# ON THE PROBLEM OF HEAT AND MASS EXCHANGE BETWEEN LIQUID METAL SURFACE AND STRUCTURAL ELEMENTS IN FAST REACTORS

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U S S R

Paper to be presented at the IWGFR Specialists' Meeting "Heat and Mass Transfer in the Reactor Cover Gas", October 8-10, 1985, England.

Abstract.

For the development of means ensuring normal operating conditions of the fast reactor vessel some design procedures for calculating temperature conditions of its structural elements over the liquid metal surface are required. The radiative heat transfer from the liquid metal surface playing an important part at working temperatures (550°C), the effect of experimentally detected fog formation process (not taken into account before) upon the radiative heat exchange has been considered.

A simplified heat transfer model based upon separation of thin thermal boundary layers and of the main volume at a constant temperature has been proposed. Calculation relationships for the heat flux from the reactor vessel roof have been obtained by solving a one-dimensional equation of radiation transfer within the boundary layer and a three-dimensional one in the bulk volume at an approximation of moments with Marshak boundary conditions.

Evaluations performed have shown a possibility of a considerable decrease of the vessel roof temperature due to fog formation. The observed asymmetry of the temperature distrubution in the cover gas is explained in this case greater fog density near the evaporation surface and by a possibility of some radiative energy loss due to evaporation from the droplets surface.

Integration of pool-type fast reactors into nuclear power calls for solving a number of complicated technical problems. As was shown by experimental and design studies /1/, strength and leak-tightness of the main reactor vessel are of primary importance for a safe and reliable operation of the BN-600 plant.

A strength analysis aimed at proving an accuracy of design estimates of the normal operating life of the BN-600 vessel most stressed elements (Fig. 1-a) and at the verification of its safe operation for the guaranteed service life has used thermometry results as initial data for temperature distributions calculation. The greatest temperature drops were in the vessel roof at the gas-coolant interface. The stress level in the roof and in the support structure being a sum of total and local temperature stresses is rather high. The results obtained have shown an acceptable accuracy of previously made design studies. It should be noted that in the BN-600 there is only a small gap between the coolant surface and the vessel roof that substantially simplifies the conditions of liquid metal - vessel roof heat exchange determining the vessel roof temperature level, and no detailed study of these processes has been required.

Somewhat different design of the BN-1600 reactor as compared to the BN-600 (Fig. 1a), the presence of considerable cover gas volume between coolant and the reactor vessel roof allow to expect substantially greater difference in temperatures as compared to the BN-600 reactor and, respectively, substantial thermal stresses at the sodium-gas interface.

In order to ensure favourable operating conditions for the vessel due to provision of "cold" coolant circulation at its side surface the temperature of this vessel part is maintained at a level of ~ 400°C. The provision of the same temperature conditions for the roof calls for taking some measures. At the BN-600 reactor the roof is made to the tapered shape that allowed to arrange sodium circulation at its larger part /1/. Similar solution was adopted at the BN-800 reactor (Fig. 1-b).

The development of thermal insulation working in the gaseous atmosphere containing sodium vapour presents a complicated engineering problem.

In large (scale) power reactors of the BN-1600 type (Fig. 1-c) there does not seem feasible to retain the solutions adopted in the BN-600 and BN-800 reactors for the reactor roof. Therefore, in this case heat exchange between the flat uncooled (on the inside)-roof of the reactor vessel and the coolant surface is of primary importance.

Calculations by generally accepted (conventional) methods show the vessel roof temperature to be close to the coolant surface temperature, i.e., 500 - 520°C. Therefore, heat insulation on the roof on the sodium side should be provided. At the same time the results of studies on the determination of heat fluxes from the roof and of the temperature distribution in the cover gas, e.g., published in /2-4/, proved to be rather unexpected and do not conform to the presen viewpoints based on which this reactor component is being designed. At a sodium surface temperature of 550°C the heat flux from the roof was $\sim 600\ w/m^2$ and the temperature of steel structures facing the sodium surface was 350°C. The main temperature drop was observed within the layer of $\sim 15$ mm at the sodium surface and the temperature in the middle part remained approximately constant and equal to $\sim 400$°C (Fig. 2). Attempts to obtain similar results by calculations, as will be shown, to a first approximation, cause a revision of present ideas on heat and mass exchange problems under the conditions considered.

Let us determine from the experimental temperature profile (Fig. 2) the heat flux from the roof under generally accepted heat and mass transfer assumptions. Heat from the coolant surface is transferred to the roof mainly by convection and radiation.

