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FOREVER Experimental Program on Reactor Pressure Vessel Creep Behavior and Core Debris Retention

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ABSTRACT: The FOREVER experimental program is concerned with the phenomena of melt-vessel interactions during a postulated severe accident in a light water reactor. The present investigation is focused, in particular, on the thermal loadings and the mechanical response of the reactor pressure vessel during the late phase of in-vessel core melt progression when vessel failure and in-vessel molten core retention issues become important. The results of the FOREVER/C1 integral experiment on melt pool natural convection and vessel-creep deformation are presented and analyzed. During this experiment, the vessel wall, heated to about 800°C and pressurized to 26 bars, was subjected to creep deformation in a 24-hours non-stop test. The FOREVER/C1 test is the first integral experiment, in which a decay-heated oxidic melt pool was maintained in long-term contact with the hemispherical lower head of a pressurized, creeping, steel vessel. A sizeable database was obtained on vessel wall creep deformation rates, melt pool temperatures, melt pool energy split, heat transfer rates, heat flux distribution on the melt (crust)-vessel contact surface, and vessel temperatures. The data can be employed for validation of the melt pool convection and of the structural mechanics codes.

1 INTRODUCTION

Recently, the later stages of the in-vessel melt progression of a hypothetical severe accident in a light water reactor (LWR) has attracted significant attention in the nuclear engineering community. The purpose is to *(a)* determine the mode and timing of the reactor vessel lower head failure, which in turn, determines the loadings on the containment, and *(b)* determine the feasibility of retaining the core melt within the lower head without failing it, through cooling the vessel wall either internally or externally, or both.

Depending on accident scenarios, reactor design and accident management procedures, the in-vessel core melt/debris configuration may be different, figs.1-2. In general, the heat, transferred from the debris to the vessel, will cause the vessel heat-up and reduce the vessel strength. As a consequence, the lower head wall can be subjected to significant thermal and pressure loads, and there exists a possibility for lower head failure due to melting or creep rupture (fig.1).

It was suggested recently, that the presence of water in the reactor lower plenum prevented the TMI-2 failure. The vessel gap cooling is proposed as an efficient mechanism of keeping the vessel wall cool and preventing the vessel failure. The success of this mechanism largely depends on *a)* whether a gap exists between the corium melt crust and the creeping vessel and *b)* whether the water can penetrate into the gap. Since the core melt relocation, debris bed formation, crust formation and vessel creep are highly three-dimensional, it is difficult to predict a pattern of water channeling in-between the vessel wall and the debris. Another important question is whether gap thermal hydraulics allows water ingression to sufficient depth to cool the lowermost region of the vessel, and prevent its creep failure.

Table 1: *Review of prior experimental research*

%	*Institution/Organization*	*Method of study*	*Comments.*
1	(KfK, Germany), [1].	+uniaxial tensile tests.	+High-temperature creep and tensile data for German RPV steel (20MnMoNi55).
2	(INEL, NRC, US), [2].	+uniaxial tensile tests.	+High-temperature creep and tensile data for US RPV steels (SA533B1 and SA508-CL2).
3	(CEA, France), [3].	+uniaxial tensile tests.	+High-temperature creep and tensile data for French RPV steel (16MND5).
4	RUPTHER experimental program (France).	+Pressurized thin shell carbon steel cylinders. +Temp. up to 1000°C.	+Multiaxial creep rupture data for high-temperature, conditions.
5	(Kurchatov Inst., Russia), [4]	+uniaxial tensile tests.	+High-temperature creep and tensile data for Russian RPV steel (15X2HMFA).
6	LHF experimental program, (SNL, US), [5]	+1/5th-scale carbon steel pressure vessel. +P=10MPa, T up to 1000 K. +Resistance heaters for thermal loading.	+Global creep rupture. +Effect of penetrations. +Effect of heat flux peaking. +Hemispherical/cylindrical

