CHARACTERIZATION OF PWR VESSEL STEEL TEARING UNDER SEVERE ACCIDENT CONDITION TEMPERATURES

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ABSTRACT

In the event of a severe core meltdown accident in a pressurized water reactor (PWR), core material can relocate into the lower head of the vessel resulting in significant thermal and pressure loads to the vessel with the possibility of the release of core material towards the containment. The determination of the mode, timing, and size of lower head failure is of prime importance in the assessment of core melt accidents as they define the initial conditions for ex-vessel events such as core/basemat interactions, fuel/coolant interactions, and direct containment heating. Of equal importance is the understanding of the mechanism of lower head creep deformation and failure, as well as developing predictive modeling capabilities to better assess the consequences of ex-vessel processes should lower head failure occur.

In the framework of a research programme in partnership with IRSN and EDF, an original characterization programme of vessel steel tearing properties at high temperature based on tearing tests on Compact Tension (CT) specimens has been conducted. The aim of this experimental study is to complete the mechanical properties database of 16MND5 steel and to contribute to the definition of a tearing criterion of French RPV steel at temperatures relevant of severe accident conditions.

The paper presents the experimental programme conducted on various French RPV 16MND5 steels for temperatures ranging from 900°C to 1100°C. The influence of metallurgical composition on the kinetics of tearing is investigated as a previous work on different RPV steels has shown a possible loss of ductility at high temperatures depending on the initial chemical composition of the vessel material.

INTRODUCTION

In PWR severe accident scenarios, involving a relocation of corium (molten core materials) into the lower head, the possible failure mode of the RPV, the failure time, the failure location and the final size of the breach are regarded as key elements, because they play an important role in determining the loading, the ex-vessel phase of the accident and possible rupture of the containment (Fig 1).

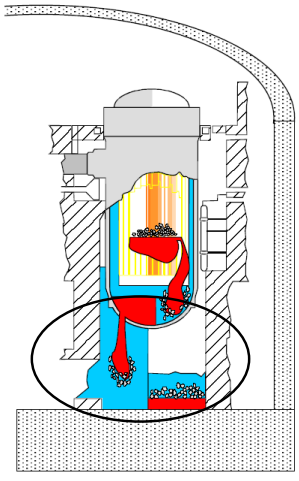


Figure 1 :RPV failure with corium

During a severe accident, the integrity of the reactor pressure vessel is threatened by the corium pool at the base of the vessel. The temperature exchange could result in local heating or partial melting, leading to the initiation of a breach in the zone of the vessel with the highest temperature.

The vessel failure, also depending on the primary pressure, can be initiated either by plastic instability or creep mechanisms.

Since the TMI accident that occurred in the United States in 1979, many theoretical and experimental investigations, relating to lower head mechanical behaviour under severe thermo-mechanical loading during a core meltdown accident have been performed. Mechanical analysis of the vessel failure process faced difficulties related to failure criteria and to the material data used. The need to better understand the physical phenomenon relating to lower head deformation led CEA to launch in 1995 the research programme “RUPTHER" [1] which was aimed at developing an improved modelling of the vessel behaviour. The experimental programme included the characterization of the French PWR vessel steel 16MND5 at high temperatures and identification of model parameters intended to describe the local material behaviour. This modelling was based on a description of the plasticity and considers creep, possibly coupled with a damage variable. To validate the models, tests were performed on 16MND5 steel tubes in mechanical situations featuring the same basic characteristics as during the severe accident scenarios (pressure and thermal load).

This type of mechanical analysis can be used to consider material behaviour up to failure initiation characterized by the beginning of the opening of the vessel. Nevertheless, the analysis has its limits for the description of breach propagation at high temperatures.

Despite this effort, some key issues concerning the severe accident management had not been sufficiently investigated and particularly the phenomenology and kinetics of vessel breaching and the final state of the RPV (small hole or "guillotine" break). In order to assess the risks of complete unzipping of the vessel, which are of major safety concerns with regards to molten corium ejection and ex-vessel initial conditions, there was a need to calculate the breach propagation in the RPV, and therefore the final breach section..

In order to characterize the timing, mode and size of a possible lower head failure (LHF) during a core meltdown accident, several large-scale LHF experiments were performed under the USNRC/SNL LHF programme [2]. In the framework of the LHF and OLHF (OECD-LHF) programmes, one fifth scale lower head vessel failure experiments were performed by Sandia National Laboratories on hemispherical specimens, subjected to internal pressure and thermal loading with maximum temperature close to 1000°C [2],[3]. The CEA participation in these programmes was on the one hand the interpretation of the experimental results, either employing simplified energetic models or 3D finite element models and on the other hand to characterize tensile and creep behaviour to determine the model parameters (Fig. 2).