One can judge of the free convection motion intensity by Raileigh (Ra) number which in the present experiment is $\sim 10^8$. At such Ra numbers there should be observed turbulent convection characterized by the formation of thin thermal boundary layers /5/. The middle part of the volume due to mixing has practically constant temperature that is observed in the experiment considered /4/. For the heat flux evaluation let us present the convection problem as heat exchange between a "body" at a constant temperature located in the middle of the volume and boundary surfaces by means of heat conduction through the thin boundary layers. Then local Nusselt number at the roof determining the heat flux will be:

$$Nu_B = \frac{h}{\delta_B} \Big/ \frac{T_0 - T_2}{T_1 - T_2} \qquad (1)$$

In the experiment the boundary layer at the sodium surface is clearly marked. Hence the layer thickness and the middle part temperature can be obtained. At the same time the experiment does not give any information about layer thicknesses at other bourdary surfaces. Therefore, let us express $\delta_B$ for which purpose let us write the heat balance equation under the assumption of equal thicknesses for layers at the roof and at the side surface:

$$S_{Na}\frac{\lambda}{\delta_H}(T_1 - T_0) = (S_{Na} + S_{бок})\frac{\lambda}{\delta_B}(T_0 - T_2) \qquad (2)$$

For ( 2 ) we obtain

$$T_0 = \frac{\alpha\gamma}{1 + \alpha\gamma} T_1 + \frac{1}{1 + \alpha\gamma} T_2 \,, \qquad (3)$$

where

$$\alpha = \frac{S_{Na}}{S_{Na} + S_{бок}} \;; \quad \gamma = \frac{\delta_B}{\delta_H}$$

Using (1), (3) with $T_0 = 400°C$, $\delta_H = 0.015$ m. $h = 0{,}6$ m, $\alpha = 0.62$ /4/ we find $Nu_B = 19$, $q_K \cong 200$ w/m$^2$. From analyzing (3) one can assume that a large temperature drop at the sodium surface is explained by two causes: by a possibility of heat sink through the side surface and by worse heat conduction properties of the lower boundary layer because of its greater thickness ($\gamma = 0{,}5$).

The radiative heat flux for transparent medium can be estimated from the well known relationship:

$$q_r = \frac{1}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \sigma \left( T_1^4 - T_2^4 \right) . \qquad (4)$$

Taking $\varepsilon_1 = 0.1$, $\varepsilon_2 = 0.4$ from (4) we obtain $q_r$=1445 w/m$^2$. Thus, the total heat flux calculated from, along the experimental temperature profile is equal to $\sim$ 1650 w/m$^2$ that is considerably higher than the experimental value ($\sim$600 w/m$^2$).

The estimates presented reveal the determining influence of radiation upon heat transfer. But at the same time they give some ground to assume that (gaseous) atmosphere filling the volume impedes the radiation propagation by sheelding the radiation surface of hot sodium thereby reducing the radiant heat flux. An analysis of published data /6-8/ has shown that in the high temperature sodium surface-inert gas system there is intensive evaporation from the coolant surface into the reactor vessel volume. Under developed turbulent convection conditions, as was noted above, a thermal boundary layer is formed. If the temperature gradient within this layer is sufficiently large and, therefore, the sodium vapour saturation pressure sharply decreases then the partial vapour pressure determined by boundary layer diffusion may exceed the saturation pressure. This results in the formation of fog consisting of fine sodium droplets. Fog formation hinders sodium vapour partial pressure flattening by means of diffusion and respectively, increases the evaporation rate. Relationships obtained on the basis of the model presented here, described well the available experiments on the determination of the evaporation rate. In a number of experiments the fog-formation process was observed visually /7,8/. And in /8/ where evaporation within the cylindrical volume from the sodium surface at a temperature of 550°C was studied it was possible to measure droplets concentration and their size in the middle part.

Therefore, in the cover gas volume, besides sodium vapour and argon, there are sodium drops forming fog which is likely to shield (screen) the radiation surface. If should be noted that the experiments presented in which fog formation was observed were carried out as applied just to cover gas conditions over the sodium surface in fast reactors but with the aim to find out the causes of deposits in the gaps connected with the volume. There was made no relation between fog formation and heat transfer to the roof. However, the above consideration shows that it is possibly the effect of fog upon the radiation heat flux that ultimately determines heat transfer to the roof and probably the temperature gradients obtained in /4/. Only in the last experiment /2,3/ the effect of fog formation upon heat transfer was studied and an attempt to take this phenomenon into account was made in calculating the heat flux to the roof.

