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SOME PROBLEMS ON THE THERMAL STATE OF THE EXTERNAL CORIUM CATCHER AND ON SELECTING ITS OPTIMUM STRUCTURE

F. A. Akopov,[a] **A. S. Vlasov,**[a]
L. A. Dombrovskii,[a] **L. I. Zaichik,**[a]
Yu. A. Zeigarnik,[a] **V. N. Mineev,**[a] **and**
O. M. Traktuev[b]

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The thermal state of a molten corium and of the walls of the storage chamber of an EPR external corium catcher has been analyzed. It is shown that the strong nonuniformity of distribution of the heat-flux density over the surface of the storage chamber of the catcher makes it impossible to coordinate with the required degree of accuracy the processes of melting of a taphole and the processes of dilution of the oxide component of the melt (required to ensure the inverse stratification of the corium) with sacrificial concrete. Additional technical measures are required to ensure the effectiveness of the catcher.

Different versions of the external corium catcher for confinement of a melt in the case of an accident beyond the design basis at a nuclear power plant with high-power reactors ($N_e > 1000$ MW) are being developed at present because of the fact that for reactors of such power it is technically impossible to prevent the failure of the high-pressure vessel and to confine the molten corium within it only by cooling the exterior surface of the vessel.

One of the most thoroughly worked-out versions is the project of a catcher for a European pressurized reactor (EPR) [1–4]. In this project, the problem of confinement of a molten corium is realized by pouring it over a horizontal surface of large area (~180 m^2) with subsequent cooling by water of both the casing of the catcher and of the melt directly by feeding the water to its free surface. Good spreadability of the melt over the catcher surface is guaranteed by the addition of SiO_2, FeO_x, CaO, and some other materials that reduce the viscosity and the liquidus and solidus temperatures of a melt. A decrease in the height of the melt layer in pouring on a large surface reduces the density of the heat flux removed both from the free surface of the melt and to the base of the catcher.

The main refractory material used in such a catcher is zirconia (ZrO_2) ceramics, which withstands the thermochemical action of the majority of components of a molten corium (metals of the iron group do not interact with ZrO_2, while UO_2 forms a continuous series of solid solutions with it with a solidus temperature not lower than 2500^{o}C).

However, ZrO_2-ceramics fails by interaction with incompletely oxidized zirconium that partially takes the oxygen from it and by interaction with iron (ferric) oxides that impregnate zirconia ceramics at temperatures above 1300^{o}C, dissolve it at high temperatures, and form solutions with it at lower temperatures [5, 6]. In all cases, the ceramics loses its strength properties and chemical resistance.

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[a]Joint Institute of High Temperatures, Russian Academy of Sciences, Moscow, Russia; email: zeigar@oivtran.iitp.ru; [b]Institute of Nuclear Reactors, Russian Scientific Center "Kurchatov Institute," Moscow, Russia. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 75, No. 1, pp. 3–8, January–February, 2002. Original article submitted May 22, 2001.

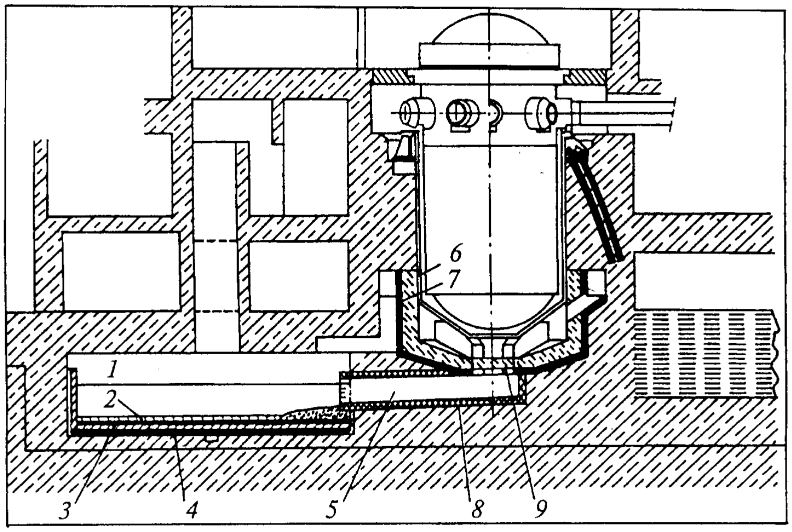

Fig. 1. Schematic of localization of a melt in an EPR [3]: 1) compartment of spreading (bed); 2) sacrificial material (concrete + metal); 3) layer of zirconia; 4) system of cooling of the base; 5) sloping channel; 6) sacrificial material; 7) protective layer; 8) zirconia; 9) melted taphole.

