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STRUCTURAL–TECHNOLOGICAL STRENGHTS AND WORKING CAPACITY OF MATERIALS

Initial Data and Criteria for the Reasoning Procedure for the Safe Operation of Pipelines and Housing of Equipment of FBR under Conditions of Sodium Leakage via Through Crack and Its Combustion

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Abstract—Criteria of the safety assessment procedure are described with regard to pipelines of the FBR secondary loop. The short-term and long-term properties of strength and ductility, fracture toughness, creep rate, and creep crack growth rate within the temperature range of 550–800°C for steel 08Cr16Ni11Mo3 are given. The most probable scenario of sodium combustion is proposed. Results of the testing procedures in a straight section of the pipeline DN 900 with the sodium leakage via through cracks and its combustion on the external surface are presented. A diagram of the admissible states of the pipeline concerning the discharge of sodium is constructed.

Keywords: fast breeder reactor (FBR), equipment, safe operation, through crack channel, sodium discharge, evaluation criteria

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INTRODUCTION

In order to carry out a compliance assessment of pipelines and housing of equipment of the primary and secondary loops of FBR developed by safety evaluation criteria, it is required to complete the following operating sequence:

—perform analysis of loading conditions and select reference sections (section candidates);

—form a database for short-term and long-term properties, crack growth rate, fracture toughness of the calculated sections within the operating temperature range;

—construct diagrams of the structural integrity by limit states of depressurization, fractures, and discharge and duration of sodium leakage;

—perform analysis of possible scenarios of sodium combustion and evaluate the influence of high temperatures on meeting safety criteria.

A complex of the required data of material properties for practical implementation of the calculated assessment and an algorithm of selection for section candidates are formed in this work; safety evaluation criteria for discharge, volume of the leaking sodium, and combustion time are formulated. Calculation of section candidate of DN 900 pipeline for correspondence with safety criteria during sodium combustion is carried out.

INITIAL DATA

For calculation of safety criteria of the considered part of the pipeline or equipment housing, a database of the initial data including the following factors is formed:

—structural and technological version of pipelines and equipment housing;

—conditions for temperature and power loading in all calculation modes, including transition modes;

—mechanical and physical properties of the base metal and welded seam metal with the allowance for their in-service change;

—sensitivity of the leakage detection system q_0;

—registered and emergency volumes of leaking sodium V_F and V_A.

Mechanical properties of the base metal and welded seam metal with the allowance for their in-service change owing to thermal aging on the considered time base includes the following:

—short-term properties of strength and ductility in the initial state (Fig. 1);

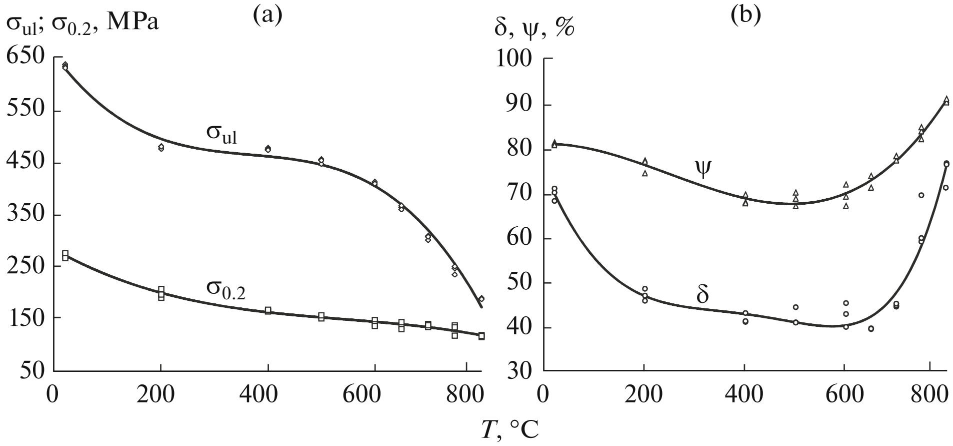

Fig. 1. Temperature dependence of short-term strength properties (a) and plasticity (b) of steel 08Cr16Ni11Mo3 in the initial state.

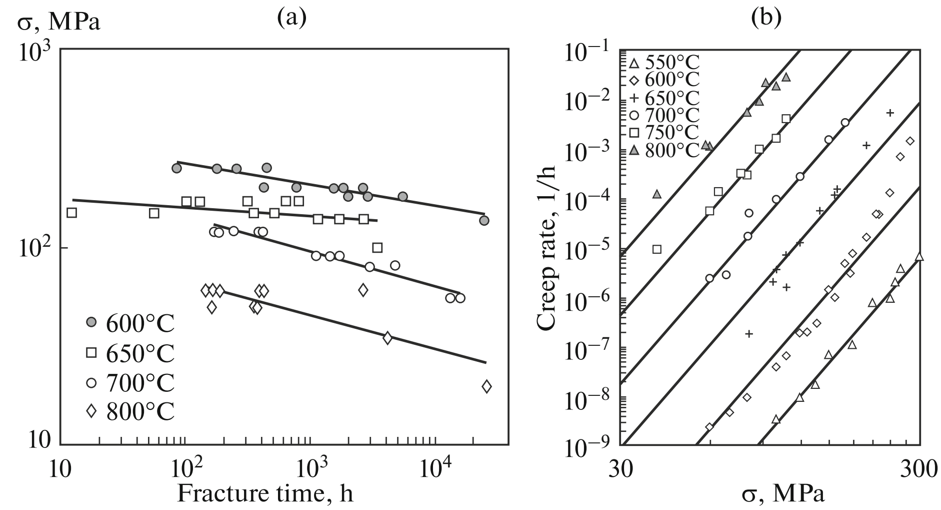

Fig. 2. Dependences of long-term strength (a) and steady creep rate (b) for steel 08Cr16Ni11Mo3 within the temperature interval of 550–800°C.