There naturally arises a question of the validity of the above estimates on the basis of which the assumptions were made which practically determine possible physical picture of the phenomenon and furnish the basis for constructing a heat transfer model and for heat flux calculation. The validity of the radiative flux estimate seems to cause no doubts. Therefore, an assumption of non-transparency of the medium is sufficiently credible, the more so as fog was experimentally detected as was noted above. In any case its effect upon radiation should be taken into account. But is this effect determining in heat transfer? The answer to this question depends on the accuracy of the convective heat flux estimate. Flux calculation were based on the assumption that heat transfer within the boundary layer was realized by means of heat conduction. Experimental data show that this model gives exact results in a limiting case of $Ra \to \infty$ and works sufficiently well at great Ra corresponding to turbulent conditions. To describe the turbulent convection, a more precise heat transfer model was suggested : at the hot surface there grows a boundary layer which after having achieved a definite thickness "breaks away" forming a "thermal tail (train )"and gives way to a well mixed medium from the middle part. Heating of medium within the layer is carried out by means of heat conduction. This model is experimentally confirmed by observed "thermal tails". Though later on /9/ there appeared some data indicative of the boundary layer stability and of the formation of "tails" on its surface due to heating of the medium through the layer by means of heat conduction. However, all this indicates the validity of the considered approach to the convective heat flux evaluation.

Let us assume that in the middle part where constant temperature is maintained due to good mixing a condition of rediation equilibrium is fulfilled.

A more general relationship may be suggested by expressing the relative boundary layer thickness in (1) in terms of Ra and $Ra_h$ using (3) we obtain:

$$Nu_\delta = C \cdot Ra^{1/3}, \qquad (5)$$

where $C = \frac{(\alpha\gamma)^{1/3}}{\gamma}\left(\frac{\alpha\gamma}{1+\alpha\gamma}\right)^{4/3} Ra^{-1/3}$ ; $Ra = \frac{g\beta(T_1 - T_0)h^3}{\nu a}$

After handling (treating) the experiment /4/ we obtain C=0.021. The relationship suggested was obtained from a single experiment and can be used only at Ra numbers sufficiently close to the experimental one ($\sim 10^8$).

Therefore, as the convection flow estimate seems to be ~~concrete~~ correct, an assumption of preferential heat transfer by radiation and, thus, of the determining effect of non-transparency of medium is quite justified.

Let us now consider the combined action of convection and radiation under the assumption non-transparency of the medium. In the middle part where constant temperature is maintained due to good mixing there is also apparently no radiation heat exchange between volume elements. Therefore, the radiation flux is here equal to zero and a condition of radiation equilibrium is automatically fulfilled which is expressed by equality of heat absorbed by a volume element and of that given up by it.

Then heat transfer is presented as heat exchange between some "body" in the middle part of the volume of a constant temperature and the boundary surfaces through the boundary layers by means of heat conduction and radiation similar to the above mentioned case with transparent medium. Let us calculate at what radiation properties of the medium there can be observed a heat flux and temperature profile obtained in experiment /4/. For this purpase, within the frames of the proposed model a problem of combined heat transfer by radiation and heat conduction within the limits of the boundary layer should be solved. As a first approximation let us assume radiation and heat conduction not to interact with each other. Then the transport equation will become :

$$\frac{\partial^2 G}{\partial \tau^2} = 0 \tag{6}$$

Let us write boundary conditions for this equation in the Marshak form. From the condition of radiation equilibrium in the middle part it follows:

$$G - 4\sigma T_0^4 = 0 \tag{7}$$

With account of (7), boundary conditions for the lower and other boundary layers under the assumption of equality of optical thicknesses of layers near the roof and side surface will be as follow (Fig. 2):

$$\begin{cases} \varepsilon_1 G_1(0) - \frac{2}{3}(2-\varepsilon_1)\frac{dG_1(0)}{d\tau} = 4\varepsilon_1\sigma T_1^4 & (8) \\ G_1(\tau_0^{(1)}) = 4\sigma T_0^4 & (9) \end{cases}$$

$$\begin{cases} G_2(0) = 4\sigma T_0^4 & (10) \\ \varepsilon_2 G_2(\tau_0^{(2)}) + \frac{2}{3}(2-\varepsilon_2)\frac{dG_2(\tau_0^{(2)})}{d\tau} = 4\varepsilon_2\sigma T_2^4 & (11) \end{cases}$$

The temperature of the side surface is assumed, here and below, to be equal to the roof temperature. By solving (6) in combination with (8-11) we obtain for the lower boundary layer:

$$q_r = \frac{4\varepsilon_1}{3\varepsilon_1\tau_0^{(1)} - 2(2-\varepsilon_1)}\,\sigma\,(T_1^4 - T_0^4)\,, \qquad (12)$$

for other boundary layers:

$$q_r = \frac{4\varepsilon_2}{3\varepsilon_2\tau_0^{(2)} - 2(2-\varepsilon_2)}\,\sigma\,(T_0^4 - T_2^4)\,. \qquad (13)$$

