THERMAL ANALYSIS OF THE STEEL CONCRETE CASK CONSTOR

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ABSTRACT

In this article the methods used for thermal analysis of the CONSTOR steel concrete cask for spent nuclear fuel transport and storage under normal and accident fire conditions are presented.

The methods are valid to calculate the heat transfer in the inner cavity of the gas filled cask when the main part of the residual heat is transfered by means of radiation and conductivity. The calculative model covers the heat transfer in the assembly both under symmetrical and non-symmetrical boundary conditions, the latter are typical for multi-places casks or canisters.One of the main features of the method is the real multi-rod assembly substitution by homogenous heat releasing bar with effective heat conductivity enclosed into the heat conducting casing which models assembly cover or basket tube. Two-zone model is used with separate consideration of heat transfer in the rod bundle inner zone and in the edge zone disposed between the edge row of rods and casing.

The method have been verified by experimental data obtained by means of electricaly heated bundle model consisting of 127 rods and a good correspondens has been shown.

For the casks with a metal-concrete body a method and code for thermal analysis during the accident fire conditions has been elaborated. The method includes elements of the joint thermal-strength calculation of the cask body and allows to carry out calculations taking into account disappearance and arising of new gaps and cavities and altering their widths in time.

The joint thermal and thermal-strength analysis has made clear some peculiarities of the multilayer cask body response in different regimes and allowed to determine its design. In an adopted cask construction the outer liner is not directly bound with the inner one and with the system of reinforcing rod heat conductors which are welded with the inner liner. The relatively free outer liner provides reliable heat contact in the cask body under normal stationary conditions and increases essentially a cask fire resistance under accidents. Resulting cask construction is unloaded from thermal stresses in this way.

The fire-protecting effect of the free outer shell is shown most clearly under conditions when the environment temperature rises gradually, that is typically for ship-hold fire.

INTRODUCTION

Thermal analysis of the casks and their content under normal and fire accident conditions during spent nuclear fuel transport or storage is an integral part of any safety analysis report. Due to this, great attention is paid to elaboration of reliable methods and computer codes for the thermal analysis of casks. This paper describes the composed numerical-analytical method for the calculation of assemblies steady state thermal conditions and the numerical method used for cask non-steady-state thermal analysis under fire accident conditions.

The method for assemblies steady-state thermal analysis has been elaborated mainly for the basket constructions usually used in Russia and consisting of several rows of basket tubes tied by a few diaphragms, however it can be easily adapted for other basket construction. The method have been verified by experimental data and a good correspondence has been shown.

THE MODEL OF STATIONARY HEAT TRANSFER IN THE CASK INNER CAVITY

For calculation of conductive-radiative heat transfer in the basket with spent nuclear fuel assemblies (Fig.1) the non-linear equation of heat balance (1) is composed for each row of basket tubes with assemblies. It is assumed that the temperatures of the assemblies disposed in the same row are equal.

$$M_i Q_{as} + \sum_{k=1}^{n} Q_{i,k}^{cond} + \sum_{k=1}^{m} Q_{i,k}^{rad} = 0 \qquad (1)$$

M_i - quantity of assemblies in the row i;

n - number of the rows with which the row i has conductive interactions;

m - number of the rows with which the row i has radiative interactions;

Q_{as} - mean heat decay power of one assembly per unit of its active length

$Q_{i,k}^{cond}$ - linear heat fluxes by heat conductivity between rows i and k

$Q_{i,k}^{rad}$ - linear heat fluxes by radiation between rows i and k

Methods for $Q_{i,k}^{cond}$ and $Q_{i,k}^{rad}$ determination are stated in detail by L. Fromzel (1997).

For determining the correlation between the mean temperatures on the inner T_{in} and outer T_{out} parts of basket tube perimeter the analytical solution for two-dimensional temperature distribution in the assembly disposed in the basket tube is obtained. The following assumptions have been introduced into calculative model (Fig.2):

- the part of perimeter within the angles $\pm\omega_1$ receives the heat from the rows of basket tubes disposed nearer to the cask centre and opposite part of the perimeter within the angles $\pm\omega_2$ transfers the heat to the external rows of basket tubes or to the cask body;
- the parts of perimeter facing to the basket tubes disposed in the same row are assumed to be adiabatic;
- the real assembly disposed in basket tube is substituted by homogenous cylindrical heat releasing bar with heat conducting and not heat releasing casing.

