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EFFECTIVENESS OF UNLOADING NPP PIPELINE SECTION WITH A PIPE WALL THINNING DEFECT BY MOUNTING A BAND OR A WELDED COUPLING

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ABSTRACT

Formation of erosion-corrosion wear defects in NPP pipelines is one of the urgent problems of nuclear power engineering. During pipeline repair, a defective section is cut out and a new pipe spool is mounted using welding, which is a rather labour-consuming process, and requires draining of the transported liquid. To prolong the service life, a defective pipeline section can be reinforced by mounting a repair structure, for instance a band or a welded coupling. In order to substantiate the rationality of application of reinforcing structures in pipeline repair, the finite element analysis of the stress-strain state of a rectilinear pipeline section with an erosion-corrosion wear defect under the impact of internal pressure, as well as evaluation of the effectiveness of unloading a defective section in the case of application of a reinforcing structure of the type of a band or a welded coupling in repair were performed. The analysis results have shown a high effectiveness of applying such structures. The obtained results can be used in substantiation of introduction of alternative technologies for repair of pipelines in the Ukrainian NPP, predominantly technological ones, particularly in those cases when repair by traditional methods is not possible or rational for technical or economic reasons.

KEYWORDS: NPP, pipeline, erosion-corrosion wear, wall thinning defect, reinforcing structure, band, coupling, stress-strain state, ductile fracture, finite element method

INTRODUCTION

Formation of erosion-corrosion wear (ECW) defects in pipelines of nuclear power plants (NPP) is one of the urgent problems in nuclear power engineering [1, 2]. Erosion-corrosion wear is a combination of two processes - mechanical wear of the pipeline wall metal due to the action of erosion and chemical fracture due to the action of corrosion [3–5]. As a result of the combination of these two phenomena, the resistance of a pipeline to loads decreases and the tendency to the occurrence of critical defects and material fracture grows [1, 6, 7].

In practice, in case of ECW detection, a defective section of an NPP pipeline is cut out and a new pipe spool is mounted using welding. Such repair takes place during shutdown of a power unit and when it is possible to drain the transported liquid. Also, an alternative technology is available, namely, to prolong the service life, a defective pipeline section can be reinforced by mounting a repair structure, for instance a band or a welded coupling [8–10, 15]. Pipeline banding is reinforcing with metal rings, a band, a wire or nonmetallic materials along the perimeter of its wall. Possible options as to the method of mounting a band in the form of metal rings on a defective pipeline section are shown in Figure 1. Mounting a welded coupling (Figure 2) is used to reinforce a defective section and eliminate leakage by sealing a reinforcing structure with welds. Repair with mounting a coupling or

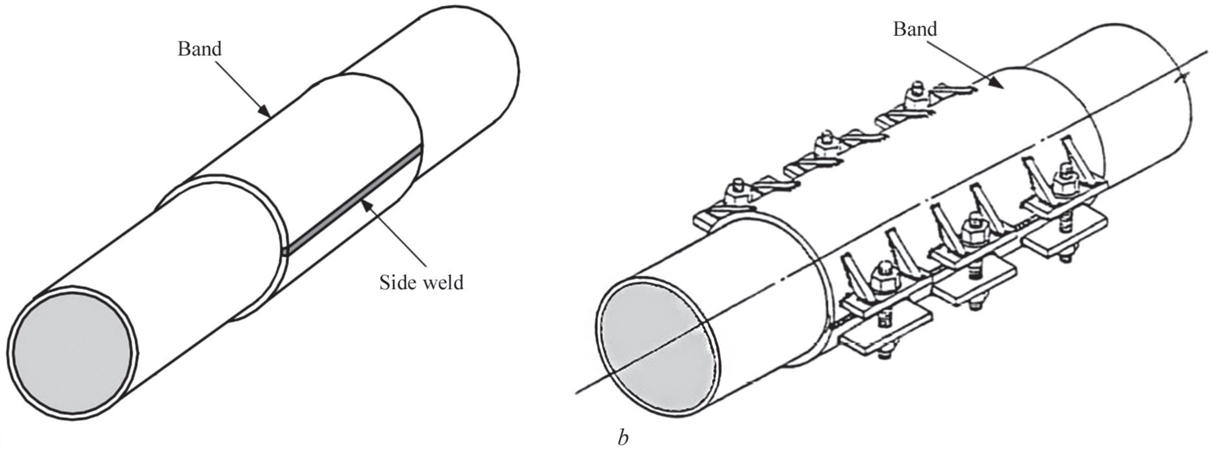

Figure 1. Types of bands according to the method of mounting: *a* — welded; *b* — on bolted joints

