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Theoretical and Experimental Modeling of the Multiple Pressure Tube Rapture for RBMK Reactor. Part I

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ABSTRACT

Rupture of a single fuel channel (pressure tube) or several fuel channels of the RBMK may occur in service conditions on NPPs with a variety of initiating events. It is assumed in RBMK Safety Cases that the force of the escaping fluid will not cause neighboring channels to break. This assumption has not been justified. Hence, an analysis of the multiple pressure tube rupture (MPTR) possibility is needed.

The analysis of the MPTR problem requires performing a series of theoretical and experimental studies of separate physical processes running in the RBMK reactor, as well as development of mathematical models and their physical equivalents. The experimental rigs concerned the MPTR problem have been designed and constructed at Electrogorsk Research & Engineering Center, Russia.

Investigation of the circumstances and mechanisms of a single channel rupture at the various conditions and scenarios is one of the main stages of the MPTR problem analysis. Theoretical models of the single channel rupture under thermal and mechanical loading have been developed including a channel constrained by the graphite block. Deformation of the channel under internal pressure and localized thermal action is modeled within the framework of the nonlinear shells theory taking into account physically nonlinear material behavior. Computer program based on these models enables to describe the thermomechanical deformation of a single channel and to predict rupture moment.

Theoretical studies were accompanied by experimental modeling single channel rupture by means of series experimental examinations at TKR-F test rig (Model of an Accidental Channel). This test rig represents a model of the single disrupted fuel channel in a surrounding graphite column. Experimental examinations make possible the development and verification of theoretical models and make more exact the conditions and mechanism of a single channel rupture.

Theoretical and experimental modeling consolidation sets out technique of the authentic analysis of the circumstances and mechanisms of the MPTR.

KEY WORDS: RBMK, safety cases, pressure tube rupture, theoretical and experimental modeling

INTRODUCTION

Test Facility TKR-F (Fuel Channel - Rupture - Fragment) represents a fragment of RBMK fuel channels (FC) and is designed to study conditions of deformation and rupture of a single FC in emergency conditions. The series of experimental investigations carried out on the facility is a part of the comprehensive research program devoted to the problem of the RBMK FC rupture development according to the multiple pressure tube rupture scenario. The initiating event at likely implementation of the scenario with a sequential multiple FC rupture is a break even one of them. To assess scenario probability and its consequences the initiating event – rupture of a channel, is to be modeled. The experimental investigations on the TKR-F facility involve in determination of thermal and mechanical effects which combination may result in FC rupture.

Appropriate calculation support, enabling to schedule experimental investigations, particularly, to determine pressure required for breaking a tube, time from tube heating initiation to its rupture, range and distribution of temperature fields in a tube, is required at the preparatory stage of researches on TKR-F facility. On the other hand, the integrated computer code allowing to describe these processes, and, as consequence, to predict emergency origin and its consequences, is the important tool for analyzing processes proceeding in the reactor space during accident situation development.

MATHEMATICAL MODELS OF CHANNEL TUBE HEATING, DEFORMATION AND BREAKING

The following mathematical models of the physical phenomena and processes are developed:

1) Thermophysical model of a heating source (thermite blocks).
2) Model of heat transfer from the internal source of heating to the tube surface.
3) Model of temperature fields retiming in the tube wall.
4) Model of deformation and breaking of a tube under local thermal action and internal pressure which defines the mode of tube deformation during thermomechanical effect up to its rupture.

The mathematical model of heat transfer from the source (thermite block, FA) to the tube and dynamic redistribution of temperatures field in the tube wall is based on the following substantive conditions.

1) Heat radiation (radiant heat exchange) is a mechanism for heat transfer from the heat source to the tube surface.
2) Convective heat transfer between tube surfaces and air /steam are considered.
3) Heat radiation from the tube surface during its heating is considered.
4) Processes of a heat transfer due to heat conductivity are considered only on the median surface of the tube, and heat-balance equations are entered for the entire tube wall.
5) The calculated heating temperature of the tube surface corresponds to average temperature on the tube wall thickness.
6) The reference tube wall temperature is determined on the basis of the experiment conditions.
7) Heat-insulating conditions for the tube edges, that are temperature influence is localized in the area removed from the tube edges, are established.

The formulated conditions of the mathematical model are based:

* on the analysis of experimental data about heating source;
* on comparison of characteristic heat transfer times through the steam and typical times for tube wall heating.

The thermophysical source model is based that initially its temperature has a predetermined value (“instantaneous firing”), determined by physical and chemical parameters of a thermite block, and the external surface temperature decreases by the exponential law. As it is shown below, such simple (two-parametrical) source model of a source allows to modeling tube heating with acceptable accuracy. The target of the experimental investigations being performed now on the TKR-F test facility is to improve the heater’s design. The results obtained from these experiments will form a basis for the improvement of the mathematical models used for describing the heater and model of heat transfer from the heater to the tube.

