THE COMPARISON OF HIGH-TEMPERATURE CREEP DEFORMATION AND FAILURE OF RBMK AND CANDU PRESSURE TUBES

Oleg Yu. Novoselsky and Vladimir N. Filinov
Research & Development Institute of Power Engineering, Russia

Vladimir A. Gashenko and Olga N. Abakumova
Elektrogorsk Research and Engineering Center of NPP Safety, Russia

ABSTRACT

The experimental investigation of RBMK pressure tubes ballooning during overheating was carried out in RDIPE and EREC (Russia). The test results were treated to obtain pressure tubes creep rate data. The correlations for high-temperature creep rate of Zr+2.5%Nb alloy have been worked out by means of treatment a lot of proper test data. Well-known creep-equations for pressure tubes of CANDU reactor were used and modified. The validation of modified creep-equations was done using the results of RBMK pressure tube ballooning tests. Creep-rate equations were presented as a computer code where the activation energy of creep is determined as a function of current tube temperature. The test data obtained were used to develop the pressure tube failure criteria at accident heating. The comparison of temperature criterion correlations for RBMK and CANDU pressure tubes showed the good agreement in wide range of tube temperature and channel pressure.

INTRODUCTION

The integrity of pressure tubes (PT) of reactor fuel channels (FC) during normal operation and accidents is the indispensable condition of safe operation of NPPs with the RBMK reactor. The investigation of PT behavior during accident heating of a single channel or a group of channels above plastic deformation onset temperature is very important task. Such accident heating caused the single PT rupture in RBMK reactor in 1975, 1982, and 1992.

HIGH-TEMPERATURE CREEP RATE

The calculation assessment of PT behavior at accident heating with computer codes suppose the use of the experimental correlations for high-temperature creep rate (creep-rate equations) for Zr+2.5%Nb alloy, which is the material of RBMK pressure tubes. Working out of these creep-rate equations is possible by means of treatment a lot of proper experimental data.

The experimental investigation of RBMK pressure tube ballooning during overheating was carried out in RDIPE and EREC (Russia). The accident heating was modeled with sections of regular RBMK pressure tube and scaled in the ratio 1:4 Zr+2.5%Nb simulators. Some of the tests were carried out with graphite blocks. The tube wall temperature, channel pressure and external tube radius increment were measured during the tests. In the tests the pressure range was 0.2-8.2 MPa, temperature range was 300-1300 ^{o}C and heating rate range was 0.1-80 ^{o}C/s.

The test results were treated to obtain PT creep rate data. Well-known creep-rate equations for pressure tubes of CANDU reactor, that are made from Zr+2.5%Nb alloy, were used. These equations were obtained in AECL (Canada) (Shewfelt, Lyall, et al., 1984) on the base of tensile tests using the specimens cut out from CANDU PTs. The validation of AECL creep-rate equations was done on the base of results of RBMK PT ballooning tests. The comparison of calculation results using the AECL creep-rate equations with test data showed that these equations are not quite suitable for modeling of RBMK pressure tubes ballooning. The difference of RBMK and CANDU PTs manufacture technology and heat treatment is probably the reason of insufficient compliance.

Therefore the AECL creep-rate equations were modified for more accurate modeling of RBMK PT ballooning at accident heating. These modified creep-equations were used in computer code KATRAN elaborated at RDIPE for analyzing PT behavior at accident conditions. The KATRAN code solves the plane and axial-symmetric problem of pressure tube deformation. The transverse stress is calculated assuming that the tube was thin-walled and thus $s_q=pr/d$, where p is the internal pressure, r is the mean radius and d is the tube wall thickness. The increase in the transverse stress during ballooning caused by the increase in radius and decrease in wall thickness is taken into account. The model of stress-strain state of PT realized in the KATRAN code uses stress and strain intensities as the characteristics of great plastic deformation: $s_i=(\sqrt{3}/2)s_q$ and $e_i=(2/\sqrt{3})e_q$. The detailed description of the PT stress-strain state model used in KATRAN code is given in (Novoselsky & Filinov, 1997). Dynamics of tube temperature and internal pressure in the channel is used as input data to make the calculation.

The correlations for transverse strain rate in KATRAN code are presented as functions of the transverse stress, tube wall temperature and heating rate. In contrast to AECL correlations the creep activation energy in KATRAN code is not a constant but a variable value that is determined at each time step as a function of current temperature of PT. The transverse strain rate is calculated at every time step using current values of PT temperature, transverse stress and activation energy. The PT transverse strain increment and current value of PT transverse strain is calculated at every time step using the transverse strain rate obtained.