The melt spreading over the catcher is stratified into the oxide and steel components; the components are immiscible. If no special measures are taken, the layer of oxides which are formed in the reactor core where the bulk of the incompletely oxidized zirconium is also dissolved has a higher density and is located at the bottom. Residual heat release occurs precisely in this layer.

Using the effective thermal conductivity model developed at the Institute of High Temperatures of the Russian Academy of Sciences [7, 8], we calculated the thermal state of a molten corium in the catcher and that of the casing of the catcher. The algorithm of numerical solution of the conjugate problem took into account the distinctive features of the transfer of heat by free convection at larger Ra numbers, formation of oxide crusts, melting of the walls (interaction of the wall material with the corium), and radiative removal of heat from the free surface of the melt. The calculation results have shown that a long stay of the melt under conditions of regular stratification of the corium increases the hazard of the thermochemical action of the oxide melts on ZrO_2-ceramics.

The concept of the external catcher of a European pressurized reactor [1] assumes the employment of a certain complex of methods to protect the ZrO_2-ceramics-based refractory coating. By decreasing the density of the oxides through dilution of them with a sacrificial material one attempts to realize the inverse stratification of the corium in the catcher where the metals and not the oxides are found to be at the bottom now and are in contact with the ceramics. To realize this idea the catcher is manufactured in the form of two interconnected compartments: a storage chamber (SCh), or a pit, and a compartment for spreading and subsequent confinement of a molten corium, or a bed (Fig. 1).

The storage chamber is designed to accumulate the molten corium which gradually flows out of the vessel and to prepare ("condition") it for subsequent spreading and transition to the state of inverse stratification in the second compartment of the catcher. For this purpose a layer of sacrificial concrete (SC) based on Fe_2O_3 and SiO_2 is additionally placed on the surface of a ZrO_2 refractory coating. The interaction of the sacrificial concrete with the corium must ensure the complete oxidation of the zirconium left in the corium, dissolution of UO_2, and reduction in the density and the solidus temperature of the oxide part of the molten corium. The calculated time of confinement of the corium in the storage chamber required for completion of these processes and for melting of the steel (with an area of 2.4 m^2) plate (taphole) at its bottom which closes the exit to a connecting channel is about 4700 sec [3].

The concrete base of the compartment of spreading is protected by three layers (from top to bottom): the layer of sacrificial concrete based on iron oxide and borosilicate glass (SiO_2, B_2O_3, and Al_2O_3), the protective layer of steel, and the ZrO_2 refractory layer. The dissolution of sacrificial concrete in this compartment must ensure the inverse stratification of the melt owing to an additional reduction in the density of the oxide part below the density of the metal part. Finally, the oxide layer must emerge and be located above the metal layer which is in contact with the refractory material.

Another very important problem is simultaneously solved. It is well known that in interaction of a molten metal with water it is probable that a vapor explosion (more precisely, explosive boiling of the water) and intense generation of hydrogen will occur, whereas in interaction of the melt of oxides, and primarily of uranium oxide, with water one observes no explosive boiling and the intensity of generation of hydrogen is lower. Thus, when the inverse stratification is carried out, the contact of the metals with water is eliminated since the water is fed to the free surface of the melt on attainment of the inverse stratification.

