EFFECT OF ECCENTRIC LOCATION OF THE RBMK CPS DISPLACER GRAPHITE BLOCK IN THE SHIELDING SHEATH

A.I. DOSTOV, Russian Research Centre "Kurchatov Institute"

123182, Moskow, Kurchatov sq., 1, Russia,
E-mail : dostov@dcnr.vver.kiae.ru

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ABSTRACT
Temperature conditions and accumulation of Wigner energy in the graphite block of the RBMK reactor CPS displacer is examined. It is shown, that at eccentric location of the block in the shielding sheath average temperature of the block drop sharply. Due to the design demerit quantity of the stored energy in the block may be so great, that its release will result in melting of the displacer tube.

INTRODUCTION
Displacers of water are provided in Control Power System (CPS) of RBMK reactor. Each displacer consists of a cylindrical graphite block set into an aluminium alloy tube. In neutron irradiation Wigner energy is accumulated in the graphite of the displacer. Till now accumulation of energy in the graphite block was determined subject to the condition of its concentric location in the shielding sheath. At this condition temperature of the block for average heat source power in the block graphite exceeded 100 °Ñ, stored energy was found to be relatively small so that effects which occur through its release might be neglected /1/. However the conditions of assembling, transportation and installation of displacers in the core do not guarantee concentric location of the block about the shielding tube. Consequently eccentric location must be considered as more likely when the reactor safety is analysed. Because of misalignment of the block its average temperature decreases and amount of stored energy increases. In the present work this fact is proved on the basis of analytical solution of the heat conduction equation in the block. It is shown that release of the stored energy may lead to melting of the displacer tube in design accidents initiated by loss of coolant in the CPS cooling circuit

ANALYTICAL SOLUTION
The temperature field in the graphite block can be found, by a method of final differences, basically . However appropriate codes are the property of firms and there are certain difficultlies to use them. Moreover, they are not verified on solution of a similar sort of problems, as a rule. So we conside that it is important to perform analytical estimations of graphite temperature.The model suggested below, allows to make it.

In Fig.1 the mutual arrangement of the graphite block and the tube of the displacer is shown at some eccentricity $\varepsilon = \Delta/\Delta_0$, where Δ=ÀÂ - the misalignment of the centres of the block and the tube, Δ_0 - the nominal gap. At eccentricity a gap δ=DE will be a function of angle φ and it can be determined easily from triangles ADC and BDC:

$$\delta=\sqrt{R^2-(\Delta\sin\varphi)^2}-\Delta\cos\varphi-r_0 \qquad (1)$$

where R - the internal radius of the tube, r_0 - the radius of the block. At small Δ/R the equation (1) can be replaced as follows:

$$\delta=\Delta(1-\cos\varphi) \qquad (2)$$

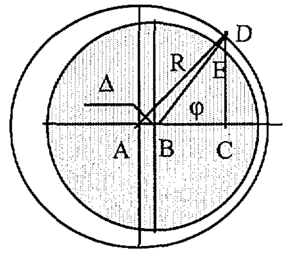

Fig.1 Eccentric location of the graphite block about the tube

The displacer is cooled by water in an annula~~r-channel formed by the dis~~placer tube and the tube separating the CPS channel from the graphite moderator. At concentric location of the block one can use the well known solution of an axisymmetric problem of heat conduction in a multilayer cylinder to calculate a linear heat flux from the graphite block to a coolant

$$q_l = \frac{\pi(t_w - t_o)}{\frac{1}{2\lambda_g}\ln\frac{d_1}{d_o} + \frac{1}{2\lambda_{al}}\ln\frac{d_2}{d_1} + \frac{1}{\alpha d_2}} \qquad (3)$$

Here t_0 and t_w are coolant temperature and block surface temperature respectively, d_0,- the block diameter, d_1, d_2 - the inner and outer diameter of the displacer tube respectively, α - the coefficient of heat transfer from the block surface to the coolant, λ_g - the coefficient of gas in the gap, λ_{al} - the coefficient of heat conduction of the tube material.