—yield point determined by isochronic curves and rupture strength (Fig. 2a);

—dependence of the steady-state creep rate (Fig. 2b);

—isochronic stress-strain curves (Fig. 3);

—dependences of the cyclic and continuous (Fig. 4) static fracture toughness;

—J_R curves and their parameters J_c and K_c under conditions of crack growth by 0.2–0.5 mm (Fig. 5);

—K_c^{mat} fracture toughness under creep conditions (Fig. 6);

—parameters of deformation curve at short-term loading;

—short-term strength properties after aging (Fig. 7).

Minimum and maximum properties providing a conservative nature of calculations are used across the entire aggregate of data. For example, mechanical properties of steel are considered as minimal and crack growth rate at fatigue and creep are considered as maximal.

Below are the temperature dependences of the short-term characteristics of strength and ductility (Fig. 1), long-term strength (Fig. 2a), and creep rate (Fig. 2b) of steel 08X16H11M3 obtained by results of our own tests within the temperature interval of 550–800°C and published sources [1].

According to set procedure, the TDFAD (time dependent failure assessment diagram) development and ε_{ref} assessment are based on isochronic stress-strain curves (Fig. 3) and parameter $\sigma_{0.2}(\tau)$ on the set time base τ. They also may be applied for creep consideration at numerical calculations of the strain-stress state (SSS) of cracked section in elastoplastic layout on the set time base.

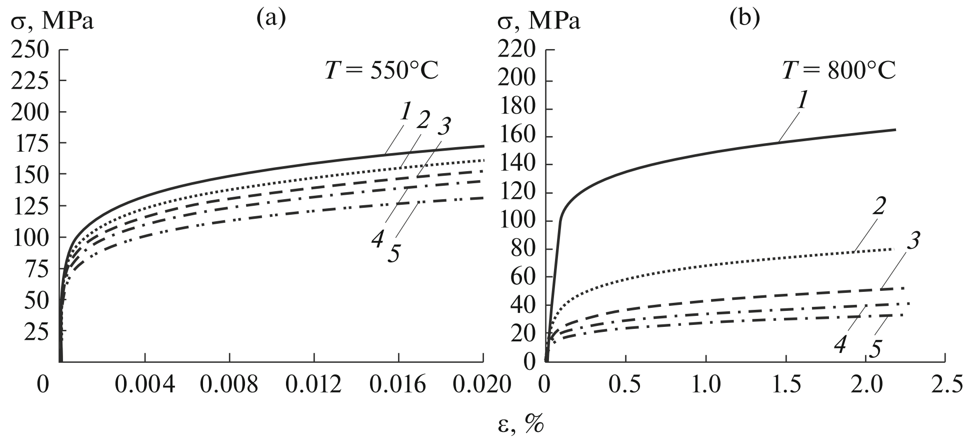

Fig. 3. Isochronic stress-strain curves for steel 08Cr16Ni11Mo3 at temperatures of 550 (a) and 800°C (b).

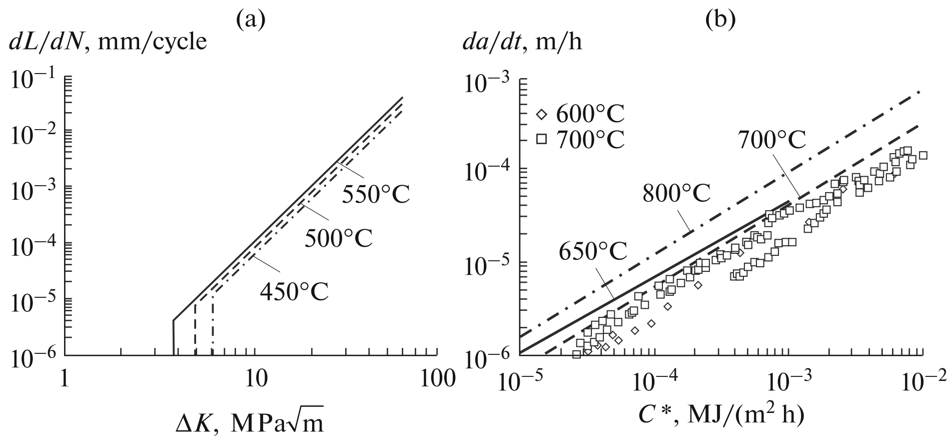

Fig. 4. Dependences of crack growth rate under fatigue (a) and creep (b) for steel 08Cr16Ni11Mo3.

The dependences of the steady-state creep rate (Fig. 2b) at uniaxial tension are described by Newton's law

$$\dot{\varepsilon} = B\sigma^{n_c}, \tag{1}$$

where B and n_c are material constants depending on temperature.

Isochronic stress-strain curves for steel 08Cr16Ni11Mo3 [2] are given as an example (Fig. 3).

In order to determine the geometry of surface and through cracks by formula (8),* the data concerning fatigue crack growth and creep crack growth [3, 4] are used. Data concerning the creep crack growth are also used for assessment of time allowance for remediation of sodium combustion by criteria (7). Figure 4a shows that the fatigue crack growth rate hardly depends on temperature and the dependence of the creep crack growth rate is not monotonic (Fig. 4b).

The type of temperature dependence of the creep crack growth rate and the data on creep crack growth rate which are used for assessment of the time allowance for remediation of sodium combustion by criteria (7) are given in the previous article of the present collection of work. The temperature dependence of the guaranteed fracture toughness J_c (Fig. 5a) is used for calculation of the critical crack length under condition of its initiation. Let us mention that fracture toughness J_c depends on service duration and temperature. Figure 5b shows the lower envelope of J_{1c} values depending on the Hollomon–Jaffe parameter for welding seam of steel AISI 316 [5] after thermal soak. The guaranteed $J_{1c}(T)$ dependence given in Fig. 5a, as the most conservative one (including aging influence) in comparison with the curve given in Fig. 5b, is recommended for use in safety margin.

