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Study of tearing behaviour of a PWR reactor pressure vessel lower head under severe accident loadings

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In PWR severe accident scenarios, involving a relocation of corium (core melt) into the lower head, the possible failure mode of the reactor pressure vessel (RPV), the failure time, the failure location and the final size of the breach are regarded as key elements, since they play an important part in the ex-vessel phase of the accident.

Both the LHF and OLHF experiments as well as the FOREVER experiments revealed that initiation of the failure is typically local. For the case of a uniform temperature distribution in the lower head, crack initiation occurs in the thinnest region and for the case of a non-uniform temperature distribution, it initiates at the highest temperature region. These experimental results can be modelled numerically (but more accurately with 3D finite element codes). The failure time predictions obtained using numerical modelling agree reasonably well with the experimental values.

However, the final size of the failure is still an open issue. Analyses of both the LHF and OLHF experimental data (as well as of that from the FOREVER experiments) do not enable an assessment of the final size of the breach (in relation with the testing conditions and results).

Indeed, the size of breach depends on the mode of crack propagation which is directly related to the metallurgical characteristics of the RPV steel. Small changes in the initial chemical composition of the vessel material can lead to different types of rupture behaviour at high temperatures. Different rupture behaviours were observed in the LHF and OLHF experiments using the SA533B1 steel. Similar observations were previously noticed during a CEA material characterization programme on the 16MND5 steel. To determine crack propagation and final failure size, 3D modelling would thus be needed with an adequate failure criterion taking into account the variability in behaviour of the RPV material at high temperatures.

This paper presents an outline of the methodology being used in a current research programme of IRSN, in partnership with CEA and INSA Lyon. The aim is to model crack opening and crack propagation in French RPV lower head vessels under severe accidents conditions. This programme was initiated in 2003 and is made up of five main sections, namely an inventory of the different French PWR lower head materials, metallurgical investigations to better understand the cause of mechanical behaviour variability that is observed and related to material microstructure, Compact Tension (CT) testing of specimens to characterize the tear resistance of the material, validation of the modelling using experiments on tube specimens and the development of a new failure criterion for the 3D finite element models.

1. Background

1.1. Global phenomenon in severe accident

During a severe accident, the integrity of the reactor pressure vessel is threatened by different phenomena. While the core melt flows to the bottom of the RPV, erosion of the vessel wall by impinging corium jets can take place; the interaction between the

corium and the residual water in the lower head can lead to a steam explosion. Additionally, if the vessel survives the transition phase, it can be threatened by the corium pool at the base of the vessel.

In the case of wall erosion by the corium jet, the phenomenon is more intense when either the corium quantity is high or the residual water level is small. Under these conditions, rapid rupture can occur when the jet comes into contact with the vessel wall. However, some experiments performed at jet temperature up to 2500 K demonstrated the formation of a crust between the melt wall and the jet which reduced significantly the rate of erosion (Saito et al., 1990). Other factors can reduce the erosion phenomenon, namely the variability of contact location, the presence of residual water and a limited duration of contact. Other experimental results relating to corium jet impingement such as surface erosion and crust formation can also be found in the CORVIS programme (Brosi et al., 1997).

Contact between the corium jets and the residual water could also result in a rapid and intense generation of steam which could lead to a peak in internal pressure and a possible steam explosion. This could be followed by a strong shock wave capable of damaging the vessel. Despite its low probability, this rupture mode cannot be ignored and studies continue to investigate this phenomenon (Theofanous et al., 1999; Sehgal et al., 2005).

In the case of the formation of a corium pool at the lower head, the temperature exchange between the corium pool and vessel could result in local heating or partial melting. This temperature exchange is more important when the corium mass is large. The phenomenon of corium relocation to the lower head was observed in the TMI-2 accident in 1979 (Wolf et al., 1993). However, in this accident, vessel integrity was maintained and analyses concluded that this was due to the existence of cooling channels inside the debris bed and gaps between the debris and the vessel (Stickler et al., 1993). The gaps permit the circulation of water or steam. Calculations demonstrated that a minimal volume of cooling channels within the debris and a minimal gap size are sufficient to reduce the temperature exchange between the debris and the vessel wall. It is also important to mention the beneficial effect that high pressure can have on corium cooling in this situation. The rise of critical flux is proportional to the root of the pressure, thus the maximum thermal power evacuated from the debris bed by water is increased at higher pressure. Additionally as the vessel wall deformation increases by plasticity/creep with high pressure, the gap size between the debris bed and the vessel increases.

Finally, overheating of the corium pool at the bottom of the lower head can lead to the melting of the tube penetration welds and these constitute the regions where subsequent breach of the vessel can be initiated.

1.2. Physical phenomena during the corium relocation phase

The situations examined below correspond to scenarios of corium relocation into the lower head. In these scenarios, the failure time of the vessel, the rupture location and the breach size are considered as key elements because they play an important role in determining the loading and possible rupture of the containment.

