A MODEL OF THE DYNAMIC FAILURE OF THE FUEL ELEMENT OF A REACTOR WITH THE UNCONTROLLED INTRODUCTION OF POSITIVE REACTIVITY

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Introduction. Hypothetical breakdowns of nuclear reactors associated with the uncontrolled introduction of positive reactivity have lately been the object of intensive study, because of their possible serious consequences. Intensive experimental studies have been conducted within the framework of the American SPERT, TREAT, and PBF programs [1, 2], on the Japanese NSRR pulse reactor [3-6], and on the domestic IGR and GIDRA installations [7, 8] in order to determine the threshold value of energy release at which the fuel element fails, and also to analyze the consequences of failure of fuel elements for the active zone of the reactor. Analysis of experimental data reveals several basic mechanisms of failure: 1) cracking of a cold casing caused by its high-speed deformation under the influence of internal pressure; 2) melting of a casing; and 3) oxidation of the surface of a casing at the stage of film boiling and cracking at the cooling stage. The first of these processes is observed during the action of a pulse (as a rule, ≤ 1 sec), while the other processes occur over long periods of time (1-20 sec). The actual mechanism of the failure of a fuel element depends on the specific energy release and duration of the pulse.

As a rule, the mechanism of rupture of a cold fuel element casing is realized at several large values of energy release in comparison with the threshold value and is accompanied by intense dispersion of fuel (the degree of which, in particular, is determined by the pressure in the fuel element at the moment of failure). In this case the consequences for the active zone of the reactor are extremely catastrophic, due to the powerful hydrodynamic processes that develop in a steam explosion.

The present article examines the mechanism of failure of fuel elements under the influence of short pulses of energy release with a duration of less than 1 sec. It is assumed that the casing of the fuel element fails as a result of high-speed deformation under the influence of external pressure. This type of model was used in [4, 5] to calculate the increase of pressure in fuel elements filled with water. The increase in the internal pressure was associated only with the heating and vaporization of water. The present article also considers the thermal expansion and melting of the fuel and the presence of gas in the gap and within the fuel. Within the framework of a single approach both the dynamics of the behavior of the fuel element (in particular, the increase in internal pressure), and the magnitude of the failure threshold as a function of the parameters of the energy release pulse and the initial state of the fuel element are described.

A Model of the Behavior of the Fuel under the Influence of Pulsed Energy Release. Pulsed energy release leads to heating and thermal expansion of the fuel and possibly to its melting. The increase in the fuel volume causes an increase in the internal pressure in the fuel element, under the influence of which elastoplastic deformation of the casing occurs. When the deformation reaches a critical value, the casing fails. The increase in internal pressure significantly affects the gas both directly under the casing 2 (gap 3) and in the pores of the fuel pellets (Fig. 1). As long as the temperature of the fuel 1 is small in comparison with the melting temperature, the gas in the pores does not have a noticeable effect on the deformation of the fule, such that only the gas in the gap is compressed. When the temperature of the fuel approaches the melting point, the fuel plasticizes and begins to compress the gas in the pores. In the general case the pressure increase within the fuel element will be determined by th equation of state of the medium, which has three phases: solid, liquid (melting), and gas. The specific volume V of such a medium may be represented in the form

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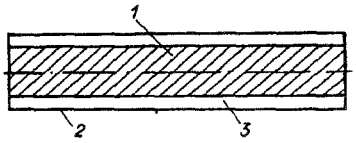

Fig. 1

$$V = \sum_{i=1}^{3} m_i V_i, \quad \sum_{i=1}^{3} m_i = 1 \tag{1}$$

(m_i are the relative masses of the phases and V_i are their specific volumes). The values of the index i = 1, 2, 3 correspond to the solid, melted, and gas phases. For sufficiently short pulses, the diffusion of the gas phase may be ignored, since the magnitude of m_3 remains constant during the entire loading process. Here m_3 may be expressed in terms of the initial volume concentration of the gas α_{30}.

$$m_3 = \frac{V_{10}}{V_{30}} \frac{\alpha_{30}}{1 - \alpha_{30}}, \tag{2}$$

where it is assumed that in the initial state there is no melting. Since $V_{10} \ll V_{30}$, the mass fraction of the gas is always small.

