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The Numerical Study of the RBMK Fuel Channel Pressure Tube Creep and Rupture under Accident Conditions

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ABSTRACT. Three accidents with in-core single fuel channel ruptures occurred at the NPP with RBMK reactors showed that the failures of the fuel channels were induced by the creep phenomena in the RBMK pressure tube (PT) under elevated temperature and pressure. The complicated nature of the fuel channel behaviour during accident conditions, an interaction of the PT with graphite elements calls for the utilization of the detailed thermomechanical computer codes for the prediction of the fuel channel behaviour and its failure. The validation of these codes is a focus of the ongoing of the numerical and experimental programs which have been carried out at EREC (Elektrogorsk town, Russia). The preliminary results on the numerical simulations of the PT behaviour and prediction of its rupture under extreme conditions are discussed in this paper. Numerical simulations of the PT creep were carried out by means of the domestic finite element ASHTER-TK code for various accident scenarios. The post-test simulations of six small-scale experiments which carried out at K-6 test facility (EREC, Russia) showed the good correlation with experimental data. Results of this comparison and a brief description of these tests are presented herein.

1. INTRODUCTION

A single fuel channel (FC) rapture in the channel-type reactors is one of the possible scenarios of design-basis accidents. The analysis of accidents in the RBMK-type reactors (in 1975, 1982 and 1992) in which a single FC sustained failure has revealed that the principle cause of FCs breakdown was the rapture of the FC pressure tube due to its high-temperature creep. By the design the FC consists of a pressure tube (PT) which incorporates a fuel assembly in its interior space and whose external surface is brought in touch with the hard contact graphite rings. Fitted on the graphite rings are graphite blocks. This structure is placed in the vertical position and makes up the FC. Investigations performed into the deformation and failure of the single PT in the conditions of an accident of LOCA, which are exemplified by a discrepancy between the fuel assembly energy emission and coolant flow rate in the channel, have disclosed that the creep and failure of the PT and its interaction with the graphite components of the FC are rather complicated processes in character as far as their thermophysical behaviour is concerned. In terms of evaluation of the time of the RBMK FC margin to failure in accident conditions and determination of the nature of succeeding accident phases in progress after the FC failure, the feasibility of an adequate numerical modelling of such accident processes is a topical task.

Beginning from the year 1993, the EREC (Electrogorsk Research Engineering Centre – Russia) initiated a work program on investigation of thermomechanical behaviour of the RBMK FC components under the conditions similar to various accident situations in the RBMK-type reactor. This program included a series of experiments to be conducted on the K-6 small-size test facility, as well as realization of the comprehensive thermomechanical code ASHTER-TK for numerical modelling of diverse accident scenarios. The above-mentioned program of studies comprised also investigations into the process of creep and failure of tubular specimens when they exposed to the joint action of the variable temperature field and internal pressure. The experimental results obtained through the tests were used for verifying the design code ASHTER-TK and design models realized therein.

The finite element code ASHTER-TK was developed in the EREC by the authors of the present paper to provide a means for simulation of a wide range of accidents in the RBMK which lead to overheating of the PT. This code will make it possible to simulate 2-D and 3-D thermomechanical processes in the FC with due account for the variable contact boundaries (tube expansion, breakdown of hard contact rings, their caving on the block and etc.) and the conditions of heat transfer in the system under test. In making a thermal analysis the consideration is given only to the most common heat transfer conditions, non-linear character of the relationship between the thermophysical/thermomechanical properties of the structural materials and the temperature, as well as to the phase transformations connected with the process of melting of the system components being investigated. To depict the rheological effects inherent to the FC tube deformation, the code concerned employs one of the versions of the energy creep model which allows to describe the creep process at all its stages. Such approach enables the researchers to combine the task of the strain-stress analysis with the task of evaluating the structural materials marginal conditions. The above-mentioned code ASHTER-TK will provide a means for carrying out thermomechanical analysis of the RBMK FC behaviour when used either as an independent unit or as a part of an integral code intended for performing comprehensive analysis of various aspects of an accident in the RBMK.

Presented hereinafter are the results of the post-test numerical analysis of a series of experiments conducted on the K-6 test facility in 1994 – 1998. The numerical modelling applied for the post-test calculations was accomplished through the use of the ASHTER-TK code.