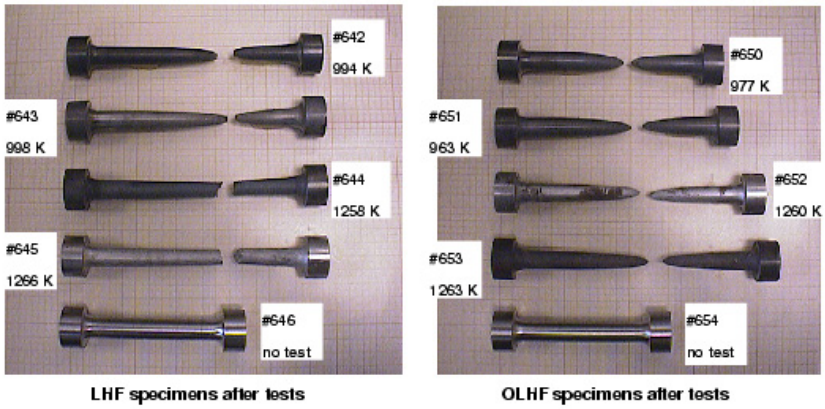


Figure 2 :*Characterization creep tests on LHF/OLHF steels*

These experiments revealed the existence of variability in material failure behaviour at high temperatures (loss of ductility). Indeed, considering different steels with the same specification (SA533B1), slight differences in chemical composition (trace elements) led to significantly different failure behaviours. This material failure variability, encountered in uniaxial tensile tests, showed that LHF steel was less ductile than OLHF steel. Similar differences were also observed in the framework of the RUPTHER programme, conducted on different generations of PWR pressure vessel steels with different sulphur contents.

First numerical interpretations of Sandia’s experiments clearly showed that a failure criterion using a strain parameter was more suitable for the OLHF material (more ductile) whereas for the LHF material, a failure criterion using a damage limit was more appropriate. More recent interpretation has not improved predictions in the case of an unstable breach which leads to a total circumferential unzipping of the lower head.

The RUPTHER, LHF and OLHF experiments were made on vessels or tubes under pressure, in which the response to the loading was dynamic. Simpler quasi-static tests are needed in order to characterize the PWR vessel steel tear resistance at very high temperatures.

The objective of this study is to obtain tearing parameters by experiments on Compact Tension (CT)

specimens and to look at their dependency on the metallurgical compositions of the 16MND5 steel used in the French RPV. After having performed an inventory of the different French RPV steels, two of them having different sulphur contents [4] were chosen for the tests.

PROPAGATION KINETICS STUDY IN TERMS OF TEARING

Once the breach is formed, with its geometrical singularities, fracture mechanic approaches can be used. In this framework, due to the complexity of the problem and as the behaviour is nonlinear, we focus on an analysis based on energy calculations (global approach) with the J integral. Conventionally, the tearing behaviour is characterized by curves representing J versus the crack growth Δa. However, many studies show that there is a problem of transferability of the experimental characterizations of small specimen to structure components because it turns out that the J-Δa curves depend on the geometry, of the triaxiality, and thus do not constitute an intrinsic material characteristic.

In the framework of a thesis [5], Marie proposed to consider the energy dissipated in the fracture process, per unit of crack area, without taking into account the part of the plastic energy dissipated in the structure. This criterion was formulated into several formulation, consisted with different level of accuracy. An engineering scheme has then been proposed, which can be graphically explained: This dissipated energy, on transition from state A_i to state A_{i+1} (for crack growth δa), corresponds to the plastic part of area $A_iB_iA_{i+1}D_i$, between the load-displacement curves for crack lengths a_i and a_i+δa (Fig. 3), which can also be obtained by considering the variation of the plastic part of J during a crack growth (from a_i to a_i+δa).