As it is necessary, to determine two unknown values $\tau_0^{(1)}$ and $\tau_0^{(2)}$ from two experimental conditions, then the third uncertain value, the upper boundary layer thickness, will be taken equal to the lower layer thickness. Therefore, with account of radiation within the frames of assumptions made, local Nusselt number will be

$$Nu_\delta = \left(\frac{Ra}{Ra_\delta}\right)^{1/3}(1-\theta)^{4/3} + c_2(T_1-T_2)^3\left[(\theta_0-\theta)^4 - (\theta_0-1)^4\right]\frac{h}{\lambda}\,, \qquad (14)$$

where

$$\theta = \frac{T_1 - T_0}{T_1 - T_2}\,;\ \theta_0 = \frac{T_1}{T_1 - T_2}\,;\ c_2 = \frac{4\varepsilon_2}{3\varepsilon_2\tau_0^{(2)} - 2(2-\varepsilon_2)}\,. \qquad (15)$$

The first term in (14) describes the convection heat conduction and is easily got from (5) under the assumption of $\gamma = 1$. The unknown value is determined from the heat balance condition similar to (2) :

$$\left(\frac{Ra}{Ra_\delta}\right)^{1/3}\left[\alpha\theta^{4/3} - (1-\theta)^{4/3}\right]\frac{\lambda}{h} = c_2(T_1-T_2)^3\left[(\theta_0-\theta)^4 - \right.$$

$$\left. -(\theta_0-1)^4\right] + \alpha\, c_1(T_1-T_2)^3\left[(\theta_0-\theta)^4 - \theta_0^4\right]\,, \qquad (16)$$

where

$$C_1 = \frac{4\varepsilon_1}{3\varepsilon_1 \tau_0^{(1)} - 2(2-\varepsilon_1)} \qquad (17)$$

Taking $T_0 = 400°C$, $q = 600\ w/m^2$ /4/, from (14), (16) we obtain $\tau_0^{(1)} = 18$; $\tau_0^{(2)} = 5$.

Large asymmetry of optical layers is determined by the observed temperature of the middle part. If no equality of boundary layer thicknesses near the roof and at the sodium surface is assumed, then there will apparently be no such great difference. In any case it may be stated that the effect obtained is also responsible for the great temperature drop at the sodium surface.

It is interesting to determine what do optical thicknesses asymmetry and their relatively great absolute value mean from the physical point of view. The optical density is determined for spherical particles :

$$\tau = \pi R^2 N \left( Q_a + Q_s \right) H \qquad (18)$$

From (18) it is evident that the optical thickness at the sodium surface should in this case be higher too, as it can be said at once that below both the concentration of particles and the boundary layer thickness are higher. But here the scattering and absorption efficiency coefficients depending on the particle size can play a significant part too. One can assume that at the surface there are more particles of such size that most effectively reduce radiation. A relatively large value of the optical thickness leads to the assumption of the presence here of such particles which very markedly affect the radiation. It may turn out that such a reduction of radiation may be caused even not by drops but by "clusters" made up of several atoms of sodium and always present in vapour. However, one should be careful concerning this conclusion as at lower degrees of roof blackness considerably lower optical thicknesses are required to explain the results of the experiment. To find out the main factor determining the value and asymmetry of optical thicknesses it is necessary to obtain the distribution of particles in size within the volume of the medium and to calculate their radiation properties. It is also necessary to refine the degrees of surface blackness under real conditions as they may greatly affect the final result. Such calculations will allow to refine the physical picture of the phenomenon that can prove to be not quite the same as presented in this paper.

Therefore, the above consideration shows that the main cause of radiation heat flux reduction may be the presence of rather dense fog. The development of a great temperature drop can be explained: by a possibility of heat sink through the side surface, by a large thickness of the boundary layer at the sodium surface, by higher reduction of the radiation flux by the cover gas at the sodium surface. The model considered allows to carry out only estimated calculations but, in our opinion, it indicates correctly the trend of research.

It should be noted that if the proposed model of heat transfer to the roof proves to be correct then there will be no necessity in additional measures on heat insulation of the roof. In this case, the provision of heat insulation on the sodium side not only useless but can result in the opposite effect, i.e. in cooling down of the roof. From this point of view the operating experience of the French reactor Phenix is extremely significant where, due to the delay in the roof temperature rise relative to the vessel side temperature, it proved to be necessary to increase the time of approach to power that resulted in considerably worse reactor characteristics. Therefore, due to great practical importance of the problem considered its further more detailed experimental and theoretical research is required.