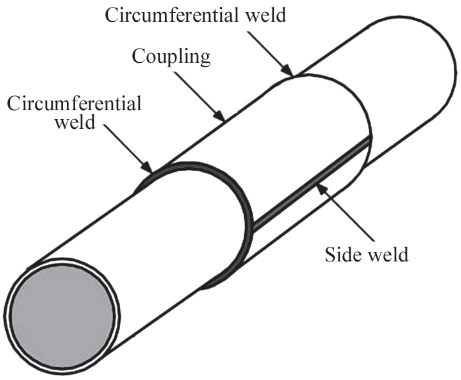

Figure 2. Reinforcing a defective pipeline section with a welded coupling

a band may be rational, as it is less labour-consuming than replacing the entire section, does not require draining the liquid from the pipeline and can be performed even when a power unit is operating.

A band differs from a coupling in the fact that it is mounted on the pipeline without welding-on to the supporting pipe. It provides reinforcement of a defective section and, if necessary, can be easily dismantled for a major pipeline repair. A band can also be used multiple times. The use of a band is rational only for those defects that will not lose their tightness over a long period of operation or as a temporary measure before the next planned repair [9].

THE AIM OF THE WORK

is to substantiate the use of alternative repair technologies for pipelines with ECW defects for the needs of nuclear power engineering, to develop mathematical models and to conduct a finite element analysis of the stress-strain state (SSS) of a rectilinear pipeline section with an ECW defect under the action of internal pressure, as well as to evaluate the effectiveness of unloading a defective section in the case of using a reinforcing structure of the type of a band or a welded coupling in the repair.

When assessing the admissibility of a pipeline section with an ECW defect for further operation, the limiting condition of the pipeline is evaluated from the point of view of ductile fracture, for example, based on the results of predicting the intensity of plastic deformations in the defect zone. The influence of the geometric parameters of a reinforcing structure (thickness, length, and initial gap between the outer surface of the pipeline and the inner surface of a reinforcing structure) on the operability of a rectilinear pipeline section with an ECW defect was investigated using the finite element method.

PROBLEM STATEMENT

As an example, a rectilinear pipeline section was considered, which has standard dimensions and loading parameters for NPP technological pipelines (material — steel 20): outer diameter D = 630 mm, wall thickness s = 25 mm, design pressure P = 11.8 MPa, temperature T= 300 °C.

The critical, i.e., unacceptable geometric parameters of a pipeline wall thinning defect (Figure 3) were determined in accordance with the MT-T.0.03.224-18 procedure [11, 18], which regulates the procedure for calculating the allowable thickness of elements of NPP pipelines of carbon steel, which are subjected to erosive and corrosive wear and which was put into operation by the SE NNEGC “Energoatom” in 2019. An express assessment of the acceptability of a pipeline section with different geometric parameters of an ECW defect for further operation was carried out and based on its results, the dimensions of a critical wall thinning defect were determined, namely, an idealized ECW defect of a semi-elliptical shape with a length $2L = 4s$ = 100 mm, width $2h = 2s$ = 50 mm, with a depth a = 20 mm (Figure 3).

The dimensions of a reinforcing structure of the type of a band and a coupling were chosen as follows (Figure 4): inner diameter D = 630 mm, half-length L_b = 630 mm, thickness $s_b = s$ = 25 mm. The geometric

