RUPTHER - AN ORIGINAL EXPERIMENTAL APPROACH FOR PLASTIC AND CREEP FAILURE STUDY OF RPV STEEL

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The overall objective of this experiment is to get a validated model for the degradation of the reactor pressure vessel (RPV) bottom in case of a severe accident with corium flow. A simple experimental testing device has been designed in order to obtain significant thermo-mechanical loadings. The steel used is 16MND5 (eq. A508 Cl3), it was extracted from a real pressure vessel. A cylinder is heated in its central part by induction (max. 1400°C) and loaded by internal pressure (max. 100 bars). First experimental results of failure are presented.
An important problem encountered in this study is the need of a good knowledge of the mechanical properties of the pressure vessel steel at high temperatures. In order to overcome this problem, an extensive program of tensile and short term creep tests (1-125 h.) is carried out.

INTRODUCTION

The mechanical behaviour of Reactor Pressure Vessel (RPV) lower head in extreme case of accident such as core melting is a rather complex phenomenon. The whole loading history of the RPV can include pressure variation (decrease or increase) combined with thermal gradients (global or local). These possible histories will induce different mechanical behaviour covering all the possible panel from elasticity to plasticity and viscoplasticity. Some metallurgical changes (such as phase transformation, grain growth, recovery...) can also occur and could also be coupled with the deformation process. During TMI 2 Vessel Investigation Project (OECD-NEA-TMI-2 (1993)), 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 in extreme case involving corium flow. A simple experimental testing device, called

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Rupther, has been designed in order to obtain realistic thermo-mechanical loadings. A cylinder is heated in its central part by induction (max. 1400°C) and loaded by internal pressure (max. 100 bars). These experiments can can lead to 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 joint 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 (Devos et al. (1996)) :

- Small size, simple shaped specimens ;
- Biaxial loading ;
- Temperatures within the same range as the real case ;
- Thermal loading combined with the mechanical one.

This gave 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 :

- 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.

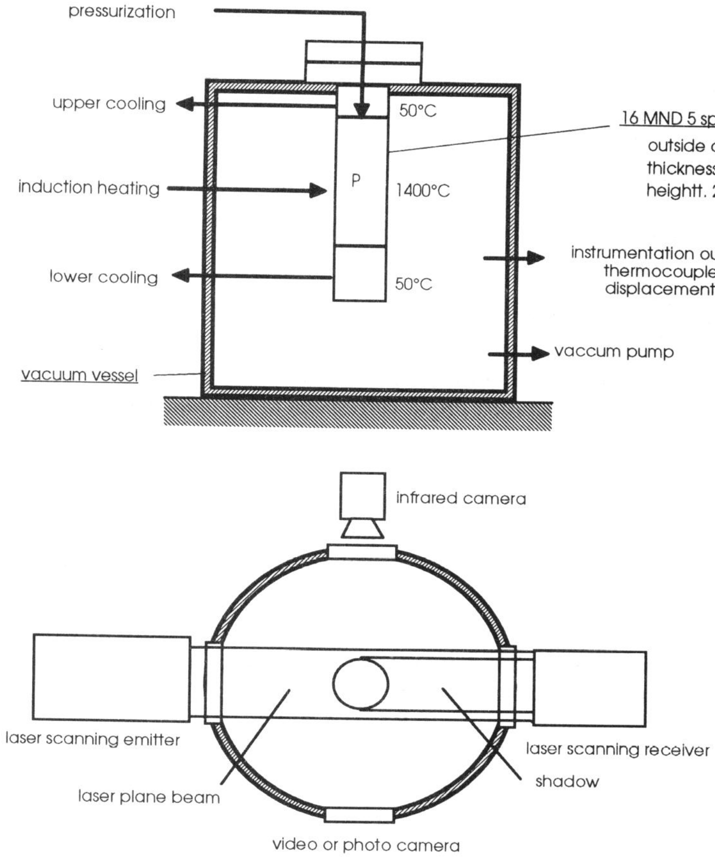


Fig. 1 : Rupther experiment

First experimental tests

After some preliminary tests, the first tests took place in air. They were performed under rising pressure at 1000 °C and 1100 °C. They showed some interesting features of this type of experiments :

- Rupture occurs by local piercing after unstable bulging of the tube ;
- Circumferential strain is limited outside the bulging area ; this can be related to the low elongation at maximum load at these high temperatures ;
- Temperature profile along the cylinder axis shows a gaussian curve type (figure 2) with a maximum corresponding to the symetry plane of the coil.

