PACS: 81.65.K; 28.41.T

CALCULATION OF TEMPERATURE FIELDS IN AMPOULES UNDER THE RADIATION TREATMENT BY ELECTRONS WITH ENERGY 10 MeV

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To obtain the temperature fields in ampoules under the radiation treatment we use the one-dimensional equations of the thermal conductivity on the coordinates along the axis which is congruent with the direction of the beam. The results of the calculations of temperature fields within the ampoule are discussed for two cases: for the ampoule with the molten fluorides mix between three tested Hastelloy specimens (in section 1); and for the ampoule with exhalations of ftuorides salts (in section 2). These two situations are differed as in the energy losses of electron beam, as well in the mechanism of heat transport, that leads to essentially different temperature fields inside of the ampoule. It is shown that for ampoule with fluoride salts exhalations the stationary temperatures strongly depend from heat transport mechanisms and from layers thickness, that leads to conclusion about necessity to take into account both mechanisms of heat transport (thermal radiation and thermal conductivity) simultaneously.

INTRODUCTION

When the projecting the EITF test bench the choice of the geometry of the irradiated ampoules was made so that the energy losses of electron beam were equal to the amount of thermal energy irradiated by target. During the treatment mean current was regulated so that the temperature of the surfaces of ampoules was 650°C. temperature fields within the ampoule is heterogeneous because of the intrinsic heterogeneity of its construction [1], and the finite values of the ampoule contents' thermal conductivity coefficient. It is known that the corrosion processes are controlled by the velocity of chemical reactions and the diffusion transport which are essentially temperature dependent. That's why the knowledge of the temperature distribution inside ampoules is very crucial when one analyzing the tests results. The distribution of energy losses of the electron beam within the ampoule was received by means of Monte-Carlo calculations in Ref. [2]. The ampoules and the assemblies are such that with sufficient accuracy we can consider the distribution of the energy losses and of the temperature as one-dimensional and essentially dependent only on the coordinates along the axis which is congruent with the direction of the beam. This means that we can use the one-dimensional equation of the thermal conductivity to obtain the temperature fields. We have not precition values of thermal conductivity coefficients of the molten fluorides mix, and of tested metallic specimens at the temperature $T \geq 650$ °C, and the data from Refs.[3-4] was used at the numerical estimation.

According to our estimations the temperature in the middle of the ampoule is nearly ten degrees greater than on the surface of the ampoule. This result allow us to consider the evalution data from Refs.[3-4] satisfactory if the analysis of experimantal data for corrosion of tested metallic spacemens does not require calculations of greater accuracy.

Here the results of the calculations of temperature fields within the ampoule are discussed for two cases: for the ampoule with the molten fluorides mix between three tested metallic spacimens (in section 1); and for the ampoule with exhalations of ftuorides salts (in section 2). The later situation can take place in the case when the temperature of the molten fluorides mix is compared with the sublimation temperature, and the tested metallic specimens are located in exhalations of fluorides salts. These two situations are differed in the energy losses of electron beam, as well in the mechanism of heat transport, that leads to essentially different temperature fields inside of the ampoule.

1. THE CALCULATION OF TEMPERATURE FIELDS WITHIN THE AMPOULE WITH THE MOLTEN FLUORIDES MIX

Taken into account that the sizes of intrinsic heterogeneity (≤ 0.2 *cm*) along axis *x*, which is congruent with the direction of the beam (see fig. 1), are much less than vertical dimensions of ampoule (5 *cm* along axis *y*) [1], we can use the one-dimensional equation of the thermal conductivity for calculation of the temperature fields $T(x)$

$$c_v \frac{\partial T}{\partial t} + div J_E = Q \cdot$$

Here $J_E = -div\kappa\nabla T$, $Q = -div J_E$ and κ is thermal conductivity coefficient. Energy flux $J_E(x)$, transported at point *x* by electron beam with initial energy E_0 is equal to

$$J_E(x) = J_E(-b) - \frac{W}{SE_0}\int_{-b}^{x}\frac{\partial E(x')}{\partial x'}dx', \quad J_E(-b) = \frac{W}{S}, \tag{1}$$

where $J_E(-b)$ is flux energy on irradiated surface S of the ampoule, which is equal to beam power W on $1cm^2$, $\partial E(x)/\partial x \equiv \varphi(x)$ is energy losses of electron at point *x*. Here $E(x) = E_0 - \int_{-b}^{x} \frac{\partial E(x')}{\partial x'} dx'$, (2)

is the energy of an electron at point *x*.

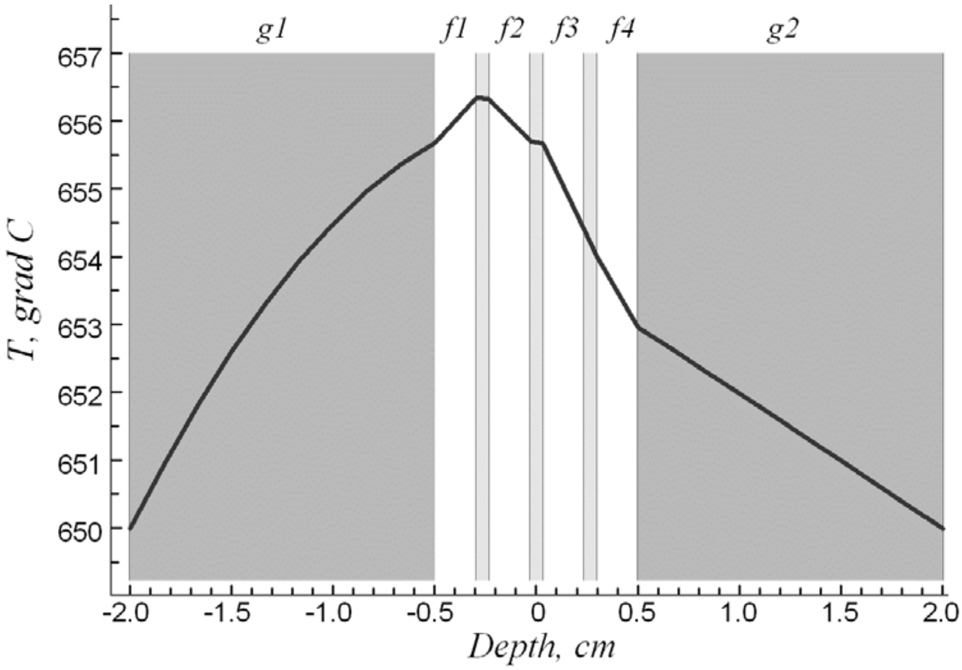

Fig. 1. Temperature fields within the ampoule with molten fluoride salts under the radiation treatment