Validation of AECL creep-rate equations and KATRAN code deformation model was realized by means of comparison with the test results obtained in RDIPE and EREC during modeling the RBMK pressure tube accident heating. Figures from 1 to 3 show the test results in comparison with the creep strain predictions obtained by numerically integrating AECL creep-rate equations and with KATRAN code using the measured temperatures.

Figure 1 shows the comparison results of AECL and RDIPE predictions with the experimental simulating of accident heating of the PT due to FC dry-out at full channel power. The experiment has been carried out using a section of regular PT. The asterisk indicates the moment of PT rupture. The results of comparison indicated a good agreement between the RDIPE predicted values and measurements in terms of such parameters as PT rupture temperature, time before rupture and transverse strain at tube rupture. At the same time there is an essential difference between AECL and RDIPE predictions.

Figures 2 and 3 show the comparison of measured strain in tests used scaled simulators with AECL and RDIPE predictions. Tests were done under full and decreased pressure in the tube. As evident, there is reasonable agreement between the predicted and measured transverse creep strain both for AECL and RDIPE calculations.

As the analysis shows the predicted strain obtained with the AECL correlations essentially exceeds the measured rupture strain and predicted strain obtained with the code KATRAN, for a regular RBMK PT. This circumstance, probably, reflects real distinctions of alloy properties, of which the CANDU and RBMK pressure tubes are made. To check this assumption the validation of KATRAN code model was carried out using the Canadian data given in (Shewfelt, Godin, et al., 1984). The results of comparison of the predicted and measured transverse strain are shown in Figures from 4 to 6. As can be seen there is good enough agreement between AECL and RDIPE predictions for low (Figure 4) and middle (Figure 5) pressures, but RDIPE predicted creep strain is lower at high pressure in the tube (Figure 6).

It is necessary to note, that the calculation model of deformation used in the code KATRAN, is purely phenomenological and, therefore can be easily adjust under anyone data received in the tests with pressure tube ballooning under overheating. The use of variable parameters instead of constant values in creep-rate equations allows them to be used for predicting of RBMK pressure tube ballooning in wide range of accident conditions. When new test data will be available, the more accurate definition of calculation model will be possible.

HIGH-TEMPERATURE FAILURE CRITERIA

The test data obtained during the experimental investigation of RBMK pressure tubes ballooning caused by internal pressure during overheating were used for development of various experimental failure criteria of PT at accident heating: temperature, strain, stress and energy failure criteria description of which being given in (Novoselsky & Filinov, 1997). The correlations for these failure criteria were obtained for two ranges of heating rate. Potentiality of the pressure tube rupture during heating is assessed by application of the KATRAN computer code using four criteria of PT rupture.

Figure 7 shows the temperature failure criterion in the form of the tube rupture temperature T_{wr} dependence on the channel pressure. The data are classified by the heating rates, the experiments with graphite blocks are marked with black symbols. The shaded region covers all combinations of T_w and p parameters in case of rupture. At higher heating rates the values of rupture temperature (dark-gray region) proved to be higher than the values obtained for low rates (light-gray region). There is a range of low probable combinations of the tube temperature and pressure above the upper boundary of the region, the range of nonrupture values of T_w and p, being depicted below the rupture range. Approximating curves for rupture temperature (^oC) at low and high heating rates, depending on pressure p value (MPa), are shown in solid lines:

curve 1 ($u_T \leq 1$ $^oC/s$):

$$T_{wr}=796.4 \times p^{-0.0988} \qquad (1)$$

curve 2 ($u_T > 1$ $^oC/s$):

$$Twr=975.1 \times p\text{-}0.1334 \qquad (2)$$

The curves for temperature failure criterion of the CANDU reactor pressure tubes obtained by Canadian specialists (Kundurpi & Archinoff, 1986) are given in Figure 7 in fine lines as the comparison of CANDU and RBMK data. In the range of the RBMK operational pressure (7-8 MPa) a good enough agreement of the temperature failure criteria of the RBMK and CANDU pressure tubes is observed. It should be noted that the Canadian failure criteria were obtained as calculation results with use the NUBALL computer code, but RDIPE failure criteria are the approximation of data obtained during tube ballooning tests. Thus we can consider the comparison results in Figure 7 as the verification of the temperature failure criterion obtained for CANDU pressure tubes. Correlations (1) and (2) can be used in thermal-hydraulic codes for the evaluation of possibility of pressure tube rupture without thermal-mechanical calculations.