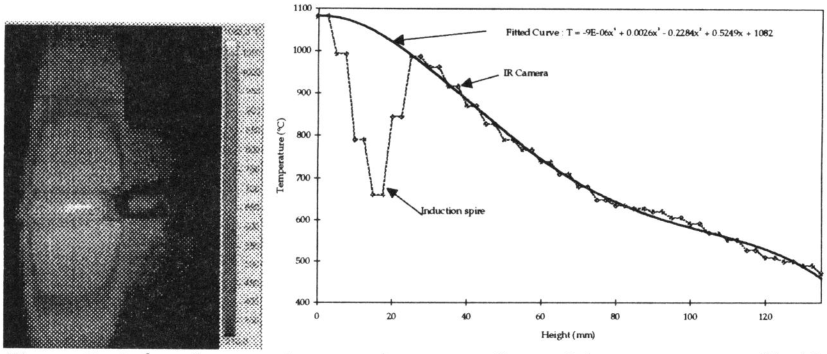


Figure 2 : *Infrared camera image and corresponding axial temperature profile (the discontinuities in the temperature profile correspond to the induction loops).*

Interpretations

These tests were interpreted with two sorts of tools :

- Analytic formulas giving ultimate pressure of cylindrical shells ;
- Axisymmetric finite elements calculations based on Von Mises plasticity without damaging.

The analytic formula used for the determination of the pressure at which instability occurs is based on the dependence of circumferencial stresses for a cylindrical shell under internal pressure :

$$P_{inst} = \frac{2 \cdot R_m \cdot (1 + A_g) \cdot e}{D}$$

with Rm : Ultimate tensile strength (MPa),
Ag : Elongation at maximum load (%)
e : Wall thickness (mm)
D : Internal diameter (mm)

Several finite element (FE) calculations were also undertaken with various thermal fields. Table 1 summarises the results of all the assessments.

Test #	Target Temperature (°C)	P_{inst} Experiment (Mpa)	P_{inst} Eq. (1) (Mpa)	P_{inst} FE target T (Mpa)	P_{inst} FE max T (Mpa)
1	1000	1.21	1.16	1.88	1.28
2	1100	0.58	0.9	1.42	-

Table 1 : *Experimental and calculated instability pressure for the two first experimental Rupther tests.*

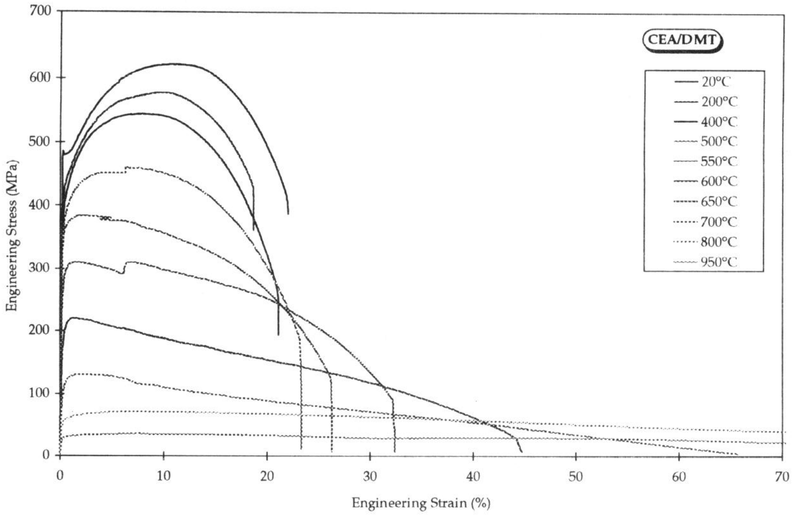
The failure pressure can be approximated quite satisfactorily applying simple equation (1) of ultimate pressure of pressurised cylinders. This equation does not take into account the end caps effects and the temperature gradient along the cylinder. These factors tend to increase the instability pressure, so that finite element calculations first seem to give an over-estimated prediction. But, in fact the temperature is not identical for all meridians and if the hottest one is considered the agreement is rather good (see table 1). The FE calculation for the hottest meridian has only been carried out for the test performed at 1000°C because it was better instrumented than the one at 1100°C.
These first tests will be followed by tests under maintained pressure at the same temperatures and tests under maintained or rising pressure at 700 °C and 1300 °C.