The physical variables which influence the failure time are the primary pressure and the internal vessel temperature (which are related to the mass and the characteristics of the corium). The primary pressure of the vessel is generally uniform; however, it can rapidly increase by water injection into the vessel. The vessel temperature is strongly related to the heat flux transferred through the vessel thickness. The rupture location essentially depends on the temperature distribution within the vessel and the failure onset will occur in the zone with the highest temperature. The other zones susceptible to fail are those where there is vessel wall thin-

ning (e.g. by erosion by corium jets) or where there are singularity zones (e.g. the tube penetration zone and the associated welds).

Vessel failure can be initiated either by plastic instability or creep mechanisms. When the membrane stress exceeds the material strength (which reduces significantly with increasing temperature) plastic deformation occurs. Creep is an active deformation mechanism at temperature above 800 K. When the temperature reaches a higher value through the complete wall thickness then creep deformation can occur even at low pressure.

After crack initiation, crack growth strongly depends on propagation mode, which is directly related to the metallurgical characteristics of the vessel material. Slight differences in chemical composition, including trace elements, can lead to different high temperature failure behaviour (brittle or ductile). In this respect, different steels can lead to completely different breach sizes, as observed in scaled experiments (Chu et al., 1998) and (Humphries et al., 2002).

2. Previous experimental programmes and modelling investigations

In the framework of an experimental research programme on RPV failure behaviour concerning the relocation of corium to the lower head, SANDIA National Laboratories carried out two integral experimental programmes "LHF" (1994–1999) and "OLHF" (1999–2002) (Chu et al., 1998; Humphries et al., 2002). The second programme was an extension of the first, and was carried out within an international OECD framework. Eight tests were carried out in the LHF programme (see Fig. 1) and four tests in the OLHF programme. The same type of 1/5-scale RPV lower head was used in the two programmes. However, it should be noted that the vessel wall thickness in the OLHF tests was twice that in the LHF experiments in order to study the influence of the wall temperature gradient.

Several spatial temperature heat flux distributions were used, namely edge-peaked distributions (corresponding to the edged-peaked heat flux distribution of a convecting molten pool), centre-peaked distributions (reminiscent of the hot spot in the TMI-2 accident) and uniform distributions (scenarios where core melt gradually relocates to the lower head). The experimental protocol imposed a fixed rate of temperature increase until rupture of the lower head occurred.



Fig. 1. LHF 1/5-scale lower head failure test apparatus.

The LHF Tests were carried out at constant pressure (seven tests at 10 MPa and one at 5 MPa). Two of these tests were intended to study of the behaviour of the tubular penetrations. As for the OLHF tests, only uniform heating was used and two pressure levels were considered, 5 MPa and 10 MPa. The last two tests of the OLHF series were dedicated to study the influence on the failure mode of a rapid pressure transient from 5 to 10 MPa and to investigate the effect of the penetration on failure behaviour (pressure of 5 MPa). Tests with penetrations generally led to leakage from welds between the vessel and tube penetrations, this led to test interruption due to depressurisation.

In these series of tests, detailed attention was paid to failure times, failure modes and breach sizes. It should be emphasised that the LHF and OLHF programmes allowed development and validation of models, both of which are necessary for the study of vessel thermo-mechanical behaviour prior to failure. The different models developed within the framework of these programmes are presented briefly below.

- Two simplified models 1D and 2D were developed by IRSN (Koundy et al., 2005; Koundy and Cormeau, 2005). The 2D simplified model was recently implemented in the integral severe accident ICARE-CATHARE and ASTEC IRSN codes. In the framework of SARNET (Network of Excellence on Severe Accidents—6th Framework Programme of the European Commission) (Albiol et al., 2007), a comparison of the computed results obtained from this 2D simplified model with those results from the EDF code (Code_Aster) and the FZR code has been made.
- 2D finite element models were developed by the other OLHF partners, namely AVN (SAMCEF), CEA (Cast3m), GRS (Adina), SNL (Abaqus), UJV (Systus) and VTT (Pasula). A benchmark comparing the calculated results obtained using the 1D and 2D models, with the OLHF1 experimental results (OLHF's first test), showed that failure times and rupture locations were generally well estimated and coherent with the experimental data (Nicolas et al., 2003).
- 3D finite element models were also developed by AVN, CEA and SNL and used in the OLHF1 benchmark; they accurately predicted the deformed shape of the vessel.