Energy losses due to the processes of ionization and atomic excitation, are well discribed by Bloch-Bethe formula for a target with thickness less than the track lengh for electron[5]. The target ampoule is made from the Carbon-Carbon (C-C) composite material. But for C-C composite material lengh of electron track is ~2*cm*, and this formula cannot be used for thick layer (here thickness of C-C composite layer is 1.5 *cm* (see fig. 1)). The region

$$-b < x < -a, \ \ a < x < b$$

are the first (g1)and the second (g2) C-C composite layers ($b = 2cm, \ a = 0.5cm$) with thermal conductivity coefficient $\kappa_g \mid_{T=900K} \approx 0.7 \times 10^7 \frac{erg}{cmKsek}$ [3]. For a thick target the main problem in energy losses calculations consists in taking into account multiple scattering of electrons, and in the calculation of the energy losses profile for each layer we used the results of the Monte Carlo computer modeling method from Ref. [2]. For the first C-C composite layer (g1) the mean value is $\bar{\varphi}_{g1}(x) = \varphi_{g1} \approx 3MeV/cm^3$, and for second C-C composite layer (g2) it is

$$\bar{\varphi}_{g2}(x) = \varphi_{g2} = 0.03 MeV / cm^3 .$$

The inside of the ampoule $-0.5 \le x \le 0.5$ has four the layers of molten fluorides liquid mix (the thickness of each layer is equal

$\Delta_{f1} = \Delta_{f2} = \Delta_{f3} = \Delta_{f4} = 0.205cm$),

and three layers of tested metallic specimens (species of Hastelloy Nickel-Molybdenum-Chromium alloy), the thickness of layer is equal $\Delta_{h1} = \Delta_{h2} = \Delta_{h3} = 0.06cm$, (see fig. 1). According Ref. [2] the mean values of energy losses in these layers are equal to

$$\varphi_{h1} \approx 8\frac{MeV}{cm^3}, \ \varphi_{h2} \approx 7\frac{MeV}{cm^3}, \ \varphi_{h3} \approx 0.65\frac{MeV^3}{cm^3}, \qquad (3).$$

$$\varphi_{f1} = 7\frac{MeV}{cm^3}, \ \varphi_{f2} = 5\frac{MeV}{cm^3},$$

$$\varphi_{f3} = 0.6\frac{MeV}{cm^3}, \varphi_{f4} = 0.09\frac{MeV}{cm^3}.$$

For the thermal conductivity coefficients κ_f of molten fluoride salts and tested metallic specimens κ_h at $1000K \ge T \ge 923K$ we used evalution data from Refs. [3-4]: $\kappa_f \approx \kappa_h \approx 0.2 \times 10^7 \frac{erg}{cm \ K \ sek}$.

At thermal balance we can find the stationary distrbution of temperature fields within the ampoule from thermal conductivity equations with the source of heat (energy flux J_E) and sink of heat due to thermal radiaton by C-C composite layers in camera σT^4 where σ is Stephan-Boltzman constant. Let $T_{g1}(x), \ T_{g2}(x)$ be the temperature fields for C-C composite sides of the ampoule, $T_{fi}(x)$ is the temperature field for *i*-th molten fluorides liquid mix layer fi (*i*=1,2,3.4), and $T_{hi}(x)$ is the temperature field for *i*-th tested metallic specimen hi (*i*=1,2,3).

1.1. THE TEMPERATURE FIELD FOR THE C-C COMPOSITE FIRST LAYER

Thermal conductivity equation for the C-C composite first layer $-2 \le x \le -0.5$ is

$$\frac{\partial}{\partial x}\kappa_g \frac{\partial T_{g1}(x)}{\partial x} = \frac{\partial}{\partial x} J_E(x),$$

$$\sigma T_{g1}^4(-2) = \kappa_g \frac{\partial T_{g1}}{\partial x}\Big|_{x=-2}, \qquad (4)$$

where $T_{g1}(-2) \sim 650$ºC is the temperature of the irradiated surface of the first C-C composite layer.

Second boundary condition is

$$\kappa_g \frac{\partial}{\partial x} T_{g1}(x)\Big|_{x=-0.5} = \kappa_f \frac{\partial}{\partial x} T_{f1}(x)\Big|_{x=-0.5}, \qquad (5)$$

and then after integrating (4) from -2 to x we get

$$\kappa_g \frac{\partial T_{g1}(x)}{\partial x} - \kappa_g \frac{\partial T_{g1}}{\partial x}\Big|_{x=-2} = J_E(x) - J_E(-2), \qquad (6)$$

and taking into account the first boundary condition at $x=-2$ (4), we receive

$$\kappa_g \frac{\partial T_{g1}(x)}{\partial x} = \sigma T_{g1}^4(-2) + J_E(x) - J_E(-2) = \sigma T_{g1}^4(-2) - \frac{W}{SE_0}\int_{-2}^{x}\frac{dE(x')}{dx'}dx'. \qquad (7)$$

So after integrating (7) from -2 to x, we receive the temperature field for the first C-C composite layer $T_{g1}(x)$:

$$\kappa_g[T_{g1}(x) - T_{g1}(-2)] = (x+2)\sigma T_{g1}^4(-2) - \frac{W}{SE_0}\int_{-2}^{x}dx'\int_{-2}^{x'}\varphi_{g1}(x'')dx'',$$

where

$$\int_{-2}^{x}dx'\int_{-2}^{x'}\varphi_{g1}(x'')dx'' = \int_{-2}^{x}dx''\varphi_{g1}(x'')\int_{x''}^{x}dx' = \int_{-2}^{x}dx'\varphi_{g1}(x')(x-x').$$

The temperature difference on the boundaries of first **C-**C composite layer is

$$\kappa_g[T_{g1}(-0.5) - T_{g1}(-2)] = 1.5[\sigma T_{g1}^4(-2) - \frac{1.5W}{2SE_0}\varphi_{g1}]. \qquad (8)$$

1.2. THE TEMPERATURE FIELDS IN THE INSIDE OF THE AMPOULE

Taking into account that all seven layers in the inside of the ampoule have essentially different values of energy losses, we must receive thermal conductivity equations separately.