In solving the problem on distribution of temperature fields in the tube a transfer to a bidimentional task on the basis of linear approximation of a heat flow in radial (across the wall) direction is realized. It allows, on the one hand, to simplify essentially the solution, and on the other hand to consider sufficiently accurate (square-law approximation) temperature gradient in the radial direction.

As a deformation model the model of a piecewise-homogeneous tube is used along its generatrix consisting of separate different module parts (elements) within which the Jung’s module is constant complying with average temperature within the tube fragmentation element. The given model is analogue of a finite-elemental model. It should be noticed that the advanced approach exploits the exact solution of equations describing the tube mode of deformation within the bounds of the shell model. That makes possible big elements (in comparison with linear or quadratic approximation in the method of finite elements) and reduces the calculating time and required computer resources.

On thermal exposure and internal pressure the model of tube deformation and rupture is based as follows:

Temperature distribution is specified by maximal temperature in the central (vertically) part of the tube and by the gradients directed along the tube generatrix and its perimeter.

1) Temperature gradients along the tube perimeter are small (only first member of asymptotic expansion is considered).
2) In consequence of temperature dependence of the Jung’s module an induced heterogeneity on deformation properties is originated.
3) Deformation of a tube is happened within the generalized Hooke’s law for physically nonlinear, isotropic medium with the Jung’s module depending on temperature.
4) Deformation of a tube is described within the shell deformation model subject to temperature dependence of the Jung’s module.
5) The model for calculation of the tube mode of deformation considers the induced heterogeneity along the tube generatrix at its heating by a local source.
6) Average tube section longitudinal pressures are absent.
7) The limiting tube state is determined from achieving tensile strain by equivalent pressure in view of its temperature dependence**.**

The developed mathematical models are implemented numerically as a computer program calculating temperature and critical pressure (i.e. pressure providing a tube rupture at its temperature), and also to define the time from the heating source effect initiation up to its rupture at various geometrical, thermophysical and mechanical parameters of experiment.

CALCULATION MODELING OF CHANNEL TUBE HEATING, DEFORMATION AND RUPTURE

Let us proceed to the analysis and comparison of the estimated tube rupture time and temperature dynamics with experimental data. Fig. 1 represents experimental data (symbols) on temperatures according to indications of thermocouples T.03.09 and T.03.10, registered in research experiment performed on December 04, 2001 in test facility TKR-F. The thermocouples were located in the most heated tube section, and, as consequence, the tube was broken just in this section. We shall note, that zero in displaying of experimental data corresponds to "initiation" of the specified thermocouples indications.

Let us calculate the dynamics of the tube wall temperature before breaking and critical pressure determining the tube rupture moment, on the parameters given below (other parameters of calculation correspond to the TKR-F design philosophy):

* Reference source temperature - 1800°C
* Representative source time (time of reduction of surface temperature by e = 2.718 times) - 600 sec
* Tube material - Zr+2.5%Nb alloy
* Initial tube temperature - 290°C
* Pressure - 7,8 MPa
* Factor of convective heat exchange with steam - 200 W / (m2K)
* Factor of convective heat exchange with air - 10 Вт / (м2ЧК)
* Factor of block emitting/absorption - 0,9
* Factor of tube emitting/absorption - 0,5

Calculation results of the average (along thickness) tube wall temperature dynamics are represented as a full curve in Fig. 1. We shall note, that the presented data correspond to axisymmetric position of heating source.