The relations of diameters d_1/d_0 and d_2/d_1 for a examined design are close to 1 and therefore the formula (3) can be replaced by the appropriate expression for a infinite plate with large accuracy:

$$q_F = \frac{(t_w - t_o)}{\frac{1}{\alpha} + \frac{\delta}{\lambda_g} + \frac{\delta_{al}}{\lambda_{al}}}, \qquad (4)$$

As heat flow in the gas gap in azimuth direction is negligibly small, width of the gap in (4) can be introduced as function of φ according to the equations (1) or (2). That is

$$q_F(\varphi) = \frac{t_w(\varphi) - t_o}{\frac{1}{\alpha} + \frac{\delta(\varphi)}{\lambda_g} + \frac{\delta_{al}}{\lambda_{al}}} \qquad (5)$$

Within the famework of the accepted model the stationary temperature field in the graphite block can be found as the solution of the Poisson's equation under a boundary condition of the third type:

$$\frac{\partial^2\theta}{\partial\rho^2} + \frac{1}{\rho}\frac{\partial\theta}{\partial\rho} + \frac{1}{\rho^2}\frac{\partial^2\theta}{\partial\varphi^2} = -1 \qquad (6)$$

$$\left.\frac{\partial\theta}{\partial\rho}\right|_{\rho=1} + Bi(\varphi)\theta(1,\varphi) = 0 \qquad (7)$$

In these equations:

$$\theta = \frac{(t - t_o)\lambda_{Gr}}{q_v r_o^2}$$ - dimensionless temperature (8)

$$Bi(\varphi) = \frac{K(\varphi) r_o}{\lambda_{Gr}}$$ - number Bio (9)

$$K(\varphi) = \frac{1}{\frac{1}{\alpha} + \frac{\delta}{\lambda_g} + \frac{\delta_{al}}{\lambda_{al}}}$$ the heat transfer coefficient (10)

q_v - power of internal sources of heat, $\rho = r / r_o$ - the dimensionless radius, r - a current radius, r_0 - the graphite block radius, λ_{Gr} - the heat conduction coefficient of graphite.

The typical relations of Bi against φ are shown in a Fig. 2 at different misalignments of the block.

The technique of the solution of system of the equations (6) - (7) was given in /2/. Its main steps are presented here. If $Bi = Bi^* = const$, where Bi^* is the maximum value of Bi on the block surface, then we have the solution:

$$\theta^* = \frac{1}{2Bi^*} - \frac{\rho^2}{4} + \frac{1}{4} \qquad (11)$$

$$Bi^* = \frac{K^* r_o}{\lambda_{Gr}} \qquad (12)$$

$$K^* = \frac{1}{\frac{1}{\alpha} + \frac{\delta_{al}}{\lambda_{al}}}, \qquad (13)$$

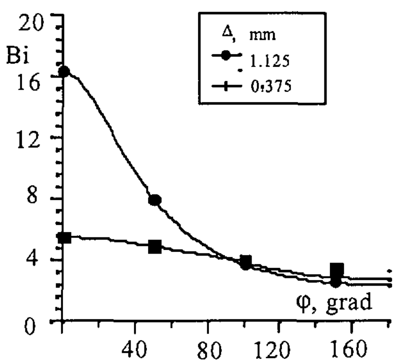

Fig.2 The typical Bi vs. φ relations

Let's introduce the function $\vartheta = \sum_i \vartheta_i$ such that $\theta = \vartheta + \theta^*$. Then

$$\frac{\partial^2 \vartheta_i}{\partial \rho^2} + \frac{1}{\rho}\frac{\partial \vartheta_i}{\partial \rho} + \frac{1}{\rho^2}\frac{\partial^2 \vartheta_i}{\partial \varphi^2} = 0 \tag{14}$$

$$\left.\frac{\partial \vartheta_i}{\partial \rho}\right|_{\rho=1} + Bi(\varphi)\vartheta_i(1,\varphi)|_{\rho=1} = [Bi^* - Bi(\varphi)]\vartheta_{i-1}\,|_{\rho=1} \tag{15}$$

where $\vartheta_0 = \theta^*$. First let us find the solution ϑ_1^0 equations (14)-(15) for i=1 and a boundary condition

$$\frac{\partial \vartheta_1^0}{\partial \rho} + Bi^*|_{\rho=1} = f(0), \tag{16}$$

assuming that $f(0) = a$, *if* $-\beta \le \varphi \le \beta$ and $f(0) = 0$, *if* $\beta < \varphi < 2\pi - \beta$.