In the first layer $f1$ of molten salts

$-0.5 \le x \le -0.295$ **t**he energy flux is equal

$$J_E(x) = \frac{W}{SE_0}[E(-0.5) - \int_{-0.5}^{x}\varphi_{f1}(x')dx'],$$

$$E(-0.5) = E_0 - \int_{-2}^{-0.5}\varphi_{g1}(x)dx$$

and the first integral of thermal conductivity is equal to

$$\kappa_f \frac{\partial T_{f1}(x)}{\partial x} - \kappa_f \frac{\partial T_{f1}}{\partial x}\Big|_{x=-0.5} = -\frac{W}{SE_0}\int_{-0.5}^{x}\varphi_{f1}(x')dx'. \qquad (9)$$

After integration of (9) with the use second boundary condition (6) we receive the equation for the temperature fields

$$\kappa_f[T_{f1}(x) - T_{f1}(-0.5)] = [\sigma T_{g1}^4(-2) - \frac{W}{SE_0}\int_{-2}^{-0.5}\varphi_{g1}(x)dx](x+0.5) - \frac{W}{SE_0}\int_{-0.5}^{x}\varphi_{f1}(x')(x-x')dx',$$

and the temperature field with mean values of energy losses is equal

$$\kappa_f[T_{f1}(x) - T_{f1}(-0.5)] = (x+0.5)[\sigma T_{g1}^4(-2) - 1.5\frac{W\varphi_{g1}}{SE_0} - \frac{W\varphi_{f1}}{2SE_0}(x+0.5)]. \qquad (10)$$

The substitution of x=-0.295 into (10) gives us the equation for the temperature $T_{f1}(-0.295)$ at the right hand boundary of the first layer of molten salts

$$\kappa_f[T_{f1}(-0.295) - T_{f1}(-0.5)] = 0.205[\sigma T_2^4(-2) - \frac{W}{SE_0}(1.5\varphi_{g1} - 0.205\varphi_{f1}/2].$$

In the first layer $h1$ of Hastelloy

$-0.295 \le x \le -0.235$ **t**he energy flux is

$$J_E(x) = \frac{W}{SE_0}[E(-0.295) - \int_{-0.235}^{x}\varphi_{f1}(x')dx'],$$

$$E(-0.295) = E_0 - 1.5\varphi_{g1} - 0.205\varphi_{f1}$$

and after integration we receive $T_{h1}(x)$

$$\kappa_f[T_{h1}(x) - T_{f1}(-0.295)] = (x+0.295)\times \times\{\sigma T_{g1}^4(-2) - \frac{W}{SE_0}[1.5\varphi_{g1} + 0.205\varphi_{f1} + (x+0.295)\varphi_{h1}/2]\}. \qquad (11)$$

The substitution of x=-0.235 into (11) gives us the equation for the temperature $T_{h1}(-0.235)$ at the right hand boundary of the first layer of Hastelloy

$$\kappa_f T_{h1}|_{-0.235} = \kappa_f T_{f1}(-0.295) + 0.06\{\sigma T_{g1}^4(-2) - \frac{W}{SE_0}[1.5\varphi_{g1} + 0.205\varphi_{f1} + 0.06\varphi_{h1}/2]\} \quad (11a).$$

In the second layer $f2$ of molten salts

$-0.235 \le x \le -0.03$ **t**he energy flux is

$$J_E(x) = \frac{W}{SE_0}[E(-0.235) - \int_{-0.235}^{x}\varphi_{f1}(x')dx'],$$

$$E(-0.235) = E_0 - 1.5\varphi_{g1} - 0.205\varphi_{f1} - 0.06\varphi_{h1},$$

that leads to the equation for the temperature $T_{f2}(x)$

$$\kappa_f [T_{f2}(x) - T_{h1}(-0.235)] = (x + 0.235) \times$$
$$\times \{\sigma T_{g1}^4(-2) - \frac{W}{SE_0}[1.5\varphi_{g1} + 0.205\varphi_{f1} + \quad (12)$$
$$+ 0.06\varphi_{h1} + (x + 0.235)\varphi_{f2} / 2]\}.$$

Taking x=-0.03 we find the temperature $T_{f2}(-0.03)$ at the right hand boundary of the second layer of molten salts:

$$\kappa_f T_{f2}(-0.03) = \kappa_f T_{h1}(-0.235) + 0.205 \times$$
$$\times \{\sigma T_{g1}^4(-2) - \frac{W}{SE_0}[1.5\varphi_{g1} + 0.205\varphi_{f1} + \quad . \quad (13)$$
$$+ 0.06\varphi_{h1} + 0.205\varphi_{f2} / 2]\}$$

For the rest temperature fields

$T_{h2}(x),\ T_{f3}(x),\ T_{h3}(x),\ T_{f4}(x)$ in the inside of the ampoule the similar calculations are consequtively repeated, and we determine the temperature fields by means of the system of equations:

Second Hastelloy layer

$$\kappa_f [T_{h2}(x) - T_{f2}(-0.03)] = (x +$$
$$+ 0.03)\{\sigma T_{g1}^4(-2) - \frac{W}{SE_0}[1.5\varphi_{g1} + \quad (14)$$
$$+ 0.205\varphi_{f1} + 0.06\varphi_{h1} + (x + 0.03)\varphi_{f2} / 2]\},$$
$$\underline{-0.03 \le x \le 0.03.}$$