Fig. 2 shows a comparison of the final OLHF1 lower head elongation estimated by different models. The curves (8) and (E) correspond to the IRSN 2D simplified model calculation and the experimental result, respectively. Discrepancy of failure times (maximum uncertainty not exceeding 15%) is regarded here as satisfactory, taking into account the uncertainty of the choice of the initial time ($t=0$) and the onset of non-linear creep deformation

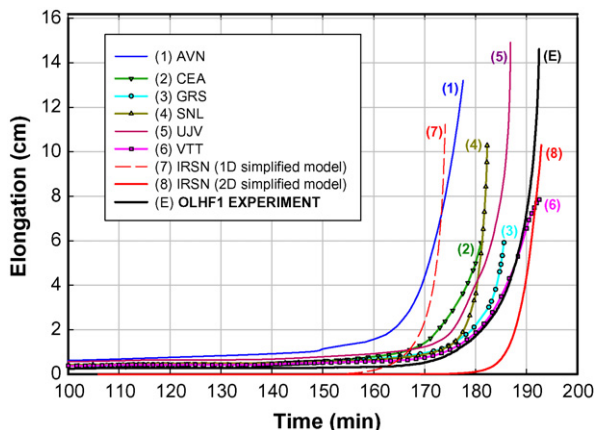


Fig. 2. Comparison of the OLHF1 lower head elongation using different models.

determined by different models. However, a study of the sensitivity of the material properties which takes into account the uncertainty in the material property variation (tensile property fitting parameters, creep coefficients) carried out by Nicolas et al. (2003), showed that the maximum discrepancy relating to failure time could be as high as 33%.

The other conclusions resulting from the analyses and interpretations of the LHF and OLHF experiments are as follows (OLHF Seminar, 2002):

- the LHF and OLHF experiments highlighted the variability of the failure behaviour of RPV materials near to 1273 K (either brittle or ductile). The influence of this variability on the final breach size and the difficulties for the existing models of taking this variability into account (which appears to be strongly related to the presence of certain metallurgical elements, e.g. sulphur, aluminium nitride, etc) became apparent,
- the experimental results do not enable a method for estimating the breach size in accordance with the testing conditions (and thus any extension to the case of a reactor). The use of 3D finite elements is considered to be essential together with an adequate failure criterion that is able to take into account the material behaviour variability.

In parallel to the LHF and OLHF experiments, it is necessary to mention the FOREVER experiments (Sehgal et al., 2003, 2005), performed at the Royal Institute of Technology (RIT) in Stockholm. In these experiments, the RPV lower head was simulated with a geometrical scale factor of 10. The experimental protocol consisted of pouring a binary oxide melt (30 wt% CaO and 70 wt% B₂O₃) simulating corium, at a temperature of approximately 1473 K into the lower head. This temperature was maintained using internal heater rods and the lower head was pressurized to 2.5 MPa until vessel failure occurred. The FOREVER tests are the only known integral in-vessel retention experiments and have been used for model validation purposes. They led to a number of important insights into vessel behaviour under the influence of a melt pool and pressurisation.

It is also necessary to recall the RUPATHER experiments performed by CEA from 1995 to 1999 (Devos et al., 1999). The purpose of this programme was material characterization and to model the behaviour of PWR vessels, subjected to severe accident loading conditions. The RUPATHER programme comprised of four parts. The first part related to the characterization of 16MND5 steel (tensile and creep tests from 873 K to 1573 K), the second part concerned modelling, the third part consisted of performing experiments at high temperatures on tubes for model validation and the last part related to metallurgical analyses. The tubes used were subjected to internal pressure and externally heated to very high temperatures (973–1573 K). The cylindrical shaped tubes were chosen for their simplicity and they also allowed a better control of various parameters without losing the essential characteristics of the problem under investigation (material, loading and mode of failure). The RUPATHER programme constituted the first characterization campaign of French RPV materials (16MND5) under typical severe accidents conditions. Nevertheless, the development of the programme highlighted certain deficiencies.

In order to clarify the origin of the variability of the RPV failure behaviour observed during the LHF and OLHF programmes (which seems to depend strongly on the material microstructure, and which has a direct influence on the final breach size), IRSN has undertaken a research programme in collaboration with CEA and INSA Lyon. A broad outline of this programme is given below.

3. Current joint research programme

The current research programme of IRSN in close partnership with CEA and INSA Lyon, was initiated in 2003 (just after the OLHF programme) and was made up of several more or less parallel tasks. The programme relates to French RPV materials in order, on the one hand, to complement the existing database of material characterization and, on the other hand, to be able to apply the results of this programme to French reactors.

The purpose of this paper is to present the different actions and especially the different experimental and numerical methodologies used in the programme. The experimental results and the modelling resulting from the programme will be the subject of later publications.

The programme first consisted in carrying out an inventory of the properties and metallurgical compositions of materials used for French RPV (private contract between IRSN and FRAMATOME). Five materials were then selected for the study, having metallurgical and mechanical properties sufficiently different, while remaining within the permitted 16MND5 steel material specification.

The tests were carried out in laboratories located at three different sites:

- CEA/Grenoble, conducted material characterization experiments on small cylindrical specimens at high temperatures (1173–1373 K) together with microscopical and image analyses. These experiments were aimed at better understanding the (metallurgical) cause of the failure mode variability of the materials.
- CEA/Saclay, performed material characterization experiments on Compact Tension specimens at very high temperatures with the aim of characterizing the RPV material properties and tear resistance, which are essential for crack initiation and propagation studies. These tests are useful for crack modelling and will allow the influence of metallurgical composition on the tearing kinetics to be studied.
- INSA Lyon, conducted tearing tests on plates and pressurized tubes at high temperatures, in order to characterize the crack propagation velocity. Only tests on plates will be presented in this paper.