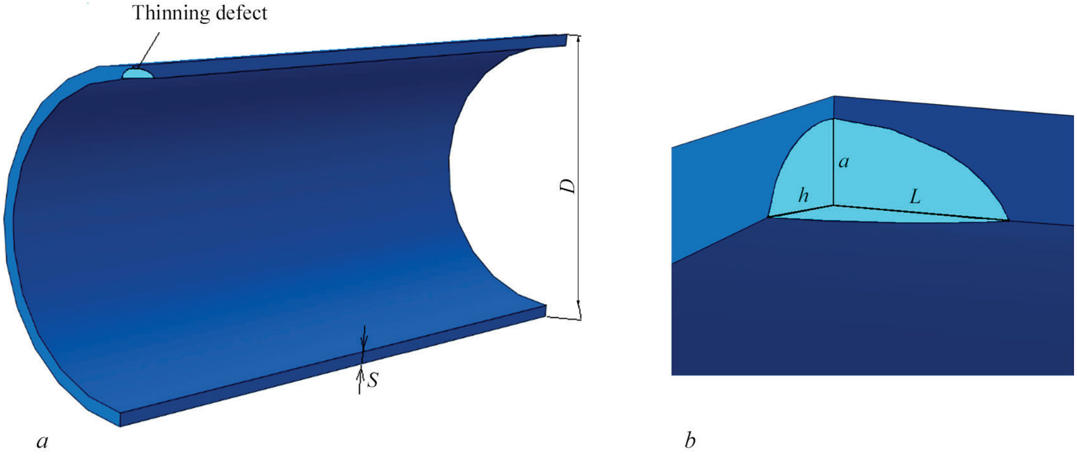

Figure 3. Geometric model of 1/4 of a rectilinear defective pipeline section (*a*) and internal semi-elliplyptical wall thinning defect (*b*)

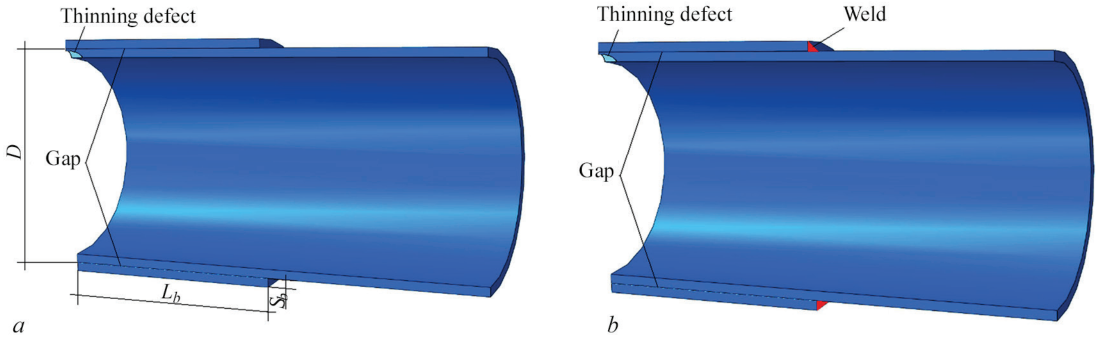

Figure 4. Geometric models of a rectilinear pipeline section, reinforced by a band (*a*) or a welded coupling (*b*)

models of a band and a welded coupling differ only in the presence of circumferential welds for joining a coupling to the pipeline.

DEVELOPMENT OF FINITE ELEMENT MODEL

According to the specified parameters, a geometric and finite element model of a rectilinear pipeline section with a thinning defect was built (Figure 3). Taking into account the presence of two planes, the model includes 1/4 of this pipeline section with a defect. The following mechanical properties of the material were used: Young's modulus $E = 2.1\cdot10^5$ MPa, Poisson's ratio $\mu = 0.3$, yield strength for steel 20 at a temperature of $T = 300$ °C, $\sigma_y = 177$ MPa [12]. Similarly, finite element models with the use of reinforcing structures of the type of a band and a welded coupling were created (Figures 4, 5).

The problem of SSS of a pipeline section is considered in an elastic-plastic formulation, since under the action of internal pressure in the zone of a wall thinning defect, the formation and propagation of plastic deformations is probable. Deformation strengthening of the material in the developed model of elastic-plastic deformation is not taken into account, which makes the model more conservative in terms of determining plastic deformations. The design pressure $P = 11.8$ MPa is applied to the inner surface of the pipeline and the defect zone. The boundary conditions in the form of axial tensile stresses σ_{zz} are added to the end surface of the model having the value [14]:

$$\sigma_{zz} = \frac{P\frac{D}{2}}{2s} \rightarrow \sigma_{zz} = 72.6\ \text{MPa}. \qquad (1)$$

The minimum size of a finite element (hexagonal volumetric element) is 3 mm (Figure 5). The model of a pipeline section with a wall thinning defect consists of 149556 elements, and the model with the use of a repair structure consists of 213316 elements. The minimum size of a grid element was chosen on the condition that the value of the maximum equivalent plastic strain changes by less than 5 % when the grid size is reduced twice.

