Transactions of the **14th International Conference on Structural Mechanics in Reactor Technology** (SMiRT 14), Lyon, France, August 17-22, 1997

PW/4

Rupther - An original experimental approach for creep failure study of RPV steel

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Abstract

Rupther experiment is designed in order to get validated models for the degradation of RPV bottom head in case of a severe accident with corium flow. A simple experimental testing device has been designed in order to perform realistic thermo-mechanical loading on a cylinder. It is externally heated in its central part by induction (max. 1300°C) giving an axial thermal gradient. The cylinder is then mechanically loaded by internal pressure (max. 100 bars) until failure occurrence.

Introduction

The mechanical behaviour of Reactor Pressure Vessel (RPV) lower head in extreme case of an accident such as core melting is a rather complex phenomena. The whole loading history of RPV can include pressure variation (decrease or increase) combined with thermal changes (globally or locally). These possible histories will induce different mechanical behaviour covering all the possible domaines from elasticity to plasticity and viscoplasticity. Some metallurgical changes (such as phase transformation, grain growth, recovery...) can also occur and could be coupled with the deformation process. During TMI 2 Vessel Investigation Project [1], serious attempts were made for the prediction of the margin to failure of the RPV. They faced specific difficulties connected with the failure criteria and with the lack of material data.

The overall objective of the present project is to get validated models for the mechanical behaviour of the pressure vessel bottom head in extreme case involving corium flow. A simple experimental testing device, called Rupther, has been designed in order to obtain realistic thermo-mechanical loadings. A cylinder is heated in its central part by induction (max. 1300°C) and loaded by internal pressure (max. 100 bars). These experiments can reproduce instantaneous or delayed plastic instability of cylinder wall. The instrumentation was carefully designed in order to get a good knowledge of experimental conditions and use them as an input for finite element calculations. The steel used is 16MND5 (eq. A508 Cl3), it was extracted from a forged part intended for fabricating a RPV. A companion characterisation program was planned for tensile and creep behaviour from room temperature up to 1300°C.

Rupther experiment

Description

The basis for experimental validation was designed in order to be an analytical experiment with the following characteristics [2] :

- Small size, simple shaped specimens ;
- Temperatures within the same range as those involved in severe accident ;
- Thermal loading combined with the mechanical biaxial loading.

