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Effect of penetrations on the lower head vessel failure under coupled melt pool convection and creep

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Abstract

The EC-FOREVER (The European Commission's Failure Of REactor VEssel Retention) experimental program is concerned with the phenomena of melt pool convection and vessel failure occurring during the late phase of the in-vessel progression of a postulated severe accident in a Pressurised Water Reactor(PWR). Tests were performed at prototypic conditions of high temperature employing a 1:10 scale reactor pressure vessel(RPV). The hemispherical lower head of the vessel was made of 16MND5 French RPV steel. Additionally, eight Iconel-600 penetration rods, each having a dimension of 4 mm diameter and 6.5 cm length, were inserted and welded at the bottom of the vessel. Upper cylindrical part of the vessel was made of 15Mo3 German steel. Melt pool convection is established by heating a binary-oxide ($CaO-B_2O_3$) melt mixture with a special heater. Melt pool temperature was maintained at $\approx 1300^0$C. The creeping of the vessel wall was obtained by pressurising the vessel up to 25 bar, representing the depressurised severe accident scenario. The most interesting aspect of the present experiment is that failure did not occur at any one of the penetration rod positions, but occurred at the location of hot zone which was at $\sim 70^0$ from the bottom of the vessel. The failure did not occur at the location of maximum strain but occurred at the location of maximum temperature. The shape of the failure was like a fish mouth but fish mouth opening is significantly lower in cross-sectional area compared to that in the LHF/OLHF experiments performed at SNL.

Key words: Vessel Creep Failure, Penetration, Coupled convection and creep, Lower head failure

Introduction

Motivation of the present series of tests in the EC-FOREVER experimental program is to study the vessel failure behaviour under thermal and pressure loadings that are generated during the late phase of the in-vessel hypothetical core melt down scenario.

Lower head of a reactor vessel is subjected to significant thermal loads after the relocation of molten core materials in it. In a severe accident scenario, the water remaining in the lower head may boil off and, in time, corium debris would re-melt forming a melt pool which will undergo natural circulation in the lower head. Thermal and pressure loads would lead to creep of the vessel material due to loss of its strength at high temperature and creep deformation will eventually fail the vessel. Failure of lower head initiates the ex-vessel phase of severe accident, and its characteristics determine the initial conditions of the subsequent loadings in the containment. An early failure of the containment due to such loads, as for example from a steam explosion, can lead to a large release of radioactivity to the environment.

The EC-FOREVER tests performed so far focus on obtaining the initial conditions for an ex-vessel accident progression. These can be identified as: (1) failure time of the lower head after the accident initiation, (2) mode and location of the failure, (3) the amount of melt discharge after the vessel failure, and (4) rate of enlargement of the lower head failure site caused by the flow of melt through it. Information on the rate of enlargement was provided in Sehgal *et al* (1999a). Very little knowledge base is available on the mode and location of the lower head failure, in particular for the bounding late phase in-vessel scenario in which the lower head is full of a melt pool undergoing natural circulation, while the vessel is under pressure. In this scenario, the vessel wall experiences a non-uniform temperature distribution generated by the convection process. The dominant mechanism of the lower head failure is creep and it is well known that the various vessel steels differ in their creep properties.

The creep process determines the failure time of the lower head, which is important for accident termination and management. The larger the time available, the greater is the probability of preventing the vessel failure through the operator's action of adding water to the vessel and the containment to cool the vessel from outside. Additionally the amount of melt discharged from the vessel depends on the mode and location of failure. This is the most important initial condition for the containment loading, in particular for the steam explosions and direct containment heating phenomena. One of the important questions for the vessel failure process is the location of failure in a vessel in which penetrations are present. The objective of the EC-FOREVER test described here is to answer this question.

Previous Studies

There have been a number of experimental studies dedicated to the investigation of creep deformation and failure of RPV steels. Many of these are uni-axial tests at a single prescribed temperature to characterize the creep behaviour (Muller and Kuhn, 1991, Thinnes et al., 1994, Sainte, 1995, Degaltsev et al., 1997). In RUPTHER experiments, multi-axial creep deformation data were obtained using pressurised thin shell cylinders, up to the elevated temperature of 1000^0 C. Prototypic 1:5 scaled steel vessels were employed by Sandia National Laboratory (SNL) to study creep behaviour. These lower head failure (LHF) experiments (Chu *et al,* 1998) were performed at >100 bars and the lower head was heated by an arrangement of electrical heaters inside the vessel. There was no melt present in the lower head.

The LHF tests were performed with different types of heating distributions, viz, uniform, edge-peaked and hot spot and the results pertaining to time of failure, location of failure site and the overall strain at failure were obtained. For uniformly heated vessels, the failure location was at the minimum wall thickness, somewhere between 60^0-80^0 below the equator. When penetrations were present (LHF-4), the failure occurred due to weld failure at one of the penetrations. The overall strain rate at failure site was about 30%. In contrast, for the edge-peaked heating pattern (to approximately simulate the melt pool convection), the failure occurred (~35^0 below the equator) at the location where the maximum temperature occurred. The overall strain rate at failure site was only 10%. Owing to the very high pressure, the wall thickness reduced by about 90% before failure of the vessel except in one of the tests performed at the lower pressure of 50 bars (LHF-7), in which it is reduced by only 60%. In the LHF tests, the test mode was to maintain a pressure level and raise the temperature in a specified transient until the creep failure occurred. The highest external vessel temperature level was $\approx 750^0$ C.

