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THE METHOD FOR MEASURING RESIDUAL STRESS IN STAINLESS STEEL PIPES

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ABSTRACT

The main reason of appearance and growth of corrosion damages of the nuclear steam generator heat exchanger tubes is the process of stress-corrosion cracking of metal under the influence of residual tensile stress. Methods used in the production for estimating residual stresses (such as a method of ring samples) allow measuring only the average tangential stress of the pipe wall. The method of ring samples does not allow to assess the level of residual stress in the surface layer of the pipe. This paper describes an experimental method for measuring the residual stresses on the pipe surface by etching a thin surface layer of the metal. The construction and working principle of a trial installation are described. The residual stresses in the wall of the tubes 16 × 1.5 mm (steel AISI 321) for nuclear steam generators is calculated.

Keywords: *heat exchange pipes, stress corrosion cracking, residual stresses, stress distribution, stress measurement.*

INTRODUCTION

The main factor which defines the life of steam engine is a state of heat exchange pipes. The mechanisms of formation and propagation of damages in the steam exchange pipes are studied well by the personnel of Central Research Institute of Structural Materials «Prometey» (St. Petersburg) and Experimental Design Bureau «Gidropress» (Podolsk). One of the main damages of nuclear heat exchange pipes is stress-corrosion cracking: it is a destruction of metal under the influence of tensile operating and residual stresses with simultaneous impact of corrosive environment. The amount and character of residual stress in the pipes influence on operation properties of steam exchange pipes, and especially their corrosion resistance [1 - 5].

The main problem of investigations in the sphere of residual stress in pipes is a complication of their reliable measurement. The experimental methods of residual stress measurement, for example - the method of ring test, have some drawbacks. In particular it does not allow evaluating of residual stresses distribution in pipe wall thickness [6, 7]. Lately the works have been published where the authors analyze distribution of residual stresses in volume of rods and pipes. The most part of these methods of «indirect» residual stresses defining allows estimation of stress tensor components on the base of experimentally determined deformations [8 - 10]. In this case the main complication is a measuring of deformations.

The authors [9] offer estimation methods of residual stresses on the base of energetic approach. The drawback of this method is that initial data for this estimation is tangential residual stress $\sigma_{\varphi\varphi}$ measured by the method of ring test.

EXPERIMENTAL

This paper describes the method of longitudinal residual stress defining $\sigma_{\varphi\varphi}$ on the surface of a pipe by the

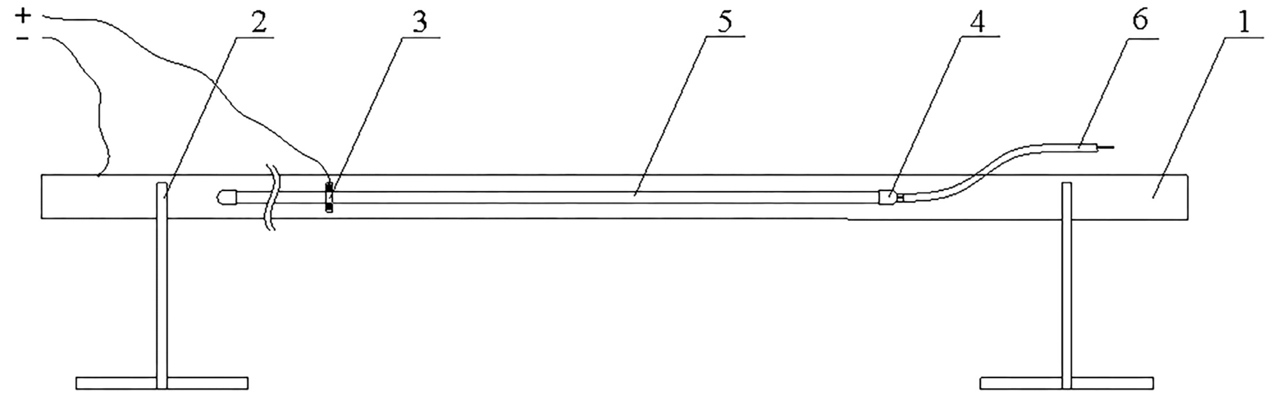

Fig. 1. Machine diagram for defining residual stresses in pipes (1 - bath; 2 - support legs; 3 - bearing; 4 - moveable grip; 5 - sample; 6 - flexible rotary drive).

method of etching. If we know this surface stress we can define the rest components of residual stresses tensor in pipe wall [6]. According to this method the layer of metal is stripped from the pipe surface, and then the value of pipe longitudinal elastic relaxation Δl is measured. On one hand the thickness of stripped layer ΔR must not be large-scale, in order to define residual stresses in the thinner surface layer as possible, and on the other hand is can not be too small-scale, for engineering capability to fix changes of pipe length after etching.