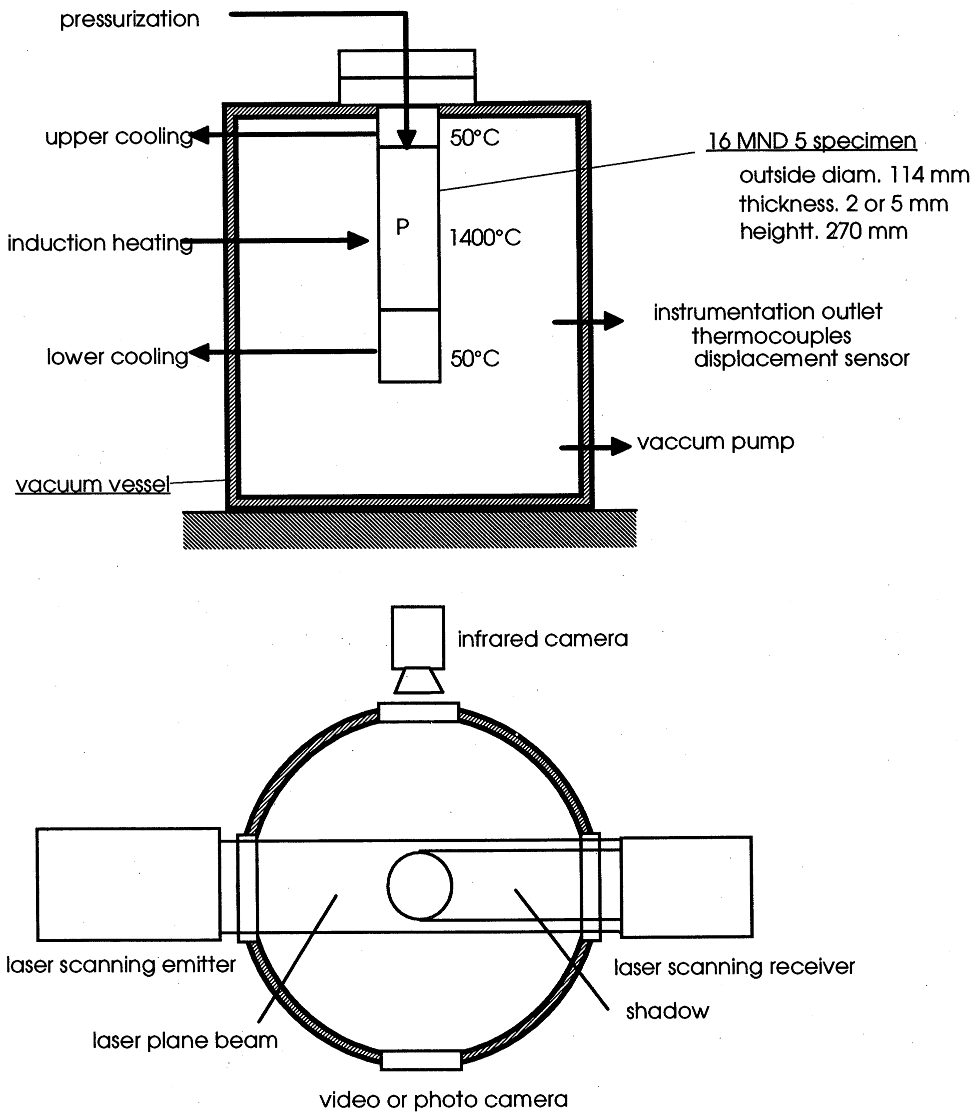


Fig. 1 : Rupther experiment

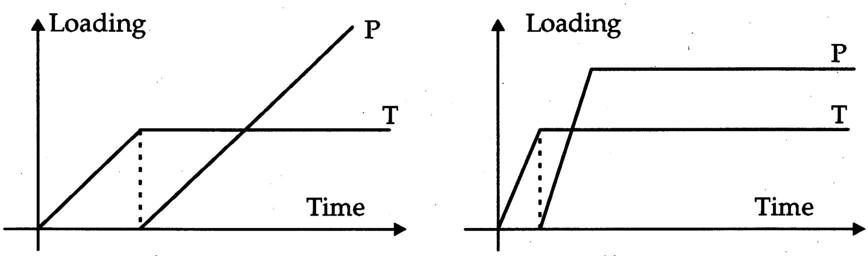
This resulted in the experiment called RUPTHER. A 4" diameter cylinder is submitted to internal pressure while being heated by induction in its central section on a limited height (figure 1). The test takes place in a guard vessel under vacuum or inert gas protecting the specimen from oxidation. The instrumentation has been carefully designed in order to reduce the need for contact with the hot specimen :

- Temperatures are measured at some points with thermocouples, while a general map is acquired by an infrared camera ;
- Diametral deformation in the central section is measured with a laser scanning shadow technique.

Two basic types of tests in steady thermal state can be run on this facility (figure 2) :

- Fracture tests : pressure is increased up to rupture ;
- Creep tests : pressure is kept constant until rupture occurs.

Of course, other types of tests are possible, with variable pressure and temperature.



a) Fracture test *b) Creep test*

Figure 2 : *Different types of loading schemes with Rupther.*

Experimental creep test results at 700°C

After some preliminary tests and fracture tests at 700°C, 1000°C and 1100°C [3], the first creep test was performed at 700°C under argon atmosphere and the corresponding results are reported below.

Temperatures and pressure evolutions

The loading scheme is as defined in figure 2-b but the real evolution has been recorded during the test and is reported in figure 3. The internal pressure load is equal to 33 bars and has been well regulated during the whole test period. Concerning the temperature, the regulation is done at an arbitrary point of the mid-plane and the target value is 700°C. However, the temperature does not remain perfectly axisymmetric during the entire test and the worst case (occurring at the piercing point) is presented in figure 3.