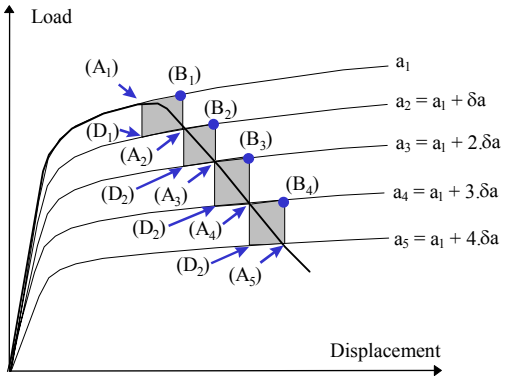


Figure 3 : Calculation of the energy dissipated in crack growth

This variation is linked to the crack growth δa by a constant which is a material parameter, called Gfr. It allows us to define a propagation criterion expressed by Eq.1:

$$G_{fr} \cdot \delta a = J_{pl}(a + \delta a) - J_{pl}(a) \tag{1}$$

In Marie's scheme, identification of the tearing behaviour can be summarized with the determination of G_{fr} and Ji that represents the toughness and tearing resistance of the material. These two parameters only dependent on the material can thus simulate tearing propagation over very large crack propagation. The calculation of the propagation consists of series of crack growths.

It is important to note that this criterion was developed for ductile tearing where no viscosity effects are observed. In the application here, it is assumed that the viscosity effects are negligible in the CT test. It is clear that it is not completely right but from a pragmatic point of view, if results obtained for different specimens provide consistent results, we will consider that this assumption is acceptable.

Nevertheless, it raise the question of the applicability of this criterion for high strain rate situation as it can appears during severe accidents, which is not discussed in htis paper.

DESCRIPTION OF THE EXPERIMENTAL PROGRAMME

The objective is to perform simple quasi-static tests, at very high temperatures in order to characterize the tearing phenomenon for the 16MND5 PWR vessel steel with the possibility of applying the Ji-Gfr approach..

CT specimens which are often used for the experimental study of fracture mechanics have been used. With this type of standard specimens, the analysis of the tests can be done on the basis of sets of formulas that are already available, (A16 appendix of the RCC-MR [6]). However, due to the temperature, the available space in the furnace,

the specimen used had non-standard dimensions. Some dimensions were increased in particular to avoid the ovalisation of the holes where loadings were applied to the specimen. A particular machining was carried out to allow for the measurement of the opening of the notch since these tests are practiced at very high temperatures.

The specimens were extracted from a 16MND5 forged steel part intended for use in a RPV vessel for the primary coolant circuit. Two steels have been studied within the framework of this experimental programme. The first steel considered will be referenced "A". The second steel referenced as "B" corresponds to an older RPV PWR steel with a higher sulphur content than for steel "A". Tensile tests performed at high temperatures (from 900°C to 1100°C) on these two materials have shown reduced ductility of material "B" as measured by the total elongation and the reduction of area (necking) [1]; [4].

The specimens were pre-cracked, ($a0/W \approx 0{,}56$, practically the remaining ligament equals W-a0). They include notches machined in the lateral sides to impose a state of plane strain.

The characterization of the tearing phenomenon at high temperatures was carried out in a specific furnace either under controlled atmosphere (argon) or with a primary vacuum (this last configuration has been retained). Heating is performed by 6 graphite elements. The mechanical tests are carried out when temperature is stabilized). This furnace is put in the frame of a servo-hydraulic testing machine whose loading capacity is 100 kN (Fig. 4).

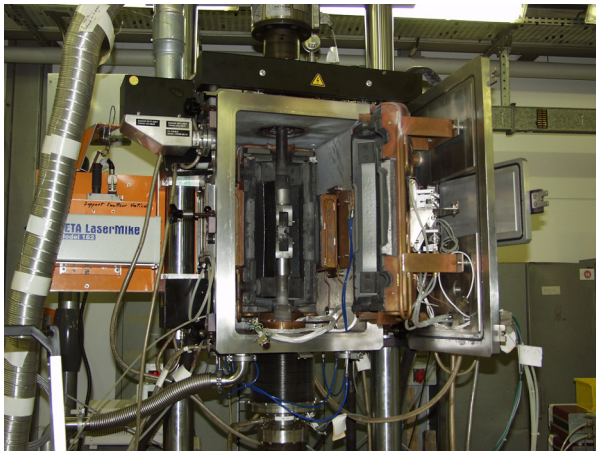


Figure 4 : Test facilities

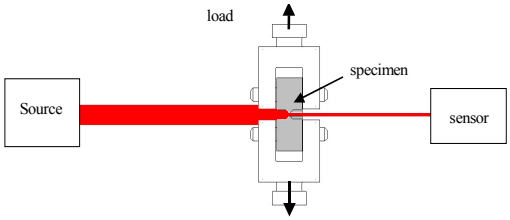


Figure 5 : Measurement of the crack opening displacement by a laserscan micrometer

The furnace has quartz windows to allow an optical measurement of the notch opening by means of a laser scan micrometer: A part of the laser beam is stopped by the specimen and the part transmitted to the receiver allows determination of the opening of the notch (Fig. 5).