If pipe external surface layer is etched and its external radius changes from R_1 to R'_1, relief of residual stresses occurs and the pipe sample length changes with value of Δl. In addition the positive value $+\Delta l$ corresponds to extension of the sample and presence of positive (tensile) residual stresses σ_z^* in the surface layer. The negative value $-\Delta l$ corresponds to shortening of the sample and this shows the presence of negative (compressive) residual stresses σ_z^{**} in the surface layer. In the first case after measuring the radius R'_1 and the sample length $l + \Delta l$, the value of longitudinal residual stress in etched layer can be defined by the formula:

$$\sigma_{zz}^* = E\frac{\Delta l}{l}\cdot\frac{R'^2_1 - R_2^2}{R_1^2 - R'^2_1} \quad (1)$$

where R'_1 is the pipe external radius after etching of layer thickness of R_1 - R'_1, l - length of the sample operating part before etching, E - the modulus of elasticity of the pipe metal.

In the second case, etching of metal layer from internal surface rises from R_2 to R'_2. The pipe sample also changes length with a value of Δl. In this case the value of longitudinal residual stress in etched layer can be defined by the formula:

$$\sigma_{zz}^{**} = E\frac{\Delta l}{l}\cdot\frac{R_1^2 - R'^2_2}{R'^2_2 - R_2^2} \quad (2)$$

where R'_2 is the pipe internal radius after etching with the layer thickness R'_2 - R_2.

One of the etching process complications is an irregularity of etching because of the occurrence of etching products close to pipe surface which prevent regular process behavior. That is why the authors have decided to use rotation of sample during etching process for control of etching regularity.

The machine. For testing the method of residual stress in the pipes the laboratory machine was developed and constructed.

The sketch diagram is presented in Fig. 1.

The fixed elements of the machine are bath *1*, leaned against support legs *2* and steel ribbon put in the bath. The rotating force is given to the sample *5*, fixed in movable grips *4* through the flexible drive *6* from the engine. The current is supplied from a rectifier through bearing *3* to the sample *5* and steel ribbon. The main peculiarity of this machine is the possibility of rotation of the pipe during etching process. All the elements of the machine drive, which contact with the electrolyte, are made of polytetrafluorethylene F4 (PTFE) or polypropylene (PPR) and this secures their resistance in corrosive environment and provides also electrical insulation. As an electrolyte a solution of acids with a content: H_3PO_4 – 86 %, Cr_2O_3 – 12 % and H_2SO_4 - 2 % is used. The current rectifier is used in this experiment - it allows controlling output current and voltage during operation.

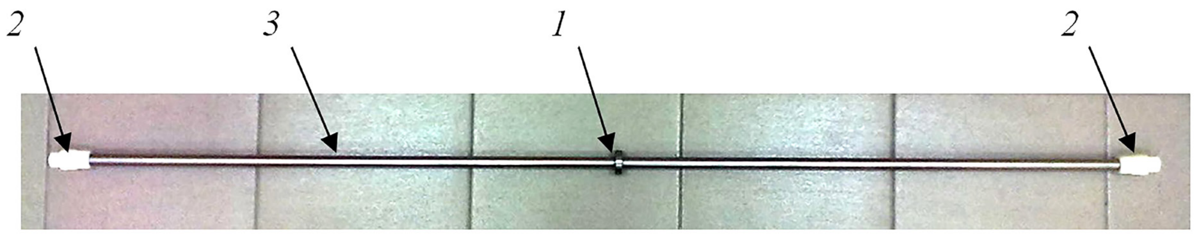

Fig. 2. The sample prepared for the experiment (1 - bearing; 2 - polypropylene obstructions; 3 - pipe).