Figure 8 shows the strain failure criterion in the form of rupture strain intensity dependence e_{ir} upon the pressure tube temperature T_w. The results are classified according to the heating rates and presence of graphite blocks. The shaded region designates the measured values of rupture strain. At low heating rates (light-gray region) the rupture strain proved higher than in case of high (dark-gray region) ones. In the range of 750-760 ^oC the superplasticity of the Zr+2.5%Nb alloy has been clearly pronounced, moreover, higher strain values are reached at low heating rates, while at high rates the tube material is in superplasticity state for a short period of time. Experimental investigation of plastic elongation of Zr-2.5wt%Nb alloy under high-temperature conditions (Rosinger & Unger, 1979) confirm nonmonotonous character of rupture strain - temperature dependence and superplasticity of zirconium alloys, as well as the influence of strain rate on the value of rupture strain. But the superplasticity region of CANDU PT alloy is at a higher temperature that of RBMK (~820 ^oC). A great dispersion in the values of rupture strain even for the same heating rate makes obtaining of the correlations $e_{ir}(T_w)$ highly problematic. When analyzing the PT behavior during accident heating, curve 1 may be used, which approximates the values of strain intensity in case of rupture for low heating rates depending upon the tube temperature (^oC). Curve 2 is equation of the lower boundary of rupture region and it can be used for conservative evaluation of PT rupture potentiality.

curve 1 ($u_T \leq 1$ $^oC/s$):

$$eir = 111.76 - 50.076 \times 10-2 \times Tw + 74.197 \times 10-5 \times Tw2 - 36.209 \times 10-8 \times Tw3 \quad (3)$$

curve 2:

$$eir = 36.025 \times 10-2 - 65.302 \times 10-5 \times Tw + 45.826 \times 10-8 \times Tw2. \quad (4)$$

Obtaining of reliable correlations for rupture strain is possible, provided dependence e_{ir} upon a more complex argument is used. In (Novoselsky & Filinov, 1997) such a criterion is presented as a function of tube material properties, stress intensity and pressure.

CONCLUSIONS

The use of modified high-temperature creep equations and failure criteria for the predicting of RBMK pressure tube accident ballooning and rupture was verified by solving of plane and axial-symmetrical deformation problem and comparison of calculation results with experimental data. The calculations were carried out using the measured temperature and pressure histories as the input data. Good agreement between calculation results and measured values was obtained for such parameters as the rupture temperature, rupture strain and time to rupture.

The modified equations for creep rate and failure criteria can be used in three-dimensional computer codes for predicting of deformation and failure of RBMK pressure tubes at accident heating. The use of such codes will allow us to avoid unnecessary conservatism at calculation assessment of RBMK pressure tube failure during accident heating.

It should be noted that the world operational experience for channel-type reactors essentially concedes to vessel-type reactors ones. This circumstance makes exchange as very important of safety relevant information very important. First of all it concerns Canada and Russia as the countries where the most of channel-type reactors are operating. The exchange of the available information on reactor processes and on properties of reactor materials is very useful from the point of view of increasing the safety of channel reactors and efficiency of their use.

REFERENCES

Shewfelt, R.S.W., L.W. Lyall, and D.P. Godin. “A High-Temperature Creep Model for Zr-2.5wt%Nb Pressure Tubes”. *Journal of Nuclear Materials*. Vol.**125**, pp 228-235, 1984.

Novoselsky O.Yu. and V.N. Filinov. “RBMK Pressure Tubes High-Temperature Failure Criteria”: *Proceedings of the Annual Meeting on Nuclear Technology’97*, Aachen, 13-15 May 1997, pp 639-642, INFORUM GmbH, Bonn, Germany, 1997.

Shewfelt, R.S.W., D.P. Godin, and L.W. Lyall. “Verification Tests of a High-Temperature Transverse Creep Model for Zr-2.5wt%Nb Pressure Tubes”. *AECL-7813*, 1984.

Kundurpi, P.S. and G.H. Archinoff. “Development of Failure Maps for Integrity Assessment of Pressure Tubes”. *Proceedings of the 7th CNS Conference*, Toronto, June 1986, pp 22-29.

Rosinger, H.E. and A.E. Unger. “The Superplastic and Strain-Rate Dependent Plastic Flow of Zirconium - 2.5wt% Niobium in the 873 to 1373 K Temperature Range”. *AECL-6418*, 1979.

KEY WORDS

RBMK, pressure tube, Zirconium, creep, temperature, strain, failure.