In addition to the load and displacement sensors, the specimen is equipped with thermocouples.

The propagation of the crack is monitored by mean of an electric potential drop (EPD) measurement in the vicinity of the notch. After the test, the specimen was cooled with liquid nitrogen in order to break it into two parts by brittle fracture. The observation of the cracked surface allows us to determinate the average crack propagation corresponding to the precracking phase and the subsequent tearing test (Fig.6).

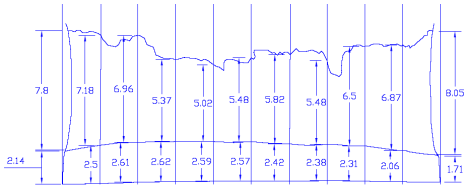


Figure 6 : Crack propagation measurementmaterial "B" experiment at 1000°C.

The goal was to build a "calibration curve" giving a relationship between the variation of the final EPD and crack propagation. This curve is intended to determine, a posteriori, the evolution of the crack during each test.

Tests were carried out with an imposed displacement of 5 mm/min until different final displacements of the hydraulic jack were reached so that several crack propagation lengths were achieved at the end of the series of tests.

During the tests some dust can deposit on the quartz furnace windows and then disturb the optical measurement. However the measurements of the jack displacement during each experiment allowed us to obtain a very satisfactory estimation of the crack opening when the direct measurement (optical) was not possible (Fig.7). The measurement of EPD generally permits the determination of the beginning of specimen tearing despite the electromagnetic environment (the high amount of current necessary for heating disturbs this measurement) (Fig.7).

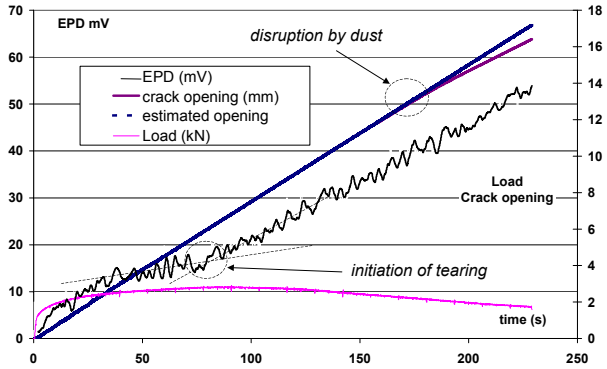
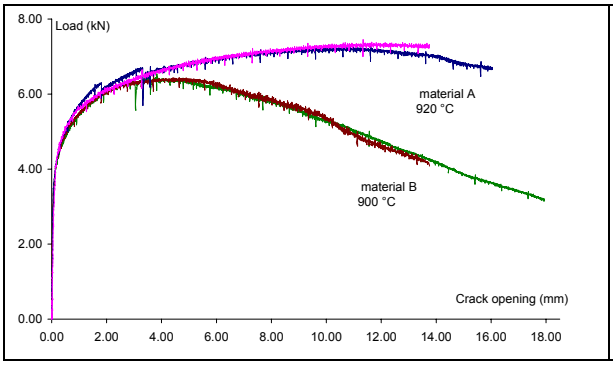


Figure 7 : Material "B" at 1100 °C

Behaviour of Materials "A" at 920°C and "B" at 900°C (Fig. 8).



material "A" at 920°C
final opening 16 mm
tearing propagation 3,9 mm

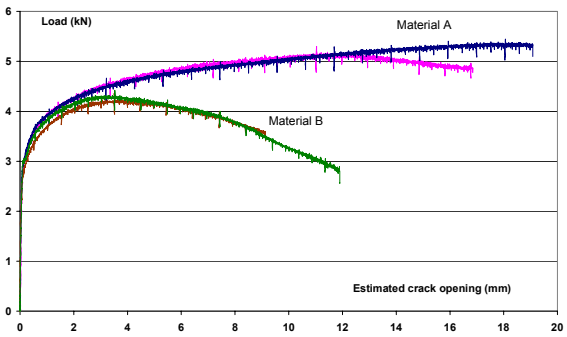
material "B" at 900°C
final opening 13.7 mm
tearing propagation 6,3 mm