2. EXPERIMENTAL SPECIMENS. BRIEF DESCRIPTION

The specimens to be tested in a number of experiments performed on the K-6 test facility within a period of 1994 to 1998 were represented by straight lengths of the RBMK FC tubes fabricated from the Zr+22.5% Nb alloy. This fragments were cut out from a non-irradiated standard tube of the RBMK FC and featured a length of from 1100 to 1400 mm with the inner diameter and wall thickness being equal to 80 mm and 4 mm, respectively. Later on, each test tube specimen was fitted out with Chromel-alumel thermocouples that were installed on its external surface, and then the model under test was secured in the vertical position in the K-6 test facility. The heating of the test models were effected by passing an electrical current through them and internally pressurized with the use of operating medium. The K-6-1994 experiment was based on the use of steam-water mixture as an operating medium, whereas in the experiments that followed the preference was given to nitrogen as a more advantageous medium. The parameters monitored and recorded in the course of each experiment included the temperature status of the fragment under test in its several sections, internal pressure, specimen radial displacement magnitude, as well as other parameters of the process. The tube radial displacement due to its creep was registered with the aid of three displacement gauges mounted in one of the tube sections. The selection of such a section was motivated by the targets and objectives of the experiment.

3. NUMERICAL ANALYSIS AND RESULTS

The post-test analysis of the experiments accomplished on the K-6 test facility in 1994-1998 was realized by application of the detailed ASHTER-TK code. Only 1/2 part of tbe test tube fragment was sufficient for numerical modelling in view of geometrical and physical symmetry of this problem. The modelling was carried out by 8-node isoparametric finite elements (FE). The original data applied for conducting numerical modelling included time variables of the temperature field in the tube under test and the internal pressure. At different time intervals these data served as output parameters for carrying out each experiment. Numerical calculations were based an the assumption that the temperature distribution would be uniform throughout the tube thickness owing to implementation of tube heating procedure in which electrical current was passed directly through the tube. The output parameters in the numerical modelling comprised the rates of creep in the model nodal points and magnitude of their displacements, as well as damage extent parameter values in each of the tube FE model. The damage extent parameter value enabled the researchers to judge the current condition of the structure material with respect to the individual FE volume. The modelling process discontinued when the damage extent inflicted throughout the tube thickness at any tube area reached a value equal to one. This testified the fact of the tube failure that had taken place in the area concerned.

The results of the post-test calculations of the experiments carried out on a single tube are presented in Figs 1 through 5. These figures show the curves of temperature variations (Ti) at specific tube points that accommodated thermocouples assigned with appropriate number (i), and the curves of pressure variations (P) in the test tube in the course of the experiment. The specific points were selected with due regard for the test tube sections where the temperature was the highest or where the tube sustained failure. Illustrated on each of these Figs (Ref. Figs 1 through 5) are also the data on the changes in the tube radial deformation which had been obtained through numerical modelling.

The K-6-94 Experiment. The objective of the K-6-94 experiment (Ref. Fig. 1) was to simulate an accident situation in tbe RBMK-type reactor as a result of an abrupt cessation of the coolant circulation through the FC. The experiment scenario was based on the assumption that the tube model would be heated from 573 K to 873 K at a heating rate of up to 10 K/s at a constant pressure of 7.5 MPa maintained in the test tube. It was suggested that the test tube should be exposed to the conditions created by the achieved temperature and pressure parameters util its failure. During this experiment the function of the operating medium used for building up pressure inside the tube was performed by steam-water mixture. Thermocouples T7, T10 and the radial displacement sensors were arranged in the sections located at distances of 350 mm and 275 mm from the top edge of the tube zirconium part, respectively. As may be seen from the curves in Fig. 1, the tube fragment failure, determined by the results of the numerical calculations, occurred after a time lapse of 205 seconds of the process, which exceeded the experimental results by approximately 25 seconds. Besides, the values of the maximum radial deformation obtained through experimentation and by virtue of calculations turned out to be equal to 0.6 and 1.1, respectively. Such an error in the results can be explained, at least, by the following:

(i) essential error in determining temperature profile along the tube height in the course of the experiment. The reason for it is a rather large pitch (not less than 100 mm) between the tube joints which incorporated thermocouples which prevented to reconstruct the tube temperature profile to the required accuracy in the area where the tube creeping process had the most vigorous aspect. According to the numerical investigations obtained by the authors of this paper, the character of temperature distribution in the area of the tube rapture is the decisive factor that has a great impact on both the tube deformation kinetics in the area concerned and the margin to failure;

(ii) «drift» of the zone of the tube mostly heated section as the experiment goes on. As is well-known, such phenomenon is caused by the procedure implying direct heating of the tested tube, as well as by the change of water level in the tube fragment during the experiment due to water evaporation. On termination of the experiment a decision was made to carry out the next experiments with the use of nitrogen for building up internal pressure in the tube.