Two different numerical models have been developed and will be validated with the experimental data. The first is a viscoplasticity model coupled with a tearing parameter G_{fr} (CEA/Saclay) and the second uses a cohesive crack method (IRSN and INSA Lyon). Both models take into account the variability in behaviour of the RPV

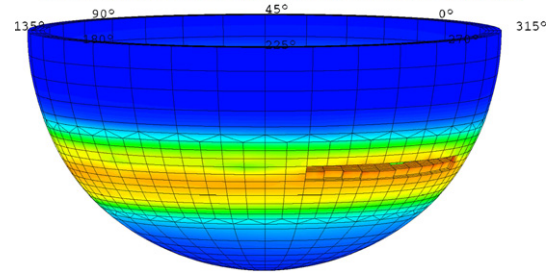
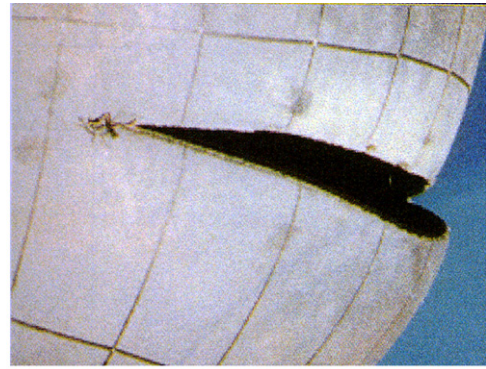


Fig. 3. Post-test view of LHF 3 and simulation result.

material at high temperatures and aim to estimate the breach size (but in different ways). Further details are presented below.

3.1. Previous modelling investigations

Only the coupled damage model will be presented here (the cohesive crack model is not yet sufficiently advanced in its development).

An original and complete model based on a 3D finite element approach has been developed in CEA-Saclay for predicting the failure propagation in a RPV lower head under severe accident conditions. The objective of this 3D model (using the CEA finite element code Cast3m) was to simulate the complete lower head deformation process leading to vessel failure and then breach propagation. The final size and location of the breach is an important issue for the numerical simulations together with the propagation velocity. The retained material model is based on the work of Lemaître and Chaboche (1990) (coupled damage viscoplasticity model) and

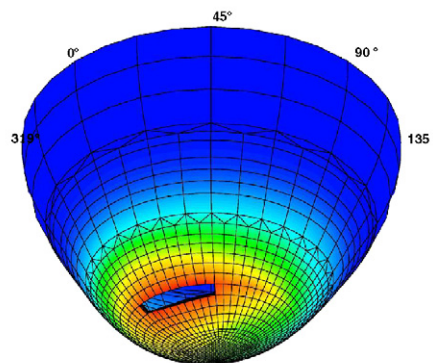
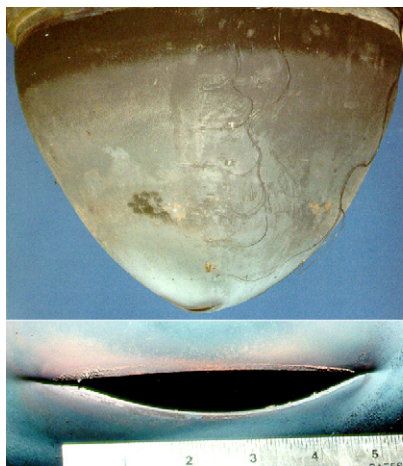


Fig. 4. Post-test view of OLHF 1 and simulation result.

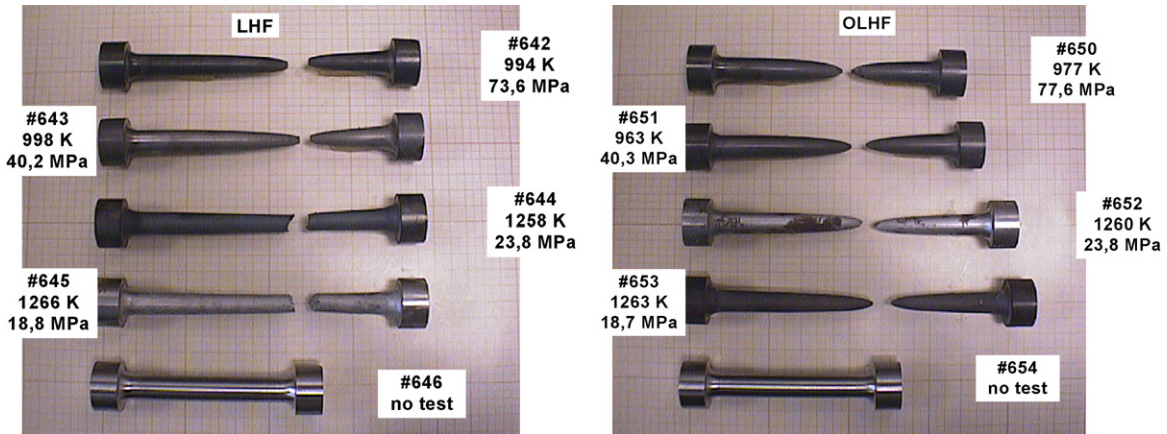


Fig. 5. Characterization creep tests on LHF/OLHF steels.

several failure criteria can be investigated: coupled creep damage, stress criterion (post-evaluation), strain criterion (post-evaluation). In order to simulate the rip propagation, “failed” elements are removed from the mesh and the pressure drop due to the hole opening is taken into account with an isothermal depressurisation model.