By use the same approach as Manteufel (1977) two-zone model is applied with separate consideration of heat transfer in the rod bundle inner zone and in the edge zone disposed between the edge row of rods and basket tube. The coefficients of effective heat conductivity in the inner and edge zones are presented in form (4).

$$\lambda_{ef} = a\ T + b\ T^3; \qquad \lambda_{ef\ edg} = a_{edg} T + b_{edg} T^3 \qquad (2)$$

a, a_{edg} -coefficients of conductive heat transfer in the inner and edge zones correspondingly;

b, b_{edg} -coefficients of radiative heat transfer in the inner and edge zones correspondingly.

Method for these coefficients calculations and also their values for the main Russian nuclear fuel assemblies (RBMK-1000, VVER-1000, VVER-440) under helium or nitrogen used as a cooling agent are presented by L. Fromzel (1997).

The equations of heat conductivity for the bar (3) and for the casing (4) are solved jointly under consideration of temperature drop in the edge zone.

$$\frac{\partial^2 t}{\partial r^2} + \frac{1}{r}\frac{\partial t}{\partial r} + \frac{1}{r^2}\frac{\partial^2 t}{\partial \varphi} = -\frac{q_v}{\lambda_{ef}} \quad (3) \qquad \lambda_c \delta_c \frac{1}{R^2}\frac{\partial^2 t}{\partial \varphi} = -\tilde{q}(\varphi) = -(q_{as}(\varphi) + q_{ext}(\varphi)) \quad (4)$$

q_V -specific volume heat release in the bar; λ_C -heat conductivity of the casing;

R -radius of the bar; δ_C -thickness of the casing.

The heat flux density $\tilde{q}$ transferred to the bar casing (basket tube) is defined as an algebraical sum of the heat flux from the considered assembly q_{as} and external heat flux q_{ext} from the other basket tubes with assemblies. The distribution of q_{ext} along the bar casing is presented in form of six terms of Fourier series under assumption that the heat flux density q_1 and q_2 (Fig.2) are described within the corresponding parts of perimeter by cosine law.

$$q_{ext} = 1/\pi\left[\left(q_1\omega_1 + q_2\omega_2\right) + \sum_{k=1}^{5} 2/k\left(q_1 \sin(k\omega_1) + (-1)^k q_2 \sin(k\omega_2)\right)\cos(k\varphi)\right] \tag{5}$$

$$q_1(\varphi) = Q_1 \frac{\pi}{4\omega_1 R}\cos\left(\frac{\pi}{2\omega_1 R}\varphi\right) \qquad q_2(\varphi) = Q_2 \frac{\pi}{4\omega_2 R}\cos\left(\frac{\pi}{2\omega_2 R}(\varphi - \pi)\right)$$

Q_1 and Q_2 - heat fluxes on the corresponding parts of perimeter.

The correlation for q_{as} is obtained by differentiating of solution of equation (3) when $r = R$. The temperature drop in the edge zone is calculated by the same manner and the following expression is obtained:

$$\Delta T_{edg} = \frac{q_l \delta_{edg}}{2\pi R \lambda_{ef.edg}}\left[1 - \sum_{k-1}^{5} k/2 * \beta_k \cos(k\varphi)\right] \tag{6}$$

q_l -linear heat release in the assembly; δ_{edg} -thickness of the edge zone

The correlation for two-dimensional temperature distribution in the assembly in polar co-ordinates under the non-symmetrical conditions of heat transfer has the following form:

$$T(\xi,\varphi) = T_{c0} + \frac{q_l \delta_{edg}}{2\pi R \lambda_{ef.edg}} + \frac{q_l}{4\pi\lambda_{ef}}\left[\left(1-\xi^2\right) + \sum_{k-1}^{5} \beta_k \xi^k \cos(k\varphi)\right] \tag{7}$$

T_{c0} - mean temperature of the casing; $\xi = r/R$ - relative radius.