Relation (1) must be fulfilled by the equations of state of each of the phases, which we select in the form

$$V_1 = V_{10}\left[1 + \beta (T - T_0) - \frac{p - p_0}{K}\right],$$
$$V_2 = V_{20}\left[1 + \beta (T - T_0) - \frac{p - p_0}{K} + \delta\right], \quad V_3 = V_{30}\frac{p_0 T}{p T_0}. \tag{3}$$

Here β is the volume coefficient of thermal expansion; K is the modulus of elasticity of the liquid and solid phases; δ is the relative variation of the volume during melting; p and T are the pressure and temperature which are considered to be identical for all phases; and the index 0 indicates the initial state of the substance. The behavior of the gas phase is described by the equation of state of an ideal gas. For the sake of simplicity, we consider the coefficients β and K to be constant and identical for the solid and liquid phases.

Substituting (2) and (3) into (1), we obtain the following equation of state of the medium:

$$V = V_{10}\left\{1 + \beta (T - T_0) - \frac{p - p_0}{K} + m_2\delta + \frac{\alpha_{30}}{1 - \alpha_{30}}\frac{p_0 T}{p T_0}\right\}. \tag{4}$$

The temperature of the medium and the melted fraction are determined from the general energy balance

$$\frac{dQ}{dt} = C_V \frac{dT}{dt} + \lambda \frac{dm_2}{dt} + p\frac{dV}{dt} + q, \tag{5}$$

where Q is the energy released per unit of mass of fuel; q is the energy flux from the fuel, going to heat the coolant and related to the unit of mass of the fuel. The temperature of the fuel over the cross section of the fuel element is considered to be constant and the heating of the casing as a result of heat transfer with the fuel is ignored. These approximations are justified for characteristic times of less than 1 sec [1].

Melting of the fuel occurs when its temperature reaches the melting point $T_s(p)$, which is found from the Clapeyron-Clausius equation:

$$\frac{dT_s}{dp} = \frac{T_s(p)(V_2 - V_1)}{\lambda}. \tag{6}$$

Let us write the relation for the heat loss q under the approximation of a constant coefficient of heat transfer:

$$q = q_0 \frac{T - T_c}{\Delta T_0}, \quad \Delta T_0 = T_0 - T_{c0}. \tag{7}$$

TABLE 1

p_0	K_0	τ_0	Y_s	G	ρ_{0T}, kg/m^3	λ, J/kg	β, deg^{-1}
Pa							
10^5	$4\cdot10^{10}$	$5\cdot10^9$	$3{,}2\cdot10^8$	$4\cdot10^{10}$	10^4	$2{,}1\cdot10^5$	$4{,}5\cdot10^{-5}$

TABLE 2

C_V, J/(kg·deg)	δ	T_{s0}, K	v_0, m/sec	N_m, 1/m^2	T_0, K	R	h	γ_*, %
						mm		
350	0,1	2920	300	10^{10}	300	5,36	0,62	10

Here T_0, T_{c0}, and q_0 are the temperatures of the fuel and the coolant, and the heat flux in the equilibrium mode of operation of the reactor, W/m^3. Since in our case the temperature of the fuel T is significantly greater than the temperature of the coolant T_c, we will henceforth assume that $T_c = T_{c0}$. We will approximate the speed of heat release by the expression

$$\frac{dQ}{dt} = \frac{Q_0}{2t_0}\,\mathrm{ch}^{-2}\,\frac{t}{t_0}, \tag{8}$$

where Q_0 is the total energy release per unit of mass of the fuel during the period of neutron flash; and t_0 is the flash period. The system of equations (4), (6)-(8) must be supplemented by relations describing the deformation of the fuel element casing.

Since the duration of the neutron pulse $t_0 \geq 10^{-3}$ sec is significantly longer than the characteristic time of the wave processes in the fuel element $\sim R/c = 10^{-5}$ sec (c is the speed of sound in the fuel), its deformation may be considered under the quasistatic approximation right up to the moment of failure. For a thin cylindrical casing, the speed of shear deformations is determined by the expression

$$\frac{d\gamma}{dt} \approx -2\,\frac{\dot{R}}{R} \tag{9}$$

(R is the current radius of the casing).