First applications of this model (OLHF Seminar, 2002) to the LHF test 3 (Chu et al., 1998) and OLHF test 1 (Humphries et al., 2002) shown a good agreement between the global behaviour of the vessel, the failure location and final breach size (Figs. 3 and 4) with the experimental results.

The best results were obtained in the OLHF1 test using a strain criterion with a failure value deduced from the experimentally determined local strain at the failure site. For the LHF3 test, the best results were obtained using a ductile damage criterion obtained from characterization creep tests. Therefore, different tearing criteria were chosen for the LHF and OLHF materials (SA533B1 steel) and this was shown to be consistent with differences observed between the two materials. Indeed Humphries et al. (2002) indicated that at high temperature (1260 K), the LHF material seems to be more “brittle” than the OLHF material:

- LHF specimens showed very little necking (Fig. 5) compared to OLHF specimens at the same temperature (1260 K),
- failure time is doubled for OLHF specimens and their minimum creep speed is half that of LHF specimens,
- elongation at rupture is 50% greater for OLHF specimens.

It is important to note that the same phenomena had been previously encountered during the characterization programme on the 16MND5 French RPV main vessel steel performed in the framework of the RUPATHER experimental programme (Devos et al., 1999). For a better understanding of this problem, a metallurgical study on LHF

and OLHF specimens has been performed in a specialised CEA laboratory at SACLAY. The explanation proposed is that Manganese alloyed steels (and RPV steels such as SA533B1 and 16MND5), could become brittle because of the sulphur in the steel. To support this, chemical analysis has shown that the LHF steel has 5–10 times more sulphur than the OLHF steel. Moreover, manganese sulphide can be observed with the Scanning Electronic Microscope on LHF fracture specimen surfaces but not on OLHF fracture surfaces. Metallographic analysis has shown that the rupture type is quite different between the OLHF specimens (longitudinal cracks and damage fracture) and the LHF specimens (transverse cracks and inter-granular fracture).

Recent work on the interpretation of LHF5 test shows that the complete circumferential unzipping of the vessel that was observed could not be predicted with the 3D breach propagation model (Fig. 6).

The most interesting difference between the LHF 5 & 3 tests is that a limited circumferential rip occurred in test LHF 3 at about 1000 K whereas in test LHF 5, an unplanned pressure transient at about 1000 K led to a dramatic failure with complete circumferential unzipping of the vessel at approximately 1100 K (a temperature where the LHF material becomes “brittle”). To improve predictions, further investigations and work are required on the tearing criterion; this is thus the objective of our current joint research programme.

3.2. Material characterization experiments on cylindrical specimens

Work to evaluate the elevated temperature failure behaviour variability of different materials corresponding to the 16MND5 steel specification is in progress. The programme consists of several tasks. An inventory of the different French PWR lower head

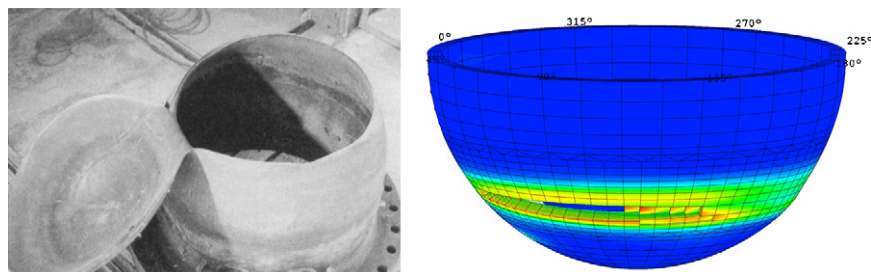


Fig. 6. Post-test view of LHF5 and simulation result.

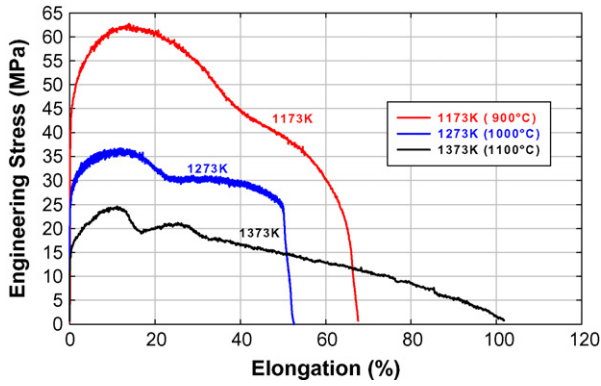


Fig. 7. High temperature tensile test curves for material B (strain rate: $5 \times 10^{-4} \text{ s}^{-1}$).

materials was first performed in order to subdivide these materials, according to their chemical composition (especially with regard to sulphur content) and their method of manufacture. After this had been completed, three materials were chosen for detailed mechanical and micro structural characterization. The sulphur contents of the three materials A, B and C correspond to the lowest, the average and the largest values observed in the various French RPV materials.