In equation (9) coefficients β_k are::

$$\beta_k = \chi_k \frac{4}{k^2}\frac{\pi R^2}{q_l}\frac{1}{\frac{R}{k} + \frac{\delta_c\lambda_c}{\lambda_{ef}} + k\frac{\delta_c\delta_{edg}}{R}\frac{\lambda_c}{\lambda_{ef.edg}}} \tag{8}$$

where coefficients χ_k in their turns are:

$$\chi_k = \frac{Q_1}{\pi R}\frac{\pi^2}{\pi^2 - 4\omega_1^2 k^2}\cos(k\omega_1) + (-1)^k \frac{Q_2}{\pi R}\frac{\pi^2}{\pi^2 - 4\omega_2^2 k^2}\cos(k\omega_2) \tag{9}$$

On the base of equation (7) the correlation for temperature distribution along the casing perimeter and the expressions for the mean temperatures T_1 and T_2 on the corresponding parts of perimeter can be obtained:

$$T_c(\varphi) = T_{c0} + \frac{q_l}{4\pi} + \sum_{k-1}^{5}\beta_k\left(\frac{1}{\lambda_{ef}} + k\frac{\delta_{edg}}{R\lambda_{ef.edg}}\right)\cos(k\varphi) \tag{10}$$

$$T_1 = \frac{1}{2\omega_1}\int_{-\omega_1}^{\omega_1} T_c(\varphi)d\varphi \qquad T_2 = \frac{1}{2\omega_2}\int_{-\omega_2}^{\omega_2} T_c(\varphi)d\varphi \tag{11}$$

Equations (1), (7) and (11) made up for each rows of assemblies are solved jointly by means of elaborated computer code and so the temperature state of any nuclear rod in each assembly can be determined.

The presented above method has been verified by the tests performed with electrically heated 127-rods models the cross-sections of which are presented on Fig.3. For non-symmetrical boundary conditions simulation on two model facets the heaters was mounted, heat abstraction was realised from two opposite facets cooled by water and two facets were adiabatic.

The comparison of temperatures measured during the test with calculated temperatures for the rods disposed on the diagonal of hexahedron is presented on Fig.4 and demonstrate the sufficient accuracy of the offered method.

MATHEMATICAL MODEL AND CODE FOR THERMAL ANALYSIS OF THE NONSTATIONARY REGIMES

A mathematical model and appropriated computational code (TRAK) were especially developed for the purposes of the nonstationary thermal analysis of casks in particular for the cask accident thermal regime analysis (Vasiljev, 1991). The TRAK code meets all requirements which are usually produced to the codes of analogous intention. In accordance with those the TRAK code

- makes provision for modelling cask constructions in detail;
- describes all range of processes determining altering heat transfer on inner and external cask boundaries. In the first place it concerns important for fire conditions heat exchange in cavities, gaps and also natural convection at the surfaces and radiation heat transfer;
- precisely follows temperature dependence of used material properties in a wide range of temperatures involved;
- can calculate an estimation of approximate errors in the solution obtained.

For the purposes of a steel concrete cask thermal dynamic analysis it is important that calculations of deformations and stresses for characteristic sections are included in the program allowing to transform the calculation area during computation according to formation of backlashes, cavities etc. Thus the TRAK code provides at the same time calculation of thermal stresses and displacements, arising, growth and decrease of gaps in the cask construction and fulfilment of temperature fields calculations with gaps of variable values.