The general solution of the equation (15) can be written as

$$\vartheta_i = \frac{A_0}{2} + \sum_{n=1}^{\infty} A_n \rho^n \cos n\varphi, \quad \text{(i=1, 2, ...)} \tag{17}$$

$$A_n = \frac{2}{\pi}\int_0^{\pi} f(\varphi)\cos n\varphi\, d\varphi \quad (n=0,\ 1,\ 2,\ \ldots) \tag{18}$$

Hence , for the boundary condition (16) we have:

$$\vartheta^0{}_i = \frac{1}{\pi}\left(\frac{2a\beta}{Bi^*} + \sum_{n=1}^{\infty}\left(\frac{2a}{\pi n}\sin \beta n\right)\rho^n \cos n\varphi\right.$$

If $a = [Bi^* - Bi(\varphi)]\vartheta^*(1)$, then one can obtain the following equation setting up the corresponding integral sum over all $\Delta\varphi$ and proceeding to its limit:

$$\vartheta_1(\rho,\varphi) = \theta^*(1)\int_0^{2\pi}\frac{Bi^* - Bi(\varphi)}{Bi^*}\frac{1}{\pi}\left(1 + \sum_{n=1}^{\infty}\frac{Bi^*\rho^n \cos n(\varphi - \varphi')}{n + Bi^*}\right)d\varphi' \tag{19}$$

The final expression for temperature distribution in the graphite block can be presented in the form:

$$\vartheta(\rho,\varphi) = \theta^*(\rho) + \theta^*(1)\int_0^{2\Pi}\frac{Bi^* - Bi(\varphi')}{Bi^*}\,G(\rho,\varphi,\varphi')d\varphi' +$$

$$\theta^*(1)\int_0^{2\Pi}\frac{Bi^* - Bi(\varphi')}{Bi^*}\,G(\rho,\varphi-\varphi')\int_0^{2\Pi}\frac{Bi^* - Bi(\varphi'')}{Bi^*}\,G(\rho,\varphi'-\varphi'')d\varphi''d\varphi' + \ \ldots \tag{20}$$

In equation (20) $G\ (\rho,\varphi-\varphi')$ - the Green's function for temperature in a point (ρ,φ) of the block -

$$G(\rho,\varphi,\varphi')=\frac{1}{\pi}\left(1+\sum_{n=1}^{n=\infty}\frac{Bi^{*}\rho^{n}\cos(n(\varphi-\varphi'))}{Bi^{*}+n}\right) \quad (21)$$

Using (20) and (21) let us define temperature on the center of the graphite block and average temperature of the block

$$\vartheta(0)=\theta^{*}(0)+\theta^{*}(1)[q_1(0)+q_2(0)+\ldots+q_n(0)+\ldots] \quad 22)$$

$$\bar{\vartheta}=\bar{\theta}+\theta(1)[\bar{q}_1+\bar{q}_2+\ldots+\bar{q}_n+\ldots] \quad (23)$$

In the equations (22) and (23):

$$\bar{\vartheta}=\frac{1}{\pi}\int_0^{2\pi}\int_0^1\vartheta(\rho,\varphi)\rho d\rho d\varphi \quad (24)$$

$$q_1(\rho,\varphi)=\int_0^{2\pi}\frac{Bi^{*}-Bi(\varphi)}{Bi^{*}}G(1,\varphi-\varphi')d\varphi' \quad (25)$$

Let's notice, that $q_1 < 1$ in each point (ρ, φ), as

$$\frac{Bi^{*}-Bi(\varphi)}{Bi^{*}}<1, \quad (26)$$

and the following relationship is satisfied

$$\int_0^{2\pi}G(1,\varphi-\varphi')d\varphi'=1. \quad (27)$$

It is obvious, that

$$q_1(\rho,\varphi)>q_2(\rho,\varphi)>\ldots>q_n(\rho,\varphi)>\ldots \quad (28)$$