Tensile testing was performed on the three materials under vacuum at different strain rates from 1073 K to 1373 K (at 100 K intervals). The total elongation and the reduction of area after fracture were used as a measure of the hot ductility. Deformation to fracture was carried out at strain rates in the range 10^{-3} s^{-1} to 10^{-5} s^{-1} . Fig. 7 shows tensile curves for the material B at 1173 K, 1273 K and 1373 K using a strain rate of $5 \times 10^{-4} \text{ s}^{-1}$. This figure indicates that the amount of elongation is a minimum at 1273 K (1000 °C).

The reduction of area as a function of temperature and strain rate for the materials A, B and C can be seen in Fig. 8. One can see that high sulphur containing materials (materials B and C) exhibits a reduction in ductility at around 1000 °C (1273 K). This corresponds to a decrease in the reduction of area (necking) from 90% to 30%. In contrast the low sulphur containing material (material A) shows a constantly high level of ductility over the entire temperature range.

Microscopic examination has been used to evaluate the nature and distribution of the metallurgical phases (sulphides, precipitates, segregations at grain boundaries, grain size, etc) within the materials, as well as the modes of failure and the associated

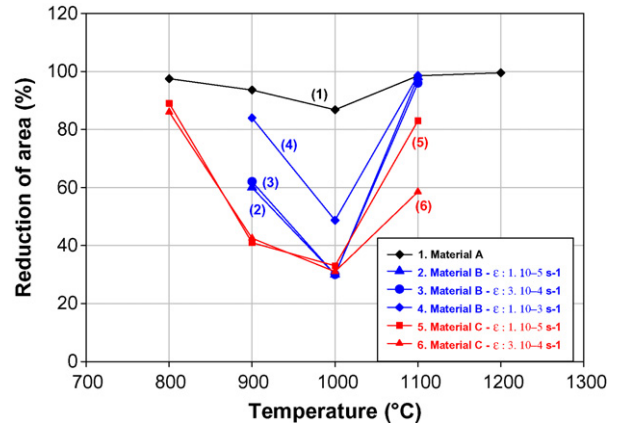


Fig. 8. Variability of the reduction of area as a function of temperature and strain rate for the three materials.

damage mechanisms. Observation of the fracture surfaces using Scanning Electronic Microscopy showed that the drop in ductility at around 1000 °C (1273 K) for the high sulphur containing materials was associated with intergranular fracture. AlN particles were observed on the fracture facets. Intergranular cracks between large sulphide particles were observed on longitudinal sections through high sulphur containing specimens tested at 1273 K. The observed reduction in ductility is thought to be determined by the interaction between the AlN precipitates and the intergranularly segregated manganese sulphides. The results of the mechanical tests (necking values and deformation at rupture) and the associated micro-structural observations will be useful for establishing a qualitative correlation between elevated temperature ductility and microstructure.

3.3. Material characterization experiments on CT specimens

The objective of this series of tests is to acquire knowledge on the phenomenon of tearing of 16MND5 steel at very high temperatures.

The RUPTHER, LHF and OLHF experiments were made on vessels or tubes under pressure, in which the response to the loading was dynamic. The aim of this experimental study is to carry out simple quasi-static tests in order to characterize material properties specifically with regard to tearing propagation.



Fig. 9. Furnace installed on a servo-hydraulic INSTRON test bench.

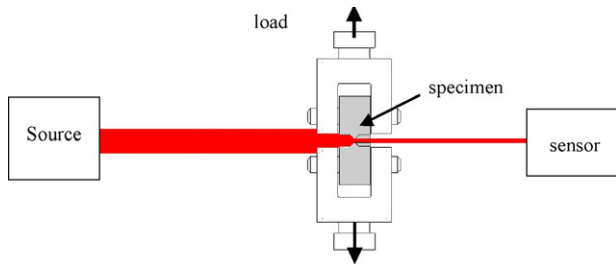


Fig. 10. Measurement of the crack opening displacement by a laser scan micrometer.

Compact Tension specimens are often used for fracture mechanic studies and the determination of material properties, and have been used in this study because formulae are available for interpretation of the tests. However, CT specimens don't have a standard geometry, their dimensions must to be large for the high temperature conditions.

We also intend to highlight the variability in the behaviour of 16MND5 materials which correspond to the RPV specifications. This has been done by examining materials originating from different generations of reactor, and determining differences in their mechanical properties.