The limiting condition of typical structures is usually determined by complex physical and mechanical phenomena, such as irreversible plastic deformation, triaxiality of stresses, subcritical fracture, interaction of subcritical defects, nucleation and propagation of macrofractures. Since pipelines with detected ECW are not characterized by sharp geometric stress concentrators, fracturing is predetermined by a ductile mechanism. A deformation criterion can be used for numerical prediction of the critical state by the mechanism of ductile fracture in the pipeline material under the internal pressure with the erosion-corrosion loss of metal [13]:

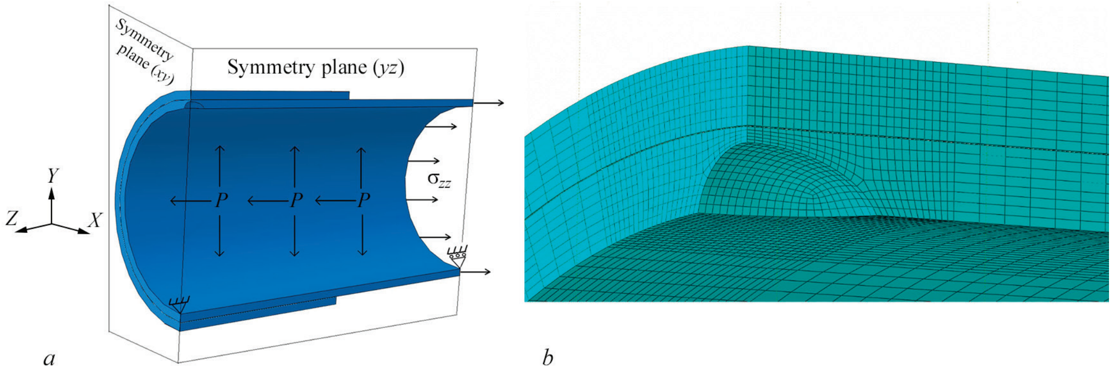

Figure 5. Finite element model of a rectilinear pipeline section with a wall thinning defect and a reinforcing structure: *a* — model scheme; *b* — finite element grid in the defect zone

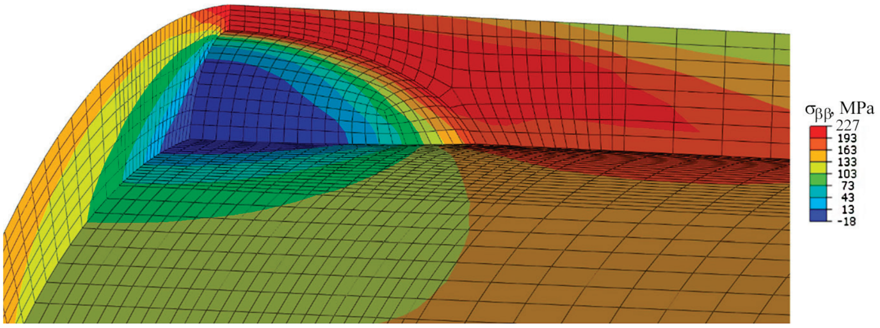

Figure 6. Distribution of circumferential stresses $\sigma_{\beta\beta}$ in the pipeline wall thinning defect zone without a reinforcing structure

$$\int \frac{d\varepsilon_i^p}{\varepsilon_c} > 1, \qquad (2)$$

where $d\varepsilon_i^p$ is an increment in the intensity of plastic deformations,

$$d\varepsilon_i^p = \\ = \frac{\sqrt{2}}{3}\sqrt{(d\varepsilon_{xx}^p - d\varepsilon_{yy}^p)^2 + (d\varepsilon_{yy}^p - d\varepsilon_{zz}^p)^2 + (d\varepsilon_{zz}^p - d\varepsilon_{xx}^p)^2 + \frac{3}{2}(d\varepsilon_{xy}^{p\,2} + d\varepsilon_{yz}^{p\,2} + d\varepsilon_{zx}^{p\,2})},$$

or in the tensor form $d\varepsilon_i^p = \frac{\sqrt{2}}{3}\sqrt{d\varepsilon_{ij}^p\, d\varepsilon_{ij}^p}$,$d\varepsilon_{ij}^p$ are the tensor components of the increment of intensity of plastic deformations; ε_c is a critical value of plastic deformation, which depends on the triaxiality of stresses, temperature, material heterogeneity, etc.