Under creep conditions, the feature of the critical crack length is application of the value K_c^{mat}—metal fracture toughness during creep on the basis of the TDFAD approach. Fracture toughness K_c^{mat} for the set value of toughness regrowth Δa may be assessed indirectly according to [6] and may be determined directly during a tensile test of cracked sample under

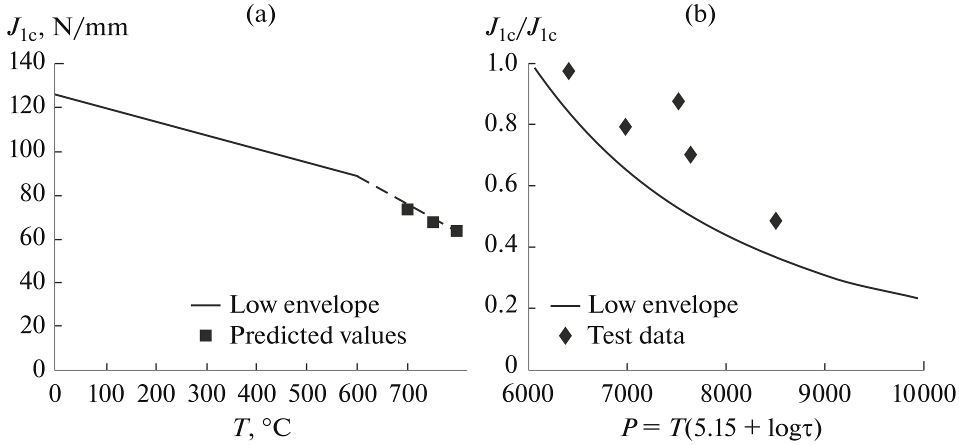

Fig. 5. Temperature dependence of guaranteed fracture toughness values (a); influence of thermal soaks for fracture toughness of steel AISI 316 depending on Hollomon–Jaffe parameter (b).

constant load [7]. It is clear that direct method of determining K_c^{mat} gives the most valid estimate. Tests are carried out with samples of CT type with recording of the P–Δ diagram (Fig. 6a) at the set value of the crack regrowth $a = 0.2$–0.5 mm. Then full displacement Δ_T is expanded into elastic and plastic components and creep component Δ_e, Δ_p, and Δ_c, respectively, as shown in Fig. 6a. The same expansion is used for obtaining the area under curve U_e, U_p, and U_c with the further determination of K_c^{mat} (Fig. 6b):

$$K_c^{mat} = \left[K^2 + \frac{E'\eta}{B_n(w - a_0)} \left(U_p + \frac{n}{n+1} U_c \right) \right]^{0.5}. \quad (2)$$

In [7], the processing of results (Fig. 6b) was carried out for all sizes of the tested samples. In our opinion, regression by samples CT-1 and CT-2 without taking into account CT-0.5 is more correct on such time base. Results of the tests CT-1 and CT-2 show that dependence K_c^{mat} on time does not have significant decrease, and for calculations in the first approximation, the value $K_c^{mat}(0)$ obtained during short-term tests may be used. During assessment of the limit state of section candidates, it is required to take into account the influence of thermal aging on the short-term characteristics of material. On the basis of the test results of austenite steel of AISI 304 and AISI 316 [8] type, it was found that the strength level, as a rule, does not decrease below the guaranteed levels, and the plasticity level may be lower than the guaranteed values. A comparison is carried out for results of the short-time break under condition of equality $T_{fulf} = T_{age}$. Let us mention that the decrease in plasticity correlates with the decrease in crack resistance J_{1c}.

It is seen in Fig. 7 that application of guaranteed values $\sigma_{0.2}$ and σ_{ul} gives a conservative assessment with calculations of the limit state by formula (6)[1].

CHOICE OF THE CALCULATED SECTION CANDIDATE

It turns out to be impossible to perform calculations against the procedure criteria along the whole length of pipelines and along the whole surface of the equipment housings. In order to decrease the labor intensity of calculations the section candidates are chosen to carry out compliance assessment of the developed procedure. A through crack is postulated in each of them. All section candidates are considered with a view to compliance of criteria.* If sections candidates meet safety requirements, it is considered that the whole studied region, as a consequence, meets those criteria as well.

Selection of the section candidates on the studied region is carried out according to the following characteristics or their combination:

—with the most accumulated cyclic and durable static damage;

—with maximum ratio of MRL (maximum rated load) to NO (Normal operation) and the most loaded at MRL (NO + SSE, NOF + SSE) (SSE is the safe shutdown earthquake; AOO anticipated operational occurrences);

—with the maximum ratio of amplitude of local bends (distribution by the wall thickness) to the resulting amplitude of common bending (distributed by

[1] See article by G.P. Karzov, P.M. Ramazanov, B.Z. Margolin, V.A. Petrov, and O.Yu. Vilensky "Formulation of Criteria and Reasoning Procedure for the Safe Operation of Pipelines and FBR Housings under Conditions of Sodium Leakage via Through Crack and Its Combustion" in this collection.

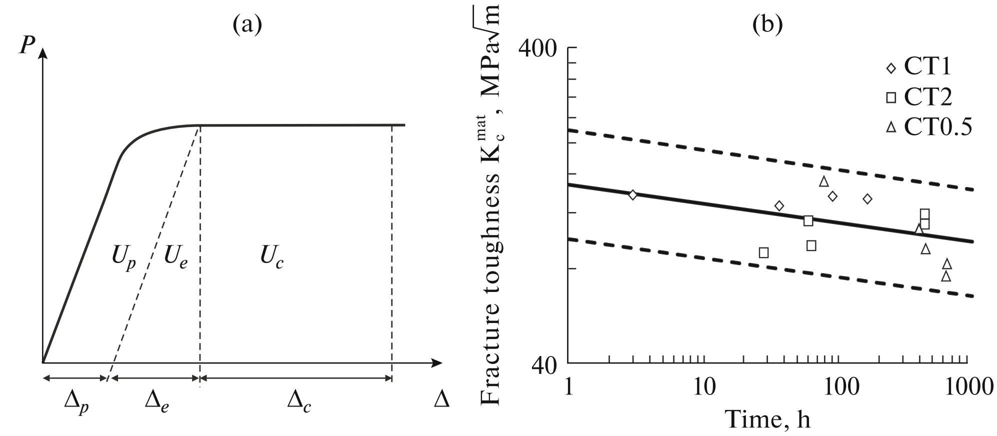

Fig. 6. *P*–Δ diagram obtained during sample test for fracture toughness under creep (a) and parameter K_c^{mat} obtained during tests of steel sample of AISI 316 grade of ST type at 550°C (b).