Before computation the geometrical area is broken by coordinated surfaces into some number of subareas, on borders of which the appropriate boundary conditions (uninterruption or outward ones) are put. The initial temperature distribution can be either entered from the outside, or generated by the program during precomputation of a stationary cask state.
The basis of the TRAK code is a solving procedure of nonstationary heat conductivity differential equation system for set of subareas which are approximating a real cask geometry region in two-dimensional space statement:

$$c\rho(r,z,T)\frac{\partial T}{\partial t} = \nabla\lambda(r,z,T)\nabla T + Q_v(r,z,t) \tag{12}$$

Dividing every subarea by finite-difference net is independent from others. The differential equation system (12) in the program is solved with splitting method by means of absolutely stable implicit and conservative finite-difference schemes of the second accuracy order for space variables. The chosen finite-difference schemes provide monotonous solution for every case including shock heat disturbing influence of a large amplitude. The high-speed linear procedures and iteration processes of a high convergence are used for solving of algebraic equation sets.

The description of heat exchange processes on outside and inside surfaces of the container, i.e. boundary conditions for the problem, as algorithm's inherent part is the characteristic feature of the code. The common form of boundary conditions at the cask surfaces is

$$\lambda \frac{\partial T}{\partial n} = \Sigma q_i\,, \tag{13}$$

where q_i is a heat flow generated by one of the possible processes. The TRAK code has at its disposal the means to determine the heat flows, which are generated on the inner and outer cask surfaces by any type heat transfer processes including a heat radiation, natural and forced convection, an ordered heat flow, with a needful heat transfer parameters automatic forming on the every integrating step. The code also calculates heat transfer parameters for gaps and inner cask cavities taking into account heat conductivity, radiation and convection.

The operator in the left side of eq. 13 may be approximated with different precision. Approximation of the first order generates an algorithmical process resulting solution, which tends to the precise one from the greater values when condensing finite-difference net. On the contrary an approximation of the second order gives a solution which tends to the precise from the smaller values side. These statements are valid when external heating conditions are constant. The difference between results of the approaches gives the way to calculate the approximation error of solution. So the advantages of finite-difference method may be used when altering finite-difference net density is easy to do without essential growth of computation time expenditures.

During its development the TRAK code was subject to a thorough verification with the help of both calculation (by certificated codes) and by experiment. The direct comparison of the TRAK program computational results with the natural test results of the TK-6 container experimental sample in the fire with following cooling down has been a major part of verification stage.

The design of the steel concrete cask body is rather complex composition from metal layers (cylindrical liners) and concrete bulk disposed between them. The last is penetrated through almost all its thickness with steel rods of armouring system, attached with inner liner and upper forged steel ring by welding. The system behaviour analysis under powerful heat flux affecting in fire situation demands, generally speaking, simultaneous solution of equations system describing dynamics of the cask thermal and thermal-stresses states. The solution of joint system, especially for cases when breaches of initial structure are possible (f.e. gaps arising or disappearance), is rather cumbersome and hardly realisable problem, taking note of computer narrow possibilities.

It is more expedient for aims of approximate estimations of cask design response on fire to use approach when solution of thermo-elasticity problem for the every integrating step of thermal problem is built for the most characteristical or key region, and for others the one is forecasted on the received base and taking into account some reasonable assumptions. Such an approach is convenient when it is necessary to determine time moment of design breaches (and hence calculation region character) and to introduce necessary changings into the solution way.

As far as for designing purposes the most interest is connected with its multi-layer body response, the central radial body cross-section was elected as such characteristic region, equally removed from upper (in forged ring) and lower (in bottom) fixations.

With such a cross-section, a rather simple solution of thermo-elasticity problem for infinity long multi-layer cylindrical shell under arbitrary temperature field may be connected. This solution is introduced into the cask dynamic temperature field code. It allows, for one side, to estimate stresses and displacements for every integrating time step of thermal equations system, and, for the other side, operatively and at any time moment to introduce necessary variations into calculation region configuration and boundary conditions on the inner cask surfaces since some assigned condition was fulfilled.

This calculation way the phenomenon of early coming off outer liner from concrete bulk with gap arising along greater part of concrete side surface was detected according to assigned maximum stress of tearing off steel from concrete. The gap value out of central section was determined on the base of elementary (but conservative) suppositions. This gap appearance changes radically the temperature field picture in the cask and following way of liners work in the fire.