RESULTS OF FINITE ELEMENT ANALYSIS OF SSS

The results of SSS numerical analysis of the given pipeline section without a reinforcing structure showed that under the action of internal pressure P = 11.8 MPa in the zone of a thinning defect, the maximum circumferential stresses of up to 227 MPa (Figure 6) occur, which exceed the yield strength of the material (177 MPa) at the specified temperature T = 300 °C, and also, of course, exceed the rated allowable stress of static strength, which is determined according to PNAE G 7-002–86 [12] under the following conditions:

$$[\sigma] = \min\{\sigma_t / 2.6;\ \sigma_y / 1.5\}. \qquad (3)$$

The yield strength and tensile strength for steel 20 at a temperature T = 300 °C are σ_y = 177 MPa and σ_t = 363 MPa, respectively. According to (3), the allowable stress is equal to $[\sigma]$ = 118 MPa.

But such an approach, based on a comparison of effective stresses in the pipeline wall due to internal pressure with the allowable static strength stresses for the pipeline material, is used in practice to select rated dimensions during designing, whereas to assess the limiting condition determined by the propagation of ductile fracture of the pipeline metal with an ECW defect, it is too conservative. Therefore, the above-mentioned (2) approach based on the analysis of the results of the increment of intensity of plastic deformations in the defect zone is more rational.

According to the results of finite element modeling, the maximum intensity of plastic deformations in the ECW defect zone is 0.0112 (1.12 %) (Figure 7, *a*), which exceeds the “conditional” boundary deformation ε_c = 0.01 (1 %) [13]. This means that the conditions for the nucleation of ductile fracture of the material are realized. In order to prevent further deformations and fracture of the pipeline, a repair of a reinforcing structure of the type of a welded coupling band can be mounted. At the same time, the maximum stresses (227 MPa) still exceed the allowable stresses of static strength, but due to mounting a reinforcing structure, the maximum intensity of plastic deformation does not exceed the boundary deformation of 1 % (Figure 7, *b*).

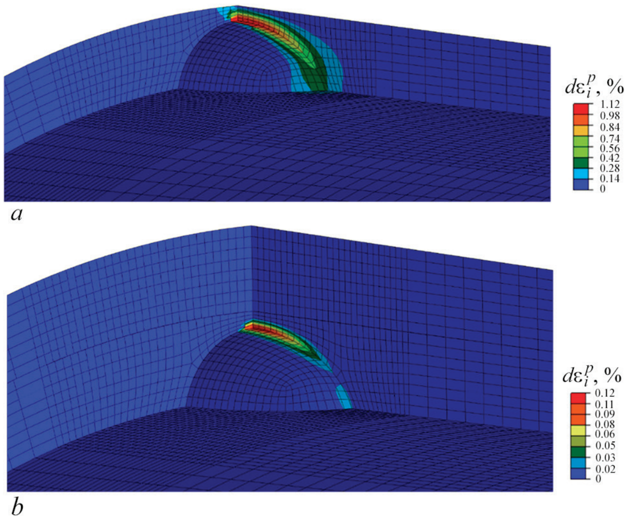

Figure 7. Distribution of the increment of intensity of plastic deformations $d\varepsilon_i^p$ of a pipeline section with a defect: *a* — without a reinforcing structure $d\varepsilon_i^p$ = 1.12 %; *b* — with a reinforcing structure $d\varepsilon_i^p$ = 0.12 % (by an order of value lower)

DETERMINATION OF THE MINIMUM WALL THICKNESS OF DEFECTIVE PIPELINE SECTIONS

In order to verify the correctness of using a deformation approach (2) for assessment of the limiting con-

Table 1. Comparison of minimum wall thicknesses in defective pipeline sections according to MT-T.0.0.03l24-18 Procedure and by the approach (2)

Pipeline parameters					MT-T.0.03.224-18		Approach (2)	
D, mm	s, mm	L/h, mm	T, °C	P, MPa	$s_{\min}$, mm	$d\varepsilon_i^p$, %	$s_{\min}$, mm	$d\varepsilon_i^p$, %
89	2.8	5.6/2.8	295	7.85	0.5	0.43	0.3	1.00
325	16	32/16	150	9.8	4.5	0.07	4.05	1.01
630	25	50/25	300	11.78	5	1.12	5.5	1.00
720	24	48/24	150	10.8	3	1.94	4.6	0.95

Note. $s_{\min}$ is the minimum acceptable thickness in the defect zone; $d\varepsilon_i^p$ is the intensity of plastic deformations.