Third molten salts layer

$$\kappa_f [T_{f3}(x) - T_{h2}(0.03)] = (x - 0.03) \times$$
$$\times \{\sigma T_{g1}^4(-2) - \frac{W}{SE_0}[1.5\varphi_{g1} + 0.205\varphi_{f1} + \quad (15)$$
$$+ 0.06\varphi_{h1} + 0.235\varphi_{f2} + (x - 0.03)\varphi_{h2} / 2]\},$$
$$\underline{0.03 \le x \le 0.235.}$$

Third Hastelloy layer

$$\kappa_f [T_{h3}(x) - T_{f3}(0.235)] = (x -$$
$$- 0.235)\{\sigma T_{g1}^4(-2) - \frac{W}{SE_0}[1.5\varphi_{g1} +$$
$$+ 0.205\varphi_{f1} + 0.06\varphi_{h2} + 0.235\varphi_{f2} + \quad (16)$$
$$+ 0.06\varphi_{f3} + x(-0.235)\varphi_{f3} / 2]\},$$
$$.\underline{0.235 \le x \le 0.295.}$$

Fourth molten salts layer

$$\kappa_f [T_{f4}(x) - T_{h3}(0.295)] = (x -$$
$$- 0.295)\{\sigma T_{g1}^4(-2) - \frac{W}{SE_0}[1.5\varphi_{g1} +$$
$$+ 0.205\varphi_{f1} + 0.06\varphi_{h2} + 0.205\varphi_{f2} + \quad (17)$$
$$+ 0.06\varphi_{h3} + (x - 0.295)\varphi_{f3} / 2]\},$$
$$\underline{0.295 \le x \le 0.5.}$$

1.3. THE TEMPERATURE FIELD FOR SECOND THE C-C COMPOSITE LAYER

In second the C-C composite layer $0.5 \le x \le 2$ the energy flux is equal

$$J_E(x) = \frac{W}{SE_0}[E(0.5) - \int_{0.5}^{x} \varphi_{g2}(x')dx'],$$
$$E(0.5) = E_0 - 1.5\varphi_{g1} - 0.205\varphi_{f1} - 0.06\varphi_{h1} -$$
$$- 0.205\varphi_{f2} - 0.06\varphi_{h2} - 0.205\varphi_{f3} - 0.06\varphi_{h3} - 0.205\varphi_{f4};$$

and the first integral of thermal conductivity equation is

$$\kappa_g \frac{\partial T_{g2}}{\partial x} - \kappa_g \frac{\partial T_{g2}}{\partial x}|_{x=-0.5} = -\frac{W}{SE_0}\int_{-0.5}^{x} \varphi_{f1}(x')dx'. \quad (18)$$

Using second boundary condition

$$T_{g2}(0.5) = T_{f4}(0.5)$$

after integration of (18) we receive second integral of thermal conductivity equation

$$\kappa_g [T_{g2}(x) - T_{f4}(0.5)] = (x - 0.5) \times$$
$$\times \{\sigma T_{g2}^4(-2) - \frac{W}{SE_0}[1.5\varphi_{g1} + 0.205\varphi_{f1} + \quad . \quad (19)$$
$$+ 0.06\varphi_{h1} + 0.205\varphi_{f2} + 0{,}06\varphi_{h2} + 0.205\varphi_{f3} +$$
$$+ 0{,}06\varphi_{h3} + 0.205\varphi_{f4} + (x - 0.5)\varphi_{g2} / 2]\}.$$

Taking x=2 in (19) we can find the temperature $T_{g2}(2)$ at the right hand boundary of the second layer of C-C composite.

Thus, in sections 1.1-1.3 we received the equations for the calculations of the temperature fields in each layer of ampoule under the radiation treatment by electrons with energy 10 MeV. These equations ought to be completed by the equation for determination of the temperature $T_{g1}(-2)$, for which above we used the result of the experimental measurements[2]. We get this equation from summarizing all the equations for the temperature difference on the boundaries of each layer:

$$\sigma[T_{g1}^4(-2) + T_{g2}^4(2)] = \frac{W}{SE_0}[\int_{-2}^{-0.5} \varphi_{g1}(x)dx +$$
$$+ \int_{-0.5}^{-0.295} \varphi_{f1}(x)dx + \int_{-0.295}^{-0.235} \varphi_{h1}dx + \int_{-0.235}^{-0.03} \varphi_{f2}(x)dx + \quad (20)$$
$$+ \int_{-0.03}^{0.03} \varphi_{h2}dx + \int_{0.03}^{0.235} \varphi_{f3}dx + \int_{0.235}^{0.295} \varphi_{h3}dx +$$
$$+ \int_{0.295}^{0.5} \varphi_{f4}dx + \int_{0.5}^{2} \varphi_{g2}dx].$$

This estimation comes to agreement with the results of measurements [1] and of our calculations

$$T_{g1}(-2) \approx T_{g2}(2) \approx 650\,^{\circ}\mathrm{C}.$$

1.4. THE RESULTS OF CALCULATIONS OF THE TEMPERATURE FIELDS

We caried out calculations of the temperature fieldsfor each layer of the ampoule under radiation treatment by electrons with energy 10 MeV. The area of an am¬poules assemblage $S_0 = 320 см^2$. The parameters of electron beam are: initial energy $E_0 = 10MeV$; power beam $W = 5kw/cm^2$. For all layers of the ampoule under radiation treatment we received nine equations with $\varphi'_{ki} = W\varphi_{ki} / SE_0$, where k is label of layer, and i is number of this layer:

The C-C composite first layer

$-2 \le x \le -0.5,\ \varphi'_{g1} \approx 1.98 \times 10^7\, erg / cm$:

$$T_{g1}(x) \cong 923 + \frac{x+2}{0.7}[4.137 - (x+2)\varphi'_{g1} / 2],$$

$$T_{g1}(-0.5) \approx (923 + 5.67)K.$$

The first layer of molten salts

$-0.5 \le x \le -0.295,\ \varphi'_{f1} \approx 4.95 \times 10^7\, erg / cm$:

$$T_{f1}(x) \cong T_{g1}(-0.5) + \frac{x+0,295}{0.2}[1.167 - 4.95(x+0.295)];$$

$$T_{f1}(-0.295) \cong T_{g1}(-0.5) + 0.66.$$

The first layer $h1$ of Hastelloy

$-0.295 \le x \le -0.235,\ \varphi'_{h1} \approx 7.26 \times 10^7\, erg / cm.$

$$T_{h1}(x) = T_{f1}(-0.295) + \frac{x+0.295}{0.2}[0.153 - 7.26(x+0.295)/2],$$

$$T_{h1}(-0.235) = T_{f1}(-0.295) - 0.02;$$

$$T_{h1,\max}\,|_{x=-0.275} \approx [T_{g1}(-2) + 6.36]K \cong 929.36K.$$

The second layer $f2$ of molten salts

$-0.235 \le x \le -0.03,\ \varphi'_{f2} \approx 3.3 \times 10^7\, erg / cm$:

$$T_{f2}(x) = T_{h1}(-0.235) + \frac{x+0.235}{0.2} \times [-0.28 - 3.3(x+0.235)/2];$$

$$T_{f2}(-0.03) \cong [T_{h1}(-0.235) - 0.65]K.$$

The second layer h2 of Hastelloy

$-0.03 \le x \le 0.03,\ \varphi'_{h2} \approx 4.62 \times 10^7\, erg / cm$:

$$T_{h2}(x) = T_{f2}(-0.03) + \frac{x+0.03}{0.2} \times [-0.96 - 4.62(x+0.03)/2];$$

$$T_{h2}(0.03) \cong T_{f2}(-0.03) - 0.33 \approx 928.67K.$$

The third layer f3 of molten salts

$0.03 \le x \le 0.235,\ \varphi'_{f3} \approx 0.4 \times 10^7\, erg / cm$:

$$T_{f3}(x) = T_{h2}(0.03) + \frac{x-0.03}{0.2}[-1.1 - 0.4(x-0.03)/2];$$

$$T_{f3}(0.235) \cong T_{h2}(0.03) - 1.14 \approx 927.40(K).$$

The third layer h3 of Hastelloy

$0.235 \le x \le 0.295,\ \varphi'_{h3} \approx 0.4 \times 10^7\, erg / cm$:

$$T_{h3}(x) = T_{f3}(0.235) + \frac{x-0.235}{0.2} \times [-1.317 - 0.4(x-0.235)/2];$$

$$T_{h3}(0.295) \cong T_{f3}(0.235) - 0.39 \approx 927.01(K).$$

The fourth layer f4 of molten salts

$0.295 \le x \le 0.5,\ \varphi'_{f4} \approx 0.09 \times 10^7\, erg / cm$:

$$T_{f4}(x) = T_{h3}(0.295) - \frac{x-0.295}{0.2} \times [-1.341 - 0.09(x-0.295)/2];$$

$$T_{f4}(0.5) \cong T_{h3}(0.295) - 1.35 \approx 925.96(K).$$

The C-C composite second layer

$0.5 \le x \le 2,\ \varphi'_{g2} \approx 0,02 \times 10^7\, erg / cm$:

$$T_{g2}(x) = T_{f4}(0.5) + \frac{(x-0.5)}{0.7} \times [-1.359 - 0.02(x-0.5)/2];$$

$$T_{g2}(2) \cong T_{f4}(0.5) - 2.7 \approx 923.02K.$$

The results of calculations of temperature fields in ampoules under the radiation treatment by the electrons with energy 10 MeV show that typical for the energy losses of electron beam maximum is situated within the first half of the middle of an ampoule and leads to the highest temperatures in the first and second layers of molten salts and the first Hastelloy (nearly 7ºC relatively of the temperature of the surfaces of an ampoule, see fig.1). We can suppose that such small (~1%) temperature heterogeneities weakly become apparent in corrosion process and we may does not take account these heterogeneities at the analysis of the testing metallic specimens if the analysis of experimantal data for corrosion of tested metallic specimens does not require calculations of greater accuracy.

But these temperature heterogeneities it is need to take into account in the case when the temperature in the molten fluoride salts (~660ºC) is compared with their sublimation temperature and over long period (~ 700 hours) of testing time metallic specimens were located in exhalations of fluoride salts under atmospheric pressure. This situation considerably distinguishes from above studied and requires to be separately studied because the energy losses of electron beam in the ampoule without molten salts **essentially distinguish** from the losses in the ampoule with molten salts as well as the mechanisms of heat transport.

2. THE CALCULATION OF TEMPERATURE FIELDS WITH IN THE AMPOULE WITH EXHALATIONS OF FLUORIDE SALTS UNDER THE RADIATION

In these section we calculate the temperature fields for an ampoule which is located in camera with temperature $T_0 \cong 30\,^{o}\mathrm{C}$ of walls, and is irradiated by electrons with energy 10 MeV . The inside of the ampoule contains three layers of tested Hastelloy spacemens, and four spaces between spacemens which are filled up by exhalations of fluoride salts under atmospheric pressure. This means that thermal conductivity equations between spacemens are homogenius

$$\kappa_{ex}\partial^2 T_n / \partial x^2 = 0, \qquad (2.1)$$

where κ_{ex} is thermal conductivity coefficient of the exhalations of fluoride salts. At thermal balance we can find the stationary distribution of temperature fields within the ampoule from thermal conductivity equations with the source of heat (energy flux J_E) and sink of heat due to thermal radiation by C-C composite layers in camera, and to thermal radiation by inner layers of the ampoule. The thermal conductivity equations for five solid state layers (two are C-C composite ones with *n*=1 and n=5 and three layers are tested Hastelloy specimens) are

$$\kappa_n \partial^2 T_n / \partial x = -\varphi_n, \quad n = 1,2...5, \qquad (2.2)$$

where κ_n is tne thermal conductivity coefficient of *n*-layer. For energy losses of electron

$$\partial E_n(x) / \partial x = \varphi_n(x)$$

in each layer we use the results of Monte-Carlo calculations [8] (see fig.2, where empty squares are energy losses of secondary electrons, and filled squares are energy losses of primary electrons).With taking into account both mechanisms of heat exchange (thermal radiation and thermal conductivity) the boundary conditions for left-hand and right-hand boundaries of *n*-th layer are

$$\kappa_n \frac{\partial T_n}{\partial x}|_{\alpha=1} = \sigma(T_{n,1}^4 - T_{n-1,2}^4) + \kappa_{ex}(T_{n1} - T_{n-1,2})l, \qquad (2.3)$$
$$\kappa_n \frac{\partial T_n}{\partial x}|_{\alpha=2} = \sigma(T_{n+1,1}^4 - T_{n,2}^4) + \kappa_{ex}(T_{n+1,1} - T_{n2})l,$$