The metal taphole at the bottom of the storage chamber is also lined with the layer of sacrificial concrete, which must pass to a melt of "conditioned" oxides in ~4100 sec (melting of the taphole metal takes 600 sec). In so doing, the process of conditioning of the molten corium and preparation of the taphole for melting turn out to be time-coordinated, to a certain extent. In premature melting of the taphole, the density of the oxides diluted with sacrificial concrete can turn out to be insufficient for the subsequent inverse stratification of the corium. The delay in the melting time of the taphole can cause a number of unfavorable consequences. They include:

(a) increased arrival of the fused fragments of the vessel, bearing structures, and structural concrete at the upper part of the melt in the storage chamber because of the increase in the degree of their irradiation by the free surface of the molten corium;

(b) erosion of the refractory material in the zone of contact with the oxide mass as a result of the total disappearance of the sacrificial concrete at this site (this process will be accompanied by the dissolution of ZrO_2 in the oxides of the melt and by the corresponding increase in the liquidus temperature and the viscosity of the melt);

(c) occurrence of the inverse stratification of the melt in the storage chamber and redistribution of the heat fluxes to the catcher walls and their deviation from the calculated values.

A delay of the complete "dissolution" of the layer of sacrificial concrete covering the taphole and of the melting of the taphole itself can be caused by the relatively low heat fluxes at the bottom. This is associated with a strong dependence of the intensity of heat transfer by natural convection on the orientation of the heat-exchange surface in the gravity field. Even in the case of unstable stratification where the layer of heat-releasing oxides is located lower than the layer of molten metals, the heat transfer to the horizontal surface is an order of magnitude lower than the heat transfer to substantially (by more than 45^o) inclined horizontal or vertical surfaces.

In (stable) inverse stratification where the layer of metal turns out to be at the bottom and the internal heat release occurs in the upper oxide layers of the melt, the situation is additionally aggravated and the heat flux to the taphole decreases still further (naturally, in relative measurement).

Let us analyze this problem in greater detail as applied to the situations that can occur in the storage chamber.

First we consider the quasistationary regime of interaction of the corium with the walls of the storage chamber in the case of ordinary stratification of a melt where the molten oxides are located at the bottom and are overlain by the layer of molten metals.

The heat balance for the oxide part of the corium basin has the following form:

$$Q = (q_1 + q_3)\,\pi R^2 + q_2 2\pi R H\,. \tag{1}$$

Here $Q = Q_0 \exp(-t/\tau)$ is the total power of the residual heat release and q_1, q_2, and q_3 are the densities of the heat fluxes to the bottom, the lateral surface, and the oxide-steel interface respectively.

Considering that the oxide basin is surrounded on all sides by an oxide crust with a temperature of the interior surface of T_m and the heat transfer by natural convection in the melt volume is sufficiently intense for the melt to have approximately the same temperature T throughout the volume, we rewrite relation (1) in the form

$$Q = [(\alpha_1 + \alpha_3)\,\pi R^2 + \alpha_2 2\pi RH]\,(T - T_\mathrm{m})\ . \tag{1a}$$

The coefficient of convective heat transfer as a function of the angle of inclination of the surface to the horizon χ is given by the relation [5]

$$\alpha \sim \frac{s^{0.75}}{\sqrt{1 + \sqrt{\dfrac{0.18}{\mathrm{Pr}\, s^5}}}}\ , \quad s = \sin(\chi/2)\ . \tag{2}$$

It follows that $\alpha_1 \to 0$ when $\chi \to 0$ and $\alpha_3/\alpha_2 = 1.3\sqrt{1+\sqrt{1.02/\mathrm{Pr}}}\,/\sqrt{1+\sqrt{0.18/\mathrm{Pr}}}$. The last expression for Pr = 0.48 (value typical of oxides) yields $\alpha_3/\alpha_2 = 1.78$. We note that the heat flux q_1 to the bottom is not equal to zero owing to heat conduction. However the thermal conductivity of the oxide components of the corium is very low; therefore, q_1 turns out to be much smaller than q_2.

$$q_2 \approx \frac{Q}{2\pi RH\,(1 + 0.9R/H)}\ . \tag{3}$$

According to formula (3), we have $q_2 \approx 0.44$ W/m^2 for the parameters in question (Q = 35 MW, R = 3 m, H = 1.5 m).