In the more recent OECD lower head failure (OLHF) tests (Chu *et al*, 2000) the depressurised severe accident scenario was modelled however, the vessel wall thickness was increased by about 2.4 times in order to obtain larger temperature difference across the wall. The vessel pressure was raised by the same factor of 2.4 to obtain the prototypic hoop stress. Again, the temperature field was raised till failure and heating was provided by a graphite induction heater installed in the vessel. The failure times in the OLHF tests were larger than those found in LHF tests. In the OLHF-3 test, a pressure transient was imposed at an elevated temperature of the vessel wall; the increase of pressure from 5 MPa (RCS pressure ~2 MPa) to 12 MPa (RCS pressure ~5 MPa) in about 5 minutes resulted in the failure of vessel within 15 minutes from the start of pressure transient. Most of the creep displacement took place after the pressure increase. In all the OLHF tests, spatially uniform heating was maintained.

The EC-FOREVER Experimental Program

FOREVER experiments were initiated at the division of Nuclear Power Safety (NPS)/ Royal Institute of Technology (RIT) under the auspices of Melt Vessel Interactions (MVI) project funded by the Fourth Framework program of European Union (see Sehgal *et al,* 1998). One FOREVER experiment was performed under 4th frame work program and later another test was performed with SKI support. The FOREVER experimental program was a continuation of the earlier program initiated in the European Union's 5th Framework program.

The idea of FOREVER experimental program is to simulate the prototypic severe accident scenario of melt pool convection in a depressurised vessel, i.e., the vessel pressure is maintained at ~2.5 MPa. Outer diameter of the vessel is ~400 mm and wall thickness is ~15 mm. Two experiments were performed with eight Iconel-600 penetrations, which were welded in the lower head of the vessel and they span 15-55^0 from the bottom of the vessel (Fig. 1) Penetrations had dimensions of ~3.8 mm diameter and a height of ~65 mm. Location of penetrations are mentioned in the table shown in Fig. 1. The details of penetrations can be seen in the Fig. 2. Vessel lower head is made of either the 16MND5 steels used in vessels of FRAMATOM plants or the American steel used in LHF or OLHF tests. Cylindrical part is made of German Steel. Material used for lower head has much greater strength at high temperature than the material used for upper cylindrical part. Characteristics of these materials can be seen in Ikonen (1999). Details of the experimental set up are available in Theerthan *et al* (2000, 2001) and Sehgal *et al* (2002).

Penetration Location

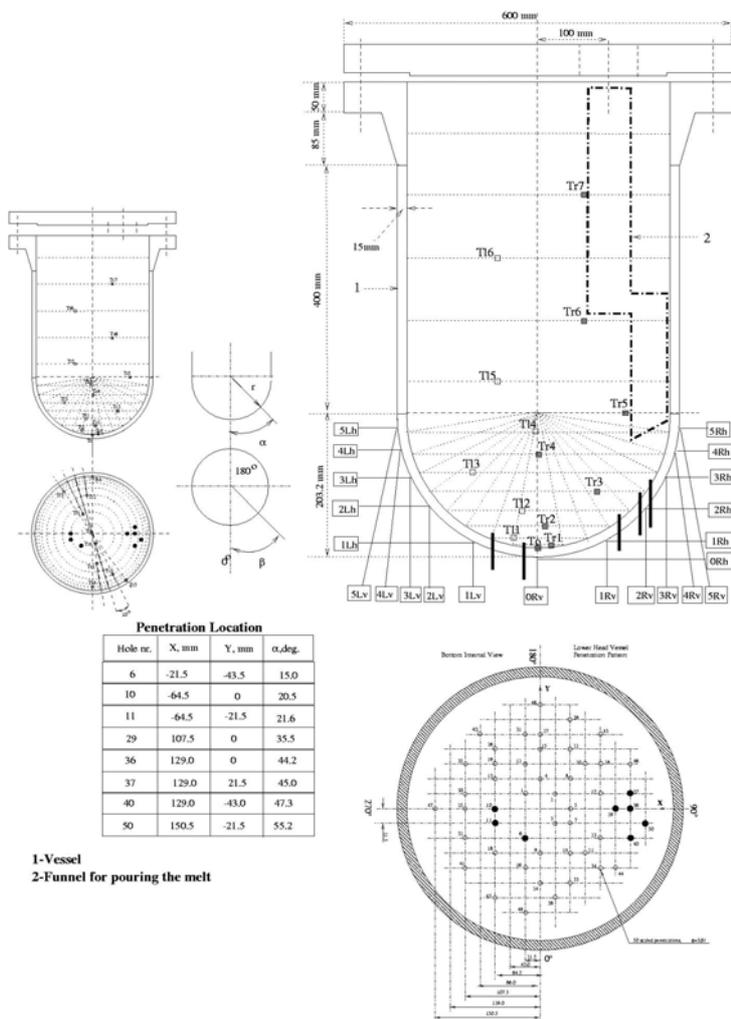| Hole nr.	X, mm	Y, mm	α,deg.
6	-21.5	-43.5	15.0
10	-64.5	0	20.5
11	-64.5	-21.5	21.6
29	107.5	0	35.5
36	129.0	0	44.2
37	129.0	21.5	45.0
40	129.0	-43.0	47.3
50	150.5	-21.5	55.2

1-Vessel
2-Funnel for pouring the melt

Figure 1: EC-FOREVER FACILITY: Instrumentation Rod Penetration Locations
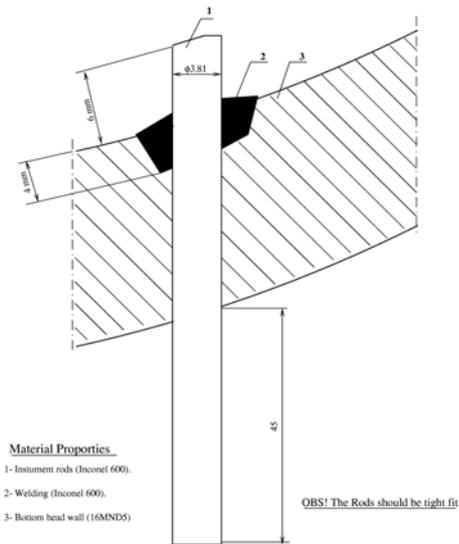
Figure-2: Instrumentation Rod Penetration Welding Details