Nomenclature.

$G$ = spatial density of incident radiation, $w/m^2$; $\mu$ = cosine of the angle between the radiation propagation direction and the axis $OY$ ; $\beta$ = radiation attenuation factor, I/m ; $\delta$ = thermal boundary layer thickness, m ; $\tau$ = optical thickness; $\tau_0^{(1)}$, $\tau_0^{(2)}$ = optical thicknesses of boundary layers at sodium surface and at other boundary surfaces, respectively; $\sigma$ = Stefan-Boltzmann constant, $w/m^2 deg^4$; $\omega$ = radiation albedo; $\varepsilon_1, \varepsilon_2$ = degrees of blackness of sodium surface and the roof, respectively; $\rho$ = reflectivity of boundary surfaces; R = mean radius of sodium mist droplets, m; N = sodium mist droplet concentration, $I/m^3$ ; $Q_a$, $Q_s$ = absorption and scattering efficiency coefficients, respectively; $q_r$ = radiation flux, $w/m^2$ ; $T$ = temperature, °C; $S_{Na}$ = sodium surface area, $m^2$; $S_{side}$ = side boundary surface area, $m^2$.

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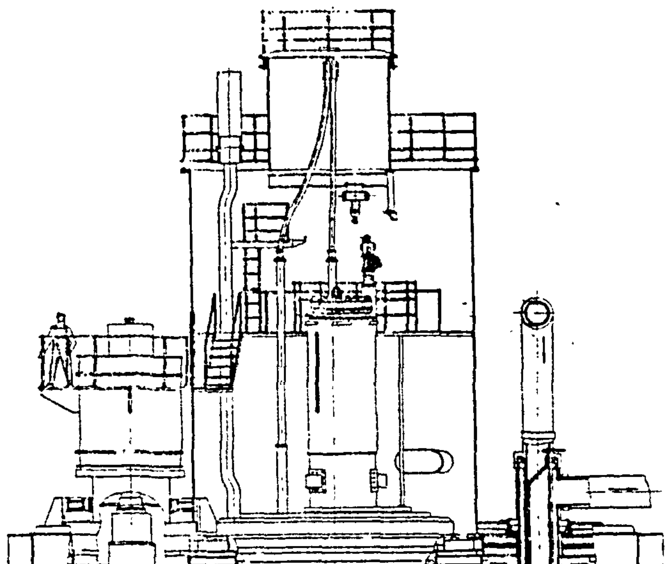


