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Structural Integrity Evaluation Method for Overheating Rupture of FBR Steam Generator Tube

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ABSTRACT

Studies on overheating rupture of the FBR steam generator (SG) tube in case of sodium-water reaction have been carried out to develop the evaluation method for the demonstration fast breeder reactor, DFBR, in Japan. This paper describes the result of creep rupture test and the rupture evaluation method.

1. INTRODUCTION

It is one of the most important subjects in FBR safety evaluation to clarify the overheating behavior of the FBR SG tube when sodium-water reaction occurs. The temperature of SG tube reaches around 1200 K in a few seconds due to sodium-water reaction. Because the SG blowdown procedure after detection of sodium-water reaction needs more than scores of seconds, the burst of SG tube could occur due to decrease of the strength of the tube. Formerly, the ductile failure criterion has been applied for the overheating rupture evaluation. This criterion is not compatible with test data, and it gives much conservative results. The creep strength of the tube material is a dominant factor for the overheating rupture of the SG tube. For this reason, we apply the creep failure criterion. The creep rupture tests have been performed at the high temperature conditions with range from 1223.2 to 1323.2 K. The test material is 'Mod.9Cr-1Mo steel', which is the candidate material for the SG tube of DFBR. The test results have shown that the instantaneous tube rupture does not occur even if the stress exceeds the design ultimate tensile strength, and that the tube rupture occurs when the holding time exceeds the creep rupture time. The test data have been suitably expressed using Larson-Miller Parameter (LMP), and the structural integrity evaluation method based on sum of the use-fraction associated with creep damage has been proposed. Based on this method, the structural integrity evaluation in the case sodium-water reaction has been performed. The results show that it is important to detect the initial leak of the tube within a short period and to reduce the steam pressure more rapidly by SG blowdown.

2. CREEP RUPTURE TEST

2.1 TEST CONDITION

Test material is Mod.9Cr-1Mo steel, which is candidate material for the SG tube of DFBR. Test piece shown in Fig. 1 is cut out from rolled plate with thickness of 20 mm. It is 6 mm in diameter of straight portion and 30 mm in gauge length.

Hydraulic fatigue test machine shown in Fig. 2 has been applied for the test. The test is performed in the air atmosphere. Stress and temperature conditions are summarized in Table 1. These conditions are decided referring overheating condition due to sodium-water reaction in SG. The rupture time and elongation are measured for each test.

The test temperature of this test exceeds transformation temperature of Mod.9Cr-1Mo steel, approximately 1100 K, and transformation of the material progresses with the passage of time. For the reason that the rise of temperature of the SG tube with sodium-water reaction is very rapid, the induction coil is applied aiming fast temperature rise in this test. The coil placed so as to give the uniform temperature in the straight portion of the test piece. Creep rupture test has been performed under the load-controlled condition. The tensile loading is applied one minute after the temperature of the test piece reaches the target temperature. The time for temperature rise is approximately 20 second. The test piece at the test is shown in Fig. 3.

2.2 TEST RESULTS

Typical elongation of the test piece is shown in Fig. 4. The secondary creep stage appears just after applying the tensile load, and the primary creep stage does not appear clearly. The test pieces after the rupture tests are shown in Fig. 5. The shape of rupture portion is very fine just like cone shape. The reduction of area is extremely large.

The data of rupture time are summarized in Fig. 6. Creep rupture times are from 70 to 80 seconds, even if the stress is equal to ultimate tensile strength. This ultimate tensile strength is the conventional one where creep effect is not considered. These results show that the SG tube does not fail instantaneously, even if the stress of it exceed the tensile strength. The test results show that the creep failure criterion is appropriate for the evaluation of overheating rupture.

The creep rupture time data, which are plotted in Fig. 7, are expressed by LMP defined by the following equation [1].

$$LMP = T\,(20 + \log t_R) \times 10^{-3} \qquad (1)$$

where T is absolute temperature (K) and t_R is creep rupture time (hr). The relationship between LMP obtained by the tests (LMP_e) and stress is given by the following equation.

$$\sigma = 1.351 \times 10^5 \times \exp\left(-0.33141 \times LMP_e\right) \qquad (2)$$

where σ is membrane stress (MPa). The rupture time for arbitrary stress and temperature is able to be calculated using Equation (1) and (2). Therefore, the failure evaluation based on the time fraction method can be performed using above two equations.