The described method has both all merits and demerits of so called "engineer" approach and may be quite useful not only before including more precise programme, but and together with one. This approach was realised in the TRAK programme.
The TRAK code was the main calculation tool with the help of which the steel concrete CONSTOR RBMK cask dynamic response was examined.

The double-purpose steel-concrete cask CONSTOR RBMK (Zubkov, 1996) developed jointly by NPO CKTI (Russia) and GNB (Germany) represents a design sample, where reliable heat removal under normal operative conditions combines with a specially high fire-resistance.
The cask design speciality is the outer liner which is not directly bound with concrete and inner liner and retains some possibility to move under heat affection both in normal and accident conditions. The cask model in the scale 1:2 was successfully tested in Germany according to IAEA Regulations by drop tests in May of 1997.

In a stationary state the inner and outer liners compress a concrete with a significant strength, providing reliable heat contact in a milti-layer construction (curve 1, fig.5).

Under fire conditions, if to treat the cask body as a continuous 3-layer shell, arising stretching stresses are those that the integrity of layer wall is impossible. Actually the effort of tearing off the outer liner from concrete corresponds to stretching stresses about 2-3 ata. That's why in the fire when power heat flows are affecting the free outer liner rather quickly (in the first 1-4 min) moves away from concrete body and forms a backlash (a gap) along all side surface and bottom. Fig.6 shows gap width changing in time. The concrete in the main remains in a pressed state, the stretching stresses are minimal (curve 2, fig.5).

The resistance of the heat transfer to the cask cavity grows sharply and the temperature difference in the gap reaches 300°C and more. On a figure 7 the temperature profiles are presented in the central section of the cask body, computed with gap (curve 1) and without it (curve 2). The concrete warming up becomes less significantly, the concrete bulk is in as though thermo-stable zone without threat to reinforced structure integrity.

As a result, an increase of the hottest spent fuel assemblies (SFA) temperature is a essentially lesser value than one in analogous cask without gap. If fire time duration is increasing (that is important for ship fire problem being researched intensively nowadays), as well as a cask decay SFA heat output, the temperature gain is markedly increasing too.
On a fig.8 the hottest SFA temperatures in CONSTOR RBMK cask with heat output 7.7 kW computed for fire of standard IAEA's parameters are showed (curve 1 - with gap, curve 2 - without gap). For comparison the computed results for the steel cask with the same loading (curve 3) are presented.

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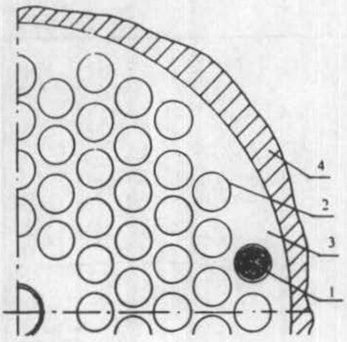

Fig. 1 Scheme of the basket
1- assembly 2- basket tube
3- diaphragm 4- cask body

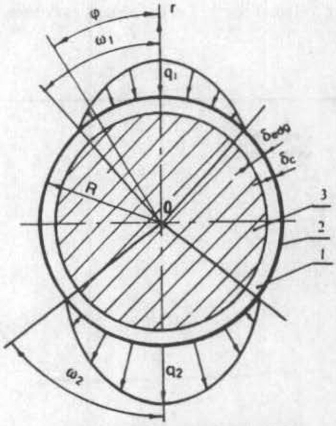

Fig.2 Calculative scheme of the assembly in the basket tube
1- heat releasing bar
2- casing
3- edge zone

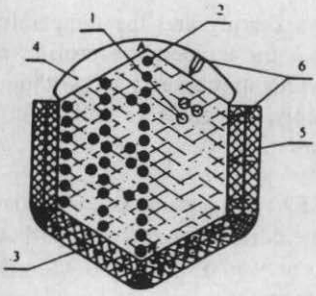

Fig.3 Rod bundle test model
1- electrically heated rods
2- rods with thermocouples
3- side heater
4- water cooled jacket
5- insulation
6- thermocouples on the bundle casing