Fig. 1 - a

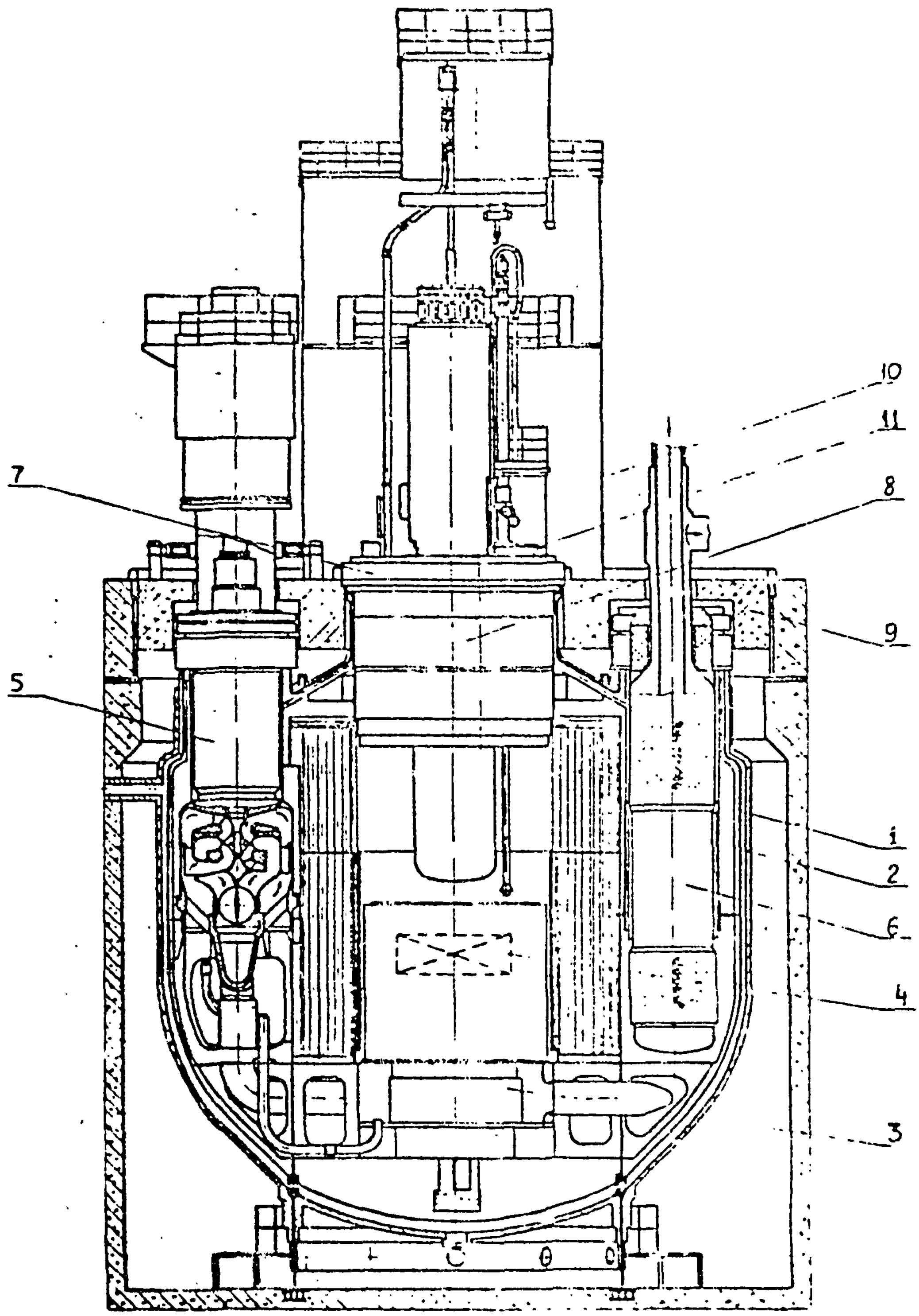
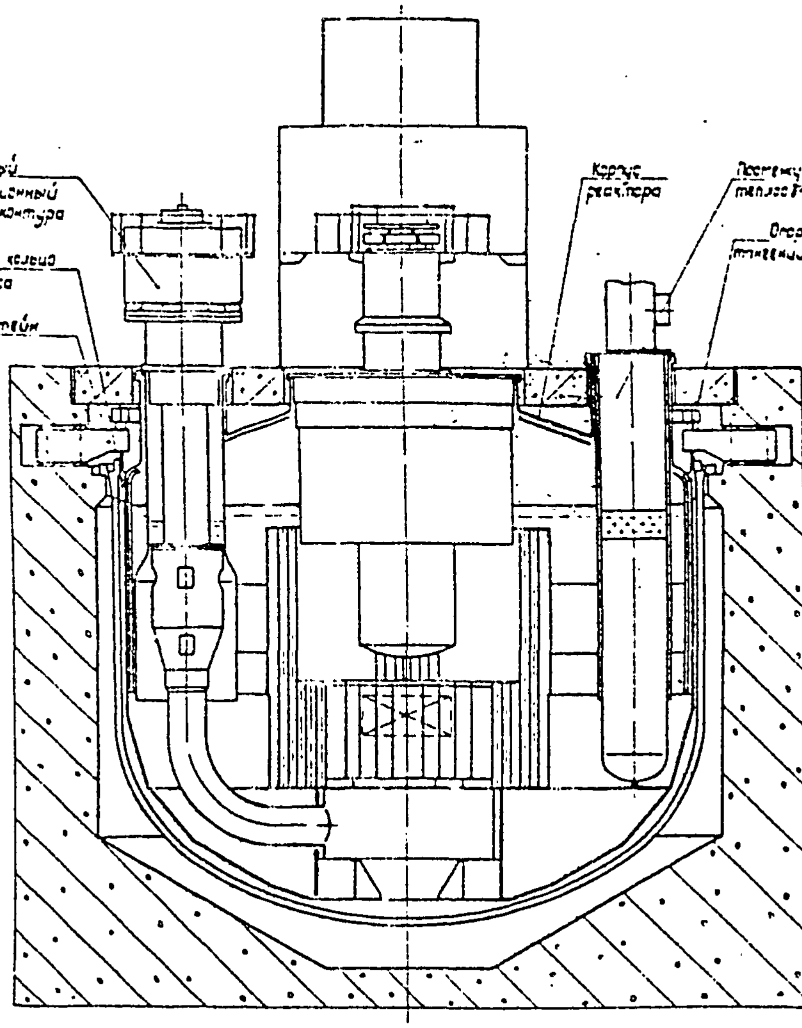



Fig. 1 - b



c)

Fig. 1. Sectional diagrams of the BN-600 (a), BN-800 (b), BN-1600 (c) reactors:

1 = vessel; 2 = containment; 3 = diagrid; 4 = core; 5 = main circulation pump; 6 = heat exchanger; 7 = large rotating plug; 8 = central rotating column with control and safety mechanisms; 9 = uppor stationary shield; 10 = recharging mechanism; 11 = small rotating plug.