The scaling considerations for the FOREVER tests can be summarized as follows: (I) 1:10 linear in geometry, (II) 1:1 in heat flux, (III) 1:10 in vessel wall temperature difference, (IV) 1:1 in hoop stress, and (V) 1:10 in thermal stress. So from the above mentioned scale, it can be identified that with the chosen vessel geometry and test conditions membrane stresses are modelled exactly while the thermal stresses are not. More importantly, in the FOREVER tests the temperature and stress distributions peak in a region of 60-90^0. So FOREVER experiments simulates prototypic reactor accident scenario. This is the major difference between the FOREVER and the Sandia LHF experiments (Chu *et al* 1998). The OLHF tests (Chu *et al* 2000) employ a larger temperature drop across the vessel wall than in the FOREVER test and achieve a closer simulation of the thermal stress, although their heat flux and temperature distributions are non-prototypic.

Experimental procedure

An oxidic melt of a mixture 30wt% CaO + 70wt % B_2O_3 undergoes convection due to the heat input by a specially designed heater (KANTHAL©SUPER, made of Molybdenum Silicate) distributed evenly inside the melt. The details design of this heater can be seen in Theerthan *et al* (2000, 2001). This binary oxide melt has properties similar to those of UO_2 + ZrO_2 mixture. In all the experiments, there is no external or internal forced cooling of the lower head. The lower head loses heat primarily by radiation and to some extent by natural convection at the external surface.

Major measurements involve temperature, vessel displacement and pressure. Melt pool and vessel wall temperatures are measured by thermocouples (TCs) and the vessel wall displacements are measured by linear displacement transducers. The locations of the temperature and the vessel wall displacement measurements are shown in the Fig. 1. Exact locations of temperature measurements will be shown in the results. Temperature and displacements are measured on both sides of the vessel to determine whether they are axi-symmetric. Exact angular locations, where displacements are measured, will be shown in the results. A pressure transducer records the pressure in the vessel.

Test vessel with its instrumentation and the induction furnace was kept inside the containment (Sehgal *et al*, 2002) for the sake of human safety. In all the tests, the vessel was pre-heated to ~500^{0}C to avoid thermal shock on the various installations inside the vessel, especially the heating element. Heater is switched off before pouring the hot oxide melt into the vessel through a funnel. Hot oxide melt is prepared in SiC crucible. After pouring the melt, the vessel opening is closed quickly and the vessel is made leak tight. Care must be taken to switch on the internal heater immediately after pouring the melt, otherwise hot melt may cool down very fast, form a crust and damage the heater element. Slowly, heater power is increased to deliver the desired power level to maintain the oxide melt at ~1300^{0}C. Time is allowed to establish a steady

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state convection of melt inside vessel. After the steady state temperature conditions are reached, pressure of 25 bar is applied to the vessel employing a balloon of Argon gas. The heater power input and the vessel pressure are kept constant and the experiment is continued till the vessel failure occurs. The containment temperature is maintained at ~50^{0}C by employing ventilation in order to assure proper operation of instrumentations. Also special fans are employed to cool the displacement transducers as they receive heat due to radiation from the vessel.

Values of the test parameters (*viz*, pressure, heat input to the melt pool etc.) are chosen for each test after a thorough pre-test analysis performed with the commercial ANSYS Multi-physics code. Some of the ANSYS calculations are reported in Willschütz *et al* (2001a, 2001b) and in a companion paper at this meeting. Pressure and temperature values chosen assure that failure occurs due to the creep deformation, in a few hours and not due to prompt plastic deformation failure ($\sigma_{ext,wall}/\sigma_{yield}>1$).

Results and Discussions

Present results focuss on the two tests---- namely EC-FOREVER-3 and EC-FOREVER-3B. These two experiments are performed to see the effect of penetrations on the vessel failure. Previously reported FOREVER experiments (Sehgal *et al*, 1999, Theerthan *et al*, 2001 & 2002) gave a realistic idea of failure characteristics of lower head made of 16MND5-French reactor steel vessel. Present two experiments are performed at almost identical experimental conditions except with slightly different melt volume. Melt volume in EC-FOREVER-3 was 14 litres and that in EC-FOREVER-3B was 12 litres. In EC-FOREVER-3 melt occupied hemispherical lower head and ~1 cm cylindrical part of the vessel. But in EC-FOREVER-3B melt occupied only the hemispherical part of the vessel. Because of the melt occupying the cylindrical part of the vessel, in EC-FOREVER-3 experiment. The vessel failed at the welding line. So our paper will focus mainly on the EC-FOREVER-3B experiment. However, major result of EC-FOREVER-3 will be mentioned as appropriate. In both the tests, the power input to the melt was ~38 kW. This maintained the maximum external wall temperature ~915^{0}C. Power input for EC-FOREVER-3 and EC-FOREVER-3B are shown in Fig. 3. As can be seen from the Fig. 3, power cut off occurred twice in EC-FOREVER-3B at ~8600 sec and ~12600 sec because of fuse failure. This will be reflected in the results of EC-FOREVER-3B during that time. However, it can be seen later that this does not affect the global objectives of the experiment. In both the tests, pressure in the vessel is maintained at ~2.5 MPa.
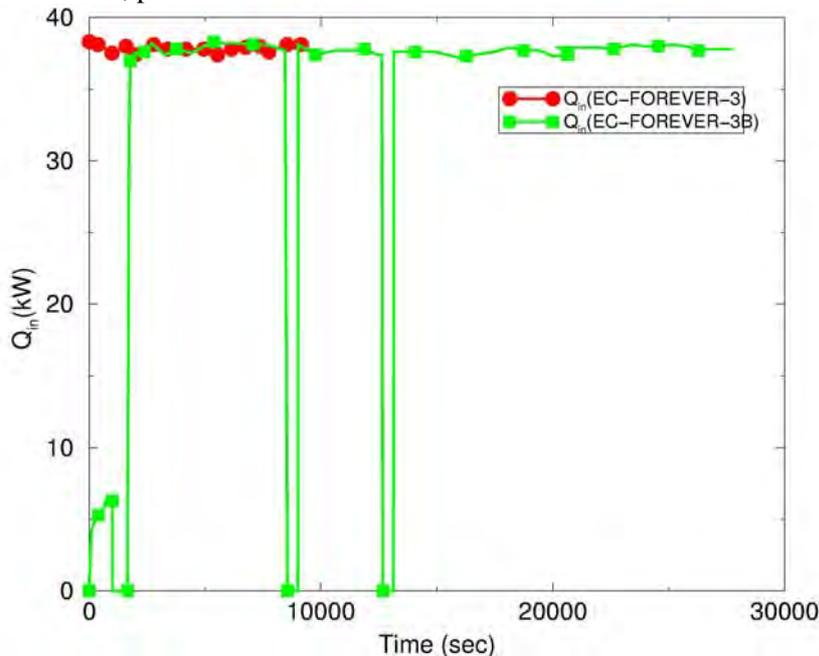