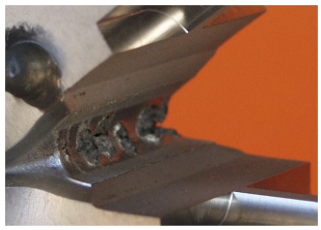
Figure 8 : Behaviour of materials close to 900°C

Although the tests were not carried out at identical temperatures, the characterization of the behaviour for various final crack propagations clearly shows that the material "B" is less ductile than the material "A". For material "B", the load carrying capabilities decrease rapidly during the test due to the quicker propagation of the crack in this material. The fracture facies presented here confirm the remarks related to the test measurements. The tearing propagation is more significant in the case of material "B", although the final opening of the notch is smaller.

Behaviour of Materials "A" at 1010°C and "B" at 1000°C. (Fig.9)

The EPD measurement during the tests performed on material "A" does not allow us to detect the tearing initiation. The failure of this material at 1000°C appears to be due to necking and the damage occurs by formation of macroscopic cavities. Larger specimen is needed to observe failure closer to tear but such a specimen would not fit into the furnace.



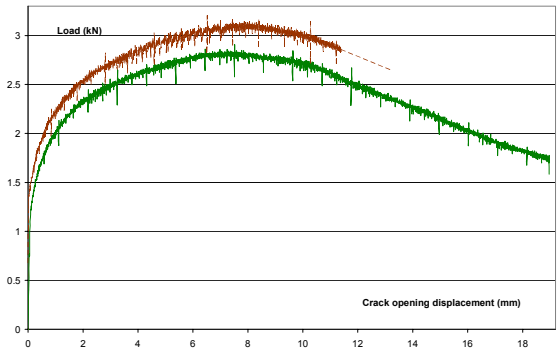


material "A" at 1010°C
final opening 16,9 mm

material "B" at 1000°C
final opening 11,9 mm
tearing propagation 6,3 mm

Figure 9 : Behaviour of materials close to 1000°C

Behaviour of Material "B" at 1100°C. (Fig. 10)



material "B" at 1100°C
final opening 11,9 mm
tearing propagation 7,3 mm

Figure 10 : Behaviour of material "B" at 1100°C

Even at 1100°C, both the measurements performed and the fracture surfaces developed indicate the reduced ductility of material "B". One can see that material tearing propagation takes place without any necking. Insofar we did not obtain tearing at 1000°C with the material "A", we did not perform any test at 1100°C with this material.

CHARACTERIZATION OF TEARING The A16 appendix of the RCC-MR [6],[7] proposes formulas and methods for the interpretation of the test results of this study and permits to calculate an experimental evaluation of the integral J.

J is expressed as the sum of an elastic term J_{el} and a plastic term J_{pl}

$$J_{el} = \frac{K_I^2 (1-\nu^2)}{E}$$

The evaluation of K_I is carried out by using the stress intensity factor formulation of the specimen.

$$J_{pl} = \eta_0 \frac{A_{pl}}{B_N (W - a0)} \qquad \text{where} \qquad \eta_0 = 2{,}00 + 0.522 \cdot \left(1 - \frac{a_0}{W}\right)$$

A_{pl}: Area under the curve representing load versus the plastic opening in the axis of the loading
B_N: Thickness of the specimen decreased by the depth of the side notches
W: Width of the specimen
a0: Length of the crack after precracking

A procedure, founded on the studies of Marie [8], [9] is defined in the A16 appendix of the RCC-MR [6] and allows the determination of the G_{fr} parameter. It is based on the calculation of the integral J modified by Ernst [10], J_M, which takes into account the influence of the crack length. The plastic part of J_M is expressed by the Eq.2 :

$$J_{Mpl} = G_{fr} . \Delta a + cst \qquad (2)$$

For a propagation of the crack from a_0 to a_i, J_{Mpl} is determined in an incremental way by using the Eq 3

$$\left(J_{Mpl}\right)_i = \left(J_{pl}\right)_i + \int_{a_0}^{a_i} \frac{\gamma}{b} . J_{pl}\, da \qquad \text{With} \qquad \gamma = 1 + 0.76\ a/w \qquad \text{and } b = w\text{-}a \qquad (3)$$

J_i corresponds to the initiation of the tearing. It was determined, with the EPD measurement, (Fig.11).