As the determining equation of plastic flow we will use a relation from the dynamic theory of plasticity [9]:

$$\frac{d\gamma}{dt} = \mu b N(\gamma)\, v(\tau) + \frac{\dot{\tau}}{G}. \tag{10}$$

Here μ is the unit order factor; b is Burger's vector; $N(\gamma)$ is the density of mobile dislocations; $v(\tau)$ is their speed; and G is the shear modulus. It is evident from comparison of (9) and (10) that the shear deformations γ and the stresses τ for the case of a thin casing are uniform over its thickness. The dependence of the speed of the mobile dislocations on the shear stresses is taken in the form

$$v(\tau) = v(\tau_0) \begin{cases} [(\tau - Y_s)/\tau_0]^3, & \tau < \tau_0, \\ [(\tau - Y_s)/\tau_0], & \tau \geq \tau_0, \end{cases} \tag{11}$$

where $v(\tau_0)$ is the speed of the dislocations at a stress, equal to τ_0 corresponding to the shift in the mechanism of movement of the dislocations; $Y_s = \sigma_s R/h$; σ_s is the yield point of the casing and the static yield point; and h is the thickness of the casing.

The equation of motion in the quasistatic case takes the form

$$\frac{\partial \sigma_r}{\partial r} + \frac{\tau}{r} = 0. \tag{12}$$

Integrating this expression over the thickness of the casing and considering the constancy of τ, we obtain the relation

$$|\tau| = (p(R, t) - p_{ex})\,\frac{R}{h} \tag{13}$$

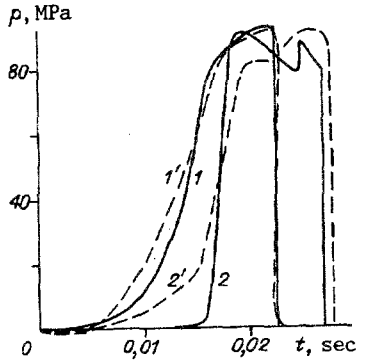

Fig. 2

(p(R, t) and p_{ex} are the pressure inside and outside the casing). Equation (11) describes elastoplastic deformations of the casing up to the moment of its failure. Here it is assumed that failure of the casing occurs when the shear deformation reaches a critical value $\gamma = \gamma^*$ characteristic of the high-speed failure of thin casings.

The system of equations (4)-(13) was solved numerically using the fourth-degree Runge-Kutta method. In the calculations the magnitude of the pressure, the temperature of the fuel, and the deformation of the fuel element casing γ were determined. The initial values of the parameters of the materials are given in Table 1 (ρ_{0f} is the initial density of the fuel element). The dimensions of the fuel element and the initial conditions of the calculation were taken from [4, 5]; an elementary diagram of a single fuel element is given in Fig. 1.

Results of the Numerical Calculations. In [4, 5] the dependence of the pressure on time in a fuel element fully or partially (30%) filled with water was obtained experimentally for pulse durations of 3.82 and 3.02 sec and for a total energy release of 670 and 880 kJ/kg UO_2 respectively. Analogous calculations carried out in accordance with the proposed model are given in Fig. 2 (solid lines), in which they are compared with experimental data (dotted lines). Curves 1 and 1′ refer to a fuel element that is fully filled with water, while 2 and 2′ refer to one that is partially filled. Analysis of the diagrams shows good agreement between the calculated curves and the theoretical ones with regard to both the pressure amplitude and the moment of failure of the fuel elements. In the calculations the squeezing of water from the gap was ignored. The increase in pressure proved to be associated basically with thermal expansion of the fuel. The contribution of the expansion of the water to the general increase in the volume of the medium under the casing of the fuel element did not exceed 20%. This is associated both with the small volume fraction and with the high pressure that significantly exceeded the critical. Taking into account the thermal expansion of the fuel permits matching of the data for the fully and partially filled fuel elements. In particular, the maximum pressure in the two cases proved to be approximately identical, which was also the case experimentally. The nonmonotonicity of the pressure that was observed experimentally for the partially filled fuel element is evidently associated with the beginning of the melting of the fuel.

