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Substantiation of FAC rate and service life estimation under operation control data

V.I. Baranenko[a], O.M. Gulina[b,*], N.L. Salnikov[b], O.E. Murzina[b]

[a] *All-Russian Research Institute for Nuclear Power Plants Operation («VNIIAES JSC»), 25 Ferganskaya st., 25, Moscow 109507, Russia*
[b] *Obninsk Institute for Nuclear Power Engineering, National Research Nuclear University «MEPhI», 1 Studgorodok, Obninsk, Kaluga Region 249040, Russia*

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Abstract

Flow-accelerated corrosion (FAC) wear is the complex mechanism of damage of elements of NPP equipment and pipelines. FAC rate is determined by such factors as corrosion of metal, flow hydrodynamics, geometry of equipment elements and pipelines, applied water chemistry regimes (WCR), duration of operation, chemical composition of the metal, thickness of deposited corrosion product film and others. Approaches to the assessment of FAC rate according to the control data are addressed in the present study. Implemented investigation was aimed at the substantiation of the methodology of calculation of FAC rate. Absence of the methodology for calculation of FAC rate does not allow verification of calculation programs, as well as the use of data of regulatory documents on the minimum permissible thicknesses [1] for evaluating the residual lifetime.

Processing of measured data allowed determining the main indexes of FAC process such as the values of wall thinning and thickening, rates of wall thinning and thickening, residual operation time to the moment of reaching the minimum permissible thickness. Reduction of thickness is determined by corrosion of metal and its increase is determined by the formation of deposited film of corrosion products.

The process of corrosion products deposition on the internal surfaces of the element proceeds simultaneously with the process of thinning of the wall. Presence of this process results in the situation when the residual lifetime of equipment elements under the conditions of deposition of corrosion products is technically increased. At the same time the real state of the wall under the layer of deposited corrosion products is unknown, as well as the initial wall thickness. In order to bring the calculated results closer to the real situation it is necessary to use substantiated and verified methodology in the calculations of FAC rate according to the data of control measurements. The implemented study allowed suggesting the methodology of calculation of FAC rate taking into account the technological tolerances on the sizes and taking into account the influence of deposits on the initial and minimum thicknesses. Safety factor was also introduced for calculating the residual lifetime which is taken into account in the international practices because of the same reason.

Introduction of correction coefficients allows enhancing the conservatism of calculations of residual lifetime characteristics by approximately 2.5 times compared with calculations performed on the base of nominal thickness.

Keywords: Flow-accelerated corrosion wear; Deposits of corrosion products; Thickness gauging data; Methodology of calculation of FAC rate; Residual lifetime; Minimal permissible thicknesses.

Introduction

Estimation of FAC rate on the base of control data contains significant uncertainties associated with presence of depositions on the inner surfaces of pipeline elements because measurement performed on the wet pipes corresponds to the combined thickness of the wall and the deposits. The problem is also further aggravated by the fact that the data of acceptance control of wall thickness of equipment elements are not available. At present the information about the influence of corrosion products deposits on the measurements of pipeline wall thickness is practically missing in the foreign reference sources. Nevertheless, technological tolerances for the pipelines manufacturing are specified in the TU 14-3-400-75 regulations. All the above mentioned factors can

* Corresponding author.
E-mail addresses: baranenko@vniiaes.ru (V.I. Baranenko), olga@iate.obninsk.ru (O.M. Gulina), salnikov@iate.obninsk.ru (N.L. Salnikov).

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really influence on the estimation of the residual lifetime of equipment.

The purpose of the present study is the substantiation of the methodology for estimation of FAC rate in the conditions of the above described uncertainties on the base of the control data.

Review of approaches to the evaluation of FAC rate applied on foreign and Russian NPPs

The following four calculation dependences for determining the wall thinning are presented in Ref. [2].

1. Calculation of the FAC rate is performed in the following form:

$$W_{FAC1} = (S_{nom} - S_{min})/\Delta\tau_{0,} \quad (1)$$

where S_{rated} is the nominal thickness, mm; $S_{\min}$ is the minimum measured thickness; $\Delta\tau_0$ is the operational time, i.e. interval from the date of the equipment element operation beginning until the control time moment, years.

2. Calculation of FAC rate is performed using maximum and minimum thicknesses determined in the same points in the course of operational control in the following form:

$$W_{FAC2} = (S_{max} - S_{min})/\Delta\tau_0, \quad (2)$$

where $S_{\max}$ is the maximum measured thickness, mm.