3. DESIGN METHOD

3.1 DESIGN EVALUATION CURVE

The design margin is introduced to the nominal data shown in Fig. 7. The standard deviation calculated from all test data is as follows.

$$\sigma = 0.001587 \tag{3}$$

Figure 8 shows the variation of the LMP, which are obtained by the tests. The experimental data observed by the tests are limited in quantity, and the margin for uncertainty is needed in the early stage of design. It is, therefore, suitable to take the design point, therefore, will be decided at μ-3σ (99.9 percentage point) to ensure large margin. The relationship between observed data and the design value is shown in Fig. 9 which shows log-normal distribution, and the LMP for design, LMP_d, is obtained from LMP_e using the following equation.

$$LMP_d = LMP_e^{(1-3\sigma)} = LMP_e^{0.99524} \tag{4}$$

3.2 STRESS EVALUATION METHOD

The membrane stress is applied for creep rupture evaluation of SG tube. In the detailed evaluation, the effective membrane stress, $\langle\sigma_m\rangle$, and membrane temperature will be evaluated using time historical FEM analysis. The following simplified method, however, can be applied in the feasibility study stages.

$$\sigma_{i,h} = \frac{r_o^2 + r_i^2}{r_o^2 - r_i^2} p_i \qquad \sigma_{o,h} = \frac{2\, r_i^2}{r_o^2 - r_i^2} p_i \tag{5}$$

$$\sigma_{i,r} = -p_i \qquad \sigma_{o,r} = 0 \tag{6}$$

$$\sigma_{i,z} = \sigma_{o,z} = \frac{r_i^2}{r_o^2 - r_i^2} p_i \tag{7}$$

$$\langle\sigma_i\rangle = max.\left[\,|\sigma_{i,h} - \sigma_{i,r}|, |\sigma_{i,r} - \sigma_{i,z}|, |\sigma_{i,z} - \sigma_{i,h}|\,\right] \tag{8}$$

$$\langle\sigma_o\rangle = max.\left[\,|\sigma_{o,h} - \sigma_{o,r}|, |\sigma_{o,r} - \sigma_{o,z}|, |\sigma_{o,z} - \sigma_{o,h}|\,\right] \tag{9}$$

$$\langle\sigma_m\rangle = \frac{\langle\sigma_i\rangle + \langle\sigma_o\rangle}{2} \tag{10}$$

where P_i is internal pressure and r is radius of SG tube, sub-i and sub-o present inner and outer surface, sub-h, sub-r, sub-z present hoop, radial and axial direction respectively.

3.3 FAILURE CRITERION FOR DESIGN

Creep rupture strength is evaluated by using membrane stress given by Equation (10) and LMP_d given by Equation (4). Failure criterion is sum of the use-fraction associated with creep damage, which is expressed as summation of each time step of use-fraction using the following equations.

$$\sum_{i=1}^{n} \frac{t_i}{t_{Ri}} \leq 1.0 \tag{11}$$

$$t_R = 10^{(1000\, LMP_d / T - 20)}$$

$$LMP_d = 35.056 - 6.8106\, log\langle\sigma_m\rangle$$

The evaluation procedure of the overheating rupture is shown in Fig. 10. In this evaluation, the stress is calculated using internal pressure taking into account the decrease of the thickness due to wastage. The temperature of the tube is calculated using flow rate and temperature of steam, temperature of sodium-water reaction area, and so on. The ductile failure criterion, which provides the lowest creep rupture time, is also included in the failure evaluation as shown in Fig. 10. It has been introduced to eliminate the effect of uncertainty of extrapolated data. Ultimate tensile strength for design, Su, which is obtained from fast tensile test to except the effect of creep, has not been obtained yet.

4. STRUCTURAL INTEGRITY EVALUATION

4.1 EVALUATION CONDITION

Using above mentioned evaluation method, the structural integrity assessment has been performed for 30 % partial load condition. This condition is critical for overheating rupture, because of less cooling capacity of the water. The SG operating conditions are summarized in Table 2. It is assumed steam leak of 1.85 kg/s at the upper part of the tube bundle, where the temperature of sodium-water reaction is relatively high because of highest sodium temperature at the normal condition. The temperature history of sodium-water reaction area shown in Fig.11 is decided considering experimental results [2]. The time history of steam/water flow rate and internal pressure of the SG tube, shown in Fig. 12, are obtained using SG blowdown analysis code. The dimension of the SG tube, 31.8 mm in diameter and 3.19 mm in thickness, is decided considering the decrease of thickness due to corrosion. The material of the tube is Mod.9Cr-1Mo steel.