dition according to the criterion of ductile fracture of a pipeline with an ECW defect, based on the analysis of the increment of intensity of plastic deformations in the defect zone, a comparison of the values of the minimum wall thickness of defective sections was made for different pipelines, determined according to the MT-T.0.03.224-18 Procedure [11] and according to the approach (2) by the method of finite element modeling. The results presented in Table 1, showed that the minimum wall thicknesses according to the Procedure in most variants are approximately equal to the results of the calculation based on the used deformation approach. Only in a one variant of the pipeline of 720×24 mm, the minimum wall thickness according to the Procedure is by 30 % lower than that calculated according to the criterion (2). I.e., the results of using the approach (2) of evaluating the critical state of ductile fracture of a pipeline with an ECW defect are consistent with the MT-T.0.03.224-18 Procedure [11, 18]. However, the wider capabilities of finite element modeling in terms of the accuracy of describing the physical and mechanical processes that determine the reliability of welded structures make it more rational for use, in particular when planning repair and restoration works.

EFFECT OF THE INITIAL GAP

The initial gap between the pipeline and repair structure significantly affects unloading of a defective pipeline section [15]. Too large value of the gap can lead to the fact that unloading a repair structure will not occur, and its mounting will not be effective. Therefore, in practice, the specialized equipment is used in order to clamp a reinforcing structure to the pipeline during mounting and provide a minimum gap. The results regarding the dependence of the increment value of intensity of plastic deformations on the gap value are shown in Figure 8.

The results of numerical prediction of the degree of unloading of the pipeline defect zone when mounting a band and a welded coupling showed that these repair structures operate to unload the wall thinning defect zone almost equally. The difference in the axial movements of a band and a coupling relative to the pipeline was not determined. But a welded coupling, due to the presence of a welded joint, additionally ensures tightness in case of defect propagation to a through defect. When the initial gap between the pipeline and a repair structure increases, the value of the maximum plastic deformations grows. With a value gap of 0.2 mm or more, a repair structure continues to operate to unload the given section, because under the action of internal pressure (11.8 MPa) in the pipeline (D = 630 mm, s = 25 mm), radial deformations arise, which amount to 0.22 mm, and the pipeline only selects the initial gap, and a band or a coupling do not reinforce a defective section. Therefore, such technological parameters as initial gap, drop of internal pressure before mounting a reinforcing structure and rising after its mounting are important.

EFFECT OF THICKNESS AND LENGTH OF A REINFORCING STRUCTURE

The effect of such geometric parameters as thickness and length of a repair structure on unloading a fractured pipeline section was considered. It is also worth noting that to facilitate the analysis, these models were built without taking into account the gap between a repair structure and a pipeline, that is, a repair

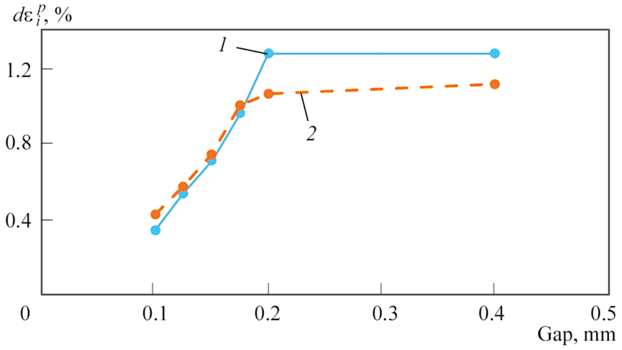

Figure 8. Dependences of maximum values of the increment of intensity of plastic deformations $d\varepsilon_i^p$ on the initial gap between the pipeline and a reinforcing structure: *1* — coupling; *2* — band

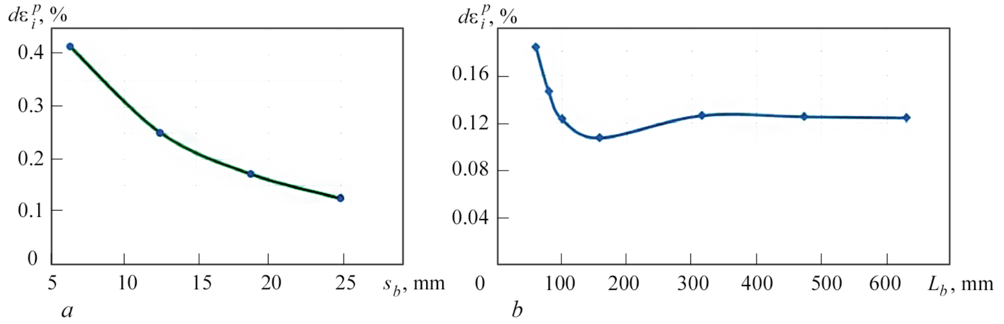

Figure 9. Dependence of maximum values of the increment of intensity of plastic deformations $d\varepsilon_i^p$ in the zone of the pipeline ECW defect (D = 630 mm, s = 25 mm) on the geometric parameters of a reinforcing structure; *a* — thickness s_b; *b* — half-length L_b