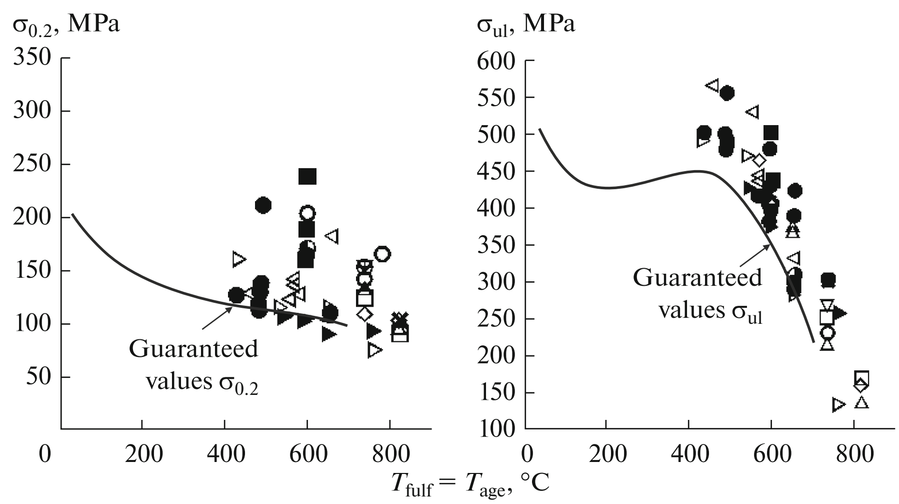

Fig. 7. Comparison of strength properties of steel AISI 316 after long thermal aging with guaranteed values.

cross section), compensation, and membrane stresses at NO and AOO modes for pipelines;

—with a high degree of certainty during nondestructive testing including cross sections accessible and partially accessible for control;

—with minimum values of short-term and long-term characteristics of strength and plasticity.

VOLUME LIMITATION CRITERIA FOR LEAKING SODIUM

The criterion of the traditional concept "leak before break" (LBB) for coolant discharge was developed and applied for reactor plants with water coolant, where severity of the loop leakage does not depend on the volume of discharged water. At the same time, high pressure in a VVER plant allows quick detection of any leakage because of high discharge. In the primary and secondary loops of FBR, the pressure is considerably lower, and the allowable volume of leaking sodium is limited by loss of circulation and violation of fire safety. That is why for safety evaluation of the pipelines of the secondary loop, the criterion which is based on volumes and average discharge of leaking sodium at the set area of the through crack was developed.

One of the leakage detection systems (LDS) in FBR envisages control of the leaking coolant on the basis of the pressure change in the gas blanket or by the sodium level in the sodium buffer tank (SBT) being part of the secondary loop. Danger of the drop in level in the SBT is connected with the decrease in argon pressure in the SBT gas blanket and circulation loss in the loop; that is why, from the moment of leakage fixation by the level of warning indication in the SBT, it is necessary to start securing the loop to avoid an

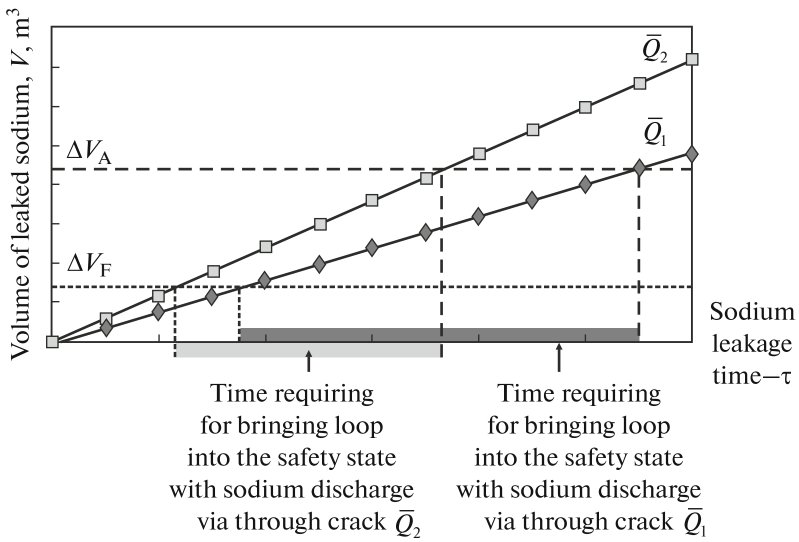

Fig. 8. Graphical interpretation of the safety criterion analysis by the volume of leaked sodium; $\bar{Q}_2$, $\bar{Q}_1$ are the averaged discharges of sodium leakage via through crack ($\bar{Q}_2 > \bar{Q}_1$); ΔV_F is the volume of leaked sodium required for actuation of the warning signal; ΔV_A is the volume of leaked sodium resulting in an emergency situation.

emergency situation (circulation loss). Therefore, the loop securing time τ_s should be less than the time in which the sodium level in the SBT decreases by the volume value ($\Delta V_A - \Delta V_F$).

Thus, two states of the loop are accepted depending on the volume of leaked sodium in the secondary loop (Fig. 8):

—drop of the sodium level or pressure in the blanket before actuation of the warning signal (the volume of leaked sodium ΔV_F corresponds to that);

—drop of the sodium level or pressure in the loop into the state where cavitation in the main circulating pump (MCP) takes place (in this case the volume of the leaked sodium is ΔV_A).

The criterion of correspondence of pipelines to the safety concept concerning volumes of leaked sodium is provision of the time period required for bringing the loop into the safety state

$$\frac{\Delta V_A - \Delta V_F}{\bar{Q}} \geq \tau_S, \quad (3)$$

where τ_S is the time required for bringing the loop into the safety state; and $\bar{Q}$ is the averaged sodium discharge through the postulated crack obtained with consideration of pressure and temperature change.