The tube failure occurred in the section located at a distance of 100 mm from the top edge of the tube zirconium part where the radial deformation amounted to 0.6 at the end of the experiment. The values of the tube temperature in the section incorporating thermocouple T7, and of the tube pressure before its rapture accounted for 930 K and 7.7 MPa.

The K-6-95 Experiment. The objective of this experiment was similar to that of the K-6-94 experiment and consisted in investigation into the behaviour of a single RBMK PT under accident situation brought about by an abrupt cessation of coolant circulation through the FC. The experiment scenario was based on the assumption that the tube model would be subjected to an uninterrupted heating from its original temperature of 620 K at a heating rate of 10 K/s until the instant of its rapture. It was suggested that, during the test, the pressure in the tube should be maintained at a constant level of 7.5 MPa (Ref. Fig. 2). Rapture of the tube under test took place after a time lapse of approximately 36 seconds since the beginning of the tube rapid heating process. The temperature in the area of rapture and the tube pressure at the moment of rapture were as high as 1035 and 6.6 MPa, respectively (Ref. Fig. 2).

The maximum tube deformation turned out to happen in the area where thermocouple T17 had been installed. The sections chosen for installation of radial displacement gauges and thermocouple T17 were located at distances of 660 mm and 900 mm, respectively from the top edge of the tube zirconium part. The tube measurements taken after the experiment demonstrated that the maximum tube defonnation amounted to 0.4, which is substantially lower that the calculated value (Ref. Fig. 2). As may be seen in Fig. 2 the curves show evidence of good agreement between the calculated and experimental time values of the tested specimen rapture which occurred approximately at the onset of the 70-th second. The most intensive radial deformation growth was detected after a time lapse of 65 seconds, and then its growth went on in line with the exponent curve (Ref. Fig. 2). As distinct from the previously conducted K-6-94 experiment, the test in question gave evidence of a slower drift of the most thermally-loaded tube section along the tube height in the process of its heating.

The K-6-96 Experiment. This experiment was aimed at solution of two tasks: (i) to obtain experimental results suitable for verification of comprehensive thermomechanical codes; (ii) to investigate into the behaviour of the FC tube under emergency conditions corresponding to an accident of partial rapture of the circulatory circuit components without operation of the emergency protection system. The variation of pressure in the tuhe and tube temperature in its most heated section (thermocouple T10), as well as the change in the tube radial defonnation witnessed during the experiment are represented by the curves in Fig. 3. As may be clearly seen from these curves, the rapture of the tube under test occurred approximately at the onset of the 183-th second when the tube temperature and the pressure in the tube were found to be equal to about 1080 K and 3.4 MPa, respectively. The tube rapture took place almost in the middle of the tube where thermocouple T10 and radial displacement gauges had been installed. The time that preceded the tube specimen failure and defined through simulations with the aid of the ASHTER-TK code appeared to be about 175 seconds (Ref. Fig. 3). The maximum radial deformation of the tube was equal to 0.67 and was located 75 mm lower than the middle part of the tube. As may be evident from Fig. 3, the most rapid growth of the tube radial deformation was witnessed on expiration of 170-th second, when the tube relative deformation was not in excess of 0.38. After a time lapse of 170 seconds the tube radial deformation was oriented in almost vertical direction (Ref. Fig. 3). The comparison drawn between the tube deformation kinetics in the section accommodating the displacement sensors and the calculated results gave evidence of good agreement.

The K-6-97 and K-6-98(1) Experiments. The specific feature of the above experiments consisted in the utilization, in the K-6-98(1) experiment, of the tube model that had already exhibited a residual creep deformation. The accomplishment of such an experiment made it possible to obtain highly valuable information to be used for verifying the thermomechanical codes and upgrading the calculation methods.