Figure 3 : Histories of heat input

Experimental Results for Temperature

Figure 4 shows the history of melt pool temperatures for EC-FOREVER-3B. Similar temperature history is also obtained for EC-FOREVER-3 but is not shown here. Two humps in the Fig. 4 are due to the power cut off during the experiment mentioned earlier. From the figures, it is observed that bottom part of the melt pool is at lower temperatures compared to those in the upper part of the melt pool. Convection motion of the melt pool is the cause of the temperature variation and this phenomena is well established. This is also seen in Fig. 5, a photograph of the vessel external surface. It is clearly seen that the melt temperatures are much higher in the upper part of the hemispherical lower head.
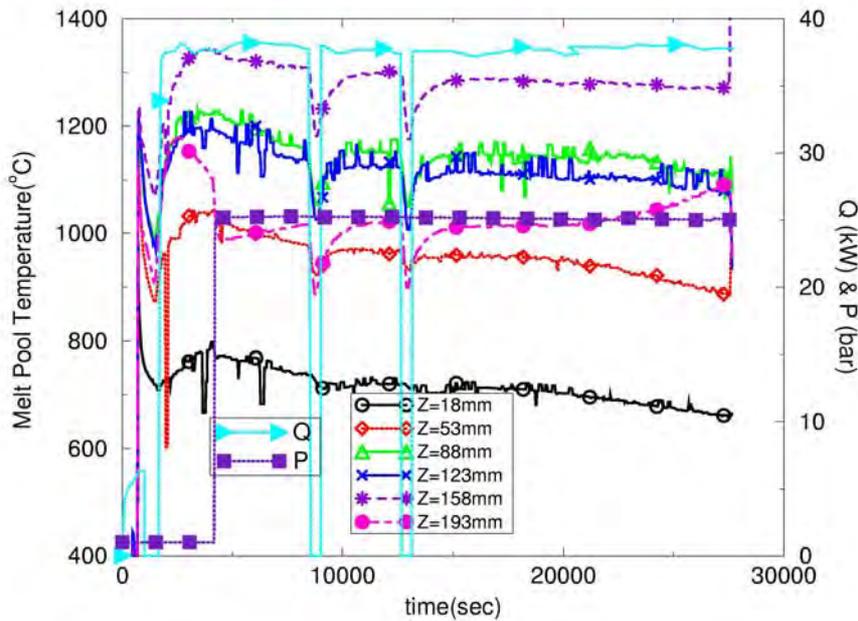
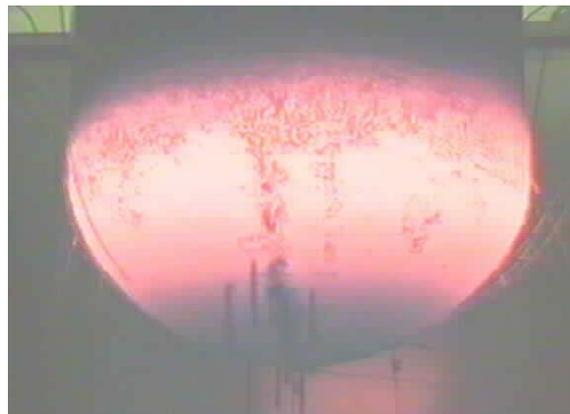Figure 4: Time histories of melt pool temperature.

Figure 5: Convecting vessel under steady state condition

Figures 6 & 7 show the time history of external wall temperature along with the time history of pressurisation for the EC-FOREVER-3B experiment. From the figures it can be identified that maximum external wall temperature occurs at an angle of around 80^0 from the bottom of the vessel. The decrease in temperature with time is due to expansion of vessel volume. As the vessel volume increases, so external surface area increases. Hence, the external wall temperature decreases for the same heat input. Similar trend of decreasing temperature was also observed in the previously reported (Theerthan et al, 2001, 2002)

experiments. In EC-FOREVER-3B, the maximum external wall temperature occurs at angle ~ 70^0 from the bottom of the vessel and a hot zone lies between the 60^0 and 80^0 angles. The location of maximum external wall temperature for EC-FOREVER-3 and EC-FOREVER-3B are different, because of the different melt volumes used for the two experiments mentioned earlier.