4.2 EVALUATION RESULTS

The time history of the temperature and the membrane hoop stress are shown in Fig. 13, and that of cumulative creep damage is in Fig. 14. The creep damage remarkably increases before SG blowdown procedure start and very little after that. The reason for this behavior is temperature drop of the tube due to increase of cooling capacity by increase of steam flow rate at the potion. This result shows that it is important to detect the initial leak within a short period to start the SG blowdown procedure. It is also important to prevent the decrease of cooling capacity during SG blowdown.

5 CONCLUSION

The evaluation method, which is based on sum of the use-fraction associated with creep damage, has been developed for overheating rupture of SG tube when the sodium-water reaction occurs. This new method, which is introduced instead of the ductile failure evaluation method, will contribute to mitigate the design condition. To improve this evaluation method, it is necessary to accumulate the creep rupture data. The ultimate tensile strength data is also necessary to provide the lowest creep rupture time. Concerning the SG design, performance of the leak detector and the blowdown system are the important items to secure the structural integrity of the tube.

6. ACKNOWLEDGEMENT

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[1] Larson, F. R. and Miller, J., *Trans. ASME*, 74-7(1952), 765.
[2] Tanabe, H. et al., The development and application of overheating failure model of FBR steam generator tubes, PNC TN9410 98-02, June (1998).