3. Calculation of FAC rate is performed using the values of minimum thicknesses determined during the preceding and the subsequent operational control measurements in the following form:

$$W_{FAC3} = (S_{min1} - S_{min2})/\Delta\tau_1, \quad (3)$$

where $S_{\min1}$ is the value of minimum thickness during the preceding control, mm; $S_{\min2}$ is the value of minimum thickness during the subsequent control, mm; $\Delta\tau_1$ is the time interval between the dates of operational control measurements, years.

4. Calculation of FAC rate is performed using average thicknesses determined during the preceding and the subsequent operational controls in the following form:

$$W_{FAC4} = (S_{av1} - S_{av2})/\Delta\tau_1, \quad (4)$$

where S_{av1} is the value of average thickness based on control data, mm; S_{av2} is the value of average thickness during the next control, mm.

Residual lifetime of pipelines elements until the minimum permissible thickness is reached is calculated according to the following equation:

$$\Delta\tau_2 = \left(S_{min} - S_{perm}\right)/W_{FAC,} \quad (5)$$

where S_{perm} is the value of minimum permissible thickness, mm; W_{FAC} is the rate of wear calculated using of one of the four formulas above (1)–(4), mm/year.

In accordance with recommendations on the efficient management of metal wear the safety factor C_{safety} [3] must be introduced. Then the residual lifetime of pipelines elements until the minimum permissible thickness is reached is determined as follows:

$$\Delta\tau_2 = (S_{\min} - S_{R.})/W_{FACi} \times C_{\text{safety}}, \quad (6)$$

where C_{safety} is the safety coefficient with minimum value to be equal to 1.1 in pursuance with recommendations of Refs. [3–5].

The presented formulas are the reference ones in the calculations of the FAC rate performed on foreign NPPs. At the same time the formulas (1)–(4) have a number of drawbacks. For instance, Eq. (1) assumes that wall thickness is nominal until the equipment operation beginning. Really there are significant deviations because of the presence of factors which are not accounted for here. Eq. (2) assumes that maximum and minimum wall thicknesses are measured at the same place and, therefore, wall thinning is limited by the local area. The formula is conservative as a whole for tee-joints and connection pipes because these components often have zones with thicknesses exceeding the nominal thickness and, therefore, it would be expected that maximum and minimum index values will be spread within wide range even before the beginning of equipment element operation. At the same time this formula is not conservative for the case when inspection are held in the areas subjected to the total thinning, for example, in the area after the feed water flowmeters. Eq. (3) assumes that measured results obtained during later measurements are performed in the same places as those obtained in earlier measurements. It is very difficult to achieve this in the practice of measurements.

Eq. (4) assumes that there is a relationship between the changes in the average thickness and the FAC rate. The formula can be correct for the total thinning but, however, for local wear the estimation obtained may prove to be incorrect.

Therefore, the problem of “reasonably conservative” estimation of the FAC rate due to the factors of uncertainty associated with implementation of control of thickness remains to be important.

Data of operational control implemented during different periods at Unit 1 of NPP Dukovany, Unit 1 of NPP Forcemark and on other NPPs, as well as the required data taken from technical documentation were used for the purpose of investigation of this type of uncertainties.

Measurements of wall thickness of the feed water pipeline 273×16 mm were performed on Unit 1 of NPP Dukovany-1 in 1995–2002 [6–8]. Data on the numbers of pipeline elements with thinned, thickened and unchanged thicknesses of wall of feed water pipelines relative to the wall nominal thickness are presented in Table 1. It follows from this table that on the average the number of measurements with thinned pipe walls amounted to 48.8%, that with thickening walls amounted to 50.9%, and that without change of wall thickness amounted to 0.3%. Total number of measurements is equal to 2902.

Values of minimum $S_{\min}$ and maximum $S_{\max}$ thicknesses, duration of operation of elements before implementation of control τ, rates of wall thinning W_{thin} and thickening W_{thick}

Table 1
Statistics of wall thickness measurements on feed water pipeline elements on NPP Dukovany-1.