In calculation of the above given criteria, the dimensions of the postulated through crack formed as a result of fatigue growth are taken to be equal to its size to the moment of jumper fracture ($a/h = 1$). With consideration of the through crack extension area, the hydraulic calculation aiming at determination of sodium discharge $\bar{Q}$ is carried out. On the basis of the obtained average discharge $\bar{Q}$ and sodium volumes ΔV_F and ΔV_A, the evaluation of conformance to the safety criteria is carried out. The evaluation scheme of sodium leakage under otherwise equal conditions (argon pressure, temperature, and crack location in the loop) for different areas of a through crack is given in Fig. 8.

CRITERIA FOR SODIUM DISCHARGE

After detecting leakage in the loop, the length of the through crack is determined by sodium discharge with the use of the dependences of liquid and gas dynamics as well as by nonlinear fracture mechanics. If the length of such crack is less than critical with the set margin coefficients, then it is stated that sensitivity of the leakage detection system is sufficient for the provision of loop safety upon pressure loss.

The basis for the developed criteria is the similar comparison of the crack critical length (maximum rated load) and postulated by the discharge (NO mode) for the set margin coefficient. The peculiarity of the postulated crack length is the correct consideration of the following parameters:

—length of the crack formed at the fatigue and static regrowth, which decreases along the wall thickness (length of the inner surface $2c_D$ is greater as compared with the outer surface $2c_{LD}$);

—hydraulic resistance created by the crack surfaces during sodium leakage;

—influence of creep in determination of the crack flow area;

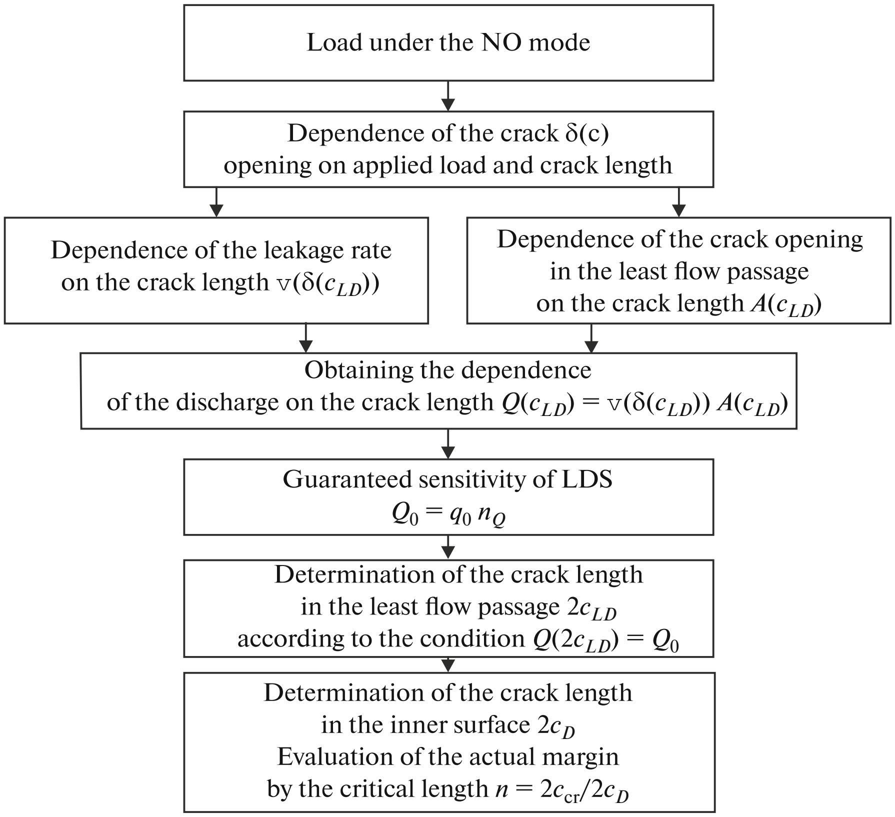

Fig. 9. Flowchart of evaluation of conformance to safety criterion of sodium discharge.

—potential of sodium combustion beyond the sealed loop as well as influence of the related increased temperatures on the mechanical properties of materials and hydraulic parameters of leakage.

The through crack of length $2c_D$ is regarded as the postulated crack with respect to leakage; sodium discharge through this crack is detected by the standard LDS for sure. Established or confidently registered sodium discharge $Q_0 = q_0 n_Q$ is determined by LDS sensitivity q_0 with set margin coefficient n_Q. Margin coefficient n_Q is introduced for excluding inaccuracies and possible errors during calculations if a large number of parameters are used; every parameter brings its inaccuracies. LDS sensitivity q_0 is such sodium discharge which may be found by the given LDS. For the LDS of the secondary loop of the FBR, sensitivity q_0 was proved at the level of 1 L/h. The margin coefficient is taken to be equal $n_Q = 3$. Calculation of correspondence to criteria concerning sodium discharge is carried out in accordance with procedure whose flow chart is shown in Fig. 9.

Length of the postulated crack $2c_{LD}$ on the outer surface is determined by the Q_0 value and loading conditions of the reference section. For this purpose, the functions of velocity and flow area are reduced to one variable, $2c_{LD}$, and the following equation is solved:

$$v(c_{LD})A(c_{LD}) = Q_0, \qquad (4)$$

where A is the area of the least flow passage; and v is the velocity of sodium flow through the crack.

It is required to mention that both the sodium flow velocity through the crack $v(2c_{LD})$ and the area of the least flow passage $A(2c_{LD})$ are functions of the crack length under fixed temperature and strain-stress state (SSS). In a more general case, it is required to take into account the SSS change, which exerts significant influence on expansion of the through crack and as a result on the area of the least flow passage and on sodium flow velocity through the equivalent hydraulic diameter.