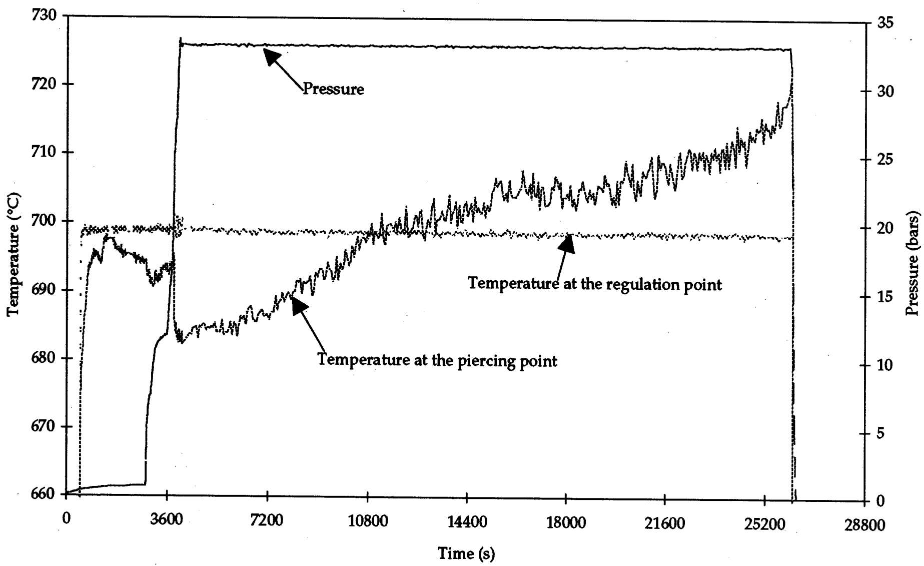


Figure 3 : *Temperatures and pressure evolutions recorded during the test.*

Axial thermal gradient
The temperature profile along the cylinder axis is extracted from the infra-red camera picture (figure 4). A fourth order polynomial was fitted to this curve in order to use it in finite element analysis.

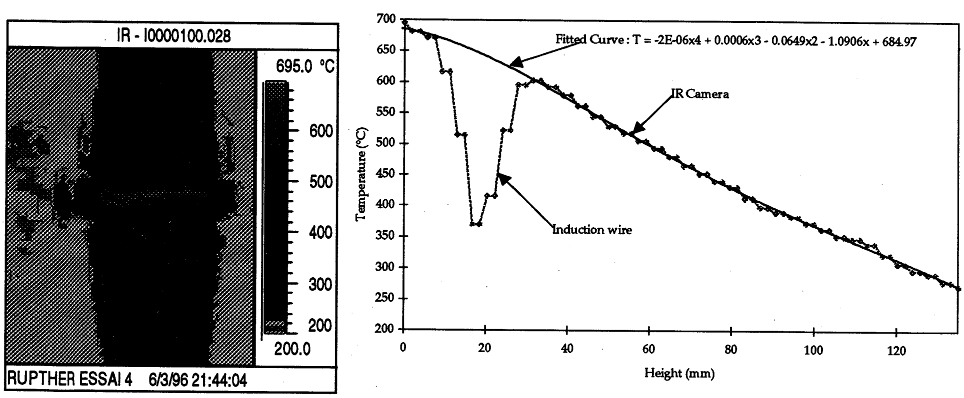


Figure 4 : *Infrared camera image and corresponding axial temperature profile (the discontinuities in the temperature profile is due to the induction coil).*

Diametral bulking
The deformation of the Rupther cylinder is recorded as diametral evolution in the mid-plane with a laser scanning shadow technique (figure 5). We also have access to the displacement of the right and left sides showing that the tube does not remain perfectly centred during the test.

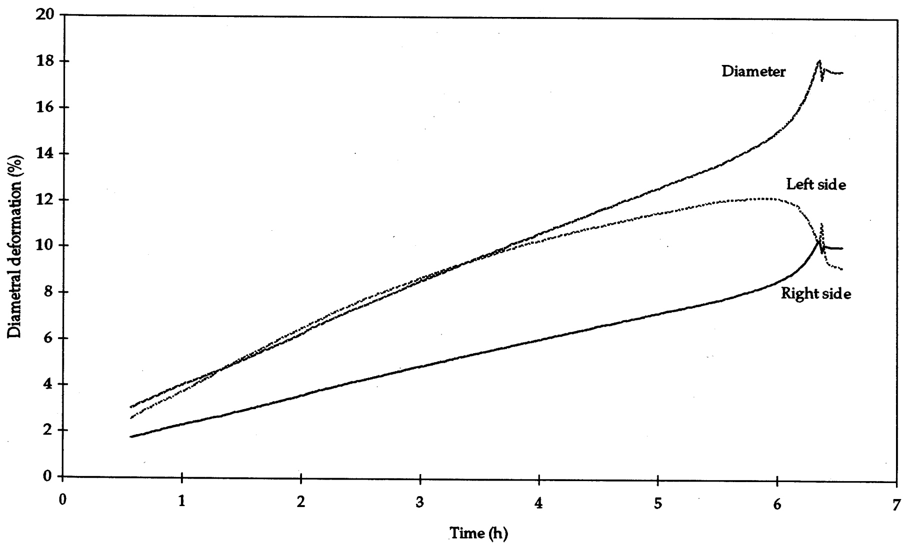


Figure 5 : *Diametral deformation at mid-plane recorded by laser scanning shadow technique.*