The high temperature tests were all made in the same furnace under vacuum or under inert atmosphere (argon) conditions, on a servo-hydraulic INSTRON test bench as shown in Fig. 9.

The Electrical potential drop measurement (EPD), in the vicinity of the notch has been used to determine the propagation of the crack. The opening of the notch was determined by means of a laser scan micrometer (Fig. 10).

Tests were carried out with different crack opening displacements in order to obtain different amounts of crack propagation at the end of the test. The aim was to determine calibration curves which relate the final EPD to the propagation of the crack. From these curves, it is possible to calculate the extent of crack propagation during each test.

Analysis of the tests has been carried out according to the A16 appendix of RCC-MR (2002). From the formulae and methods proposed, an experimental evaluation of the J integral has been performed.

- The procedure proposed by Drubay et al. (2003), developed in the framework of Marie's thesis (1999), has been used to determine the tearing propagation modulus G_{fr} . It has been shown that this parameter (G_{fr}), which can be determined from simple specimens, allows prediction to be made for more complicated structures (Marie et al., 2002). Initial CT specimen tests and modelling have been performed and the main results are:
- the specimen geometry chosen is appropriate for crack growth characterization at very high temperatures and allows the observation of enough propagation to enable a valid G_{fr} parameter to be fitted,
- comparison of initial results for the two materials shows that this approach is appropriate to characterize the observed difference in ductility at high temperatures (Figs. 11 and 12),
- the numerical simulations (Figs. 11 and 12) are able to accurately reproduce the behaviour of the specimens at high temperatures. The simulations were performed with the preliminary 3D model (using Cast3m) with a modified plasticity model that takes into account plastic strain rate and assumes that failure propagation takes place in a similar way to that observed experimentally.

These initial results are encouraging and are being followed up by complementary testing and modelling in order to deter-

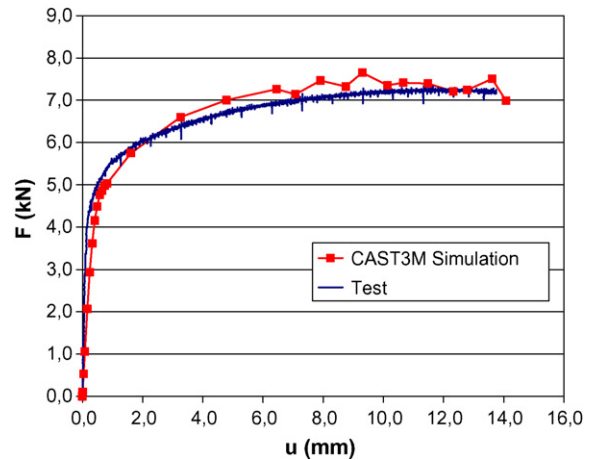


Fig. 11. Simulation of CT 701-9h specimen (1173 K, 16MND5 RUPATHER steel).

mine the sensitivity of the tearing parameter G_{fr} to temperature. This tearing parameter can then be implemented into Cast3m. This will demonstrate if the results from specimens can be used to determine the behaviour of structures (transposability). Validation will be performed on analytical tests that will be carried out at INSA Lyon. The final tearing parameter is intended to be used for modelling of crack propagation in French reactors.

3.4. Tearing tests on plates

The main objective of the experiments carried out at INSA Lyon was to measure the crack speed velocity for different 16MND5 materials at 1173 K or 1273 K.

In the tests performed, the specimen used a very simple geometry, the applied load was well defined and the temperature field was homogeneous. The specimen geometry used was a plate of 4 mm thickness and 30 mm width (Fig. 13a).

Induction heating was used to heat the specimen. The 6 kW generator enables heating of the specimen to over 1273 K if necessary. The temperature field was measured simultaneously by 4 thermocouples welded onto the specimen (as shown in Fig. 13a) and a CEDIP infrared camera. The maximum acquisition speed of the camera was $500 \text{ images s}^{-1}$. As can be seen in Fig. 13b, the specimen is fixed at both ends by water-cooled grips.

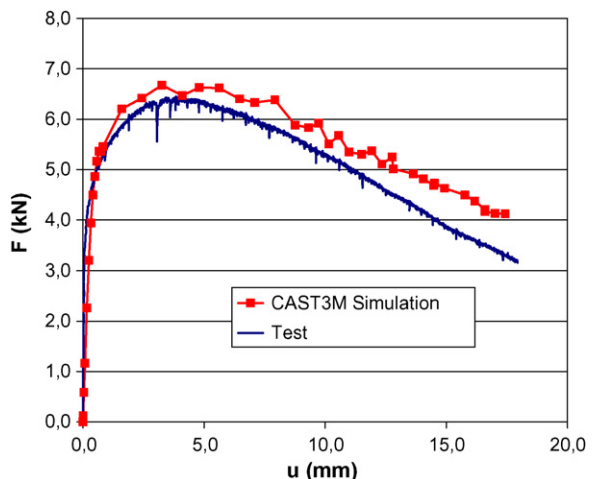


Fig. 12. Simulation of CT 704-a specimen (1173 K, 16MND5 KRAKATO steel).

