	0
11	20.8	21.8	22.5	22.8	22.4	21.9	22.1	21.4	20.8	22.0	22.8	8	2
13	24.8	24.4	21.5	20.9	22.3	21.6	21.5	22.7	20.9	22.5	24.8	6	3
15	22.2	22	21.9	21.8	21.4	20.6	20.1	20.7	20.1	21.3	22.2	8	4
Min	20.8	21.8	21.5	20.9	21.4	20.6	20.1	20.7	**20.1**	21.3	22.2	50	12
Average	22.5	23.5	23.1	22.6	22.2	22.7	22.4	22.6	21.4	**22.7**	24.2	78.1%	18.8%
Max	24.8	24.5	25.2	24.8	23.2	24.7	24.9	24.7	22.9	24.1	**25.2**		

Table 4. Wall thicknesses in circular points of WZ outlet, minimum, average and maximum thicknesses, number of measurements with values of thickness less than S_{nom} and S_r^*.

Item no.	Values of thicknesses in circular points, mm								Values of thicknesses			Number of measurements	
	12:00	1:30	3:00	4:30	6:00	7:30	9:00	10:30	Min	Average	Max	< 24 mm	< 21.6 mm
2	22.6	20.5	20.9	22.2	23.3	23.1	22.2	23.8	20.5	22.3	23.8	8	2
4	22.2	22.4	22.6	25.4	25.5	21.3	21.4	20.3	20.3	22.6	25.5	6	3
6	20.2	21.1	24.2	24.9	24.1	22.2	21	21.4	20.2	22.4	24.9	5	4
8	25.5	23.8	23.8	24	23.5	23.1	22	23.6	**22.0**	**23.7**	**25.5**	6	0
10	25.3	24.1	22.4	24.9	24.8	24.4	24.2	25.5	22.4	24.5	25.5	1	0
12	22.3	21.4	21.8	22.1	22.4	22.8	22.4	23.3	21.4	22.3	23.3	8	1
14	22.8	23	23.1	23.8	23.7	24.3	24.3	23.6	**22.8**	**23.6**	**24.3**	6	0
16	22.2	22.8	22.3	22.5	24.1	22.5	21.8	21.3	21.3	22.4	24.1	7	1
Min	20.2	20.5	20.9	22.1	22.4	21.3	21	20.3	**20.2**	22.3	23.3	47	11
Average	22.9	22.4	22.6	23.7	23.9	23.0	22.4	22.9	21.4	**23.0**	24.6	73.4%	17.2%
Max	25.5	24.1	24.2	25.4	25.5	24.4	24.3	25.5	22.8	24.5	**25.5**		

Analysis of Table 7 demonstrates that accounting of correction coefficients reduces the difference between the values of residual lifetime due to the indirect taking into account of depositions on internal surface of pipeline. Even taking into account the borehole thickness calculation produces estimations of residual lifetime which are smaller by approximately eight times for WZ inlet and by 5.8 times for outlet. Therefore, calculation methodology with introduction of correction coefficients and using the borehole thickness as the initial thickness is certainly recommended for WZ.

Bends. For calculating FAC rate and residual lifetime of bends let us examine the data of measurements performed in 1995, 1996, 2000 and 2002 on bends 06-K and 16-K of feedwater pipelines 273×16 mm of the Dukovany NPP during implementation of operational control. Selection of the bends was predetermined by the large number of measurements performed on each of the elements (from 276 to 394) (Rushchak et al. 1996).

$$W_1 = (S_{nom} - S_{min})K_{safe} / \Delta\tau_0. \quad (9)$$

The formula $W_2 = [(S_{nom} \times K_{11} \times K_{12} - S_{min} \times K_2)] \times K_{safe} / \Delta\tau_0$ (Baranenko et al. 1998) was suggested for estimating the FAC rate for straight sections of pipelines. Corresponding values of FAC rate W_2 and residual lifetime T_2 are given in Table 8. Average value of the ratio $T_1/T_2 = 1.5$, i.e. application of correction coefficients results in the reduction of the value of estimated residual lifetime of the examined bends by approximately 1.5 times.

Formula for estimation of FAC rate suggested in (RD EO 1.1.2.11.0571-2015 2012),

$$W_3 = (1{,}25 \times S_{nom} - 0{,}95 \times S_{min})K_{safe} / \Delta\tau_0 \quad (10)$$

Table 5. Values characterizing residual lifetime of WZ inlet of pressure pipelines of feed electric pump and emergency feed pumps.