Failure time and aspect ratio

The failure occurred after 6h10min by local piercing in the mid plane at the hottest point. The gas leak at failure is very limited due to the fact that the internal volume of the Rupther cylinder has been limited in order to minimise the accumulated energy. In this way, we get a good detection of the failure time and the opening (piercing) is not affected by the leak occurring afterwards.

Numerical simulations

Diametral evolution

Finite element calculations were performed with the following very simple mesh including 82 (41*2) QUA8 elements. Only one half of the cylinder is represented with axisymmetry condition and mid-plane symmetry boundary conditions. The flat cap end effect is applied via a vertical load which is pressure dependant. All the computations are performed with Castem 2000 finite element code and large strain option.

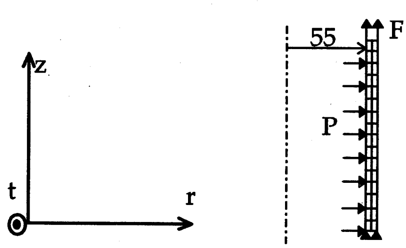


Figure 6 : *Rupther mesh.*

The material creep behaviour is represented by using a Norton-Bailey law :

$$\varepsilon_v = C1 \cdot \sigma^{N1} \cdot t^{N2} \tag{1}$$

The corresponding material parameters have been determined from creep and tensile tests ([3], [4] and [5]). The finite element calculated results in terms of diametral evolution is very sensitive to the computational hypotheses (small or large strain, actualisation of the pressure vector) and to the temperature (figure 7).

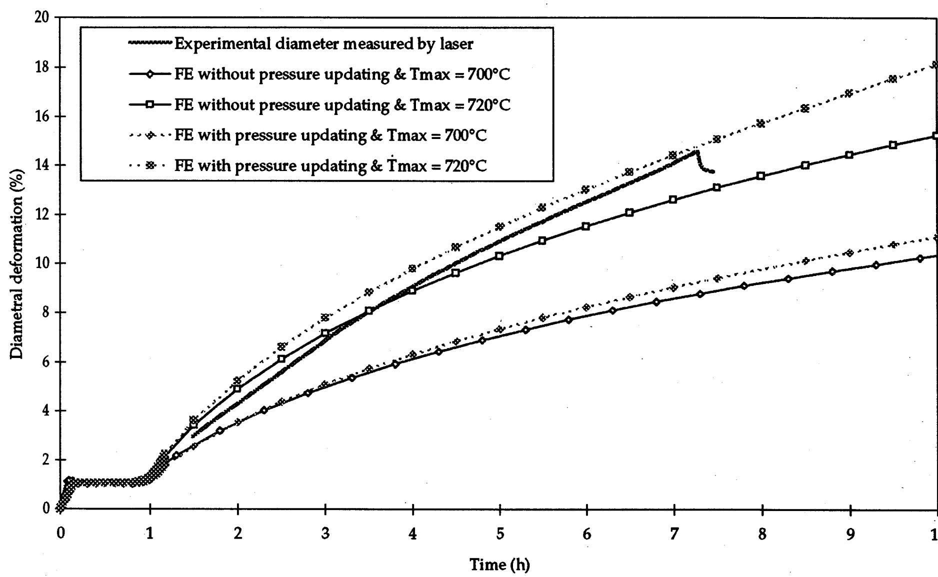


Figure 7 : *Experimental and FE calculated diametral deformation.*

Damage

The damage evolution has been evaluated for a Gauss point located near the mid-plane on the external side. The damage is calculated with the Robinson rule :

$$D = \int_0^{t_R} \frac{dt}{t_R(\sigma)} \tag{2}$$

with the Kachanov formula for t_R :

$$t_R(\sigma) = \frac{1}{r+1}\left(\frac{\sigma}{A}\right)^{-r} \tag{3}$$

At 700°C, A is equal to 122.3 MPa and r is equal to 3.86.