The tube fragment selected for testing was essentially a tube which had been used in the K-6-97 experiment and subsequently repaired. The repair procedure involved welding of a new lower reducer to the tube as the breakdown of the model under test, performed in the course of the K-6-97 experiment, occurred in the area of the lower weld joining the main tube with the «steel-zirconium» reducer. The termination of the K-6-97 experiment took place after a time lapse of 9400 seconds as a result of rapture of the tube lower weld joining the lower reducer to the main tube, and, by that time, the tube diameter in its central section appeared to be 117.4 mm which corresponded approximately to a relative deformation magnitude of 0.32.

As has been mentioned above, the same tube model was applied to tests, after being repaired, in the K-6-98(1) experiment. The change in basic process parameters evidenced during this experiment is depicted in Fig. 4 in which it is clearly seen that the specimen failure occurred by the 175-th second from the start of the test. The temperature in the middle of the tube and the pressure in the tube were, by that time, as high as 1150 K and 1.58 MPa, respectively (Ref. Fig. 4). The value of the tube radial deformation obtained by means of simulation at the instant of its rapture accounted for 1.3. According to the results of the experiment, the tube radial deformation turned out to be 0.642 in the section located 15 mm lower than the middle of the tube model where the displacement sensors had been mounted. The comparison between the calculated and experimental results related to the tube deformation in its middle section confirmed good agreement between these data.

The K-6-98(2) Experiment. The principal goal of the experiment was to derive experimental data associated with the conduct of a single tube in the RBMK FC under the conditions in which the Zr+2.5% Nb alloy exhibited its superplastic properties. The test results gained through this experiment will be used, first of all, for the purpose of verifying the thermomechanical codes, and also for further perfection of the mathematical and physical creep models utilized in these codes.

The scenario of the experiment concerned was based on the assumption that the tube should be held under a temperature of 1000 K and a pressure of 0.9 MPa as long as it withstands failure. It was anticipated that such parameters of the test process would bring about rather sizable radial deformations. The tube temperature variations in the tube central section (thermocouple T5) and the internal pressure as registered during experimentation are presented in Fig. 5. This Fig. shows also the change in the tube radial deformation obtained by virtue of modelling.

As evident from the curves in the Fig. the damage to the tube integrity was caused in its central part after a lapse of 6100 seconds since the beginning of the test process. The tube rapture appeared as a hole of 0.5 mm in diameter in the middle section of the tube model. The tube maximum deformation reached the magnitude of 1.171 in its central part. The calculated value of this parameter approximated 2.2 (Ref. Fig. 5). The time that preceded the tube specimen failure and defined through numerical modelling method was found to be equal to 5800 seconds which is less than the respective value obtained by the experiment. This fact substantiates the need of further perfection of the creep model describing superplastic behaviour of the Zr+2.5% Nb alloy and refinement of the parameters related to the material properties of this alloy susceptible to deformations under the above conditions.

Another avenue of investigations into the problem of the RBMK FC integrity is connected with the development of the integrity criteria of single FC operating in the conditions of overheating with excessive pressure built in the tube. One of the most commonly used and well-known criterion associated with the FC tube failure incorporates such parameters as the tube temperature, internal pressure and the rate of temperature growth in the form of correlative relationship. This relationship patterns were obtained by Canadian researchers [1] and in RDIPE (Russia) [2] on the basis of voluminous experimental and numerical data concerning the behaviour and failure of the FC tubes under extreme conditions. Fig. 6 shows the curves obtained in the RDIPE and approximating extensive experimental results provided by the RDIPE for two heating rates of the FC tubes. Shown in the same Fig. are the curves in the P-T coordinates derived through the use of numerical simulations with the aid of ASHTER-TK code for diverse tube heating rates, the tube temperatures and internal pressure. The comparison of the approximation curves obtained in the RDIPE on the basis of experimental data with the curves defined through numerical modelling gives evidence of their reasonably good agreement. In some sense, the calculated data serve as a supplement to these approximation curves.

4. CONCLUSIONS

The post-test numerical modelling of the experiments conducted on the K-6 test facility within a period of 1994 to 1998 has revealed that the detailed ASHTER-TK code provides a means for sufficient and adequate description of the behaviour and failure of single tubes in the RBMK FC in the conditions of the tube creep. The analysis of the results of the investigations performed substantiates the need for further perfection of the used creep model and refinement of the Zr+2.5% Nb material properties in terms of its superplastic behaviour. The data derived by application of the ASHTER-TK code may be utilized for further refining the available criteria of the RBMK fuel channel failure under the conditions of the tube temperature and pressure growth, as well as for development of new failure criteria to be used within a wide range of accident scenarios.