Samples. In the experiments samples of seamless pipes for steam engines with external diameter 16 mm, wall thickness 1.5 mm and length 1500 mm, made of corrosion-resistant steel AISI 321 with improved quality of surface (ТУ 14-3Р-197-2001) in delivery state were used. The samples were prepared preliminary. The bearing is fixed upon the pipe. In order to prevent penetration of electrolyte on internal surface of the pipe, the sample ends are isolated with polypropylene and liquid capron (Fig. 2). The capron layer isolates the sample surface from electrolyte, and gives also an opportunity to set an exact initial length of the operation part of the sample.

Research of etching kinetics. For preliminary research on etching kinetics of the pipes 16×1.5 made of AISI 321 in the chosen electrolyte, the experiments of surface layer etching were carried out on short samples. It has been found that for obtaining qualitative surface, the current should be not more than 1-2 A, because at high rate of etching an irregular etching of metal and stripping of grain boundaries can occur. The result is a function of pipe diameter and etching time (Fig. 3).

Therefore it has been discovered that for the experiment on this machine it necessary to use current $I = 2$ A and diameter changing rate will be 1.3 um/min.

Experiment. The change in external diameter of sample *5* (Fig. 1) with preliminary blocked pipe ends with polypropylene and liquid capron and the fixed bearing *3* in the grips *4* on the flexible drives *6*. After that the current contacts are connected to the steel ribbon and bearing, and the whole moveable construction is immersed in the bath *1* filled with electrolyte. The drive of sample rotation is switched on, the electric circuit is closed, and the etching process starts. After the estimated time and removal of external layer the diameter and length of the sample are measured.

In the case of etching of internal surface of the pipe, measured by internal diameter, the sample *5* is wrapped around by an insulator for guarantee of absence of external surface etching. Then the bearing *3* is fixed, the pipe ends are isolated, and then the experiment operation continues in the same way as in the case of

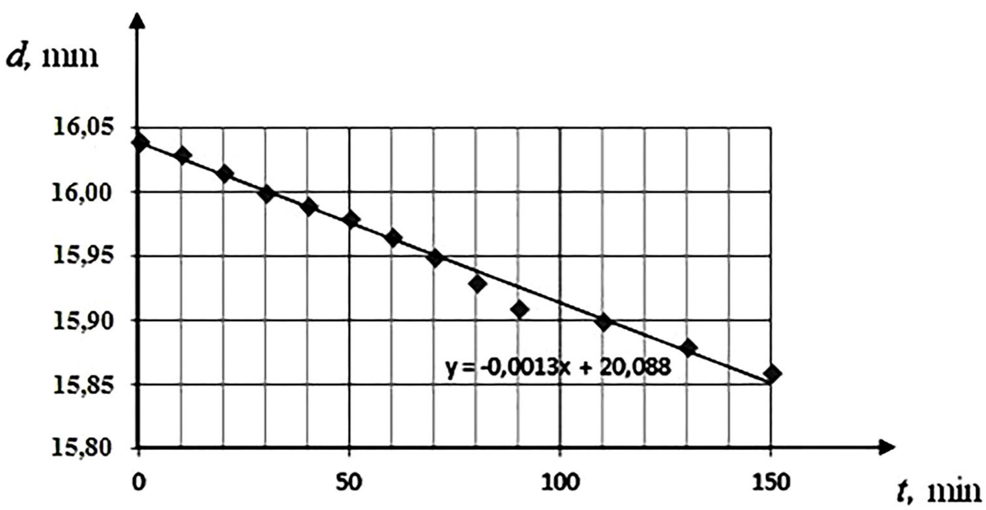

Fig. 3. Changing of the sample diameter in the process of etching.