Then, by the observation of post-cracked surfaces (cf Fig.6), the average crack propagations at the beginning (pre-cracking value) and at the end of the tests permitted to calculate the crack growth Δa. which was represented versus the final EPD measurement for building the "calibration curve Δa (ΔEPD)". Then, by interpolating the real-time measurement of EPD with the " calibration curve " we obtain the crack length during each test (Fig 11).

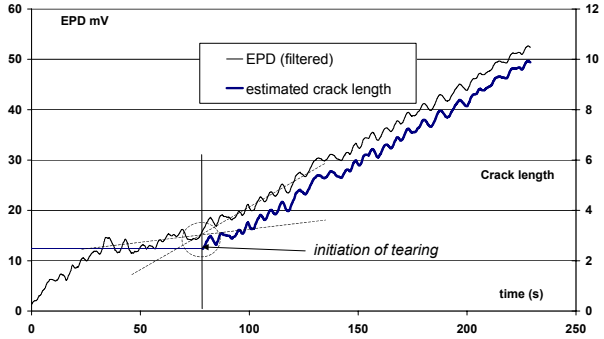


Figure 11: Determination of the beginning of tearing and of the crack growth

J_{Mpl} is determined according to the formulas. The curve representing J_{Mpl} versus the crack length is fitted to obtain the G_{fr} value (Fig. 12).

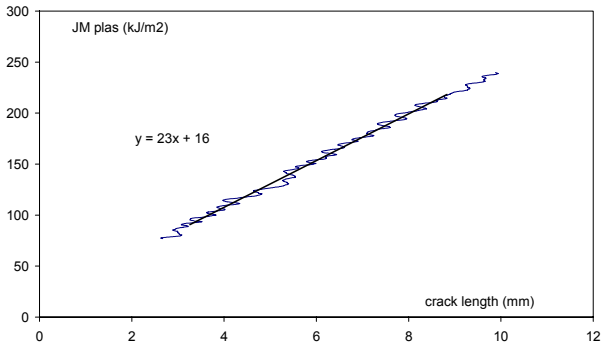


Figure 12 : Fit of the JMpl (a) curve

The interpretations of the tests performed on the 16MND5 steel lead to the following results .

For material "A"

The values could not be identified beyond 920°C. At temperatures above 950°C, the size of the specimen inhibits the initiation of tearing (very significant crack tip blunting). There is no effective tearing and the tearing parameters cannot be obtained.

At 920°C, we obtain: $J_i = 300$ kJ/m^2, $G_{fr} = 74$ kJ/m^2

For material "B"

at 900°C: $J_i = 125$ kJ/m^2, $G_{fr} = 47$ kJ/m^2

at 1000°C: $J_i = 62$ kJ/m2, $G_{fr} = 32$ kJ/m2

at 1100°C: $J_i = 72$ kJ/m2, $G_{fr} = 23$ kJ/m2

These results tend to show a significant decrease of the resistance to tearing initiation of steel "B" at 1000°C. They also indicate that the material referenced to "B" has less ductile behaviour than material "A".

These characterization tests and the parameter identification are followed by complementary modelling in order to implement the J_i-G_{fr} approach in the CEA finite element code CAST3M [11] and to simulate the propagation of the breach with the final goal of confirming its transposability from specimen to structures [12].

CONCLUSIONS

The aim of the work presented is the characterization of tearing resistance at elevated temperatures of the PWR vessel steel (16MND5). In particular, the variability of mechanical properties with the specifications of the PWR vessels has been studied by investigating steels originating from reactors of different generations. It has been found the metallurgical composition can have a significant effect on tearing kinetics.

The analysis has been carried out on the basis of the rules described in the A16 Appendix of RCC-MR [6] and evaluations of the integral J and of the energy parameter G_{fr} (tearing criterion) are proposed. These evaluations confirm that sulphur plays an important role in the loss of ductility of the steel at high temperatures.

These tests can now be used as a basis for numerical studies with computer codes using finite elements.The aim is to use the G_{fr} criterion to simulate the tearing propagation. After being validated on the tests performed on the CT specimens, this modelling could then be applied to study the propagation of a breach in a vessel in the case of a severe accident.

It is important to note that this criterion was developed for ductile tearing where no viscosity effects are observed. In the application here, it is assumed that the viscosity effects are negligible in the CT test. It is clear that it is not completely right but from a pragmatic point of view, if obtained results provide consistent results we will consider that this assumption is then acceptable. Nevertheless, it raise the question of the applicability of this criterion for high strain rate situations as it can appear during severe accidents, which is not discussed in this paper.

ACKNOWLEDGMENTS

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