structure starts operating for unloading immediately. The results of the analysis of the effect of a change in the thickness at a constant length of a structure and a change in the length at a constant thickness, respectively, were shown on the diagrams (Figure 9).

As is seen from Figure 9, *a*, when the thickness of a repair structure decreases, the maximum value of the equivalent plastic deformation grows. On the other hand, when the half-length of a repair structure is reduced, as shown in Figure 9, *b*, from 630 mm to ≈300 mm, the intensity of plastic deformations almost does not increase, and when it decreases to 150 mm, their values are the lowest. From this it can be concluded that the use of a too long repair structure is not rational, and shortening its length to 300 mm will reduce the costs on repair of a fractured pipeline section.

EFFICIENCY OF UNLOADING DUE TO A REINFORCING STRUCTURE

To check the efficiency of the repair, the load on a defective pipeline section was calculated before the repair and after mounting a reinforcing structure. The ratio of unloading due to mounting a reinforcing structure is determined by the formula:

$$\eta = 1 - \frac{P_{ld}}{P_l}, \tag{4}$$

where P_{ld} is the limit pressure in a defective pipeline section without a reinforcing structure; P_l is the pressure at which the ultimate plastic deformation ε_c = 0.01 is reached in a defective pipeline section with a reinforcing structure.

The calculated unloading ratios of the considered typical variants of the pipelines were recorded in Table 2. The determined values of the unloading ratios (0.43–0.51) of defective sections when using a reinforcing structure of the type of band with a thickness equal to the wall thickness for the pipelines of different sizes showed the high effectiveness of applying such structures.

PREDICTION OF LIFE OF A DEFECTIVE SECTION AFTER REPAIR

The residual service life of a defective pipeline section with an ECW defect can be estimated [16]:

$$t_r = \frac{s_r - s_{\min}}{w_{\mathrm{ECW}}}, \text{ if } s_r > s_{\min}, \tag{5}$$

where s_r is the residual wall thickness in the defect zone, mm; $s_{\min}$ is the calculated minimum acceptable wall thickness, mm; w_{ECW} is the rate of ECW defect propagation, mm/year.

The period of safe operation of a defective pipeline section with an ECW defect after mounting a reinforcing structure can be predicted from the condition of propagation of a wall thinning defect into a through defect. If a band or a coupling of the same thickness as the pipeline is mounted, then in the case of defect propagation, the through wall thinning will ensure strength, and for a coupling — also the tightness of the section. Thus, if we make an assumption about the

Table 2. Determination of unloading ratios η of pipeline sections when mounting a reinforcing structure

D, mm	s, mm	P, MPa	T, °C	$L/h/a$, mm	$s_{\min}$, mm	Critical pressure P, MPa		η
						P_{ld}	P_l	
89	2.8	7.85	295	5.6/2.8/2.3	0.5	7.85	16	0.51
325	16	9.8	150	32/16/13.5	2.5	9.8	18	0.46
630	25	11.78	300	50/25/20	5	11.78	21	0.44
720	24	10.8	150	48/24/19.5	4.5	10.8	19	0.43
820	18	1.57	188	36/18/16	2.0	6	11	0.45

constant propagation rate of an ECW defect, the term of safe operation t_r of a defective pipeline section with a mounted band or a coupling is:

$$t_r = \frac{s_r}{w_{\mathrm{ECW}}}, \tag{6}$$

The propagation rate of an ECW defect w_{ECW} can be determined in a first approximation based on the data regarding the service life of a pipeline section before repair t_E, year, and the difference between the initial s and the residual s_r wall thickness in the ECW defect zone at the time of repair, mm:

$$w_{\mathrm{ECW}} = \frac{s - s_r}{t_E}. \tag{7}$$

For example, for the pipeline D = 630 mm, s = 25 mm, which already operates under the action of an internal pressure of 11.8 MPa for 30 years, at a planned testing, an ECW defect with the size of 50×25 mm with a minimum thickness of 5 mm was revealed. Then, mounting a band of s_b = 25 mm thickness can extend the life of a defective section approximately by:

$$t_r = \frac{s_r \cdot t_E}{(s - s_r)} = 5{\cdot}30/(25{-}5) = 7.5 \text{ years.}$$

In the case of mounting a welded coupling, the life of a defective section can be even longer, which can be compared with the service life of a section after repair according to the traditionional technology of inserting a new spool, but this requires additional substantation of strength of circumferential welded joints under the action of internal pressure in the cavity between the pipe and the coupling.