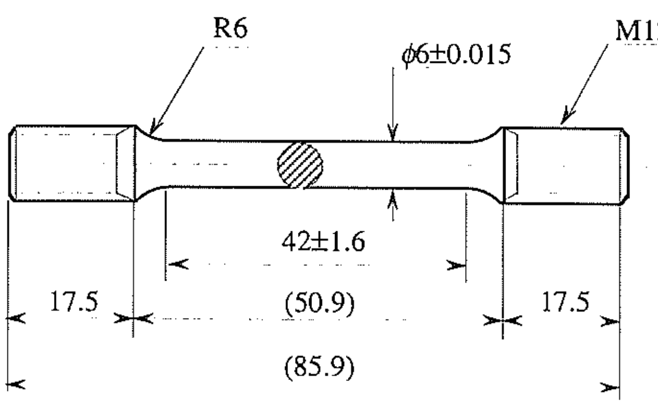

Fig. 1 Test Piece

Table 1 Test condition

Temperature (K)	1223.2, 1273.2, 1323.2
Stress (-)	0.5, 0.75, 0.85, 1.0 σ_u*

* : Ultimate tensile strength

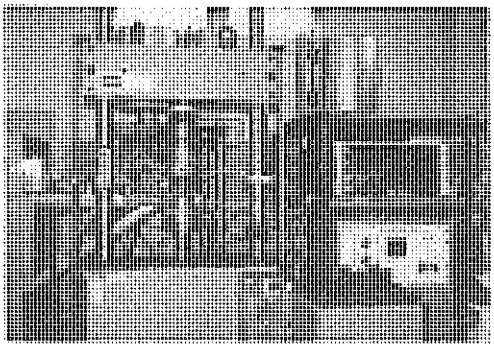

Fig. 2 Hydraulic fatigue test machine

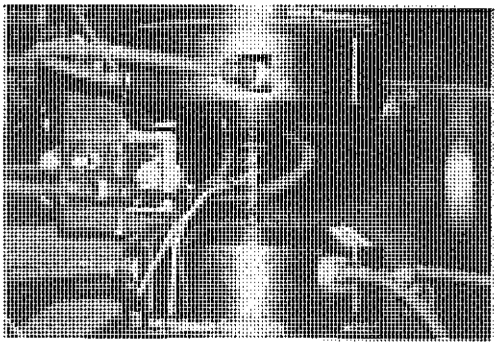

Fig. 3 Test piece at the test

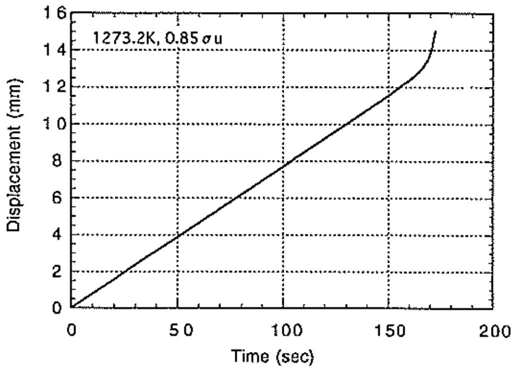

Fig. 4 Elongation of test piece

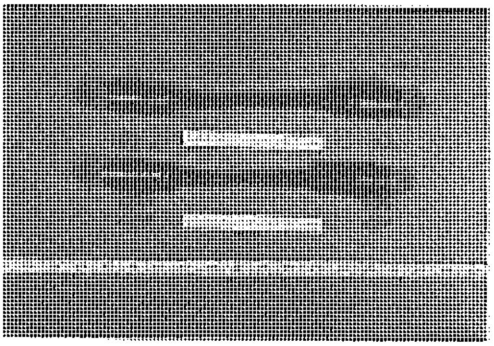

Fig. 5 Test piece after creep rupture test

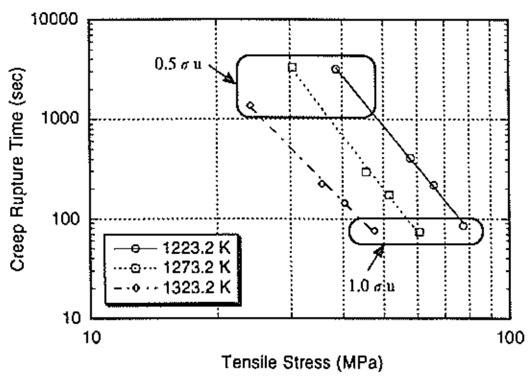

Fig. 6 Creep rupture time

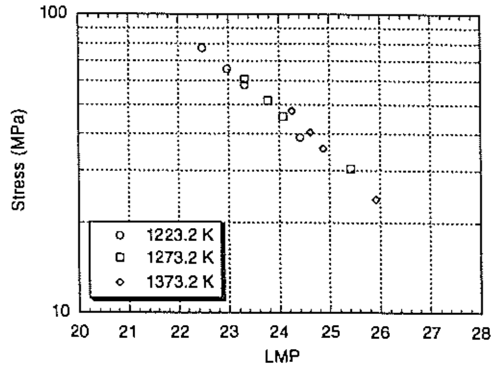

Fig. 7 Relationship between stress and LMP

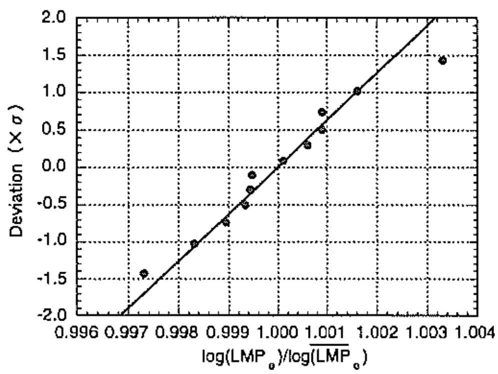

Fig. 8 Deviation of LMP

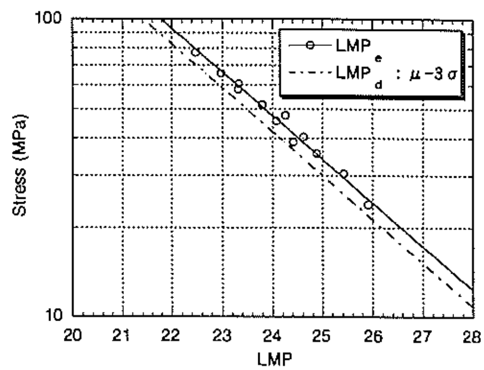

Fig. 9 LMP applied for design evaluation