The formulas given below may be used for determination of the crack length according to the postulated discharge, providing further checking calculation of the sodium leakage process (laminar or turbulent), as a simplified procedure (Fig. 9) and approximate evaluation of $2c_{LD}$:

$$2c_{LD} = \begin{cases} \left(3.1 Q_0 \dfrac{E^3 \mu h}{(k_m \bar{\sigma}_m - k_b \sigma_b)^3\, \Delta p}\right)^{0.25} \\ \text{at } \mathrm{Re}(2c_{LD}) \le 2000 \\ \left(12.9 \times 10^{-3} Q_0^2 \dfrac{E^3 \rho h}{(k_m \bar{\sigma}_m - k_b \sigma_b)^3\, \Delta p}\right)^{0.2} \\ \text{at } \mathrm{Re}(2c_{LD}) > 2000, \end{cases} \qquad (5)$$

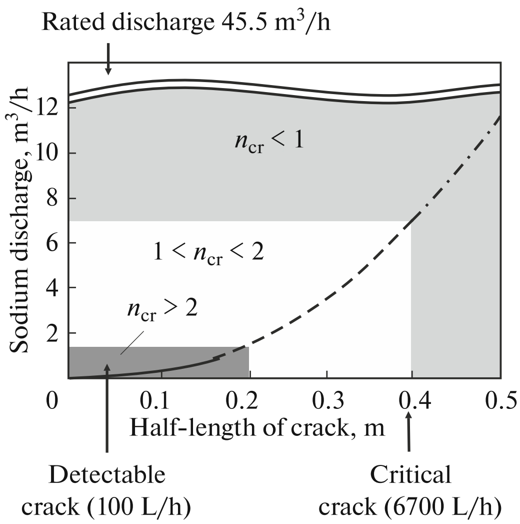

Fig. 10. Graphical interpretation of estimate of allowable states by criterion (6).

where Q_0 is the guaranteed LDS sensitivity threshold; E is the elastic modulus at the rated sodium temperature; ρ is the sodium density at the rated sodium temperature; $\bar{\sigma}_m$ are the average stresses over the wall thickness; σ_b are the bending stresses distributed over the wall thickness; k_m and k_b are coefficients depending on the ratio of crack length to circumference, for cracks of small length equal to 1 and 0.4, respectively; Δp is the sodium excess pressure; μ is the sodium viscosity; and h is the wall thickness of the considered pipeline or shell.

The crack length $2c_{LD}$ obtained by Eq. (4) or (5), depending on the ratio of bending (distributed over the wall thickness) to membrane (averaged over the wall thickness) stresses (or their amplitudes in cycle), is recalculated for the length of the crack on the inner surface $2c_D$, and assessment of conformity to the criterion is carried out by the formula

$$2c_D \leq \frac{2c_{cr}}{n_{cr}}, \qquad (6)$$

where $2c_D$ is the length of the through crack on the inner surface determined by the confidently registered sodium discharge Q_0; $2c_{cr}$ is the critical length of through crack; and n_{cr} is the margin of the through crack critical length; in the general case, $n_{cr} = 2$.

Data from calculation of Eq. (4) and criteria (6) are given in the form of the diagram in Fig. 10. The diagram shows the dependence of sodium discharge via the crack depending on its length. The diagram shows safety region where criterion (6) is satisfied—$n_{cr} > 2$; it also serves as boundaries for the LDS sensitivity threshold. Transition region $1 < n_{cr} < 2$, which does not guarantee safety, and unacceptable state $n_{cr} < 1$, when simultaneous failure by bulk cross section is possible, are also shown in the diagram;

CRITERION OF ALLOWABLE TIME UNDER SODIUM COMBUSTION

Contact of sodium with air results in its self-ignition because of its high chemical activity. The ignition point is within the interval of 140–320°C. Under normal operation, the temperature interval of sodium in the primary and the secondary loop is 350–550°C; that is why the loop seal failure inevitably leads to sodium ignition upon contact with air [9].

Satisfying the criteria of the developed procedure under conditions of sodium combustion provides timely detection of leakage. "Timely" means that leakage detection is at an earlier stage of its development, and sufficient time for transferring the damaged element of the loop into the safe condition is available before the moment of the unstable growth of the crack (critical length of the crack).

According to Russian and foreign investigations, the thermal insulation on pipelines of sodium systems fast breeder reactors may exert significant influence on the process of sodium leakage through the defect after seal failure. The character of leakage, discharge, and results of decompression may considerably differ from the cases where thermal insulation is not present or damaged [10–12]. This factor should be taken into account in analysis of emergency situations.

In analysis of the conditions of sodium combustion, the following scenarios of development may be considered:

(1) Sodium flows on the floor of the box through discontinuities of thermal insulation and burns according to the "pool" scheme (Fig. 11).

(2) Sodium combustion in close proximity to the through crack on the external surface of pipeline under thermal insulation (Fig. 12).

(3) In case of thermal insulation failure, combustion of the dispersed (sprayed) sodium with the intense heat output.

Scenario 3 is most dangerous from the point of view of temperature and pressure increase in the box because of the more intense sodium combustion. But all pipelines of sodium systems are covered with thermal insulation and its failure is possible only with a through defect with the equivalent hydraulic diameter of more than 10 mm [10]. The hydraulic diameter of 10 mm corresponds to the greatest allowable length of a real crack of 644 mm ($\pi D/4$, $D = 820$ mm) with opening of 3 mm.

A stress level significantly higher the allowable one is necessary for such value of expansion. That is why, with the required cover, the thermal insulation integrity will not be violated, and it is quite possible that scenario 3 may take place only with the actual violation of integrity of the pipeline. Such a scenario

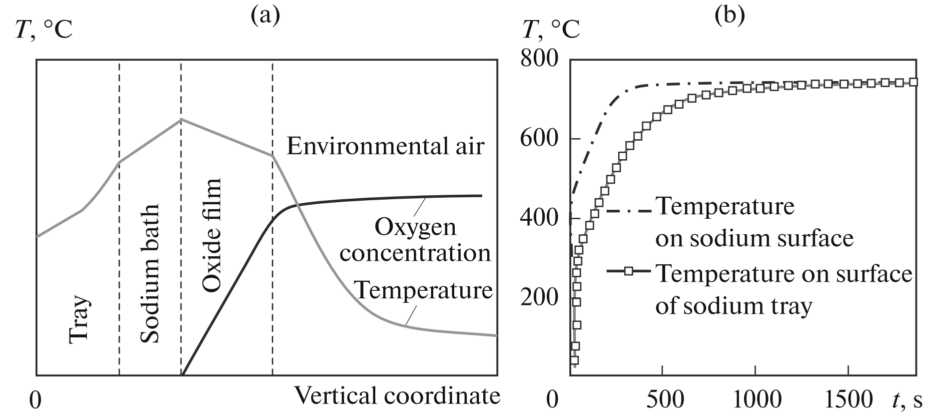

Fig. 11. Temperature distribution during sodium combustion according scenario 1 “pool”: (a) temperature pattern by thickness of structural components; (b) temperature behavior in time domain on the surface of sodium combustion.