Year of measurement	Name of the element	Thinned		No change		Thickened		Total
		Units	%	Units	%	Units	%	Units
1996	Straight section	36	60.0	0	0	24	40,0	60
1996	Straight section	16	66.7	0	0	8	33,3	24
1996	Straight section	28	46.7	0	0	32	53,3	60
1996	Tee-junction	38	69.0	0	0	17	31,0	55
1996	Bend 02	162	51.9	1	0.3	149	47,8	312
1996	Bend 06	172	46.2	0	0	200	53,8	372
2002	Bend 06	163	45.5	1	0.3	196	54,4	360
1995	Bend 16	197	50.0	1	0.3	196	49,7	394
1996	Bend 16	166	48.7	2	0.6	173	50,7	341
2000	Bend 16	172	51.2	1	0.3	163	48,5	336
2000	Bend 18	89	28.5	3	1.0	220	70,5	312
2001	Bend 30	177	64.1	1	0.4	98	35,5	276
Total, average value*		1416	*48,8	10	*0.3	1476	*50.9	2902

calculated using the differences between the nominal and the minimum measured thicknesses and differences between the maximum measured and the nominal thicknesses, respectively, are presented in Table 2.

Besides that values of wall thinning rate W_{thin}^{c} calculated using *CHECWORKS* computer code are also presented. Maximum thinning relative to the nominal thickness is equal to 21%, maximum thickening is equal to 31% which exceeds the positive tolerance on the wall thickness of pipe lines equal to 20%. The above results are the evidence that corrosion products deposition influences on the results of measurements of wall thickness during of operation control. FAC rate calculated using *CHECWORKS* computer code exceeds the value of one calculated using the control data from 2.20 to 5.67 times.

Correction coefficients

Analysis of operational control data allows making the conclusion that calculation of FAC rate needs in at least three coefficients taking into account pipeline manufacturing and corrosion products depositions because wall thickness includes both deposits and undamaged metal. Then Eq. (1) for estimation of FAC rate will be as follows:

Table 3
Tolerances on pipe line wall thickness in accordance with TU 14-3-400-75.

Types of pipes	Maximum deviations
Cold and warm deformed pipes	± 10%
Hot deformed outside carbon and alloy steel pipes with diameter up to 108 mm	– 10%, +15%
Hot worked outside deformed outside carbon and alloy steel pipes with diameter above 108 mm	– 5%,+20%

$$W_{FAC} = [(S_{nom} \times C_{11} \times C_{12} - S_{min} \times C_2)]/\Delta\tau_0, \quad (7)$$

here C_{11} is the factor taking into account the positive tolerance on the wall thickness due to manufacturing; C_{12} and C_2 are the factors taking into account the contribution of corrosion products deposits to the initial wall thickness (nominal) measured and minimum wall thickness measured correspondently.

Determination of coefficient C_{11}. Technical specifications TU 14-3-400-75 where technological tolerances on pipeline manufacturing are provided can be applied to determinate this factor. Values of tolerances on pipeline wall thickness in accordance with TU are presented in Table 3 [9].

It is reported in Ref. [2] that according to measurement of more than 6000 samples of straight and bent pipes with diameters equal to 44.5–82.5 mm with nominal wall thickness from 3.43 to 8.64 mm manufactured from carbon steels the wall thickness has Gaussian distribution. Average value of straight pipes wall thickness coincides with the tolerance margins median. In 95.46% of all cases wall thickness is found within the limits of the tolerance margin, i.e. standard deviation is equal to one fourth of the width of tolerance margin. Minimum thicknesses of bent pipe wall are also distributed according to Gaussian distribution.

Tolerance margin for pipelines with outer diameter above 108 mm is within the range from –5 to +20%. The most probable positive tolerance for such wall thickness is +7.5% and the coefficient C_{11} would be equal to 1.075. For pipelines with outer diameter up to 108 mm the most probable positive tolerance is +5.0% and the coefficient C_{11} would be equal to 1.025.

Determination of values of coefficients C_{12}, C_{21}. Systematic data on the corrosion products deposits contribution in the maximum and minimum values of thickness of pipeline walls

Table 2
Values of wall thinning, thickening, operation time, rates of thinning, thickening and relative values.