The linear rate of thermal destruction of the concrete on the lateral wall of the chamber in the region of contact with the oxide components of the corium is

$$\dot{d} = \frac{q_2}{\rho L}\ , \tag{4}$$

where L is the effective specific heat of destruction which allows for endothermal chemical reactions, melting, evaporation of the water of hydration, etc.

Data on the values of L are incomplete and very inaccurate. In [3], it is indicated that the ratio of the energy expended on decomposing sacrificial concrete and the chemical energy liberated from the reaction of decomposition of these products (concrete with zirconium) is approximately 1:2.5. This yields L equal to approximately 3200 kJ/kg; then the corresponding rate of erosion of the sacrificial material of the lateral wall under the action of the heat flux q_2 on the source side of the oxide layer will be approximately 0.035 mm/sec for a concrete density of 4 g/cm^3, which is much lower than the erosion rate indicated in [3]. Based on the energy of formation of fayalite (Fe_2SiO_5) from the components of the concrete under the action of the heat which arrives at the wall, the value of L will be 1600 kJ/kg and the destruction rate of the concrete will turn out to be at a level of 0.07 mm/sec, which, most probably, is somewhat closer to reality, although in evaluating the actual rate of destruction of sacrificial concrete, one should take into account the contribution of the "mechanical" failure of a substance (cracking, scaling, etc.) in addition to thermal effects.

We note that on the portion of the lateral wall which is in contact with the molten steel the destruction rate is approximately twice as high because of the concentration, on it, of the heat flux arriving from the oxide-steel interface (so-called "thermal knife"). This means that the thicknesses of the sacrificial material on different portions of the lateral wall must be dissimilar. Moreover, with account taken of the uncertain position of the metal layer ("thermal knife") over the height of the storage chamber in different scenarios of flow of the corium out of the reactor vessel the thickness of the sacrificial layer in the lower part of its lateral surface must be selected with a margin.

Let us try to qualitatively represent the process of destruction of sacrificial concrete on a lateral wall. In the initial contact of the molten corium with a cold concrete wall, a crust is formed (in the oxide zone, this is the oxide crust). Its thickness does not remain constant: it decreases as the concrete is warmed up. The thermal conductivity of concrete is low; therefore, the surface temperature of the concrete wall increases rather rapidly. The maximum possible temperature of the concrete wall T_w is much lower than the melting temperature of the crust T_m, i.e., warming up of the concrete cannot lead to the melting of the oxide crust; its thickness will only decrease somewhat as compared to the initial thickness because of the decrease in the removal of heat to the wall.

As the surface of the concrete is warmed up to the temperature T_w, its thermal decomposition with the release of gaseous and liquid products begins. It is probable that the decomposition begins at a lower temperature and occurs not only on the surface but in the volume of the material as well. In the absence of reliable information on the thermodestruction of concrete we can adopt for evaluations that the decomposition proceeds on the surface at the temperature T_w and that the total heat of endothermal transformations is also absorbed on the wall surface.

As far as the subsequent process is concerned, we can assume the following two schemes:

1. Comparatively lightweight products of decomposition of the concrete are squeezed out upward along the vertical concrete wall without destroying the oxide crust, which turns out to be separated from the concrete by only a small gap. The liquid products of decomposition of the concrete squeezed out upward turn out to be on the corium surface above the layer of molten metal. In the process of squeezing out of the concrete melt, it can partially react with the oxide crust to form a comparatively low-melting eutectic, which, being mixed with the concrete melt, is entrained by it to the basin surface. In [3], these products are classified as slugs.

2. Vigorous yield of the gaseous products of decomposition of the concrete can lead to local disturbances of the integrity of the oxide crust with the formation of "geysers" of sorts. As a result, the mixing and reacting of the concrete melt with the melt of oxides in the immediate vicinity of the chamber walls rather than its displacement to the basin surface will be the dominant process. The evaluations of q and $\dot{d}$ performed earlier were, in essence, true of the second scheme of the process, though without allowance for a certain decrease in the melting temperature of the corium oxide on addition of the concrete melt. The presence of the slug crust on the free surface of the melt can markedly intensify the erosion of the sacrificial concrete of the lateral walls, especially in the "thermal-knife" zone because of a decrease in the quantity of heat removed from the free surface by radiation.