As follows from equations (22), (23) and (24):

$$q_1(0)=\bar{q}_1=q \quad (29)$$

$$q_n(0)=\bar{q}_n=q^n \quad (30)$$

Using expression for the sum of an indefinitely decreasing geometrical series, let us modify (22) and (23) as following:

$$\vartheta(0)=\vartheta^{*}(0)+\vartheta^{*}(1)q\frac{1}{1-q} \quad (31)$$

$$\bar{\vartheta}=\bar{\vartheta}^{*}+\vartheta^{*}(1)q\frac{1}{1-q} \quad (32)$$

When the graphite block is tangent to the displacer tube we have using definition (24) and equation (2):

$$q = \frac{1}{2\pi}\int_0^{2\pi} \frac{Bi^* - Bi(\varphi)}{Bi^*} d\varphi = 1 - \frac{1}{2\pi}\frac{Bi^0}{Bi^*}\int_0^{2\pi} \frac{d\varphi}{1 - a\cos\varphi} = 1 - \frac{K^o}{K^* \sqrt{1-a^2}} \qquad (33)$$

In expression (33) Bi^0 and K^0 correspond to concentric location of the block,

$$Bi^o = \frac{K^o r_o}{\lambda_{Gr}} \qquad (34)$$

$$K^o = \frac{1}{\frac{1}{\alpha} + \frac{\delta_{al}}{\lambda_{al}} + \frac{\Delta_i}{\lambda_g}} \qquad (35)$$

$$a = \frac{\frac{\Delta_o}{\lambda_g}}{\frac{1}{\alpha} + \frac{\delta_{Al}}{\lambda_{Al}} + \frac{\Delta_i}{\lambda_g}} \qquad (36)$$

In Fig.3 an element of the displacer is represented. The outer diameter of graphite block is 66 mm. The block set into an aluminium alloy tube with inner and outerdiameters 69 mm and 74 mm respectively, so that a nominal gap is Δ_0=1.5 mm and thickness of the tube wall is δ=2.5 mm. The heat conduction coefficient of a material of the tube is accepted equal λ_{Al}=175 W/m ^{0}C, the heat conduction coefficient of gas in the gap is equal λ_g = 0,029 w/m ^{0}C /3/. A heat conduction coefficient of graphite depends on a doze of irradiation. If the irradiation occurs at low temperature it can be in 10 - 20 times below the heat conduction coefficient of the not irradiated graphite. Moreover, heat conduction of graphite irradiated at temperature less than 100 ^{0}C is poorly investigated /4/. On the basis of the data and expert estimations the heat conduction coefficient of graphite is taken as λ_{Gr} =4 w/m ^{0}C in the present work. Linear heat source power in the block was taken to equal to 4.12 âò/ñì in agreement with the work /5/ data.
The displacer is cooled by water in an annular channel formed by the displacer tube and the CPS channel tube. The water temperature at the inlet and outlet of the annular channel is 35 ^{0}C and 60 ^{0}C respectively. Pressure in the channel is about 4 kg/cm^2, water velocity is equal to 5 m/s. At these condition a coefficient of heat transfer in the channel can be taken to be equal to α≅2500 w/m^2 ^{0}C. Using these geometrical and operation parameters, temperature on the center of the graphite block and average temperature of the block were evaluated. As a result it was obtained:

K^o = 19.18 w/ì^2

K^* = 2,41∗10^3 w/ì^2

Bi^* = 19,91

Bi^o = 0,1582

a = 0,9921

q = 0.9370

$$\vartheta(0) = \frac{1}{2\cdot 19.91} + \frac{1}{4} + \frac{1}{19,91} 0,937\left(\frac{1}{1-0,937}\right) = 1.022, \qquad (37)$$

or, coming back to dimensional values, one can obtain:

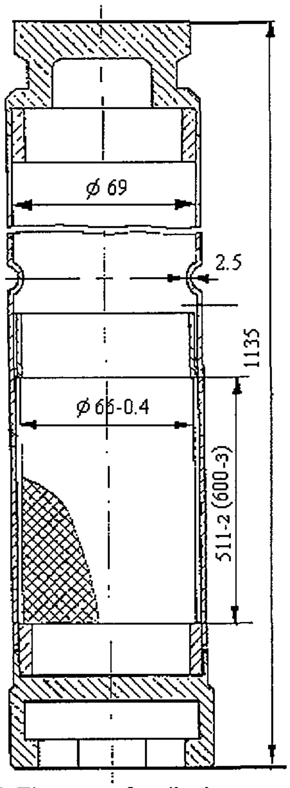

Fig.3 Element of a displacer

$$t(0) = t_o + 1{,}022\frac{q_l}{\pi\lambda_{ab}} = t_o + 1{,}022\frac{420}{3{,}14\cdot 4} \cong t_o + 34{,}2^{\circ}C \qquad (38)$$

Average temperature of the block is calculated similarly. Let us notice that $\bar{\theta}^{*}$ is:

$$\bar{\theta}^{*} = \frac{1}{2Bi^{*}} + \frac{1}{8}, \qquad (39)$$

Then we have

$$\bar{\vartheta} = \frac{1}{2\cdot 19{,}91} + \frac{1}{8} + \frac{1}{19{,}91}0{,}937\left(\frac{1}{1-0{,}937}\right) = 0{,}897 \qquad (40)$$

and

$$\bar{t} = t_o + 0{,}897\frac{q_l}{\pi\lambda_{Gr}} = t_o + 0{,}897\frac{420}{3{,}14\cdot 4} \cong t_o + 30^{\circ}C \qquad (41)$$

Let us find average of temperature of the block at its concentric arrangement. For this purpose the exact analytical solution is used:

$$\vartheta^{o} = \frac{1}{2Bi^{o}} - \frac{\rho^{2}}{4} + \frac{1}{4} \qquad (42)$$

Then

$$\bar{\vartheta}^o = \frac{1}{2Bi^o} + \frac{1}{8} = \frac{1}{2 \cdot 0,1582} + \frac{1}{8} = 3,286 \qquad (43)$$

$$\bar{t}^{\,o} = t_o + 3.286 \frac{q_l}{\pi \lambda_{Gr}} = t_o + 3.286 \frac{420}{3,14 \cdot 4} \cong t_o + 118^o C \qquad (44)$$

The ratio of average temperatures of the block at a concentric arrangement and at maximal misalignment is equal

$$\frac{\bar{\vartheta}^o}{\bar{\vartheta}} = \frac{3,286}{0,897} = 3.663 \qquad (45)$$

That is a sharp decrease of average temperature of the block .takes place at eccentricity. It is obvious, that there can be areas with temperature lower than 70 ^OC in the graphite block both at maximum eccentricity and at some smaller eccentricity. Because of that it is necessary to consider temperature of graphite to be equal to average temperature of coolant. at conservative estimations of accumulation of energy.

STORED ENERGY IN THE GRAPHITE BLOCK

It is known, that in neutron irradiation enthalpy of graphite increases. This stored energy, named also as Wigner energy, can release at increase of temperature of graphite on 40 -100 ^OC higher than operating temperature. It can result in overheating of control rods elements. At normal reactor operation there are no reasons for release of stored energy. However in some accidents heating up of graphite can be brougt about loss of coolant in circuit of cooling of CPS. It can take place, in particular, at design accidents caused by breaks of a collector, damages of a pressure head tank or manifolds of the circuit /1/.

The quantity of the stored energy in graphite is the more the lower temperature of an irradiation and the higher irradiation doze. The amount of the stored energy can reach 600 cal/g. It is believed, that the crystal lattice of graphite can store energy up to 700 cal/g. Wigner energy is characterized by three parameters - complete energy (S), rate of its release ($\partial S/\partial T$) and quantity, which can be released in isothermal annealing. Importance of third parameter was specified in the work /7/ first. If these parameters are known one can evaluate temperature of elements of design considered in concrete process of its interaction with an environment. In more detail these problems are considered in /6/. For an example on Fig.4 stored energy of a sample irradiated at temperature 30 ^OC versus dozes, and appropriate energy released at annealing temperature 800 ^OC are shown. It can be seen, that the top quantity of the released energy is 280 cal/g. In the Fig.4 the doze of an irradiation is given in terms of Mwd/At (Megawatt-days on adjacent ton). Let's show connection of these values with fluence of neutrons in a reactor RBMK.