Determination of the failure threshold of the fuel element as a function of its design and neutron pulse parameters is important for the development of norms and requirements for the safe use of reactors. As was noted in [1], one of the possible mechanisms of failure of a fuel element is oxidation and embrittlement of its casing with subsequent fragmentation at the cooling stage. However, if the pulse is sufficiently powerful, then failure may occur due to high-speed deformation during flash. The failure thresholds as a function of the duration and amplitude of the pulse given in Fig. 3 for various gas phase fractions (α = 1, 3, 5, 7%, curves 1-4) characteristize the dynamic threshold. The dotted curve corresponds to the experimental data of [7]. It is evident that there is satisfactory agreement between the experimental and calculated functions for α = 5%. Partial melting of the fuel was observed. We note that with increase in the gas fraction, the failure threshold increases. This function can be described by the expression

$$Q_* (t_0) = (290 + 240t_0) \text{ cal/g}$$

(t_0, sec). From this formula it is not difficult to obtain the following value for the threshold flash power $W_*(t_0)$:

$$W_* (t_0) = \left(\frac{1,2}{t_0} + 1,0\right) \cdot 10^3 \frac{\text{MW}}{\text{ton}}.$$

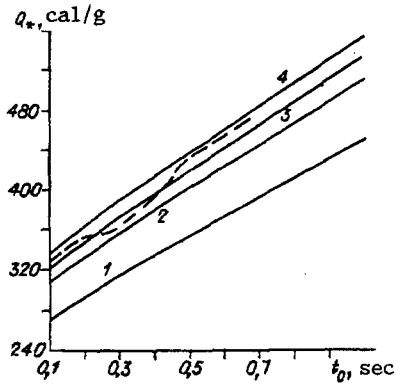

Fig. 3

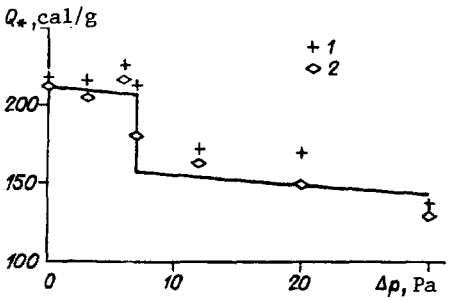

Fig. 4

It is evident that the threshold flash power decreases with increase in the pulse duration and ultimately tends to a constant value about 25-30 times greater than the nominal power of a reactor of the VVÉR type.

Let us consider the dependence of the failure threshold on the difference between the initial pressure in the fuel element and the external pressure. The corresponding experiments were performed in [6]; the external pressure was constant, and the pressure in the fuel element varied. The results of the experiments (points 1 correspond to failure, while points 2 correspond to its absence) and calculations in accordance with the proposed model (the line) are given in Fig. 4. In the calculations it was assumed that gas compression in the pores begins to play a role when the fuel temperature reaches the plastification temperature, which is about 20% less than the melting temperature and equal to ~2400 K. We note that the fuel temperature in the calculations for $\Delta p = 0.6$ MPa was close to this value. Therefore the gas fraction in the calculations for values of $\Delta p < 0.6$ MPa was taken to be equal to 5%, while for $\Delta p > 0.6$ MPa, it was taken to be 2%. With this approach the calculated function agrees satisfactorily with the experimental results.

Conclusion. This article proposes a model describing the deformation and failure of fuel elements through the action of a pulse energy release arising in particular with the uncontrolled introduction of a positive reactivity into the reactor. The basis of the proposed approach is the assumption of the dynamic failure of the casing of the fuel element through the action of internal pressure. The definitive parameter is the maximum deformation γ_*, at the occurrence of which the failure of the casing occurs. Moreover, proper selection of the equation of state of the fuel is essential. In particular, the gas fraction located both under this casing of the fuel element and within the fuel has a marked effect on the failure threshold.

Comparison of the calculation results with the experimental ones shows that this method is able to obtain a good description of the dynamic characteristics (pressure increase in the fuel element) and the dependence of the failure threshold on the duration of the pulse and the initial pressure in the fuel element. The assumption of the constancy of the maximum deformation γ_* results in the energy transferred to the fuel at the moment of failure not being dependent on the flash intensity, which is observed experimentally. The rather good agreement between the results of the calculations within the framework of the proposed approach and a wide spectrum of experimental data indicates that the model is workable. It may be used in further investigations and in modelling of reactivity accidents in reactors of various types and, moreover, in the design and licensing of fuel elements of various types.

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