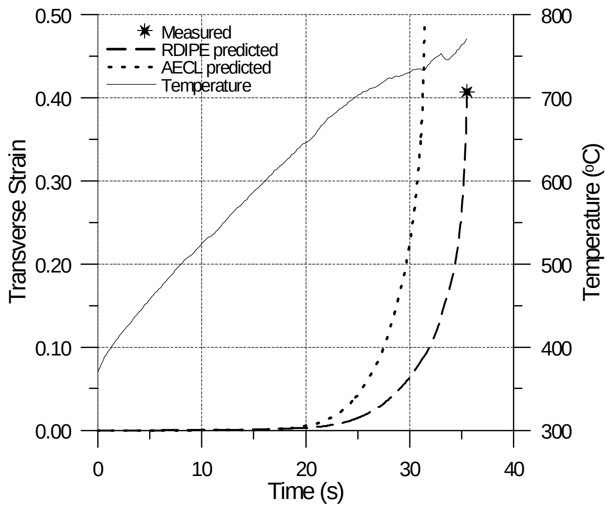

Figure 1

RDIPE-EREC Test with Regular PT (p_{rupt}=6.5 MPa)

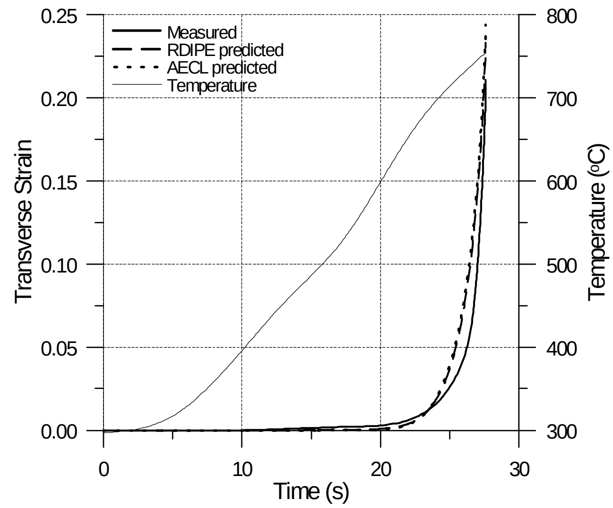

Figure 2

RDIPE Test with PT Simulator (p_{rupt}=7.9 MPa)

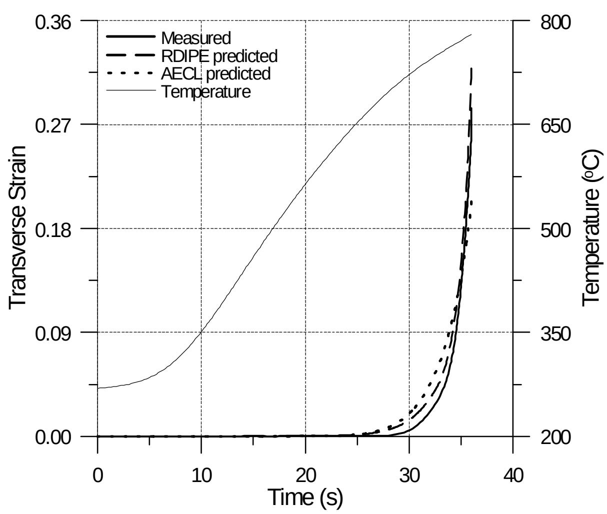

Figure 3

RDIPE Test with PT Simulator (p_{rupt}=3.9 MPa)

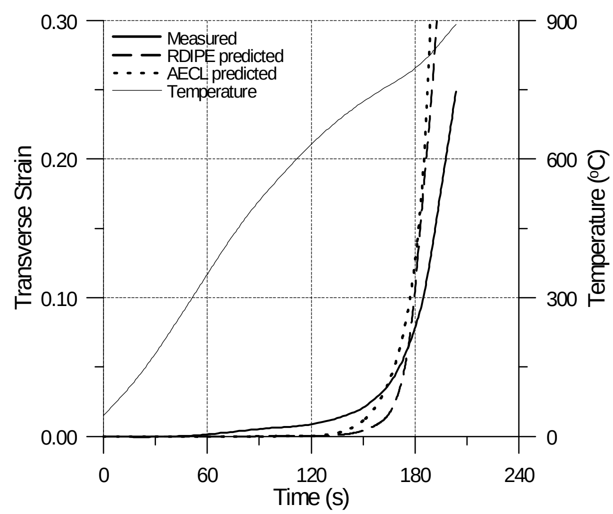

Figure 4

AECL Biaxial Test (p=1.0 MPa)