There is a stress relaxation of hot parts of the cylinder towards cold parts which is revealed by the evolution of the Von Mises stress at the Gauss point versus time (figure 8).

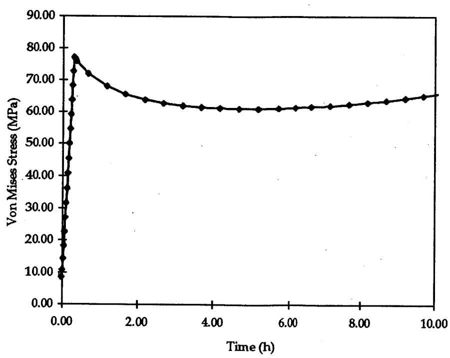


Figure 8 : *Von Mises stress at central Gauss point versus time.*

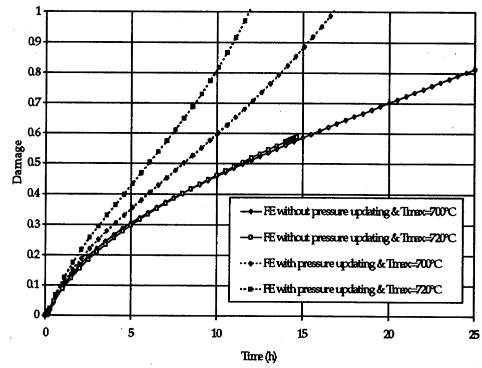


Figure 9 : *Calculated damage evolution.*

The effect of temperature and actualisation of the pressure vector on damage are particularly evident on figure 9. Nevertheless, the best estimation of failure time with $0.8 < D < 1$ gives $10\,h < t_R < 12\,h$ rather than 6h10 for the experimental value. This difference will be further commented in the discussion part.

Discussion

The failure time has been evaluated by using different methods. The corresponding results are summarised in the following table :

Method	Analytic	FE with grad T at 700°C 0.8<D<1.0	FE with grad T at 720°C 0.8<D<1.0	FE with Coupled Damage at 700°C	Experimental result
t_R (h-mn)	2	14 to 17	10 to 12	4h40	6h10

Table 1 : *Failure time estimation by analytical and finite element calculations and comparison with the experimental value.*

The analytical method is based on an elastic evaluation of Von Mises stress for a cap ended cylinder submitted to homogenous temperature.

$$\sigma_{VM} = \frac{\sqrt{3}}{2} \cdot \sigma_{\theta\theta} = \frac{\sqrt{3} \cdot P \cdot D}{4 \cdot e} \qquad (4)$$

and by using this value (81.4 MPa) in creep curves giving the stress versus failure time. By this way, we get 2 h for the failure time which correspond to an under-estimation of the experimental result and so is very conservative.

The three other calculated failure times come from Finite Element (FE) analysis. The first and second FE evaluations were performed with the axial thermal gradient, with large strain hypothesis and with updating of the pressure vector after each iteration. The only difference is the maximum temperature (700 or 720°C). Earlier (figure 7), it was seen that the case with 720°C gives a better correlation with the experimental results concerning evolution of the diametral deformation as a function of time. These two calculations give respectively 14-17h and 10-12 h which are over-estimations of the experimental failure time. They are, therefore, non-conservative.

The fourth FE estimation is carried out at 700°C with large displacement and updating of the pressure vector and with a coupled damage visco-elastic model presented elsewhere [6]. It gives 4h40min which is a conservative value, but the material parameters of this model have been determined with small strain hypothesis and we hope to improve it.
The detailed FE analysis allows a deeper comprehension of the test and the phenomenon. For example, the relaxation of the hot part towards the cold one has been found by FE analysis. The hypothesis of large strains and updating of the pressure vector are useful in the case of Rupther experiment. The sensitivity of the model with temperature is also connected with material parameters identification. The damage evolution is also very sensitive to material parameters.

Conclusions and future work

Rupther is an original experimental device which can reproduce instantaneous or delayed plastic instability of pressure cylinder wall with an axial thermal gradient. First experimental test of creep failure at 700°C was carried out with success.

Numerical analysis of the experiment is carried out with the finite element code CASTEM-2000 and the results are compared with experimental values. Visco-plasticity model is used for the material behaviour law. The creep failure time is estimated with different methods ranging from analytical to damage calculations. A further improvement will be obtained in the near future with a coupled isotropic damage model.

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