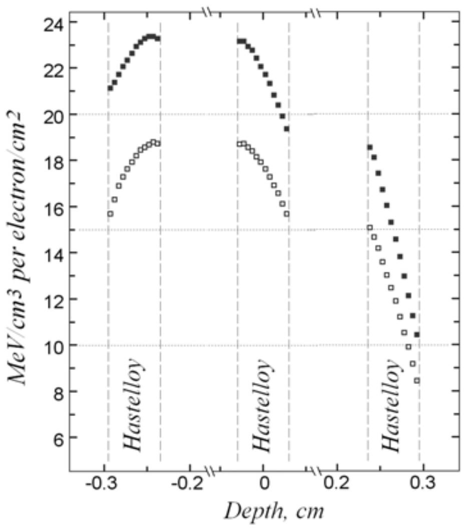

Fig. 2. The results of Monte-Carlo calculations [8] of the energy losses of electron $\partial E_n(x)/\partial x = \varphi_n(x)$ for three Hastelloy layers within the ampoule with exhalations of fluoride salts between layers

where *l* is thickness of the streak of fluorides salts exhalations between solid state layers, $T_{n,\alpha}$ is the temperature on left boundary *n*-th layer at $\alpha = 1,$ and on right one at $\alpha = 2.$ Integration of (2.2) from left boundary *n*-th layer x_{n1} to *x* leads to

$$\kappa_n \frac{\partial T_n}{\partial x} = \kappa_n \frac{\partial T_n}{\partial x}|_{\alpha=1} - \int_{x_{n1}}^{x} \varphi_n(x)dx, \qquad (2.4)$$

where $x_{n\alpha}$ is coordinate of $\alpha -$ boundary of *n*-th layer. Later on we would suppose that $\varphi_n(x) \approx \varphi_n$, and after second integration of (2.4) we have

$$\kappa_n[T_n(x) - T_{n1}] = \kappa_n \frac{\partial T_n}{\partial x}|_{\alpha=1} (x - x_{n1}) -$$
$$- \varphi_n \int_{x_{n1}}^{x} (x - x')dx'. \qquad (2.5)$$

At $x = x_{n2}$

$$\kappa_n[T_{n2} - T_{n1}] = \kappa_n \frac{\partial T_n}{\partial x}|_{\alpha=2} l_n -$$
$$- \varphi_n l_n^2 / 2 = \sigma(T_{n1}^4 - T_{n-1,2}^4)l_n - ,$$
$$- \varphi_n l_n^2 / 2 + \kappa_{ex} l_n (T_{n1} - T_{n-1,2}) / l$$

where l_n is thickness of *n*-th layer. At $x = x_{n2}$ we receive

$$\sigma(T_{n2}^4 - T_{n+1,1}^4 + T_{n,1}^4 - T_{n-1,2}^4) +$$
$$+ \frac{\kappa_{ex}}{l}(T_{n2} - T_{n+1,1} + T_{n1} - T_{n-1,2}) = \varphi_n l_n.$$

Let us to normalize the temperature on boundariesof *n*-th layer:

$$u_n \equiv T_{n1} / T_0, \; V_n \equiv T_{n2} / T_0,$$

and from two last equations we receive the system of equations of fourth order for u_n, V_n :

$$u_n^4 + (b_n + \nu)u_n = b_n V_n + V_{n-1}^4 + \nu V_{n-1} + \frac{\mu_n}{2}, \qquad (2.6)$$

$$u_{n+1}^4 - u_n^4 + \nu(u_{n+1} - u_n) = V_n^4 -$$
$$- V_{n-1}^4 + \nu(V_n - V_{n-1}) - \mu_n. \qquad (2.7)$$

$$\mu_n = \frac{\varphi_n l_n}{\sigma T_0^4}, \; b_n = \frac{\kappa_n}{\sigma T_0^3 l_n}, \; \nu = \frac{\kappa_{ex}}{l \sigma T_0^3}. \qquad (2.8)$$

Thus we received the system of the equations with boundary conditions for dimensionless temperatures on camera walls: $u_{N+1} = 1,\ V_0 = 1$. Summarizing (2.7) from n=1 to n with taking into account boundary conditions leads to

$$
\begin{aligned}
& u_2^4 - u_1^4 + \nu(u_2 - u_1) = \\
& = V_1^4 - 1 + \nu(V_1 - 1) - \mu_1 \\
& u_3^4 - u_2^4 + \nu(u_3 - u_2) = \\
& = V_2^4 - V_1^4 + \nu(V_2 - V_1) - \mu_2 \\
& \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\
& u_n^4 - u_{n-1}^4 + \nu(u_n - u_{n-1}) = \\
& = V_{n-1}^4 - V_{n-2}^4 + \nu(V_{n-1} - V_{n-2}) - \mu_{n-1} \\
& \text{-----------------------------} \\
& u_n^4 + \nu u_n = V_{n-1}^4 + \nu V_{n-1} + u_1^4 + \nu u_1 - \\
& - (1 + \nu) - \sum_{i=1}^{n-1} \mu_i
\end{aligned}
\quad , (2.9)
$$

and to the balance equation

$$u_1^4 + \nu u_1 + V_N^4 + \nu V_N = 2(1+\nu) + \sum_{i=1}^{N} \mu_i \,. \quad (2.10)$$

Rewriting (2.6) as

$$u_n^4 + \nu u_n = b_n(V_n - u_n) + V_{n-1}^4 + \nu V_{n-1} + \frac{\mu_n}{2}\,,$$

and equating right-hand part of (2.10) and (2.9), we receive the equation

$$
\begin{aligned}
& u_n = V_n + \lambda_n \\
& \lambda_n = b_n^{-1}[1 + \nu + \sum_{i=1}^{n} \mu_i - \frac{\mu_n}{2} - u_1^4 - \nu u_1]
\end{aligned}
\quad (2.11)
$$