The concrete covering the bottom of the chamber is destroyed much more slowly. If, orienting ourselves to the performed calculations, we adopt that the heat-flux density is $q_1 \approx 0.1$ MW/m^2, we obtain an approximately fourfold lower rate of thermal destruction than on the lateral surface in the zone of the oxide melt and a rate approximately one order of magnitude lower than in the "thermal-knife" zone. In so doing, the relation (given in the project of a European pressurized reactor [1–3]) of the thicknesses of sacrificial concrete above the taphole (~400 mm) and on the lateral walls of the storage chamber (~800 mm) is somewhat doubted in the context of provision of the above-mentioned "synchronization" of the moment of completion of the conditioning of the melt and the moment at which the melting of the taphole begins.

It is indicated in [3] that, by varying the fractional composition and porosity of sacrificial concrete, one can influence the destruction rate of the lower part of the storage chamber by changing the density and

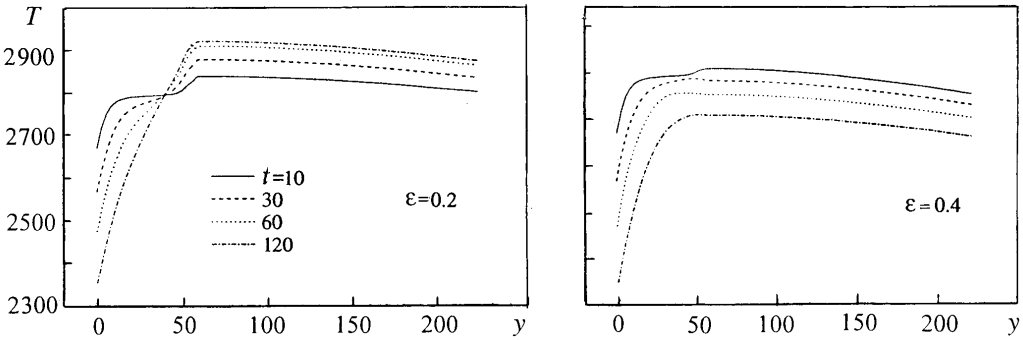

Fig. 2. Axial temperature profiles in the corium basin for different values of the effective emissivity factor ε which are attributed to different concentrations of the aerosols in the gas space of the catcher. T, K; y, cm; t, sec.

mechanical properties of the material. It is not improbable that this proviso is caused by known doubts about whether the accurate determination of the erosion time of this part of the catcher is possible.

Let us consider the version where stratification of the corium can occur before the melt is discharged into the spreading zone. In this case the "thermal knife" disappears, since the heat flux directed from the oxide-metal interface and distributed further by the layer of metals is small. The heat flux to the taphole decreases by virtue of the fact that hotter oxide components turn out to be on the basin surface. This results in a considerable increase in the density of the thermal-radiation flux from the corium basin to the open walls and roof of the storage chamber. We evaluate this effect.

The calculations performed earlier have shown that the integral (over the spectrum) density of the radiation flux is maximum on the lateral surface of the storage chamber in the vicinity of the free surface of the corium basin. The situation where a considerable amount of aerosols, i.e., products of decomposition of the concrete (we are dealing with a volume concentration of about 10^{-6}), turns out to be the most critical thermally. In this case, according to the evaluations performed, the local density of the thermal-radiation flux can attain 1 MW/m^2.

Figure 2 illustrates the influence of the aerosols on the temperature state of a corium in the basin of a storage chamber in the case of inverse stratification of the corium. This evaluation is qualitative in character, since there are no more or less reliable data on a possible concentration of the particles and their size and optical properties.

It is physically clear that the presence of the aerosols causes the effective emissivity factor ε to decrease. Figure 2 shows that when the concentration of the aerosols is high ($\varepsilon = 0.2$) the temperature of the corium basin increases (it becomes "closed" as it were to radiation), whereas for a smaller amount of aerosols ($\varepsilon = 0.4$) the temperature of the corium basin decreases owing to the removal of heat by radiation. This fact can influence the process of conditioning of the corium and introduce an additional indeterminancy into the performed evaluations of its thermal state.