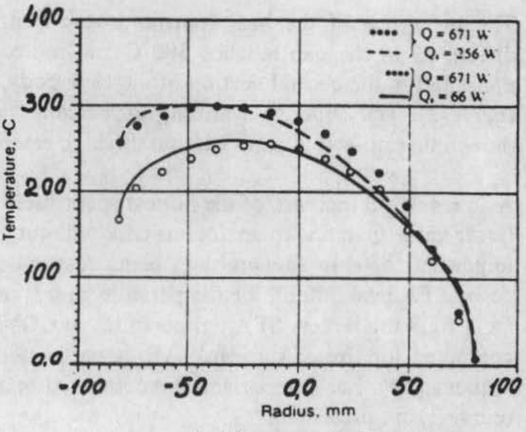

Fig 4. Temperature distribution along the bundle diagonal

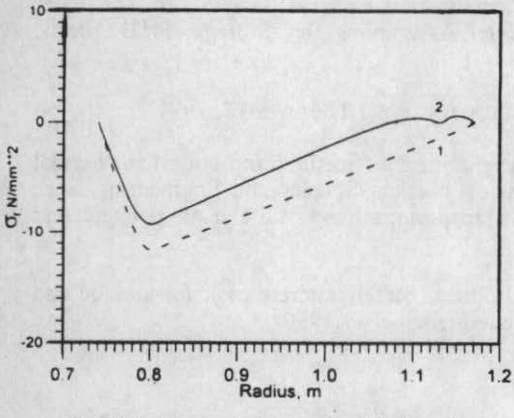

Fig.5 Radial stresses in the central cask body section

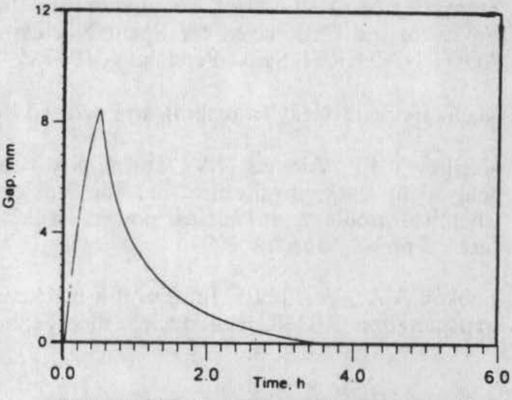

Fig 6 Changing of maximum gap between concrete body and outer liner at the fire and following cooling down

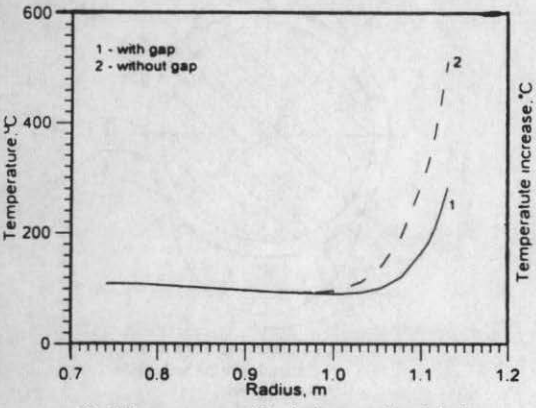

Fig.7 Temperature profiles in the central cask body section in the fire stopping time

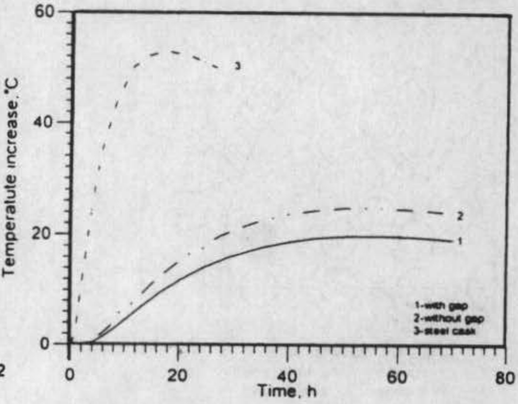

Fig 8 Increases of the hottest SFA temperature vs time for the fire test