Item no.	ΔS_{in}= $S_{av}-S_{in}$, mm	K_{12}	K_2	S_{min}	W_{FAC1}, mm/yr	T_1, years	W_{FAC2}, mm/yr	T_2, years	T_2/T_1
3	1.5	0,931	0,930	21,5	0,095	20,3	0,074	31,5	1,55
5	0.9	0,958	0,907	20,4	0,163	11,6	0,172	11,7	1,01
11	0.4	0,981	0,949	20,8	0,170	8,6	0,140	13,5	1,56
13	0.9	0,958	0,93	20,9	0,144	7,0	0,129	16,6	2,37
15	**–0.3**	1,014	0,949	20,1	0,230	2,9	0,205	6,9	2,38
								Average	1.8

Table 6. Values characterizing residual lifetime of WZ outlet of pressure pipelines of feed electric pump and emergency feed pumps 426×24 mm.

Item no.	S_{min}, mm	C_{12}	C_2	$S_{min}\times C_2$, mm	Diff.	W_{FAC1}, mm/year	Residual lifetime T1, years	W_{FAC2}, mm/year	Residual lifetime T_2, years	T_2/T_1
2	20.5	0,968	0,921	18,9	2	0,276	7,24	0,161	12,4	1,71
4	20.3	0,954	0,898	18,2	1,8	0,294	6,12	0,184	9,78	1,60
6	20.2	0,963	0,902	18,2	1,7	0,304	5,59	0,193	8,8	1,57
12	21.4	0,968	0,963	20,6	2,9	0,198	14,64	0,087	33,3	2,27
16	21.3	0,963	0,953	20,3	2,8	0,207	13,5	0,097	28,8	2,13
									Average	1.86

Table 7. FAC rate and residual lifetime for WZ inlet (W_{FAC11}) and outlet (W_{FAC21}) without correction coefficients.

Item no.	S_{min}, mm	W_{FAC11}, mm/year	T_{11}, years	Item no.	S_{min}, mm	W_{FAC21}, mm/year	T_{21}, years	T_{11}/T_1	T_{21}/T_2
3	21.5	0.004	750	**2**	20,5	0,045	44	23,8	3,5
5	20.4	0.050	38	**4**	20,3	0,054	33	3,2	3,4
11	20.8	0.033	70	**6**	20,2	0,058	29	5,2	3,3
13	20.9	0.029	82	**12**	21,4	0,008	362	4,9	10,8
15	20.1	0.062	25	**16**	21,3	0,012	233	3,6	8,1
							Average	8.1	5.8

was also applied with respect to the examined bends. Corresponding values of the rate W_3 and residual lifetime T_3 are presented in Table 9.

In accordance with formula (2) thickness of extended part of the bend is equal to

$$S_{bend}=S_{nom}(R-0.2D)/(R+0.3D),$$

where R is the bend radius. For the examined bends (90°) R = 1370 mm. Then S_{bend} = 14.5 mm and the value of factor $K_{bend} = 1 - [0.5\times(1 - S_{bend}/S_{nom})] = 0.953$.

Average value of the ratio T_3/T_2 = 0.5, i.e. calculation of FAC rate according to the formula presented in the new edition of the regulatory document (RD) (RD EO 1.1.2.11.0571-2015 2012) results in the reduction of estimated value of residual lifetime by two times relative to the formula for straight sections with correction coefficients.

Formula for calculating FAC rate taking into account the bend geometry W_4 is similar to formula (1) with corresponding replacement of S_{nom} with S_{bend}:

$$W_4 = [(S_{bend}\times K_{11}\times K_{12}\times K_{bend} - S_{min}\times K_2)]\times K_{safe}/\Delta\tau_0. \quad (11)$$

Estimated value of residual lifetime for the described case (T_4) is by 3.5 times larger than that obtained using formula (1) for straight sections (Table 10).

Thus, residual lifetime calculated according to RD is by approximately tree times less than that calculated using the formula for bends.

Summary of results for bends are presented in Table 11.

As the final result the most conservative estimation was obtained using the formula taken from RD (W_3) and the most optimistic estimation was obtained with introduction of correction coefficients for bends (W_4). Reasonable conservatism was demonstrated in this case with introduction of correction coefficients for bends similar to those for straight sections (W_2), i.e. without taking the geometry into account. However, it is difficult enough to substantiate this result and, therefore, the whole set of results must be used in order to make decision on the implementation of the next control when already expired time gets close to the minimum among the calculated values of time.

Table 8. FAC rate and residual lifetime for bends without taking (9) into consideration and with correction coefficients (1).