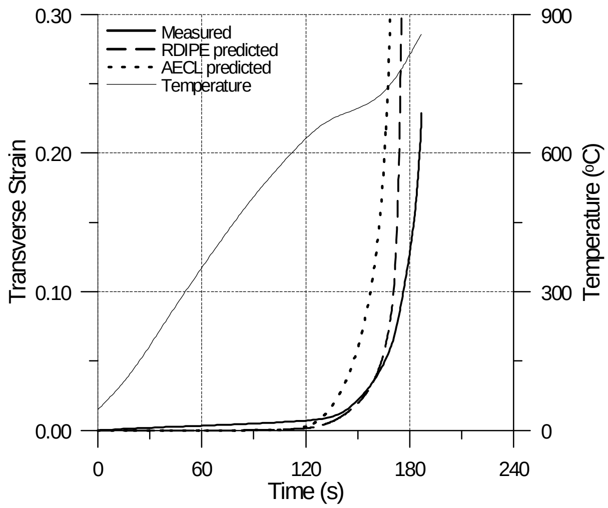

Figure 5

AECL Biaxial Test (*p*=3.1 MPa)

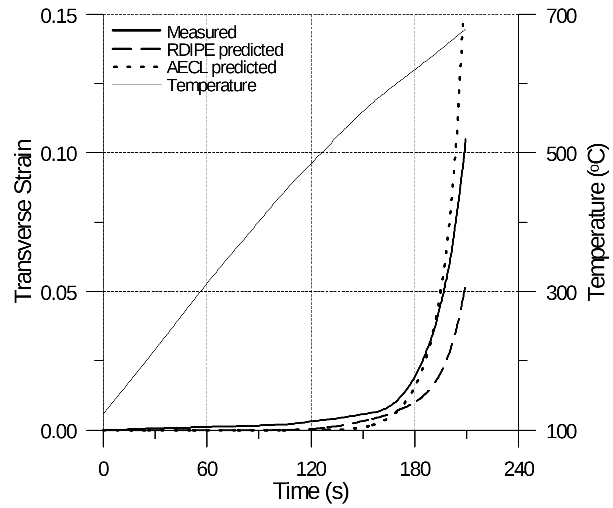

Figure 6

AECL Biaxial Test (*p*=7.2 MPa)

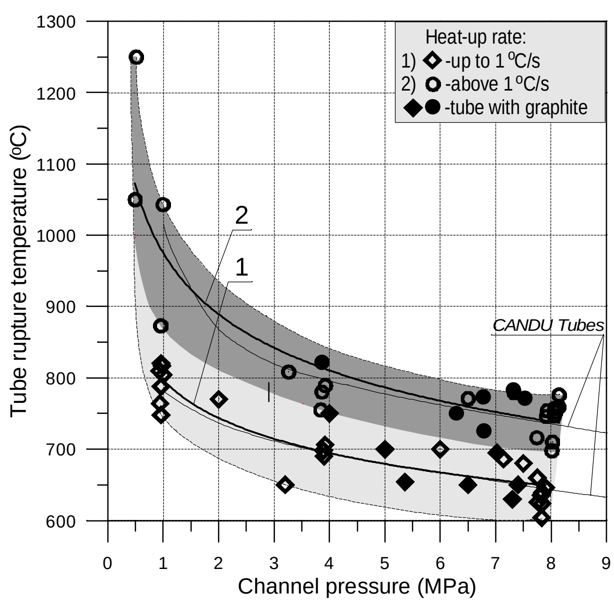

Figure 7

PT Rupture Temperature vs. Channel Pressure

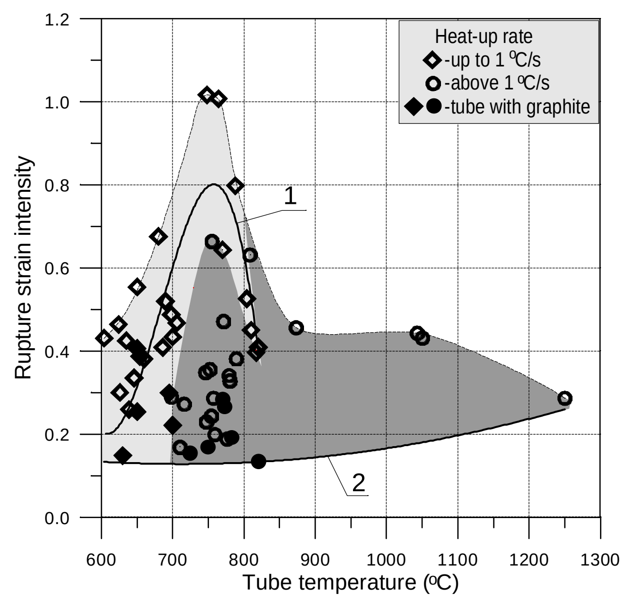

Figure 8

PT Rupture Strain Intensity vs. Tube Temperature