Bend number	Date of measurement	S_{min}, mm	S_{max}, mm	τ, years	$W_{thin}{}^{c}$, mm/year	W_{thin}, mm/year	W_{thick}, mm/year	$W_{thin}{}^{c}/W_{thin}$	$W_{thin}{}^{c}/W_{thick}$	W_{thick}/W_{thin}	S_{min}/S_{rated}	S_{max}/S_{rated}
02-K	11.09.96	12.6	19.6	11.7	0.64	0.291	0.308	2.20	2.08	1.06	0.79	1,23
18-K	14.09.96	13.7	20.5	11.7	0.64	0.197	0.385	3.25	1.66	1.95	0.86	1,28
30-K	13.09.96	12.9	18.8	11.7	0.64	0.265	0.239	2.42	2.68	0.90	0.81	1,18
06-K	18.09.96	13.0	20.9	11.7	0.80	0.256	0.419	3.13	1.91	1.64	0.81	1,31
06-K	06.11.02	13.5	18.7	17.7	0.80	0.141	0.153	5.67	5.23	1.09	0.84	1,17
16-K	11.09.95	13.8	19.9	10.7	0.65	0.206	0.364	3.16	1.79	1.77	0.86	1,24
16-K	11.06.96	14.0	20.1	11.7	0.65	0.171	0.350	3.80	1.86	2.05	0.88	1,26
Minimum		**12.6**	18.7	10.7	0.64	0.141	0.153	2.20	1.66	0.90	0.79	1.17
Average		13.4	19.8	12.4	0.69	0.218	0.317	3.38	2.46	1.49	0.83	1.24
Maximum		14.0	**20.9**	17.7	0.80	0.291	0.419	5.67	5.23	2.05	0.88	1.31

are not available. It follows from processing the control data performed on pipelines elements at the same points during different periods of operation that the values of normalized thinning and thickening may be found within the range of ±0.1 relative to the nominal values. Consequently the value equal to 1.05 can be taken as the minimum value of the coefficient C_{12} and the value equal to 0.95 can be taken as the minimum value of the coefficient C_{21}.

Taking into account the above discussed values of coefficients C_{11}, C_{12}, C_{21} and C_{safety} Eq. (7) for calculation of FAC rate may be written in the following form:

$$W_{FAC} = [(S_{nom} \times 1.075 \times 1.05 - S_{\min} \times 0.95)]/\Delta\tau_0. \quad (8)$$

In contrast to Eq. (1) dependence (8) partially removes the uncertainty associated with control of thickness while remaining within the framework of conservative estimation.

Calculation of residual life time of pipelines

Residual life time of pipelines elements until the minimum permissible wall thickness S_R is reached being calculate in accordance with the following equation:

$$\Delta\tau_2 = (S_{\min} \cdot C_{21} - S_R)/(W_{FAC} \cdot C_{\text{safety}}). \quad (9)$$

Calculation codes *CASE N*-480 and *CASE N*-597-2 [10,11] are applied for determining the minimum permissible wall thicknesses S_R on foreign NPPs. The value of minimum permissible wall thickness is determined depending on the dimensions of the damaged area. In accordance with *CASE N*-480 minimum thickness within the area of local thinning can amount to $0.3S_{nom.}$ In accordance with *CASE N*-597-2 minimum thickness within the area of local thinning can amount to $0.1S_{nom.}$ A number of issues related to the determination of minimum permissible thicknesses are examined in Ref. [3].

Acting guidance document RD EO 1.1.2.11.0571-2010 [1] is developed for determination of minimum permissible wall thicknesses for indigenous NPPs for some types of pipe elements operated at different conditions.

Determination of safety coefficient C_{safety}. It is indicated in Ref. [3] that selection of appropriate the safety factor value is the responsibility of the owner of equipment. The following rules must be taken into consideration:

- Minimum value of the safety factor is 1.1.
- The following refers to the cases when higher safety factor value must be chosen:
  - Areas where forecasted and changing minimum wall thickness is larger than the measured minimum wall thickness.
  - Pipelines or elements of equipment where no measurements were taken;
  - Uncalibrated pipelines.
  - Pipelines with indefinite operational conditions.
  - Pipelines for which it is known that ring-shaped substrates are used in them.
  - Areas located after diaphragms or control valves.
  - Areas where deteriorating situation may be associated with other sources, for instance, with cavitation or with precipitation of liquid drops.
  - Lines and/or areas within the primary cooling loop located within the zone with high flow rates.
  - Lines qualified as important for ensuring nuclear safety.
  - Lines and/or areas within the primary cooling loop located in direct vicinity of equipment important for ensuring safe operation.
  - Lines with problematic history or lines similar to lines with problematic history.
  - Lines with limited number of control data for which measurements of chromium content were not performed.
  - Lines where operational conditions have become or are expected to become more severe.
  - Use of wall thickness measurements grid with dimensions in excess of those recommended in the regulatory documentation.