With taken into account that $\kappa_{ex} \prec \kappa_n$ we can consider $\nu \approx 0$, that let us express all $V_n = V_n(u_1)$:

$$V_{N-1}^4 = [\lambda_n + (2 + \sum_{i=1}^{N} \mu_i - u_1^4)^{1/4}]^4 + 1 - u_1^4 + \sum_{i=1}^{N-1} \mu_i\,,$$

and so on to $V_1 = V_1(u_1)$, that let us to receive the equation for determination of the temperature on left-hand boundary of first C-C composite layer, u_1:

$$
\begin{aligned}
& [u_1 + \frac{1}{b_1}(u_1^4 - 1 - \mu_1/2)]^4 + u_1^4 - 1 - \\
& - \mu_1 = \left\{\lambda_2 + \left[1 - u_1^4 + \mu_1 + \mu_2 + \Lambda_3^4\right]^{1/4}\right\}^4
\end{aligned}
\quad . \quad (2.12)
$$

Here

$$\Lambda_3 = \lambda_3 + [1 - u_1^4 + \mu_1 + \mu_2 + \mu_3 + \Lambda_4^4]^{1/4}\,,$$

$$\Lambda_4 = \lambda_4 + [1 - u_1^4 + \mu_1 + \mu_2 + \mu_3 + \mu_4 + \Lambda_5^4]^{1/4}\,,$$

$$\Lambda_5 = \lambda_5 + [1 - u_1^4 + \mu_1 + \mu_2 + \mu_3 + \mu_4 + \mu_5]^{1/4}\,.$$

Thus, determination of the temperature $T_{11} = u_1 T_0$ on the left-hand boundary of C-C composite first layer for stationary regime demands of solution (2.12), which contain $u_1^{16}, \ldots$ with whole and fractional degrees. Analitical solution of this equation is difficult to find, and stationary distribution of the temperature for all layers of an ampoule was found by numerical method of solution of ten equations of fourth order (2.6-2.8) with boundary conditions $u_{N+1} = 1,\ V_0 = 1$.

2.1. NUMERICAL SOLUTION OF SYSTEM EQUATIONS (2.6-2.7)

For each layer with n=1,2,3,4,5 from (2.6-2.7) we have two reccurent formula

$$
\begin{aligned}
& V_n = f(u_n, V_n, V_{n-1}) = b_n^{-1}[u_n^4 + (b_n + \\
& + \nu)u_n - V_{n-1}^4 - \nu V_{n-1} - \mu_n/2]
\end{aligned}
\quad (2.13)
$$

$$
\begin{aligned}
& u_{n+1}^4 + \nu u_{n+1} = f_2(u_n, V_n, V_{n-1}) == V_n^4 + \\
& + u_n^4 + \nu u_n - V_{n-1}^4 + \nu(V_n - V_{n-1}) - \mu_n
\end{aligned}
\quad (2.14)
$$

Setted value u_1 from (2.13) we find V_1 with taking into account $V_0 = 1$:

$$V_1 = b_1^{-1}\left(u_1^4 + (b_1 + \nu)u_1 - V_0^4 - \nu V_0 - \mu_1/2\right)$$

For given u_1 and V_1 we find the solution of equations (2.13-2.14) for V_2, u_3 then V_3, u_4 and so on. Last step we do for V_5, u_6. Value u_6 is need to come an agreement with second boundary condition $u_{N+1} = u_6 = 1$, that we can do using variation method Neuton-Raphson for initial value u_1. At numerical solution we used the results of Monte-Carlo calculations [8] (see fig. 2) and the mean values energy losses of electron are

$$\varphi_1 \approx 1.98 \times 10^7\, erg/cm,$$

$$\varphi_2 \approx 14.52 \times 10^7\, erg/cm,$$

$$\varphi_3 \approx 13.86 \times 10^7\, erg/cm \quad ,$$

$$\varphi_4 \approx 9.9 \times 10^7\, erg/cm,$$

$$\varphi_5 \approx 0.66 \times 10^7\, erg/cm,$$

and value $\kappa_{ex} \approx 0.3 \times 10^4\, erg/cm\ K\ sek$ [3]. On fig. 3-4 we see the results of solution for two situations: **i)**on fig.3 we see temperature fields for ampoule without molten salts with taken into account only thermal radiation as between ampoule and camera wall, and so between camera layers (i.e. $\kappa_a \approx \kappa_{ex}$=0). As it is seen, the temperature on right-hand of first C-C composite layer increases on ~$5K$ from $T_{11} \approx 640$ºC on left-hand boundary.

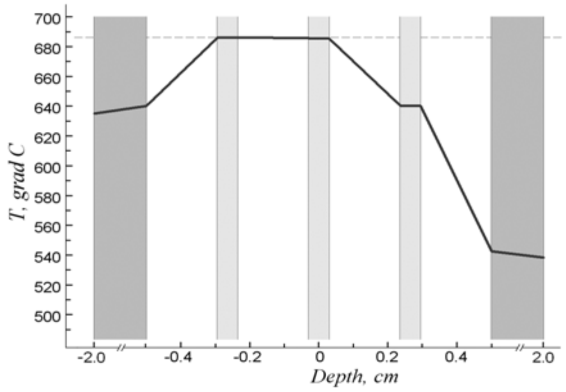

Fig. 3. Temperature fields within the ampoule without molten fluoride salts under the radiation treatment (with taken into account only thermal radiation between layers)

In Hastelloy layers we have $T_{21} \approx T_{22} \approx T_{31} \approx T_{32} \approx 680$ ºC, and then the temperature decreases to $T_{41} \approx T_{42} \approx 640$ ºC for third Hastelloy layer, and to second C-C composite layer from values $T_{51} \approx 555$ ºC to $T_{52} \approx 550$ ºC.

ii) For determination of the contributions of each the mechanism of heat transport on fig. 4 we see the results of numerical solution of system equations (2.7-2.8) with taking into account as heat exchange between solid state layers and streaks with fluoride salts exhalations and with small $\kappa_a \sim \kappa_{ex} \sim 10^{-3}\kappa_g$ [3] and so thermal radiation between solid state layers. At this case for the temperature for first C-C composite layer we have $T_{11} \approx T_{12} \approx 590$ ºC. For Hastelloy layers the temperature has maxima for l first and second Hastelloy layers