Service life of RBMK reactor control rods is 5 years, that is in view of capacity factor CF=0.8

$$08 \cdot 10^5 \cdot 365 \cdot 5 \cdot 0.8 \sec$$

At average neutron flux for a fuel cannel

$$0.9 \cdot 10^{14} neutron / cm^2 \sec$$

The neutron fluence is equal to

$$0.9 \cdot 10^{14} \cdot 0.86 \cdot 10^5 \cdot 365 \cdot 0.8 = 1.13 \cdot 10^{22} neutron / cm^2$$

It is known that mean value of fuel burn up in a RBMK reactor over 1000 days is
17500 Mw days/t

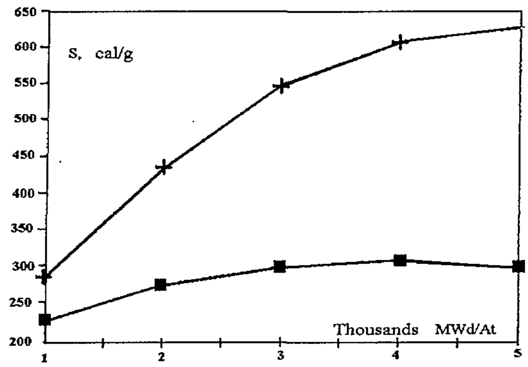

Fig.4 Stored and released energy against rradiation doze.
Temperature of irradiation 30 ^{O}C, annealing temperature 800 ^{O}C.

It means that when fluence is detemined one should take into account RBMK fuel burn up in an adjacent channel within life service of the control rods

25500 Mw days/t

As a result we obtain the following relation between the fluens and the burn up

$$[Mwdays\ /\ t] = 1.13 \cdot 10^{22}\ /\ 25500 = 4.43 \cdot 10^{17} neutron(thermal)\ /\ cm^{2}$$

These calculations show that data of Fig.4 can be used in evaluation of stored energy and energy which would be able to release during accidents mentioned above.

The rate of stored energy release can be determined on the base of annealing kinetics /8/:

$$\frac{dS}{d\tau} = -F(S)e^{-A(S)/T} \qquad (29)$$

In the equation (29) S is quantity of the stored energy remaining in the sample. Energy of activation A (S) and function of state of the sample F (S) can be derived from the Wigner energy release data in two experiments at different rates of growth of graphite sample temperature. It should be pointed out, that, as the release of the stored energy depends on features of crystal structure of graphite, it is necessary to carry out special measurements for graphite of the RBMK reactor graphite. The solution of this problem seems to be extremely tedious. The model of constant energy of activation is usually used. Moreover it is known /8/ that annealing rate will be essential dependent on conditions of heat exchange with environment and a level of temperature of the graphite block. Under such nonlinear problem any prediction would be inconvenient. At the same time release of a large amount of heat in the graphite block can result in melting of displacer tubes. 187 CPS channels have displacers. To prevent mass failure we suggest to decrease stored energy. It could be achieved either by periodic annealing of displacer graphite in special off-reactor devices, or by improvement of the displacer design so as to maintain working temperature of the block above 100 ^{O}C.

CONCLUSION

Eccentricity in the graphite block location in the displacer tube essentially aggravates the problem of stored energy. Investigations of accumulation energy in graphite and rate of its release were carried out up to middle of the sixtieth. However the results obtained do not contain data on properties of RBMK graphite, irradiated at low temperatures.

It has been shown in the present work that melting of displacer tubes can take place in accidents with loss of coolant in the CPS cooling circuit. Stored energy release in RBMK reactor in modeling the accidents can be evaluated now using the constant energy activation model only. Because of that temperature of CPS elements can not be evaluated properly.

Measures are proposed in the present work to decrease stored energy in the graphite of the displacers .

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