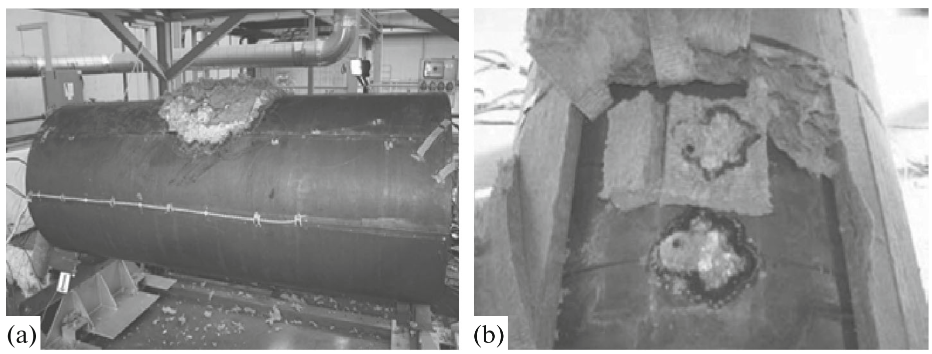

Fig. 12. Consequences of sodium leakage and combustion under thermal insulation layer on FUTUNA 2 stand (pipeline DN 800).

requires a separate study and is beyond the design basis accident and this procedure.

During sodium combustion according to scenario 1 (sodium leakage in the box), the pipelines and equipment remain protected by thermal insulation from the influence of high temperatures. In this case, analysis of correspondence to the developed criteria on the critical length of crack, discharge, volume, and time for transition into a safe condition is carried out with respect to the maximum temperature in the box, which should be lower than the maximum coolant temperature corresponding to normal operation ($T \geq 500°C$).

Consideration of scenario 2 is the most important from the safety point of view because sodium combustion leads to heating of the metal in the through crack region up to 800°C [10]. After formation of the through crack, sodium flows into a coaxial channel under the thermal insulation and ignites, heating the external surface of the pipeline. The scheme of the boundary conditions under such a scenario is given in Fig. 13a.

A field of the compressive stresses appears on the external surface of the pipeline when the temperature reaches 700°C and higher; at the same time, the carrying capacity in the area of combustion decreases. Figure 13b shows deformed state of the pipe DN 800 with the through crack located in the upper part. For the purpose of illustration, the crack edges are presented without the counterpart. Crack edges compressed by temperature deformations do not allow leakage of a large amount of sodium; in this case, the width of the disturbed zone and sodium combustion time do not exert significant influence. The sodium leakage from the crack practically stops, combustion weakens, and pipeline temperature decreases to its initial value. Compressive stresses decrease along with the temperature decrease; and therefore, the crack expands again. Thus, the self-similar process of sodium combustion and expansion and closing of the crack, with leaking sodium, is manifested.

The self-similar process of sodium leakage decreases the total amount of leaking sodium, which may apparently be ascribed to the positive aspect of sodium combustion. In this case, we observe the negative effect in form of a cyclic load in the cross section with crack. Today it is quite difficult to answer the question of which of the aspects is determinative or whether their influence is exaggerated. It is necessary

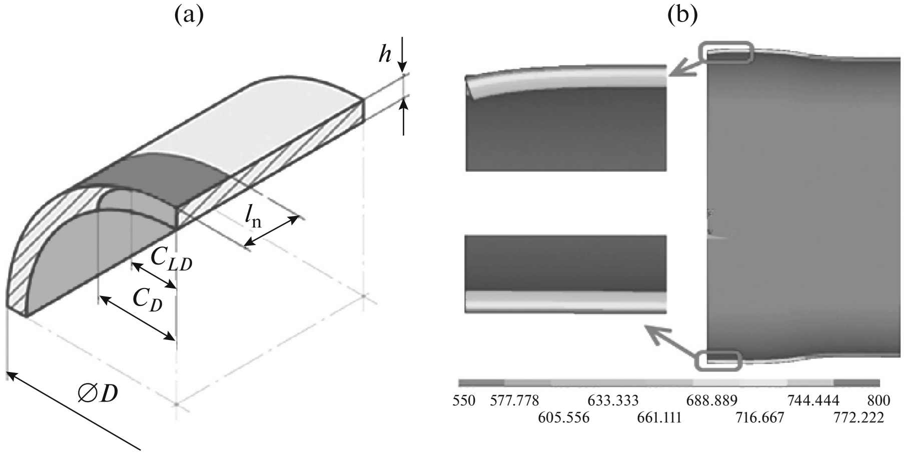

Fig. 13. Diagram of boundary conditions: (a) estimated temperature distribution; (b) deformed sate at specified boundary conditions.

to carry out experimental clarification of the boundary conditions in the through crack area during sodium combustion.

In spite of uncertainty, heating because of combustion and temperature stresses lead to decrease in the pipeline carrying capacity and contribute to crack growth under conditions of creep. In this situation, it is necessary to remove the influence of increased temperature on the damaged cross section before the crack reaches critical length and before failure by full cross section. The time for bringing the box with the damaged pipeline into a safe condition τ should satisfy the following inequality:

$$\tau < \frac{\left(\frac{2c_{\rm cr}}{n_{\rm cr}}\right) - 2c_D}{2\dot{c}n_\tau}, \quad (7)$$

where τ is the time required for bringing box into a safe condition (time for localization and firefighting operations); n_τ is the margin for bringing the box into a safe condition $n_\tau = 3$; $2\dot{c}$ is the creep crack growth rate under conditions of sodium combustion; and $2c_{\rm cr}$ is the critical length of the crack under a temperature gradient.

RESULTS OF CALCULATIONS BY CRITERIA

Testing of the procedure[2] in a real pipeline and under actual parameters of the temperature–time loading was carried out with the use of existing data on steel properties in order to make diagrams of allowable state of the candidate sections. Such testing was carried out in a simplified design with application of a number of assumptions.