Internal wall temperatures measured can not be taken as true temperatures at the internal wall surface; since each internal thermocouple (diameter ~2 mm) is kept inside a protection tube (made of stainless steel) of diameter 4 mm to preclude its corrosion and not directly attached to the wall. The assembly of internal wall thermocouple and its protection tube is, thus, positioned in the natural circulation boundary layer along the vessel wall. Very steep thermal gradient exists in the boundary layer and a correction has to be applied.
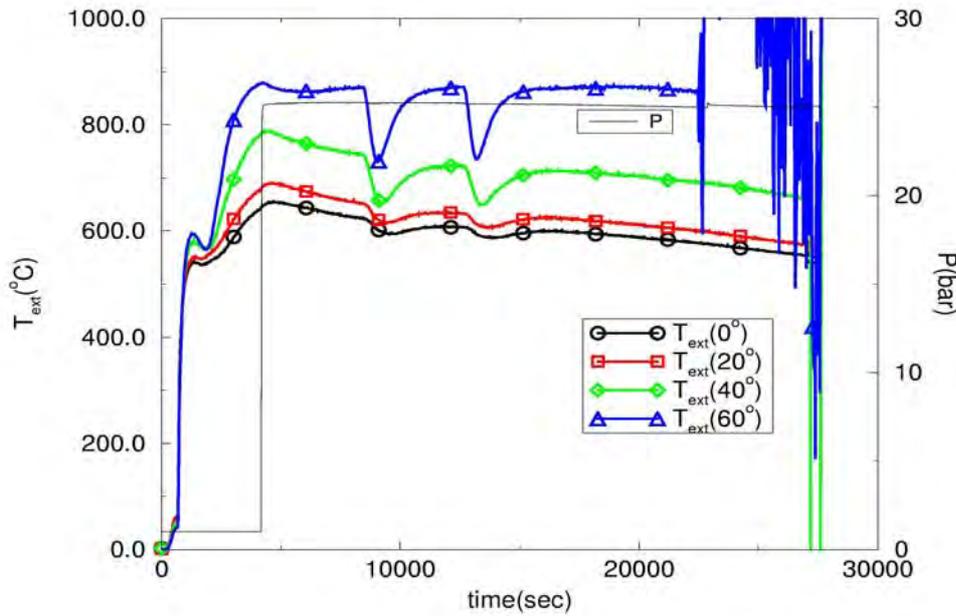

Figure-6 : Time histories of external wall temperature in the left side of the vessel in EC-FOREVER-3B experiment.
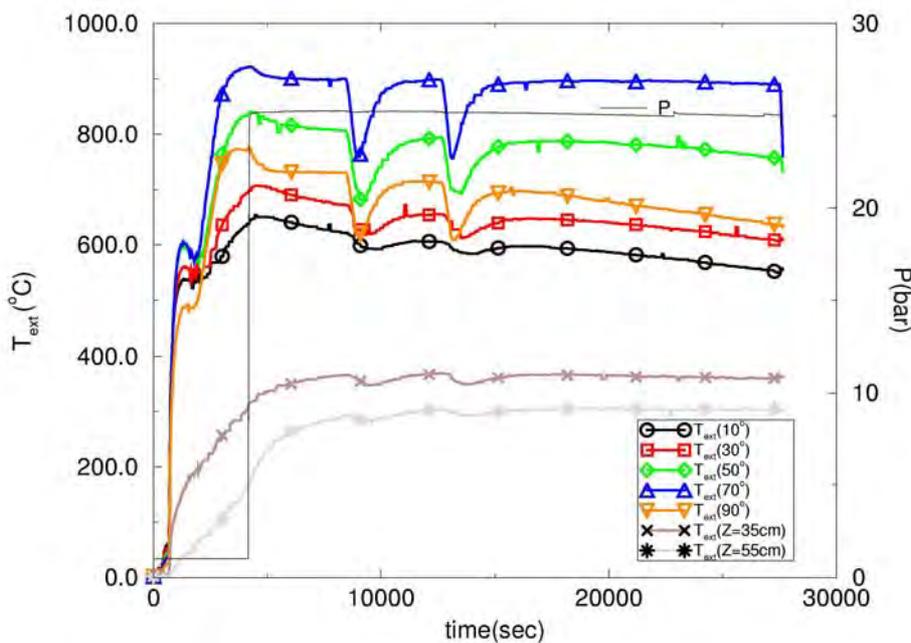

Figure-7 : Time histories of external wall temperature in the right side of the vessel in EC-FOREVER-3B experiment

The estimate of internal wall temperature can be made from the measured external wall temperature by the combination of equations (1) & (2), shown below respectively, for the heat conduction in the vessel wall and for the heat flux needed to maintain the measured temperature at the external surface.

$$k\frac{T_i - T_e}{t_w} = q_w \quad (1)$$

where 'k' is the thermal conductivity of the vessel material. The variation of the thermal conductivity of the vessel material is presented in the Fig. 8. 'T_i' and 'T_e' are the internal and the external wall temperature respectively. 't_w' represents the wall thickness of vessel material and 'q_w' is the heat flux estimated from equation (2). External wall temperature (experimentally obtained) and calculated internal wall temperature profiles are shown in Fig. 9 for EC-FOREVER-3B during the end phase of experiment
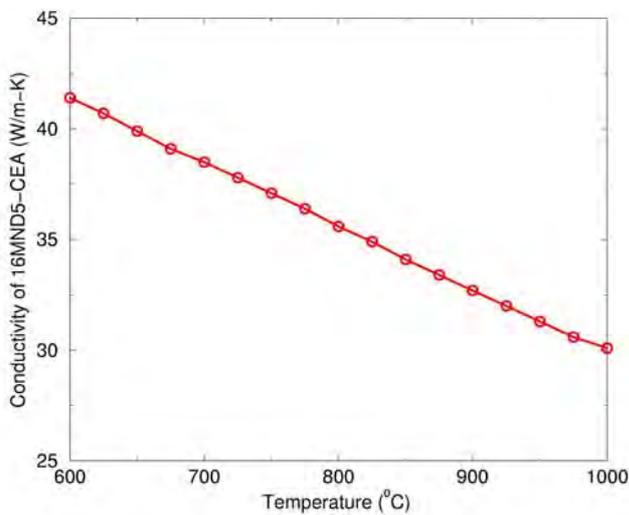