Material characterisation

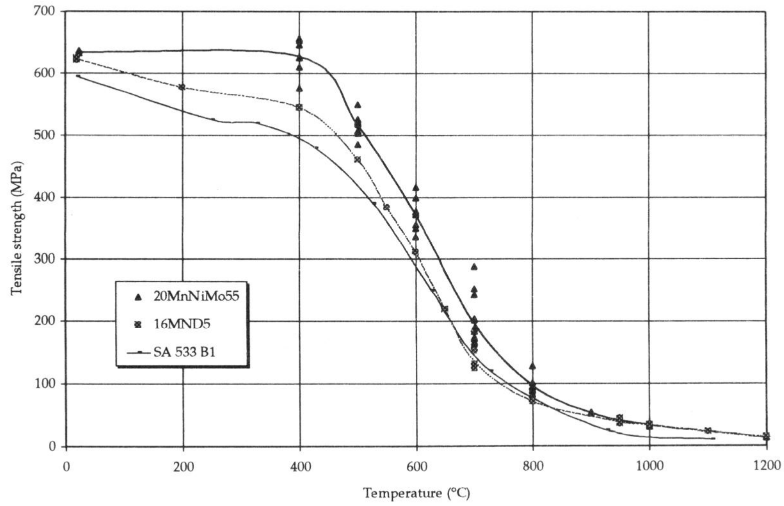
Numerical study is carried out with the finite element code CASTEM-2000. Plasticity and visco-plasticity can be taken into account and coupled with an isotropic damage model (Strub and Devos (1996)). In order to get a good description with these kind of modelisation, it was underlined that a consistent material data set is needed. This is the reason why a consequent characterisation program was undertaken ; first results are reported here.

Tensile tests

Tensile tests were carried out from room temperature up to 1250°C. All the tests were performed under displacement control with an initial strain rate equal to 1.5×10^{-4} s^{-1}. Engineering and true stress-strain curves were recorded (figure 3).
The conventional values were also recorded, such as apparent Young's modulus (E), yield strength (Rp0.2), ultimate strength (Rm), uniform elongation (Ag%), elongation (A%) and striction (Z%) at fracture. These values can be compared with results for the German steel (Jendrich et al. (1996)) and the US steel of TMI (OECD-NEA-TMI-2 (1993)). Two examples are given, the first one is for ultimate tensile strength and the second one for uniform elongation. Ultimate tensile strength as yield strength and Young's modulus abruptly decrease when the temperature exceeds 500°C. This temperature is lower than Ac1, the ferritic to austenitic transformation. The observed effect is mainly due to the fact that we are entering in the creep range.
Uniform elongation is the elongation obtain at the maximum just before necking occurs. It is related to strain hardening coefficient and indicates the ability of the material to delay the occurrence of localisation and instability. There is a temperature region (550-700°C) where this ability to homogeneous straining is reduced.