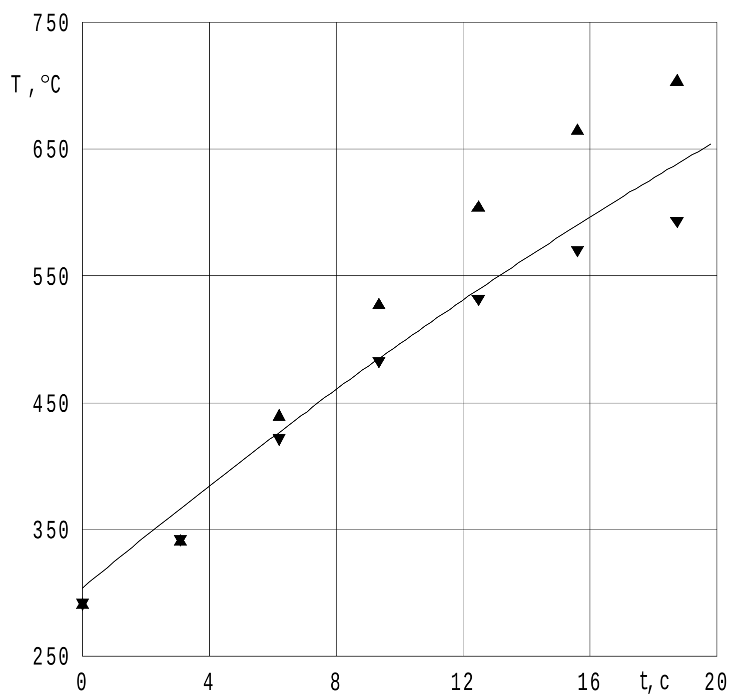

Fig. 1. The dynamics of temperature in the most heated tube section

Evidently, at the initial stage the calculated temperature values exceeds experimental data that results from the delay of thermocouple indications, fixed on the external tube surface, in relation to the average wall temperature. In six seconds of the process the calculated values are within the limits determined by the experimental data. We shall note that azimuthal (circular) temperature differential registered by thermocouples in the section studied resulted from radial displacement of the heating source about the tube axis or with heterogeneity of optical properties of its internal surface.

Fig. 2 represents calculated values of critical pressure change (dotted curve) obtained within the solution of the problem mentioned above. With the tube temperature growth, the internal pressure necessary for its rupture, decreases, and the calculated pressure values determine the tube rupture time. Apparently, by twentieth second of the process critical pressure appears equal to internal pressure in the tube that completely agrees with the experimental data.

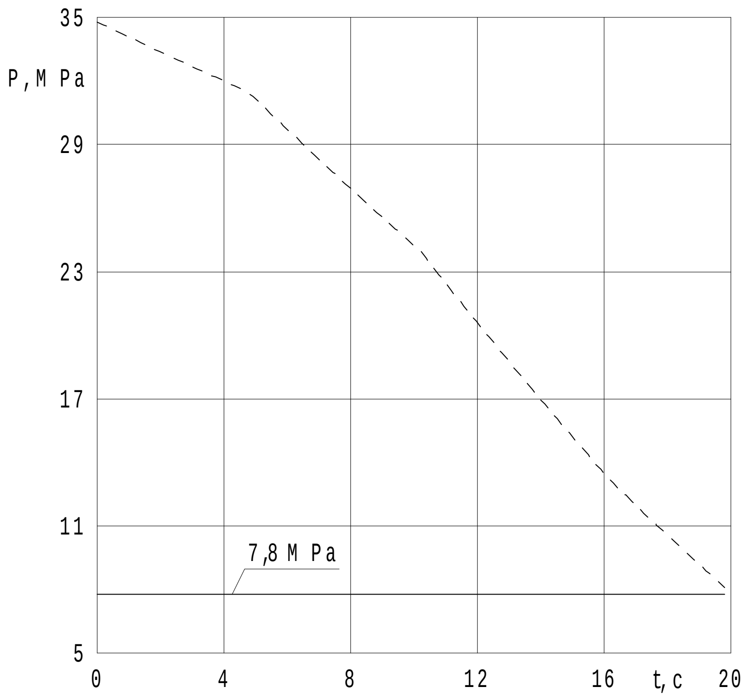

Fig. 2. Dynamics of critical pressure

Fig. 3 and 4 represent similar calculated and experimental data obtained within the analysis of research experiment on test facility TKR-F carried out on March 23, 2002. As before, experimental data on temperatures are given according to thermocouples indications, located in the most heated tube section (thermocouples T.03.15 and T.03.16). The reference temperature of the tube and internal pressure in calculation were specified according to conditions of the experiment carried out (300°C and 7,9 MPa). In this case, the characteristic source time determining its cooling time was equal to 100 sec. Other calculated parameters remained the same.

As seen from Fig. 3, the nature of qualitative relation between the experimental and calculated data on temperature dynamics is similar to that mentioned above, - at initial heating stage the calculated values outstrip thermocouples indications, and then (by the sixteenth second of the process) appear in the observed range. As it was presented above, it resulted from the lag of thermocouples indications from the average (on thickness) tube wall temperatures. Calculated temperature dynamics provides critical pressure by the twenty-eighth second of the heating process (Fig. 4), that completely agree with the experimental data.