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Figure-8: Variation of the thermal conductivity of 16MND5-CEA employed in the calculation of the internal temperatures
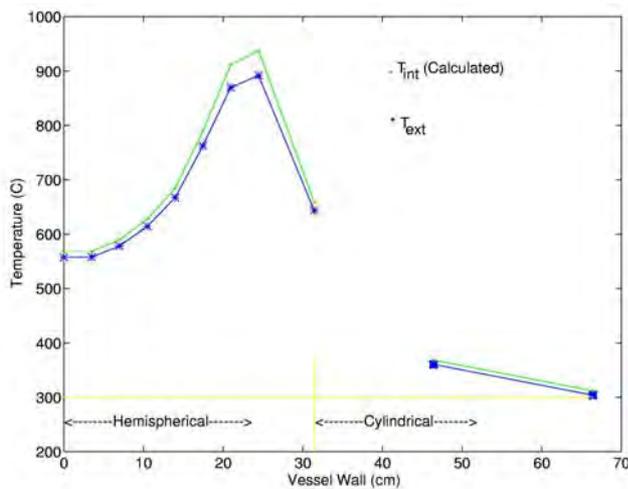

Figure-9: Temperature variation along the vessel wall.

Heat Loss Estimation

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From the external wall temperatures, the steady state heat flux at the wall can be estimated. The heat flux has two components namely (i) radiation and (ii) convection. The total heat flux on the vessel can be expressed as,

$$q_w = q_{rad} + q_{conv} = \varepsilon\sigma_r(T^4 - T_{conv}^4) + h_{conv}(T_w - T_{cont}) \quad (2),$$

where, 'h_{conv}' is the free convection heat transfer coefficient, which is of the order of 10 W/m²-K and 'T_{cont}' is the containment temperature. Containment temperature has been measured by using thermocouple and it is ~50⁰C. The Stefan-Boltzmann's constant is represented by 'σ_r'.

Vessel wall emissivity is taken as ε = 0.9. The estimated heat flux distribution is shown in Fig. 10 for EC-FOREVER-3B. The maximum value of the heat flux corresponds to the maximum temperature at the same location. The value of maximum heat flux is ~110 kW/m².
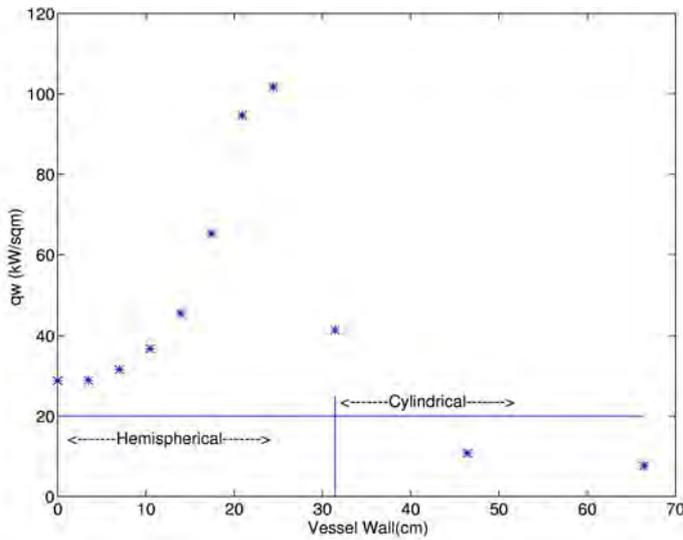

Figure: 10 Heat flux distribution along the vessel wall

Vessel Failure Mode and Location

A view of vessel during failure is shown in Fig. 11. View of the failure (post-test) is shown in Fig. 12. As can be seen from this figure, the failure mode is like a fish mouth, which occurred at ~70⁰ angle from the bottom of the vessel, i.e., at the location of the hot zone. It should be added further that failure does not occur where deformation of the vessel is maximum. The crack length for the French reactor steel is around 17% of the circumference. About 70% melt is discharged to the containment. In the case American reactor steel 80% melt is discharged to the containment. Vessel wall thickness does not change appreciably except near the failure site. This is seen in Fig. 13. At the failure site, vessel thickness was ~10 mm. Theerthan *et al* (2001) made similar observation in the case of lower head failure studies in French reactor steel without penetrations. It is significant to point out here that failure did not occur at one of the penetrations, since vessel temperatures at the location of penetrations were lower. This is contrast to LHF experiment performed at Sandia National Laboratory in which the failure occurred at a penetration. This is one of the important finding in our studies, i.e., if the penetrations are not located in the hot zone, failure will not occur there.
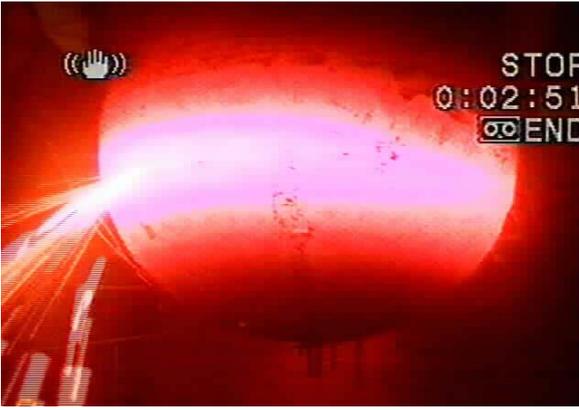
Figure- 11: View of Vessel during failure.