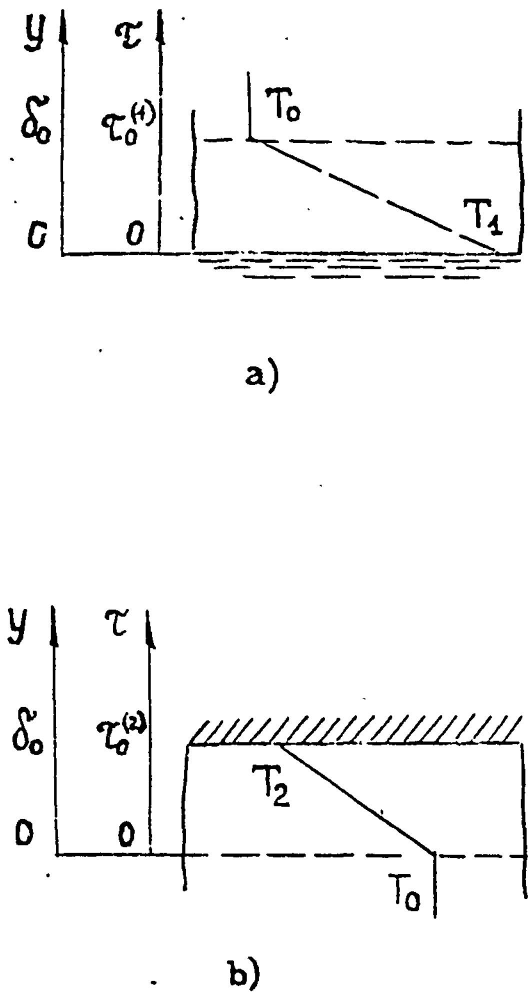



Fig. 2. Calculation schemes : a – for boundary layer at sodium surface; b – for boundary layer at the roof and side surface.