<u>Figure 3 :</u> *Engineering curves for 16MND5 steel from room temperature up to 950°C, after Sainte Catherine (1995).*



<u>Figure 4 :</u> *Variation of ultimate tensile strength with temperature for 16MND5 and comparison with SA 533B1 and 20 MnNiMo 5 5.*

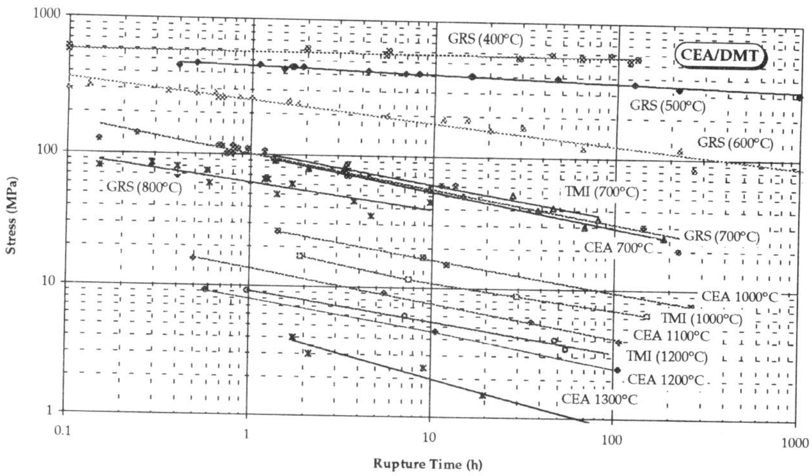


Figure 5 : *Stress versus time to failure for 16MND5 and comparison with SA 533B1 and 20 MnNiMo 5 5.*

Creep tests

Short term (1 to 125 hours) creep test are going on for 16MND5 steel. The first results in terms of stress as a function of time to failure are reported on the next figure and compared with the German (Jendrich et al. (1996)) an US steel (OECD-NEA-TMI-2 (1993)).

The results are very similar, especially at 700°C for this temperature tests have been carried out for all the three steels. At 1000°C, French steel seams to be more resistant than the US one, but at 1200°C it is the reverse. This kind of results is very useful for a quick estimation of the time to fracture with an estimated level of stress. Nevertheless, for a more detailed analysis using FE calculations, the complete creep curves are needed. They can generally be represented for the primary and secondary creep stages by a Norton-Bailey law at each temperature. An example is given for 700°C on the following figure and results are also available at 1000, 1100, 1200 and 1300°C.

More sophisticated models, taking into account the tertiary stage of creep with a damage coupled model, are also developed and used (Strub and Devos (1996)).

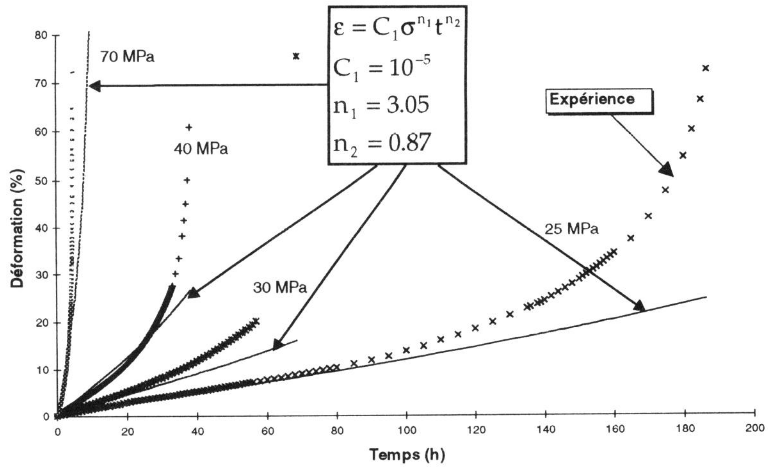


Figure 6 : *Experimental creep curves at 700°C for 16MND5 steel and fitted Norton-Bailey law.*

Conclusion and future developments

Rupther is an original experiment designed in order to study the behaviour of pressure vessel steel under severe thermo-mechanical loadings. Isothermal tests with increasing or constant pressure are going on. But, more complex loadings can be achieved in the future. A joint program devoted to material characterisation at higher temperatures than in use has been undertaken and will continue. These material data are necessary for a good interpretation of Rupther experiment with FE calculations.

This analytical experiment will be used as a validation tool for the different models which then will be applied to the prediction of pressure vessel behaviour.

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