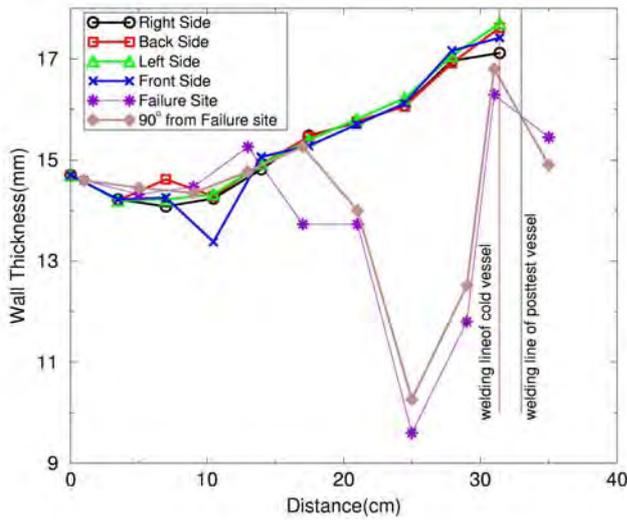Figure- 12: Post-test view of the failure mode

Figure-13: Pre-test and post-test failure thickness of the vessel wall.

Comparison with strain hardening model

Figure 14 show the hoop strain values (ε_h) as a function of time evaluated from the LPT readings for EC-FOREVER-3B experiment. They are calculated as '$\Delta\ell / r_0$', where 'r_0' is outer radius of cold vessel which is equal to 20 cm. A maximum strain of about 16% was reached at angles $\theta = 46^0$ & 60^0. Out of the 16% strain, around 3% is the thermal strain. So the rest is due to creep strain.
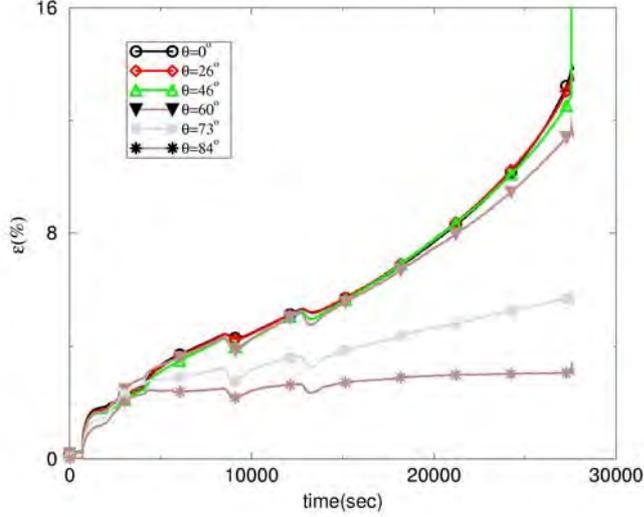
Figure:14 Measured total strain in the vessel wall for the EC-FOREVER-3B experiment

Experimentally obtained creep strains are compared with the prediction of a strain hardening (SH) model [Ikonen (1999)] which employed data obtained from creep tests performed on tensile test specimens of French steel. At high temperature and pressure, the creep rate is best described by a strain hardening model of the type

$$\frac{d\varepsilon_c}{dt} = A_T \varepsilon_c^s (\frac{\sigma}{\sigma_{ref}})^r .$$

The coefficient 'A_T' in the above equation is temperature dependent. Parameter 's' models the strain hardening (accumulation). Stress 'σ' $= P\left(0.5 + \frac{(R-h)^2}{h(2R-h)}\right)$ is the true effective Von-Mises stress and

'σ_{ref}' used to non-dimensionalise the stress term, is taken as 1 MPa. Detailed derivation of the effective Von-Mises stress can be found in Ikonen (1999). To calculate the local Von-Mises stress, spherical shape of the vessel is assumed, however, in the experiment, vessel shape does not remain spherical during the experiment. Here 'R' and 'h' are the time dependent outer wall radius and the wall thickness respectively and 'P' is the applied pressure, which is 25 bar, in the EC-FOREVER-3B experiment.

The above equation can be integrated, for a single temperature, analytically, to yield an equation of the form

$$\frac{\varepsilon_c^{1-s}}{1-s} = A_T (\frac{\sigma}{\sigma_{ref}})^r t + C_0 .$$

Constant 'C_0' is based on initial value of creep strain at the initial time. As mentioned above, 'A_T' models the temperature sensitivity of the creep process and is a sensitive function of the local temperature (Ikonnen, 1999). At temperatures >800[0]C, values of -0.47 and 3.4 were proposed for s and r respectively. It should be noted that the quoted best fits for the parameters 's' and 'r', were determined from the uni-axial tests. Hence, it was necessary to vary the values of these parameters around the best-fit values, in order to obtain an improved comparison.

In order to evaluate the strain from the SH model, the true stress at various locations on the vessel wall had to be evaluated while taking into account the radius and wall thickness variations with time. In the EC-

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FOREVER-3B test substantial reduction in wall thickness and substantial increase in vessel wall radius were observed. Using the values of wall thickness and vessel radius near the failure time will result in higher stresses and larger strains. Moreover, the failure site witnessed the maximum reduction in wall thickness (and maximum wall temperatures or maximum A_T) but not the maximum radial expansion (or maximum strain). Hence, unless these variations in wall thickness and vessel radius with time, are taken into account, the non-uniform distribution of strain with angular locations cannot be predicted correctly. Since, the variation of wall thickness with time cannot be obtained from the experiments in real time, linear variation of wall thickness was used along with the radial displacements data obtained from the experiments. Time history of linear variation of wall thickness is shown in the figure 15 for different angular location.
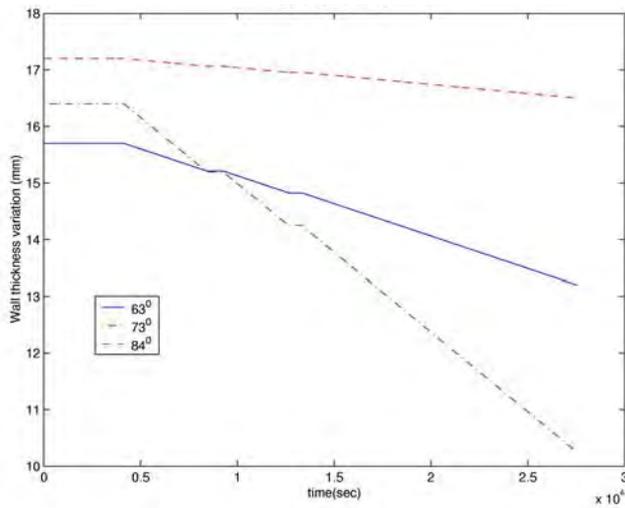

Figure- 15: Time history of linear variation of wall thickness for 60^0, 73^0 and 84^0 from the bottom of the vessel.