Bend	Year	T_{op}, years	S_{min}	S_{av}	ΔS	C_{12}	C_2	W_1	T_1	W_2	T_2	T_1/T_2
06-K	1996	11,7	12,95	16,32	0,32	0,98	0,975	0,236	26	0,329	18,7	1,39
	2002	17,7	13,5	16,13	0,13	0,992	0,990	0,128	52	0,190	35,2	1,47
16-K	1995	10,7	13,84	16,17	0,17	0,989	0,987	0,183	38,4	0,285	24,7	1,55
	1996	11,7	13,95	16,23	0,23	0,985	0,983	0,159	44,9	0,250	28,6	1,56
	2000	15,7	13,76	16,22	0,22	0,986	0,984	0,130	53,5	0,198	35,15	1,52
											Average	1.5

Table 9. Estimated values of ECW rate and remaining lifespan for bends obtained according to formula (10).

Bend	Year	S_{min}	S_{av}	ΔS	$0.95{\times}S_{min}$	W_3	T_3	T_3/T_2
06-K	1996	12.95	16.32	0.32	12.3	0.598	10.3	0.55
	2002	13.5	16.13	0.13	12.825	0.368	18.2	0.517
16-K	1995	13.84	16.17	0.17	13.148	0.582	12.1	0.49
	1996	13.95	16.23	0.23	13.25	0.524	13.6	0.475
	2000	13.76	16.22	0.22	13.07	0.401	17.3	0.492

Table 10. Estimated values of FAC rate and residual lifetime (W_4 and T_4) for bends obtained according to formula (1) taking into account the bend geometry.

Bend	Year	S_{min}	S_{cp}	ΔS	C_{12}	C_2	W_4	T_4	T_4/T_2	T_3/T_4
06-K	1996	12.95	16,32	0,32	0,98	0,975	0,205	28,4	2,75	0,362
	2002	13.5	16,13	0,13	0,992	0,990	0,107	61,4	3,37	0,296
16-K	1995	13.84	16,17	0,17	0,989	0,987	0,149	46	3,8	0,263
	1996	13.95	16,23	0,23	0,985	0,983	0,127	54,4	4	0,25
	2000	13.76	16,22	0,22	0,986	0,984	0,106	63,5	3,67	0,272
								Average	3.5	~ 0.3

Table 11. Residual lifetime for bends (summary of results).

Bend	Year of measurement	S_{min}	S_{av}	T_1	T_2	T_3	T_4
06-K	1996	12,95	16,32	26	18,7	10,3	28,4
	2002	13,5	16,13	52	35,2	18,2	61,4
16-K	1995	13,84	16,17	38,4	24,7	12,1	46
	1996	13,95	16,23	44,9	28,6	13,6	54,4
	2000	13,76	16,22	53,5	35,15	17,3	63,5

Conclusion

1. Methodologies were developed for calculating the rates of flow-accelerated corrosion and residual lifetime for bends and welding zones with introduction of correction coefficients taking into account the effects on the corrosion process produced by the manufacturing technology, as well as influence of depositions of corrosion products.

2. Reasonable conservatism of the calculations is ensured by introduction of correction coefficients and geometry of the elements. It was demonstrated that calculated results obtained taking these correction factors into account are not overly pessimistic.

3. Values of correction coefficients introduced in the calculation dependences are determined on the basis of processing the data of operational control. Calculation of FAC rate and residual lifetime of the WZ are performed using nominal thickness and borehole thickness as the initial value of thickness. Use of borehole thickness instead of nominal thickness results in the estimation of residual lifetime which is by approximately 1.9 times larger both for WZ inlet and outlet of pressure pipelines of feed electric pump and emergency feed pumps with size type 426×24 mm.

4. Calculation without introduction of correction coefficients for the borehole thickness produce estimated values of residual lifetime which are smaller by approximately eight times for WZ inlet and by 5.8 times for outlet. Therefore, calculation methodology with introduction of correction coefficients and application of borehole thickness as the initial thickness is certainly recommended for welding zones.

5. Data of measurements performed on bends of feedwater pipelines 06-K and 16-K 273×16 mm of the Duko-

vany NPP performed in the course of operational control in 1995, 1996, 2000 and 2002 are examined for calculation of FAC rate and residual lifetime. The following four formulas for calculating FAC rate were examined: for straight sections without corrections, for straight sections with introduction of correction factors, with introduction of correction factors for bends and the formula recommended in RD (RD EO 1.1.2.11.0571-2015 2012). Ambiguousness of the conclusions thus drawn requires application of the whole set of available results for making the decision on the implementation of the next control when already expired time gets close to the minimum among the calculated values of time.

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