Recommended methodology for calculation of FAC rate and of residual life time of pipelines for indigenous NPPs

It is recommended to use Eqs. (8)–(9) for performing calculations of FAC rate and calculations of residual life time of pipelines elements.

Assumptions and restrictions accepted in the calculations.

1. It is permissible to use the values of wall thicknesses obtained from operational control as the initial wall thickness value under the condition of availability of acceptance control data. In this case the coefficient $C_{11} = 1.0$ and coefficient C_{12} retains the accepted value.
2. FAC rate and residual life time of pipelines are not calculated for elements with minimum thickness exceeding the nominal value, i.e.

$$S_{\min} \geq S_{nom} \cdot C_{11} \cdot C_{12}. \quad (10)$$

3. Calculations of wall thinning performed in accordance with control data

$$\Delta S_{\text{thin}} = (S_{nom} \cdot C_{11} \cdot C_{12} - S_{\min} \cdot C_2) \quad (11)$$

are compared with calculations of values of wall thinning determined using certified software (SW).

4. The necessity of operational control of walls with minimum thickness exceeding the nominal value is established on the basis of forecast calculations performed using certified SW.

Using of software. Using of certified software allows performing calculations of both FAC rate and thinning of pipeline wall taking into account the factors determining the intensity of wearing (operating parameters, indicator values of water chemistry regimes, chemical composition of the metal, design features of the elements, operation time of the pipelines).

Forecasting calculations estimate potential wear of metal before implementation of operational control and allow

Table 4
Estimated values of FAC indexes for feed water pipeline bends.

Element	S_{rated}, mm	S_{min}, mm	S_{perm}, mm	W_{FAC1}, mm/year	τ_1, year	W_{FAC2}, mm/year	τ_2, year
Bend CC 8-7z	28	22	19.5	0.26	9.6	0.584	4.2
Bend CC 32z-31	28	22.4	19.5	0.243	11.9	0.566	5.1
Bend CC 5-4	28	21.9	19.5	0.264	9.1	0.589	4.1
Bend CC 6z-5	28	22.2	19.5	0.252	10.8	0.575	4.7
Bend CC 38-37	28	21.1	19.5	0.256	6.3	0.625	2.6
Bend CC 11z-11	28	21.9	19.5	0.265	9.1	0.589	4.0
Bend CC 11z-11	28	22	19.5	0.26	9.6	0.584	4.2
Bend CC 32z-31	28	22.5	19.5	0.239	12.5	0.561	5.3
Bend CC 32z-31	28	23.3	18.7	0.204	22.5	0.525	8.7
Bend CC 7-6	28	19.6	19.5	0.365	0.8	0.693	0.4
Bend CC 15-15z	28	19.8	19.5	0.356	1.61	0.683	0.84
Bend CC 11-10	28	20	19.5	0.347	1.44	0.538	0.92
Bend CC 31-30	28	26	19.5	0.086	75.5	0.342	19.0
Bend CC 51z-55	28	24.2	19.5	0.165	28.4	0.412	11.4
Bend CC 68z -64	28	24.1	19.5	0.169	27.2	0.416	11.0
Bend CC 63z -62	28	24.1	19.5	0.169	27.2	0.416	11.0
Bend CC 56-57	28	24.4	19.5	0.156	28.8	0.404	11.1
Bend CC 64z -63	28	24.2	19.5	0.165	28.4	0.412	11.4
Bend CC 57-58	28	24.1	19.5	0.169	27.2	0.416	11.0
Bend CC 63-63z	28	24.2	19.5	0.165	28.4	0.412	11.4
Bend 76-76z	28	22.1	19.5	0.256	10.1	0.497	5.2
Bend 20-19	28	22.8	19.5	0.226	14.6	0.466	7.08
Bend 33-32	28	22.7	19.5	0.230	14.0	0.470	6.8
Bend 70a -70	28	22.1	19.5	0.256	10.1	0.497	5.2
Bend 73-73z	28	21.2	19.5	0.295	5.76	0.528	3.2
Bend 83-84	28	21.5	19.5	0.282	7.1	0.516	3.8
Bend 71-72	28	21.4	19.5	0.286	6.64	0.520	3.6
Bend 33a -33	28	21	19.5	0.304	4.93	0.536	2.8
Bend 61z -62	28	20.9	19.5	0.308	4.54	0.540	2.6
Bend 26z -26	28	21.6	19.5	0.278	7.55	0.513	4.1
Bend 42z -41	28	21	19.5	0.304	4.93	0.536	2.8

significantly reducing the scopes of operational control and associated financial expenditures.