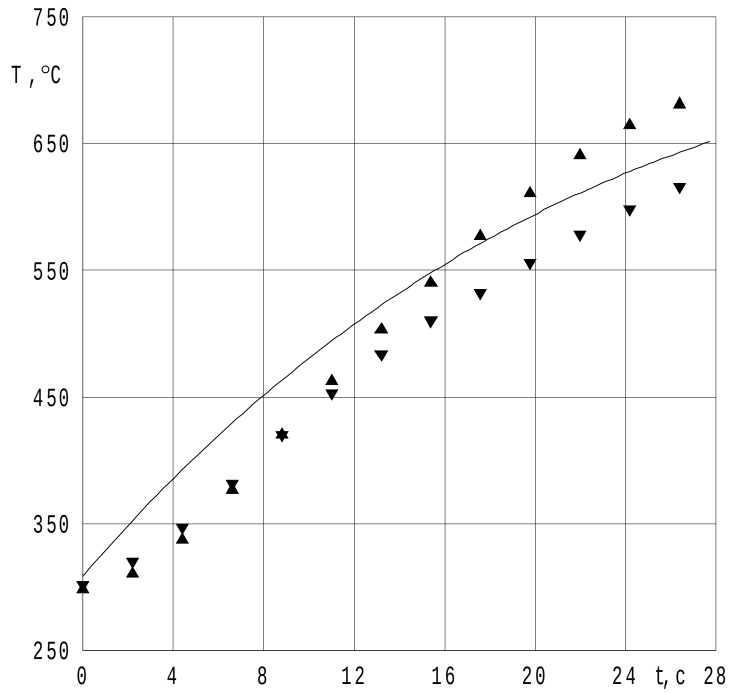

Fig. 3. Temperature dynamics in the most heated tube section

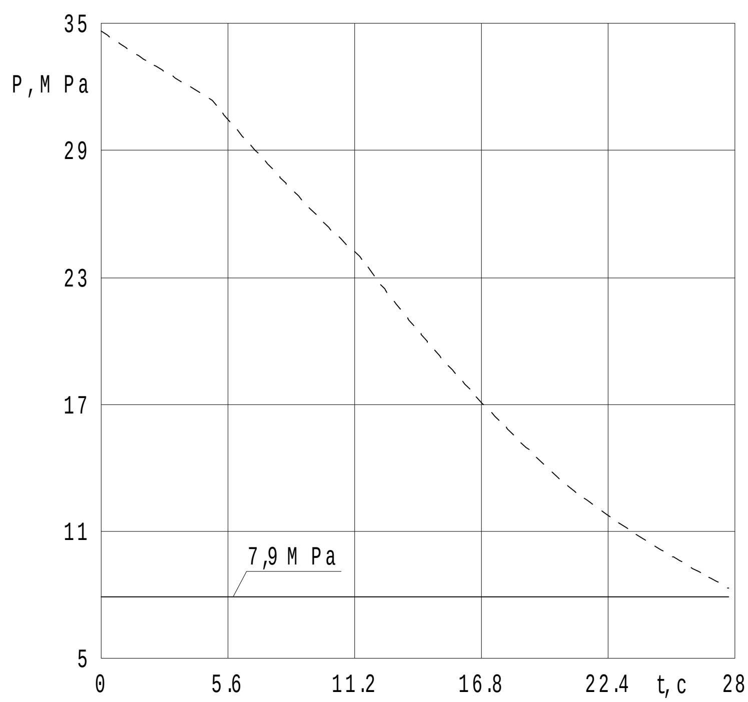

Fig. 4. Dynamics of critical pressure

Comparison of the calculated and experimental data for test 3 carried out in June 24, 2002 in test facility TKR-F with a zirconium tube, is rather difficult because the maximal temperature fixed by thermocouples during the test is 553°C. This temperature is far less than that when a break occurs (about 700°C) at a pressure of 8 MPa. Consequently, in the course of tube heating the areas of its local overheating were formed which were located out of the thermocouples location that confirmed by visual examination.

The analysis of heating process, deformation and breaking of zirconium tube in the structure of a graphite column is the next stage of the experimental researches on test facility TKR-F. Mathematical models of tube heating and deformation, which enable to analyze the tube heating and deformation processes with regard to graphite stack influence, have been developed in order to perform the calculated modeling of the above processes. Test calculations of temperature fields distribution in the tube and graphite are performed depending on thermophysical characteristics of the tube, graphite and thermite block at specified geometrical parameters. The calculations have demonstrated, that characteristic times of tube heating in a graphite column prior to achieving maximal temperature are essentially higher (5-6 times), than for the tube without graphite. This fact requires using more powerful source with shorter times for heat emission.

We also emphasize, that the mathematical models considering not only elastic, but also visco-plastic deformation both the free-of-graphite tube and the tube in the structure of graphite column is under development now. Consideration of visco-plastic tube deformation during heating and loading by internal pressure enables to solve the contact tube - graphite ring problem and to determine pressure in graphite rings. The latter, in turn, will allow to model and to define (in conditions of experiments with a graphite stack) the sequence of events during rupture of system “a tube - graphite rings and blocks”.

THE CONCLUSION

Mathematical models of heat transfer from the source to a tube, heating, deformation and breaking of a tube have been developed, implemented numerically as a computer program. The calculated values and the experimental data, demonstrating their good agreement, has been compared, that allows to make a conclusion on adequacy of the developed mathematical models and their numerical implementation. Preliminary calculated estimates of the process of heating the TKR-F tested section in the graphite accessory have been obtained. That makes it possible to schedule further experimental investigations. The developed mathematical models are the basis for creation of the integrated computer code, which should serve as the calculated tool during analysis of processes in the RBMK reactor.