The larger the residual thickness of the pipeline wall in the ECW zone and the lower rate of the defect propagation, the more rational is mounting a repair reinforcing structure, since the life of its use before the next repair will be longer. Thus, according to the requirements of GBN [17], mounting a band on the main pipeline is performed in the case when the maximum depth of single defects or group corrosion fractures does not exceed 50 % of the rated thickness of the pipeline wall.

CONCLUSIONS

According to the results of SSS analysis of a rectilinear section pipeline with an ECW defect under the action of internal pressure, it can be concluded that evaluation of the limiting condition of ductile fracture of the pipeline with an ECW defect on the basis of comparing the effective stresses in the pipeline wall from the internal pressure with acceptable stresses of static strength for the pipeline material is too conservative. It is more rational to use an approach based on the analysis of the formation of plastic deformations in the defect zone and the assumption that an increment of intensity of plastic deformations does not exceed a conditional boundary deformation, for example, $\varepsilon_c = 1$ %. The results of using this approach of assessment of the limiting condition of ductile fracture of the pipeline with an ECW defect are well consistent with MT-T.0.0.0.03.224-18 procedure, introduced into operation by the SE NNEGC "Energoatom" in 2019, which regulates the determination of acceptable thicknesses of NPP pipeline elements of carbon steels under the action of erosion-corrosion wear.

In order to substantiate the use of alternative repair technologies of pipelines for the needs of nuclear power engineering, mathematical models and means of their finite element implementation were developed to determine SSS and the limiting condition of a defective pipeline section when mounting a reinforcing structure of the type of a band or a welded coupling. The results of the finite element analysis have shown the following:

1. Unloading a defective pipeline section is significantly influenced by the initial gap between the pipeline and repair structure, since the presence of a gap causes that a repair structure begins unloading of a defective pipeline section only when this gap is selected by the pipeline due to radial deformation under the action of internal pressure during operation. It is rational to use the specialized equipment to clamp a reinforcing structure to the pipeline during its mounting.
2. Repair structures of the type of a band and a welded coupling operate to unload the wall thinning defect zone equally. The advantage of a band is a low labour intensiveness of its mounting and the possibility of its repeated use, and the advantage of a weld coupling is the guaranteed tightness in the case of defect propagation.
3. In most cases, it is rational to use reinforcing structures, whose thickness is equal to the thickness of the pipeline. When the thickness of a repair structure is reduced, the efficiency of unloading the wall thinning defect zone is significantly reduced.
4. The use of a long-length repair structure is not rational, since when the length changes to a certain value, the efficiency of unlodaing is not changed. For a local wall thinning defect, the optimal length of a reinforcing structure can be equal to half of the pipeline diameter. The use of a repair structure with an optimal length will allow reducing the costs on the repair structure material and simplifying its mounting.
5. These results can be used mainly in the repair of NPP technological pipelines, especially in the cas-

es, where repair by traditionional methods of cutting out a defective section and welding-in a new pipeline spool is not possible or rational for various reasons.

6.The calculated unloading ratio (0.43–0.51) of a defective section when mounting a reinforcing structure of a band type with a thickness equal to the wall thickness, showed high efficiency of using such structures for NPP pipelines of different sizes.

7. The term of safe operation of a defective section of the pipeline with an ECW defect after mounting a reinforcing structure can be determined from the condition of the propagation of a wall thinning defect. The larger the residual thickness of the pipeline wall in the ECW zone and the lower rate of the defect propagation, the more appropriate is mounting a repair structure, since the terms of its use before the next repair will be longer.

Thus, repair technologies of mounting reinforcing structures of the type of a band or a welded coupling can effectively reinforce NPP pipelines sections with wall thinning defects, restore their bearing capacity and may be recommended for introduction in NPP of Ukraine, mainly when repairing technological pipelines.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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