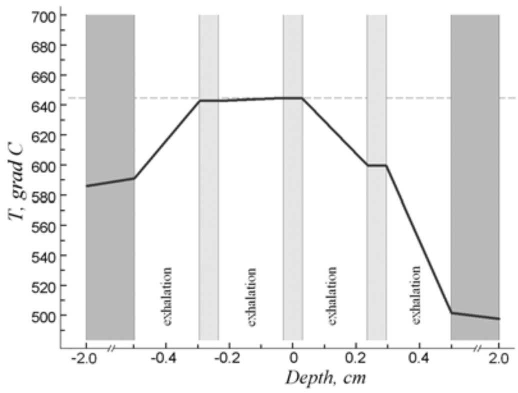

Fig. 4. Temperature fields within the ampoule without molten salt under the radiation treatment (with taken into account thermal radiation between layers as well as the heat exchange between layers and streaks with fluoride salts exhalations)

$T_{21} \approx T_{22} \approx T_{31} \approx T_{32} \approx 645$ ºC, and then slowly decreases to to $T_{42} \approx 600$ ºC. For second C-C composite layer layer $T_{51} \approx T_{52} \approx 520$ ºC.

Thus we see that for the ampoule with fluorides salts exhalations the stationary temperatures depend from heat transport mechanisms and from layers thickness. This leads to conclusion about necessity to take into account both mechanisms of heat transport (thermal radiation and thermal conductivity) simultaneously. Carried out calculations show that all sinks of heat (thermal radiation by C-C composite layers in camera and heat exchange between solid state layers and streaks with fluorides salts exhalations inside ampoule) don't lead to overheating of layers of irradiated ampoule.

This work was supported in part by STCU, Project # 294.

REFERENCES

1. V.M. Azhazha, O.S. Bakai, I.V. Gurin, A.N. Dovbnya, N.V. Demidov, A.I. Zykov, E.S. Zlunin, S.D. Lavrinenko, L.K. Myakushko, O.A. Repihov, A.V. Torgovkin, B.M. Shirokov, B.I. Shramenko. Stend dlya radiatsionnyh ispytanij konstruktsionnyh materialov v uslovyah solevogo reaktora *//Procceding XVI international conference: physics of construction matter and radiation materials science in condition of salts reactor", 6-11september 2004 г., Alushta, Crimea, Ucraine (ННЦ ХФТИ, Харьков),* с. 270

2. А.С. Бакай, М.И. Братченко, С.В. Дюльдя. Моделирование профилей поглощения энергии электронных пучков в имитационных экспериментах по изучению радиационной стойкости хастеллоя в среде расплавленных фторидов *//Труды XVI международной конференции по физике радиационных явлений и радиационному материаловедению, 6-11 сентября 2004г., Алушта, Крым, Украина. ННЦ ХФТИ, Харьков,* с. 274.

3. В.С. Чиркин. *Теплофизические свойства материалов ядерной техники.* М.: "Атомиздат", 1968,
484 с.

4. А.С. Бакай, А.В. Чечкин, В.В. Жук. *Коррозионные свойства сплавов хастеллоя в расплавах фторидных солей.* Препринт ННЦ ХФТИ (в печати, 2004)

5. L. Katz, A.S. Penfold //*Rev.Mod.Phys*. 1952, v. 24, p. 28–35.

6. Handbuch der Physic, Springer Verlag, Berlin, b. **54**, 1958.

7. И.М. Неклюдов, Б.В. Борц, В.В. Ганн, Г.Д. Толсто¬ луцкая. Методология имитации радиационных повреждений с помощью ускорителей электронов и протонов //*Вопросы атомной науки и техники. Серия ФРП и РМ.* 2003, #3, с. 62.

8. O.S. Bakaj, M.I. Bratchenko, S.V. Dyul'dya (to be published).

РАСЧЕТЫ ТЕМПЕРАТУРНЫХ ПОЛЕЙ В АМПУЛАХ ПРИ РАДИАЦИОННЫХ ИСПЫТАНИЯХ ЭЛЕКТРОНАМИ С ЭНЕРГИЕЙ 10МЭВ

А.С. Бакай, Л.В. Танатаров, В.Ю. Гончар и Г.Г. Сергеева

Для вычисления температурных полей в ампуле под облучением электронами нами использовались одномерные уравнения теплопроводности с осью *x*, совпадающей с направлением потока электронов. Получены координатные зависимости температуры для двух случаев: 1) для ампулы с расплавом солей флюорида между испытуемыми образцами Хастеллоя; 2) для ампулы с парами солей флюорида между образцами Хастеллоя. Показано, что во втором случае установившееся распределение температуры существенно

зависит от механизма переноса тепла и от толщины слоев, что позволяет сделать вывод о необходимости принимать во внимание оба механизма переноса тепла одновременно(тепловое излучение и теплопроводность слоев).

РОЗРАХУНКИ ТЕМПЕРАТУРНИХ ПОЛЕЙ У АМПУЛАХ ПРИ РАДІАЦІЙНИХ ВИПРОБУВАННЯХ ЕЛЕКТРОНАМИ З ЕНЕРГІЄЮ 10 МЕВ

О.С. Бакай, Л.В. Танатаров, В.Ю. Гончар, і Г.Г. Сергієва

При розрахунках температурних полей в ампулі під випромінюванням електронами нами використовувались одновимірні рівняння теплопровідності із вісью *x*, яка збігається із напрямком потоку електронів. Одержані координатні залежності температури для двох випадків: 1) для ампули із с розплавом солей флюориду між випробуваними зразками Хастелоя; 2) для ампули із парами солей флюориду між шарами ампули.. Показано, що у другому випадку сталий розподіл температури істотно залежить від механизму переносу тепла і товщини шарів, що дозволяє зробити висновок про необхідність одночасно брати до уваги обидва механізми переносу тепла (теплове випромінювання і теплопровідніть шарів).