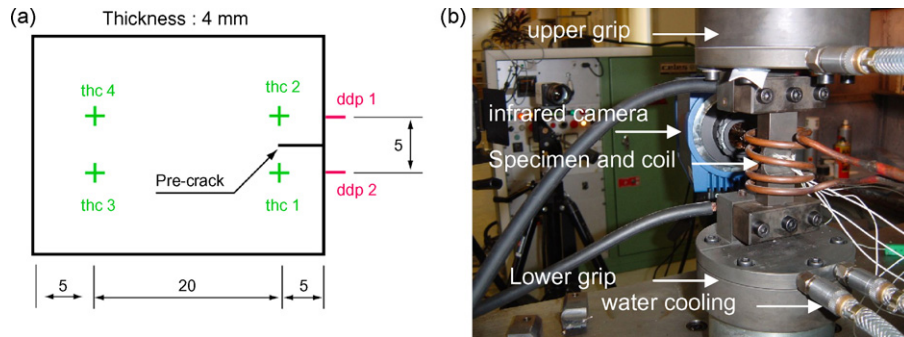


Fig. 13. (a) Geometry and thermocouple positions. (b) Experimental set-up.

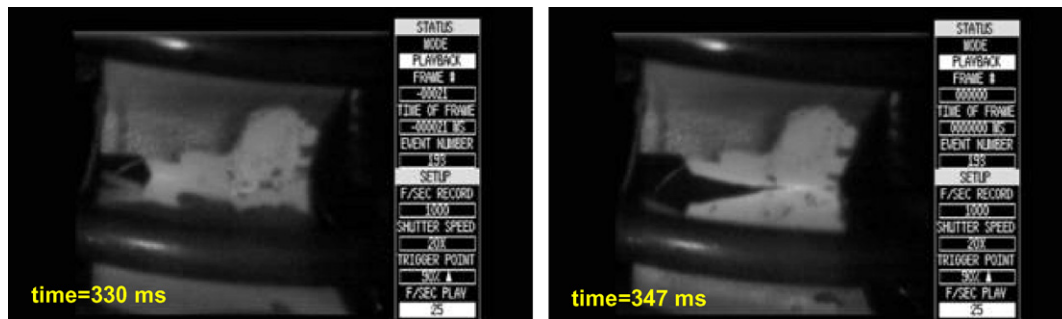


Fig. 14. Images of crack propagation until rupture.

With regard to mechanical loading, a servo hydraulic machine was used in force or displacement controlled mode. The maximum load of the machine was 250 kN, the force and displacement data were recorded at a frequency of 6 kHz during the whole test. To measure the crack speed velocity, two devices were used. Firstly, numerous images were taken with a high speed digital camera (1 kHz rate) and secondly the potential drop close to the crack was measured using a high constant current intensity (180 A). After calibration, the potential drop allows the position of the crack tip to be identified. In the case of very fast crack velocities, this kind of measurement must be very effective.

The specimen was heated at 4 K s^{-1} to 1173 K or 1273 K and held at this temperature for 30 s to homogenize the temperature field. During heating and the 30 s holding period, the force was kept constant at zero Newtons. Thereafter, a tensile force was applied at a rate of 20 kN s^{-1} until rupture.

An example of the results is shown in Fig. 14. In the first image we can observe the opening of the pre-crack caused by creep. On the second image we can see crack evolution up to rupture. Using a series of such images, it is easy to determine the crack speed by determining how far the crack propagates with time. The methodology presented has been used to compare the behaviour of the different 16MND5 materials. These results are invaluable for the validation of numerical simulations.

4. Conclusions

The numerical models (simplified or finite element) developed by the different partners (AVN, CEA, GRS, IRSN, SNL, UJV and VTT) in the framework of the LHF and OLHF programmes, have shown their capacity to predict the lower head failure time and the crack opening location. The results from the OLHF1 benchmark are generally similar for the different codes and are also in quite good agree-

ment with the experimental data. However, the study of mechanical property variability (tensile property fitting parameters, creep coefficients) performed in the framework of this benchmark, showed that the maximum discrepancy relating to failure time could be as high as 33%.

For a more accurate prediction of a crack's location and its propagation (leading to the final breach) only 3D finite element models are realistic. However, none of the models are yet able to correctly predict the crack propagation (tearing), mainly due to the variability in mechanical behaviour of the RPV material at high temperatures. To improve predictions, further investigations and work are required on the tearing criterion.

The current joint experimental programme between IRSN/CEA/INSA Lyon, on the characterization of the French RPV materials, now in its final stages, would allow us to:

- predict the brittle/ductile behaviour of RPV materials from their chemical/metallurgical composition,
- characterize the steel tearing properties at high temperatures.

This will allow a better understanding of the influence of metallurgical composition on the tearing kinetics which can initially be validated by simulating tests on tube, before being used to simulate (using Cast3m) tearing propagation in the case of a reactor.

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