Results of the section candidate calculation of the straight part of the pipeline DN 900 with allowance sodium combustion are given below as an example of implementation of criteria (3).

Loading conditions of the calculated section corresponded to the NO mode ($\sigma_{\rm m} + \sigma_{\rm bg} = 62$ MPa); calculations were carried out with overstresses in the NO mode up to allowable values ($\sigma_{\rm m} + \sigma_{\rm bg} = 1.3[\sigma] = 102$ MPa).

An equilibrium through crack with specified length ratio on the external and internal surfaces is accepted as the postulated crack:

$$\frac{2c_{\rm in}}{2c_{\rm out}} = \frac{36\ \rm mm}{45\ \rm mm} = 0.8. \quad (8)$$

Calculations were carried out for the accepted emergency volume of leaked sodium $V_{\rm A} = 2000$ L. Time $\tau_{V\rm A}$ spent for the emergency volume of sodium leakage is calculated by the formula

$$\tau_{V\rm A} = \frac{V_A}{\bar{Q}}. \quad (9)$$

The LDS sensitivity is accepted at the level of $Q_0 =$ 10 L/h. Time τ_{Q0} for sodium leakage and combustion when its discharge exceeds the value of Q_0 is accepted for registration of sodium leakage.

The approximate time for bringing the loop to a safe condition is 16 h. Starting from the moment of leakage detection, the in-plant personnel take measures to disconnect damaged section and drain it. In the process of implementation of the action plan, the sodium discharge decreases and, therefore, the time to the limiting state increases. This calculation is carried out in the conservative arrangement without taking into account the pressure drop. The results of calculations for criteria (3) are given in the table.

[2] See article by G.P. Karzov, P.M. Ramazanov, B.Z. Margolin, V.A. Petrov, and O.Yu. Vilensky "Formulation of Criteria and Reasoning Procedure for the Safe Operation of Pipelines and FBR Housings under Conditions of Sodium Leakage via Through Crack and Its Combustion" in this collection.

ANALYSIS OF THE RESULTS

The results of calculation showed that, at nominal loads (NO mode), heating of the external surface from 700°C and higher in the rated section creates a field of compressing stresses, “shutting down” the crack. In this situation, the self-similar process of sodium combustion and opening and closing of the crack with leaking sodium will be manifested. The volume of leaked sodium and the time margin during the self-similar process significantly depends on the boundary conditions. It is planned to obtain boundary conditions on the basis of experimental studies.

With the high level of stresses equaling allowable values (102 MPa), criterion (3) is not satisfied. In this case, the leakage of emergency volume (V_A = 2000 L) will come after 10 h and that is not sufficient to fulfill the action plan concerning bringing the loop into a safe condition in 16 h.

But such evaluation is performed at an excessively conservative design and requires specified determination of sodium discharge, which decreases in the process of fulfillment of the action plan owing to a decrease in pressure in the loop.

CONCLUSIONS

The procedure of calculated assessments concerning correspondence to safety criteria as applied to pipelines of the secondary loop of FBR was detailed. The methods of selection of candidate sections of pipelines were recommended; design characteristics concerning short-term and long-term properties of steel 08Cr16Ni11Mo3, fracture toughness, creep rate, and crack growth rate under creep in the temperature interval of 550–800°C were given.

Simplified evaluation of the length of the postulated through crack by discharge of sodium in a leak depending on the flow character was proposed. Currently, the LDS sensitivity in calculations of the length of the through crack is accepted as 1 L/h. The issue of sensitivity of the applied LDS (by bridging of electrical heating system) requires additional substantiation.

The procedure for calculation by registered and emergency volumes of leaking sodium was developed. The following situation is considered in accordance with the procedure: when sodium leakage leads to the pressure drop in gas blanket of the buffer tank and as a result to cavitation in the MCP. The key poing of the proposed safety criteria is the time required for the fulfillment of actions for bringing the damaged loop into a safe condition.

The criterion of the allowable time under sodium combustion conditions during loss of piping integrity was formulated. The criterion takes into account the combustion scenario, the temperature gradient appearing during sodium combustion in the through crack zone, and the crack growth during creep. The safety condition according to the criterion is the situation where the specified (allowable) time period is more than the time required for fire extinguishing.

Results of calculation for correspondence to criterion (3)

T, °C	l_{Π}, mm	$\sigma_m + \sigma_{bg}$, MPa	τ_{Q0}, h	τ_{VA}, h	Calculation data by criterion (3)
700	75	72	*	*	*
		82	5	>30	Done
		92	<1	30	
		102	<1	19	
	225	72	*	*	*
		82	*	*	
		92	16	>30	Done
		102	<1	>30	
750	75	72	*	*	*
		82	7	>30	Done
		92	<1	27	
		102	<1	14	Failed**
	225	72	*	*	*
		82	*	*	
		92	16	>30	Done
		102	2	26	
800	75	72	*	*	*
		82	6	>30	Done
		92	<1	18	
		102	<1	10	Failed**
	225	72	*	*	*
		82	*	*	
		92	15	>30	Done
		102	2	19	

* Autowave process of the sodium flowage; flow rates will be specified after experimental studies.

** Criterion was not satisfied under conservative design; amended estimate with consideration of the pressure drop in the loop is required.

Calculation of the candidate sections of pipelines DN 800 by sodium discharge and DN 900 by volume of leaking sodium was carried out on the basis of the developed criteria. It is seen from the calculation results that, for the straight part of the pipeline DN 800, the discharge criterion is met with twofold excess of the required margin. The criterion of volume limitation in the straight part of the pipeline DN 900 with allowance for sodium combustion is satisfied in most of the cases considered. In some cases, the criterion is not satisfied because of the conservative design of the problem. An amended estimate removing the excess conservatism is required.

The further direction of work is connected with clarification of boundary conditions during sodium combustion and determination of the missing time parameters (time for bringing the circulating loop into a safe condition, time for localization and firefighting operations) which are necessary for calculations with application of the developed criteria for pipelines and housing of equipment of FBR.

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