Further numerical and experimental work will cover the problems of the RBMK FC integrity and will involve the investigation of the behaviour of the system «PT – graphite rings – graphite block» in the conditions of an accident.

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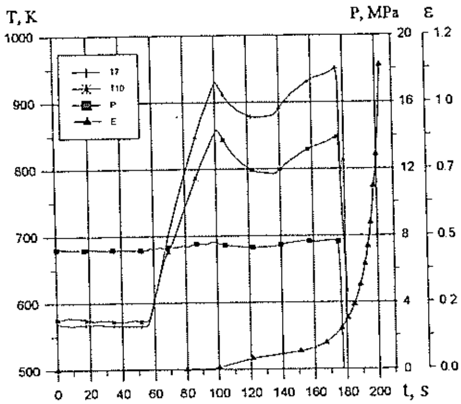

Fig. 1. K-6-94. Post-test by ASHTER-TK

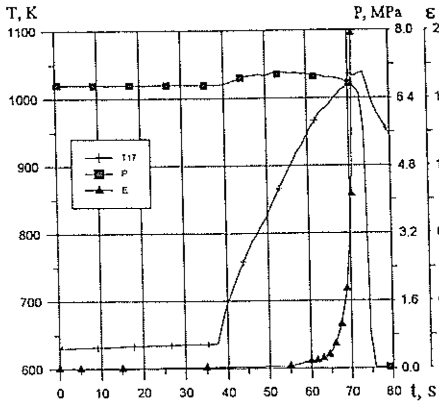

Fig. 2. K-6-95. Post-test by ASHTER-TK

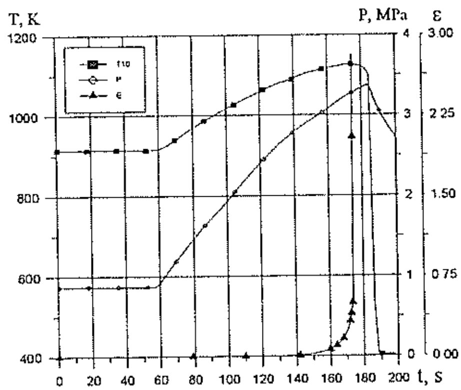

Fig. 3. K-6-96. Post-test by ASHTER-TK

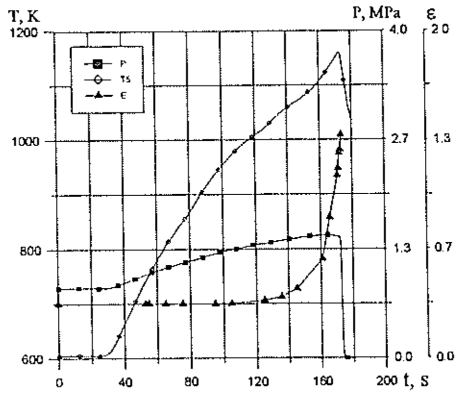

Fig. 4. K-6-98(1). Post-test by ASHTER-TK

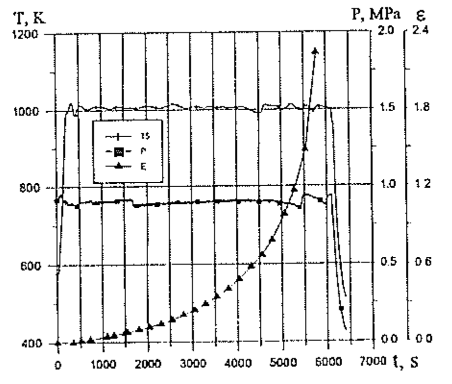

Fig. 5. K-6-98(2). Post-test by ASHTER-TK

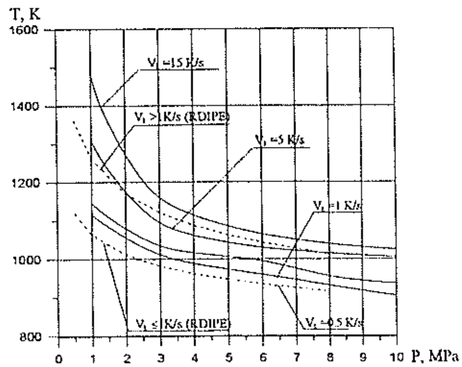

Fig. 6. Predicted RBMK PT Rupture Temperature vs. Internal Pressure (by ASHTER-TK)