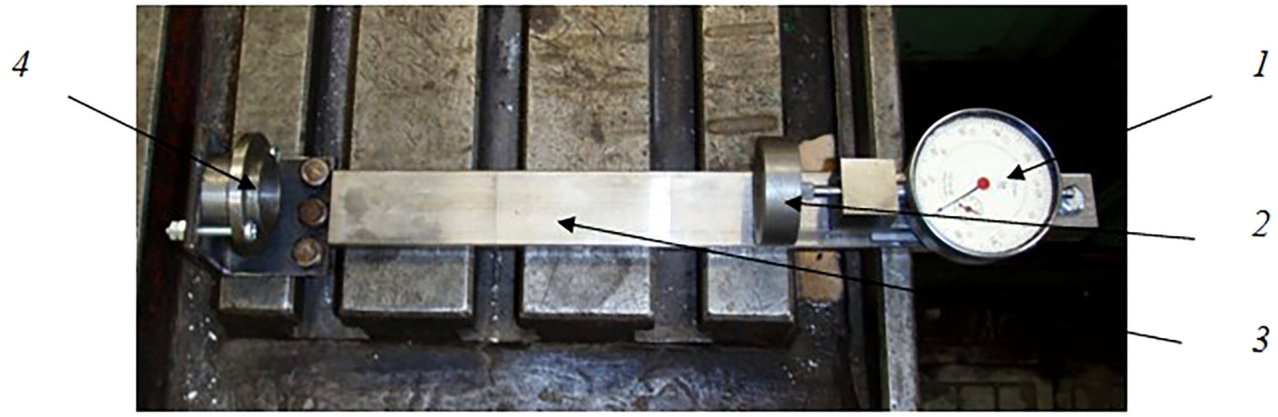

Fig. 4. Illustration of sample's length measuring principle before and after experiment (1 - dilatometer; 2 - moveable washer; 3 - rigid bar; 4 - immovable washer).

external surface etching of the pipe. The measurement of internal diameter is carried out by engineering digital plug gauge SXTD4M with dimension of 0.001 mm. The measurements are carried out in four points of the pipe cross-sections in quadrature to each other.

The measurements of sample length before and after the experiment are carried out by dilatometer fixed on rigid frame. The system for measuring of sample length (Fig. 4) includes dilatometer 1 for extension measurement, rigid bar *3* and two end washers *2* and *4*. All the elements are connected to each other and form a rigid system.

The operation part Δl of the samples after setting of obstructions and insulator was 1480 mm for all the pipes. The current was 2 A for all the samples. After measurement of elongation (shortening) of the operation part of the sample Δl after etching of the surface layer, the longitudinal residual stresses in the pipe wall σ_{zz} were calculated by the formula (1) and (2).

RESULTS AND DISCUSSION

The main objective of the experiment research is testing of new method for defining residual stresses and determination of residual stresses values in the pipe walls 16×1.5 made of steel AISI 321 (ТУ 14-3Р-197-2001). The results of measurements and calculations are presented in Table 1.

The tensor components of residual stresses in pipe wall (Fig. 5) are defined by the formulas [6]:

$$\sigma_{zz} = \frac{\sigma_{zz}^{*}\left[2\left(r-R_1\right)\left(r-R_2\right)+r\left(2r-R_1-R_2\right)\right]}{R_1^2\left(1-\bar{R}\right)} \quad (3)$$

$$\sigma_{\varphi\varphi} = \frac{\sigma_{zz}^{*}\left[\left(r-R_1\right)\ \left(r-R_2\right)+r\left(2r-R_1-R_2\right)\right]}{\mu\ \ R_1^2\left(1-\bar{R}\right)} \quad (4)$$

$$\sigma_{rr} = -\frac{\sigma_{zz}^{*}\left(R_1-r\right)\ \left(r-R_2\right)}{\mu\ \ R_1^2\left(1-\bar{R}\right)} \quad (5)$$

in the case of external layer etching;

$$\sigma_{zz} = \frac{\sigma_{zz}^{**}\left[2\left(r-R_1\right)\left(r-R_2\right)+r\left(2r-R_1-R_2\right)\right]}{R_1R_2\left(\bar{R}-1\right)} \quad (6)$$

$$\sigma_{\varphi\varphi} = -\frac{\sigma_{zz}^{**}\left[\left(r-R_1\right)\left(r-R_2\right)+r\left(2r-R_1-R_2\right)\right]}{\text{ì}\ \ R_1R_2\left(\bar{R}-1\right)} \quad (7)$$

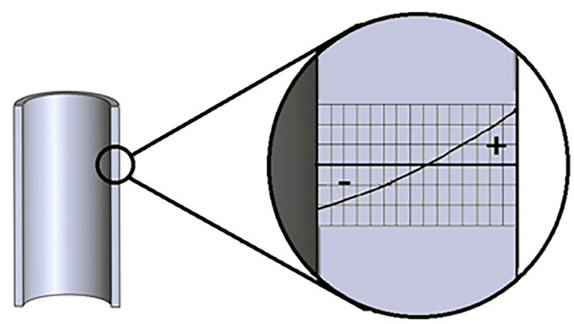

Fig. 5. Diagram of residual stress distribution in the pipe wall (sign «+» corresponds to tensile stresses, sign «-» - compressive stresses).