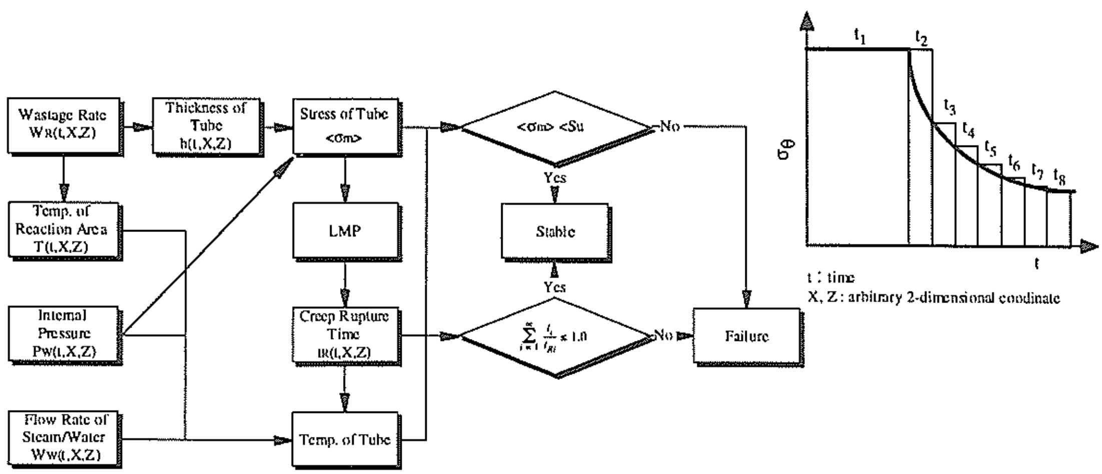

Fig. 10 Structural integrity evaluation flow

Table 2 SG operation condition

Item	Unit	30 % partial load	Full power
Sodium inlet temp.	K	716.2	793.2
Sodium outlet temp.	K	579.2	608.2
Sodium flow rate	ton/hr	1131.9	2263.9
Water flow rate	ton/hr	86.1	239.4
Steam outlet pressure	MPa	15.8	17.2
Water inlet pressure	MPa	16.0	18.7
Steam outlet enthalpy	kJ/kg	3253.1	3311.8
Water inlet enthalpy	kJ/kg	791.3	1038.3

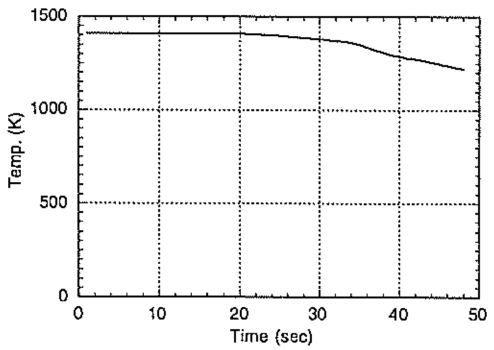

Fig. 11 Temperature history of sodium-water reaction area

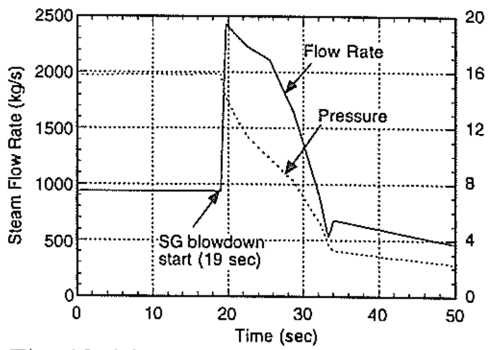

Fig. 12 Time history of steam flow rate and internal pressure of SG tube

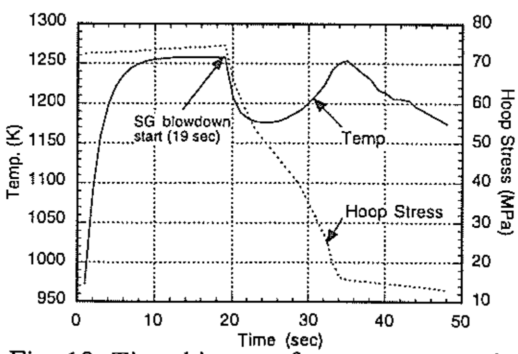

Fig. 13 Time history of temperature and hoop stress of SG tube

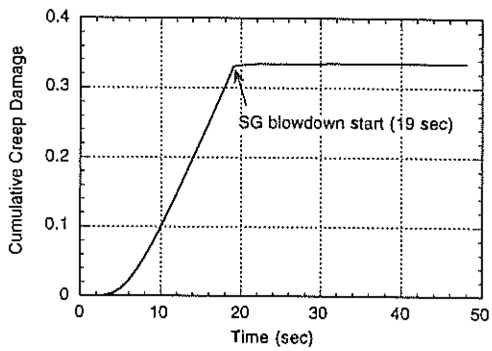

Fig. 14 Cumulative creep damage