Figure 16 shows the comparison of the measured strain at 60^0 against that obtained with the strain hardening model (SHM); understandably, only the creep strain part (*i.e.*, after pressurisation) has been compared. Differences between experiment and SHM may result from tri-axiality factor and from inadequacy of the creep model derived from uni-axial tensile tests.
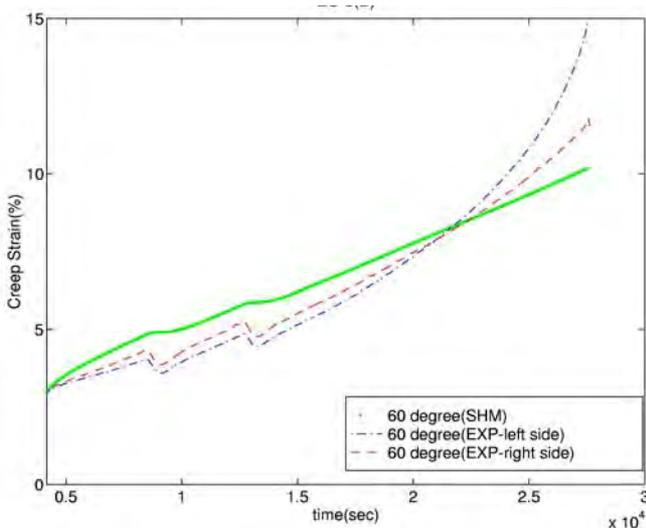

Figure-16: Coparison of measured creep strain with the predictions of the SHM model at 60^0 from the bottom of the vessel.

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Summary and conclusions

The present FOREVER experiments, presented here, investigate the creep behaviour of a 1/10th scaled reactor pressure vessel with penetrations under prototypic thermal and pressure load. Reactor vessel lower hemispherical head was made of 16MND5-French reactor steel. The upper cylindrical part of the vessel was made of German Steel. A melt pool of a mixture of $CaO + B_2O_3$ was established in the vessel lower head with the help of a custom designed heater made of $MoSi_2$ to maintain melt pool convection in the vessel. In the present studies, external vessel wall was elevated to a maximum temperature of ~915^{0}C and to a maximum pressure of 25 bar. The time of vessel failure, one of the primary results, depends primarily on the imposed maximum temperature obtained from the thermal load.

 The failure location was of greater interest in the EC-FOREVER experiments with penetrations, since there could be a competition between the failure at the penetration location (e.g. in the welding) and that in the vessel wall where the highest temperature are reached. Previously, the LHF tests had shown that the vessel failure location would be at a penetration for a uniformly heated vessel, while the EC-FOREVER tests showed that the vessel always failed where the wall temperature are the highest. It was found in the EC-FOREVER-3 and –3B tests that the failure occurred at ~70^0 above the bottom pole of the hemispherical lower had. The highest location of penetrations was 55^0 as it is in the prototypic Framatome PWR vessel and this location is not in the hot zone. We believe that a true test of the competition would be when the penetration is in the hot zone, which can occur for the case of a convecting melt pool filling lower head partially.

Failure length covered 60^0 circumferentially, which is similar to previously reported result (Theerthan *et al*, 2001). From the test data, it was found that maximum total strain of 16% was achieved before the vessel failure occurred for the French reactor steel. Major part of the total strain is creep and it is ~13%. Remaining 3% is due to thermal strain. Present experimental results provide substantial data on creep behaviour of a French reactor steel vessel with penetration at high temperature and moderate pressure. The data can serve as a benchmark for validating the multi-axial creep models in the structural codes employed by the nuclear industry.

Nomenclature

A_T constant in the SHM (sec^{-1})

C_0 constant in the SHM

P Pressure (bar)

q wall heat flux (W/m^2)

Q heat input (W)

r_0 initial external wall radius (m)

T Temperature (^{o}C)

t time (sec or min)

t_h thickness of the vessel wall (m)

Z vertical co-ordinate (m)

Greek

$\Delta\ell$ total displacement (m)

Δr radial displacement (m)

ΔX horizontal component of the total displacement(m)

ΔY	vertical component of the total displacement (m)
ε	emissivity
ε_c	creep strain $(\mathrm{mm/mm})$
ε_h	hoop strain
σ_r	Stefan-Boltzmann $(\mathrm{W/m^2}\text{--}\mathrm{K^4})$
σ	stress $(\mathrm{N/m^2})$
θ	angular location along the vessel wall $(^0)$

Subscript

cont	containment
conv	convection
ext	external wall
r,s	constants in the SHM
rad	radiation
ref	reference value
sup	supplied
w	wall

Abbreviation

corr	after correction
FOREVER	Failure Of REactor VEssel Retention
LHF	Lower head failure
LPT	Linear Position Transducer
MVI	Melt Vessel Interactions
mp	melt pool
OLHF	OECD Lower head failure
PT	Pressure Transducer
PWR	Pressurised water reactor
RCS	Reactor coolant systems
SHM	Strain hardening model
TC	Thermocouple

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