Table 1. The results of elastic relaxation changes of pipes and calculations of residual stresses.

Sample designation	Initial diameter of sample (external/internal) d_0, mm	Experiment time t, min	Finishing diameter of sample d_1, mm	Absolute elongation/shortening of sample Δl, mm	Amount of longitudinal residual stress in etched layer σ_{zz}, MPa	Amount of tangential residual stress in etched layer $\sigma_{\varphi\varphi}$, MPa	Average index of pipe wall thickness tangential residual stress $\sigma_{\varphi\varphi}^{cp}$, MPa, measured by the method of ring test
1e	16,01	120	15,86	0,09	112,75	282,06	37,58
2e	16,01	100	15,88	0,06	75,17	188,06	25,08
3e	16,01	85	15,90	0,07	87,75	219,44	31,75
4e	16,01	110	15,87	0,10	125,33	313,38	55,92
5e	16,01	110	15,87	0,10	130,00	320,50	57,67
6i	14,50	150	14,70	-0,11	-108,08	-270,19	94,33
7i	14,50	120	14,66	-0,07	-68,75	-171,94	35,67
8i	14,50	160	14,70	-0,10	-98,25	-245,63	40,25
9i	14,50	160	14,70	-0,11	-108,08	-277,69	81,83
10i	14,50	160	14,70	-0,09	-88,42	-221,06	51,00
11e	16,01	70	15,92	0,06	78,25	183,63	32,83
12e	16,01	90	15,89	0,09	114,50	286,94	54,92
13e	16,01	120	15,86	0,12	150,33	376,06	100,08
14e	16,01	85	15,90	0,07	90,17	222,19	46,25
15i	14,50	120	14,66	-0,05	-49,08	-122,81	53,83

Note: abbreviations in samples' numeration: (e) – etching of pipe external surface; (i) – etching of pipe internal surface.

$$\sigma_{rr} = -\frac{\sigma_{zz}^{**}}{\mu}\frac{(R_1 - r)(r - R_2)}{R_1 R_2 (\bar{R} - 1)} \quad (8)$$

in the case of internal layer etching.

In the calculations the modulus of elasticity of the pipe metal is taken equals to 194000 MPa, Poisson ratio - 0.3. The data obtained on the base of the measured residual stress distribution in the pipe wall 16×1.5 made of AISI 321 in the delivery state are presented in Fig. 6. Here the bullet points mark the values of stresses defined by the formulas (1) and (2). The experimental results prove presence of tensile longitudinal (Fig. 6a, 6d) and tangential (Fig. 6b, 6e) residual stresses on the surface of the pipes.

According to the information of diagrams in Fig. 6 a conclusion can be made that external surface of pipe has significant tensile residual stresses, and internal surface has compressive residual stresses.

Comparing the amounts of residual stresses in the pipes, measured by different methods, and discussing the obtained data, we can come to the conclusion that total (according to the diagrams) residual stresses correspond to the average values of tangential residual stresses, measured in the pipes by the method of ring test (See Table 1, the last column). The amount of the measured residual stresses on pipe external surface constitutes: longitudinal – from 49 to 150 MPa, tangential - from 122 to 376 MPa. In addition the average amount of tangential residual stresses, measured by the method of ring test $\sigma_{\varphi\varphi}^{cp}$ for the same pipes, constitutes from 31 to 100 MPa.