Analysis of control data on the basis of the developed methodology

Results of calculations performed according to the data of thickness gauging obtained on one of power units of NPP equipped with VVER reactors are presented in Tables 4 and 5 for bends (Table 4) and for straight parts (Table 5) of feed water pipelines. Operation time is equal to 27 years. Values of factors accepted in the calculations are following: C_{11}=1.075, C_{12}=1.1, C_{21}=0.95 and C_{safety}=1.1.

31 bends and 10 straight parts with standard dimensions equal to 530 × 28 mm and 4 bends and seven straight parts with standard dimensions equal to 426 × 24 mm with total number of bends equal to 35 and total number of straight parts equal to 17 were examined.

The following parameters are presented in the tables: nominal S_{nom} and minimum $S_{\min}$ wall thicknesses of the pipeline elements, values of FAC rate calculated without taking into account the correction coefficients W_{FAC1} and with taking them into account W_{FAC2} and values of residual life time τ_1 and τ_2, respectively.

Table 5
Estimated values of FAC indexes for straight parts of feed water pipelines.

Element	S_{rated}, mm	S_{min}, mm	S_{perm}, mm	W_{FAC1}, mm/year	τ_1, year	W_{FAC2}, mm/year	τ_2, year
530 × 28 mm							
SP* after CC 6	28	22.9	19.5	0.201	16.9	0.543	6.2
SP	28	19.6	19.5	0.365	0.3	0.693	0.14
SP	28	20	19.5	0.352	1.4	0.675	0.72
SP after bend 31-30	28	24	19.5	0.173	26.0	0.418	10.7
SP	28	23.3	19.5	0.204	18.6	0.447	8.5
SP	28	24.1	19.5	0.169	27.2	0.416	10.8
SP	28	24.1	19.5	0.169	27.2	0.416	10.8
SP after bend	28	26.3	19.5	0.073	93.1	0.331	20.6
SP after bend	28	21.9	19.5	0.265	9.05	0.501	4.7
SP after bend	28	27.2	19.5	0.034	226	0.296	25.9
426 × 24 mm							
SP	24	21.1	18.6	0.126	19.0	0.339	7.0
SP	24	21.3	18.6	0.117	22.2	0.332	7.8
SP	24	21.5	18.6	0.108	25.9	0.324	8.6
SP	24	21.1	18.6	0.126	19.0	0.339	7.0
SP	24	21.5	18.6	0.108	25.9	0.324	8.6
SP after CC 59	24	22.8	18.6	0.052	80.8	0.273	15.3
SP after CC 64	24	21.1	18.6	0.126	19.8	0.339	7.3

* SP – straight part.

Introduction of coefficients taking into account the technological tolerances on the pipe manufacturing and influence of corrosion products depositions on the nominal and minimum values of pipeline wall thicknesses results in the increase of the estimated FAC rate and, correspondingly, in the reduction of estimated residual life time by approximately 2.2 times for bends and by 3.14 times for straight parts of feed water pipelines with standard dimensions equal to 530 × 28 mm and to 426 × 24 mm.

Conclusion

1. Trend of increasing minimum wall thicknesses obtained during sequential measurements and, correspondingly, increasing residual life time is revealed on the basis of analysis of repeated measurements performed on Unit 1 of NPP Dukovany in the Czech Republic. Increase of wall thickness as compared to the nominal one can reach as high as 30%. This fact must be taken into account in the development of methodology for calculation of FAC rates for metals.
2. Calculation dependence for determining the metal FAC rate incorporating the correction coefficients taking into account the effects of technological tolerances on the wall thickness due to pipeline manufacturing, as well as effects of corrosion products deposits on the values of initial and minimum wall thicknesses was suggested.
3. It is showing that using the suggested methodology for feed water pipelines elements with standard dimensions equal to 530 × 28 mm and to 426 × 24 mm for one of NPP unit with VVER reactor results in the increase of estimated residual life time by approximately 2.2 times for bends and by 3.14 times for straight parts.

4. Thus, conservative estimation of residual life time leaves sufficient time for implementation of repeated measurements on the problematic elements and for making decisions on the replacement of the elements.

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