The action of thermal radiation on the concrete roof of the chamber is maximum when the amount of aerosols is insignificant. The upper bound of the radiation-flux density q_r can be obtained in the approximation of a transparent medium. The quantity q_r depends on the relation between the chamber diameter $D = 2R$ and the roof height H_w above the surface of the corium. As was shown in [5], the density of the integral radiation flux to the roof of the chamber can be calculated according to the following approximate formula:

$$q_r = \bar{\varepsilon}\left[1 - 2\frac{H_w}{D}\left(\sqrt{1 + D^2/H_w^2} - 1\right)\right]\sigma\left(T_s^4 - T_w^4\right), \tag{5}$$

where T_s is the surface temperature of the corium basin, T_w is the surface temperature of destroyed concrete, and $\bar{\varepsilon}$ is the reduced emissivity factor which can be taken to be 0.7 in the absence of aerosols.

In accordance with the balance relation (1) with account for (2) and the subsequent computations, we have

$$q_3 \approx \frac{Q}{\pi R^2 \,(1 + 1.1H/R)} \,. \tag{6}$$

For the parameter in question, from formula (6) we obtain $q_3 \approx 0.8$ MW/m^2. This value corresponds to the density of the integral radiation flux removed from the free surface of the basin. Without taking into account, just as earlier, the nonisothermicity of the basin surface, we will consider that

$$q_3 = \sigma \left(T_s^4 - T_w^4 \right), \tag{7}$$

whence

$$q_r = \bar{\varepsilon} \left[1 - 2\, \frac{H_w}{D} \left(\sqrt{1 + D^2/H_w^2 - 1} \right) \right] q_3 \,. \tag{8}$$

The quantity q_r decreases rapidly as the roof height H_w increases. If, for the sake of definiteness, we assume that $H_w = D$, then from formula (8) we obtain $q_r \approx 0.12 q_3 \approx 0.1$ MW/m^2, i.e., this quantity is rather small. Thus, in the absence of aerosols, the surface of the vessel in the vicinity of the free surface of the basin continues to be a critical spot.

The analysis made has shown that the uncertainty of the available data on the destruction rate of sacrificial concrete and the computational error of the intensity of the heat transfer to horizontal and mildly sloping surfaces, especially under conditions of stable temperature stratification, make it impossible to state with a sufficient degree of confidence that the "conditioning" of the melt and its outflow into the spreading zone of the catcher will occur in accordance with design conditions. The calculations show that in the case of natural development of the processes in the storage chamber it is highly probable that we can have the situation where the moments of completion of the conditioning of the melt and of the melting of the taphole will not coincide. To ensure the synchronization of these processes one must take additional technical measures. As one such measure we can mention the above-mentioned profiling of the thickness of the sacrificial-concrete layer over the height of the storage chamber. The indeterminancies in the development of the thermal state of the molten corium in the storage chamber can be smoothed by the arrangement of sacrificial concrete throughout the chamber volume, as has been implemented in the project of the corium catcher of the VVER-1000 at the Tianwan Nuclear Power Plant [9], thus ensuring a much more uniform sink of the residual heat release. The provision for mechanical opening of the taphole can be expedient. The use of sacrificial concrete based on titanium ceramics yielding lower heat release in interaction with unoxidized zirconium and simultaneously ensuring favorable conditions for subsequent immobilization of fission products is promising to a certain extent.

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NOTATION

$\dot{d}$, thermal-destruction rate; H, height; L, specific heat of destruction; N, power; Q, thermal capacity; q, heat-flux density; R, radius; t, time; T, temperature; α, heat-transfer coefficient; χ, angle of inclination of the heat-exchange surface to the horizon; ε, emissivity factor; ρ, density; σ, black-body-radiation constant; τ, characteristic time; Pr, Prandtl number; Ra, Rayleigh number. Subscripts: e, electric; m, melting; r, radiative; s, free surface of the melt; 0, initial state.

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