The presence of tensile residual stresses on pipe surface is substantiated by the character of stress-deformation state at finishing stages of pipes production [10]. For the pipes studied it is drawing and roller levelling. In the result of drawing because of different drawing of external and internal pipe walls the external layers «stretch» and as a result tensile residual stresses form

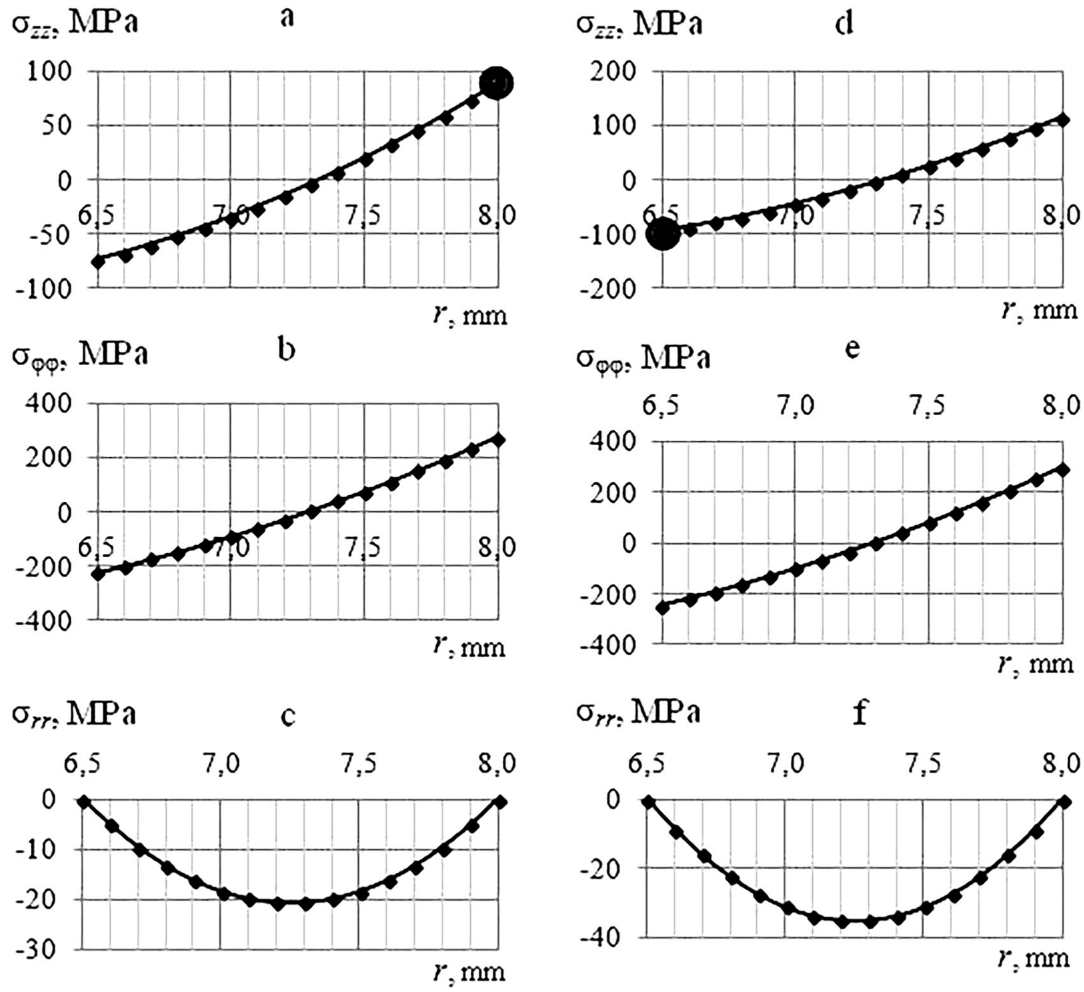

Fig. 6. Distribution of residual stresses along the pipe wall thickness (a, b, c - after the external layer etching; d, e, f - after internal layer etching).

on the surface. Besides the pipes undergo roller leveling finishing. With reverse bend on the pipes surface layers additional elastic tensile stresses form, which reduce the corrosion resistance of the heat exchange pipes.

CONCLUSIONS

The high tensile residual stresses, discovered in the surface layers of heat exchange pipes in the delivery state, reduce their corrosion resistance. The method of ring test, used by domestic pipe enterprises, does not define them.

The method offered allows defining of residual stresses in the pipe surface by easy means and easy calculation procedure. The residual stress in surface layer determined by the method, and calculated on this base distribution of residual stress, correspond to the data of other authors [7, 10].

As a results a conclusion can be made of necessity of additional control over residual stresses exactly in the finished pipe surface layers. Corrosion resistance can be improved by means of exclusion of finishing technological operations in the production cycle which promote formation of tensile residual stresses in external surface of the pipes.

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