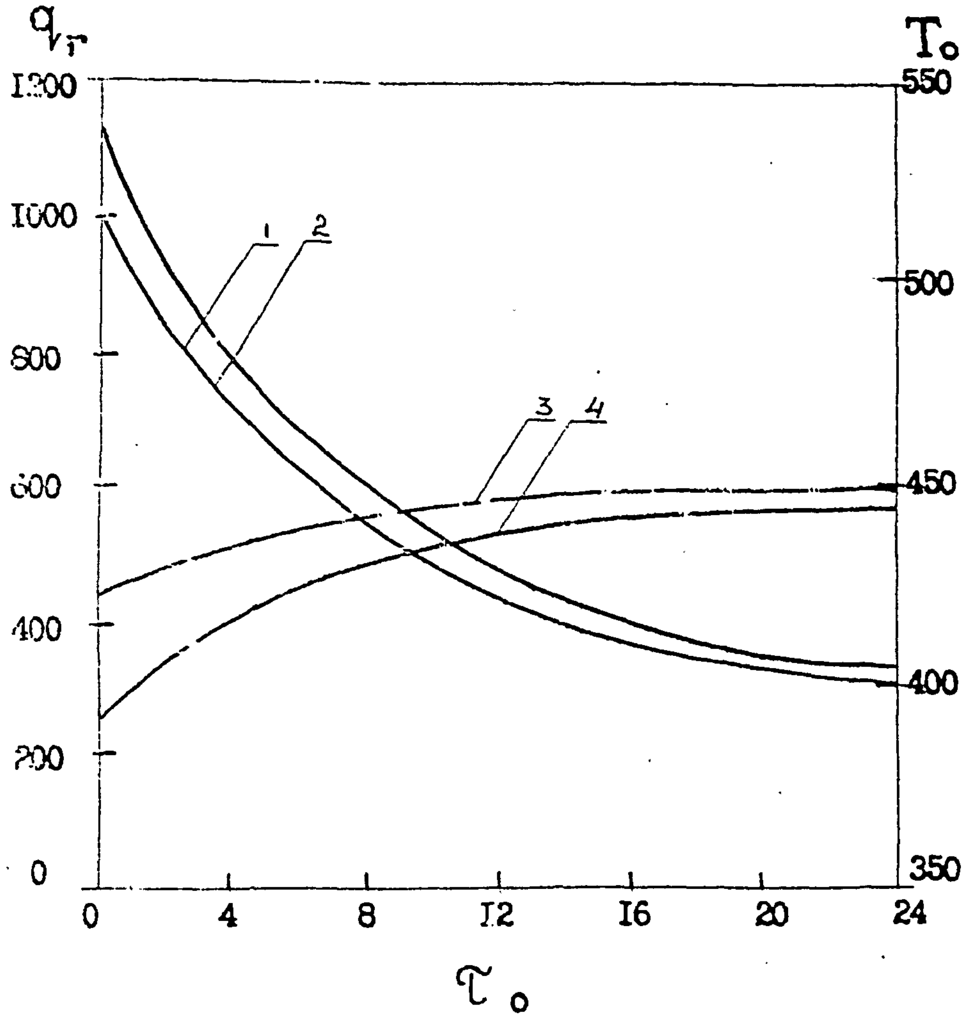



Fig. 3. Radiation flux $q_r$ (w/m$^2$) at :
$1 - \varepsilon_1 = 0.1$; $\varepsilon_2 = 0.4$; $2 - \varepsilon_1 = 0.1$; $\varepsilon_2 = 0.2$;
and the middle part temperature $T_o$ (°C) at :
$3 - \varepsilon_1 = 0.1$; $\varepsilon_2 = 0.2$; $4 - \varepsilon_1 = 0.1$; $\varepsilon_2 = 0.4$
as a function of optical thickness of boundary layers ($\tau_0^{(1)} = \tau_0^{(2)}$).

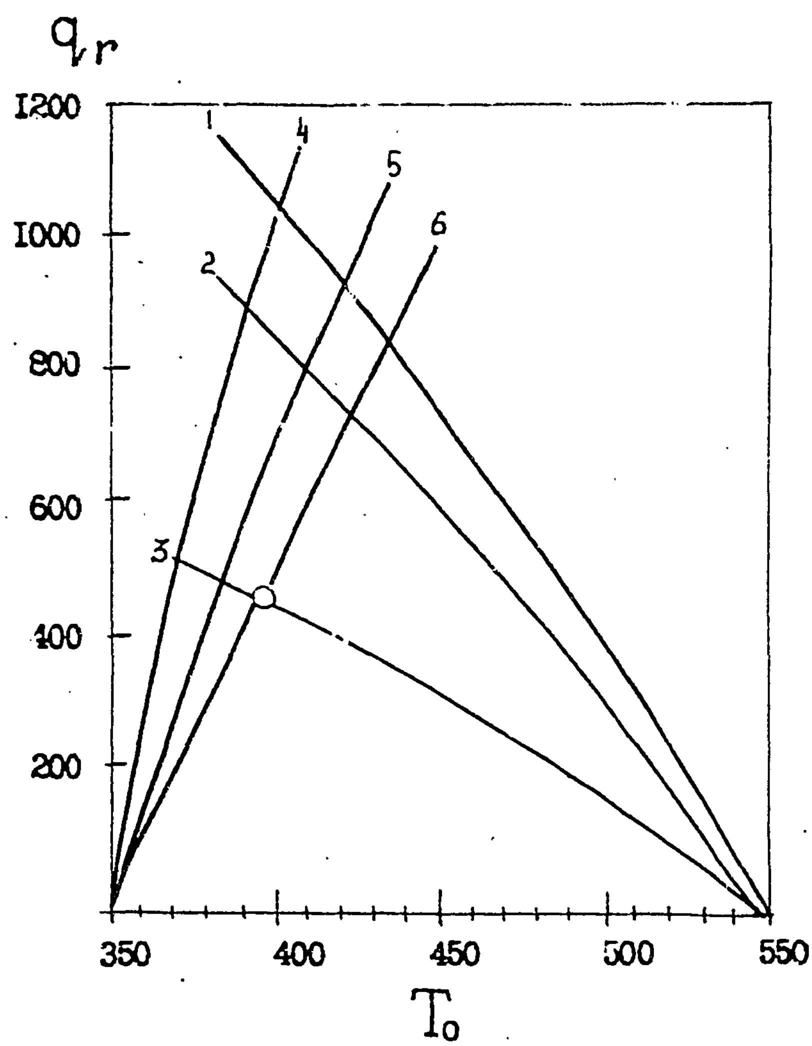



Fig. 4. Radiation flux from the lower boundary layer $q_r^{(1)}$ (w/m$^2$) at : 1 - $\tau_0^{(1)} = 1$; 2 - $\tau_0^{(1)} = 4$; 3 - $\tau_0^{(1)} = 20$; and radiation flux to the vessel roof $q_r^{(2)}$ (w/m$^2$) at : 4 - $\tau_0^{(2)} = 1$; 5 - $\tau_0^{(2)} = 4$; 6 - $\tau_0^{(2)} = 6$ as a function of the middle (central- part temperature $T_0$ (°C).