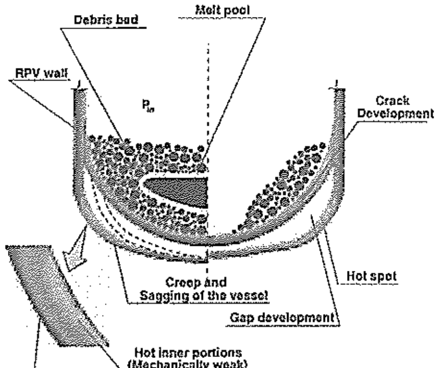


Fig. 1: *Phenomenology of global and local creep rupture.*

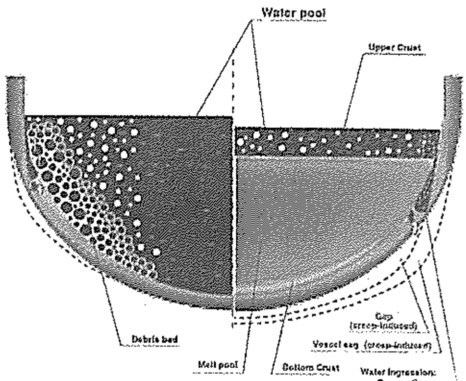


Fig. 2: *Phenomenology of water ingression and gap cooling.*

Previously, analytical research on RPV creep deformation and rupture has been performed at EPRI [6], SNL ([7]), INEL ([8]), UWM [9], UCSB [10], PSI [11], SNUK [12] and, in the EU-funded REVISA and RPVSA projects.

There have been a number of experimental studies dedicated to the investigation of creep deformation and vessel coolability and failure, Tables 1-2. Uniaxial tensile tests were conducted at KfK [1], INEL [2], CEA [3] and RRC-KI [4] to obtain data on the creep and rupture properties of the vessel steel. In the RUPTHER experiments (France), multiaxial creep rupture tests were performed using pressurized thin shell carbon steel cylinders in the temperature range up to 1000°C. Recently, experiments have been performed at SNL on creep failure of relatively large vessels, held at a pressure of 100 bars and 50 bars, while the vessel bottom head was heated to temperatures of 1000K [5]. Experiments have also been conducted at JAERI [13], KAERI [14], RRC-KI [15], FAI [16] and TUM/LAT [17] on the gap-cooling phenomenon. No

Table 2: *Review of prior experimental research (cont.)*

%	*Institution/Organization*	*Method of study*	*Comments.*
7	(FAI, US), [16].	Integral, high-temperature experiment.	vessel. +Al_2O_3 thermite melt. +P up to 100 bars.
8	(JAERI, Japan), [13].	Integral, high-temperature experiment (ALPHA Program).	+Carbon steel hemispherical vessel. +Al_2O_3 thermite melt.
9	(KAERI, Korea), [14].	LAVA experiment (integral, high-temp.): (SONATA-IV Program)	+iron thermite. +no sustained heating. +P up to 20 bars. +Carbon steel hemisphical vessel
			(about 1/8th-scale).
		CHFG experiment (separate-effect, low-temp.): (SONATA-IV Program)	+Hemisph. vessel (diameter 0.5 m). +Hemispherical 0.5-2mm gap. +P up to 10 bars. +$q_w \sim 0.1$ MW/m^2. +Coolant: water, freon 113.
10	(Kurchatov Inst., Russia), [15].	CTF separate-effect experiments (RASPLAV Program).	+Vertical gap: 0.5-2 mm in thickness/ 60-400 mm in height. +P from 0.1 to 8 MPa. +T up to 600°C.
			+Coolant: freon R113a. +Inclined (from 0° to 20° deg.)
11	(LAT/TUM, Germany), [17].	Low-temperature Separate-effect experiments	slice-type facility. +Porous debris: steel balls (4mm in dia). +Induction coil to sustain heat ($Q_{in} \sim 80$kW, $q_v \sim 10$ MW/m^3, $q_w \sim 1.4$ MW/m^2).

definite conclusions about the reliability of the gap-cooling mechanism at prototypical conditions have been reached, so far.

2 FOREVER EXPERIMENTAL PROGRAM

The FOREVER experimental program includes three major test series [18] [19] [20], fig.3a,b,c. In the first series, the FOREVER/C(reep) series, we investigate the vessel lower head deformation and creep behavior under thermal attack by an oxidic-melt pool. The focus is placed on physical mechanisms which govern the debris-vessel gap formation. In addition, the data is obtained on the creep rate at several locations on the lower head, which could be employed for validation of creep models and codes. In contrast to the SNL LHF experiments [5] (which simulate the TMI-2 scenario with 10 MPa pressure loading), the depressurized scenarios are the focus of the FOREVER tests. The second series FOREVER/G(ap) will be devoted to the gap cooling. Water will be supplied to the top of the melt pool after the vessel wall creep has occurred to a certain extent. Water ingression into the gap between the melt pool crust and the creeping vessel (if formed) will be detected by thermocouples, mounted on the inner surface of the vessel wall. In the third series FOREVER/P(enetrations), the effects of penetrations on the vessel deformation, creep and failure will be investigated.

Scaling considerations for the FOREVER/C tests were presented in the earlier cited ref.[18] and will not be repeated here. In summary, the experiment is scaled as *(i)* 1:10 geometrically, *(ii)* 1:1 in heat flux, *(iii)* 1:10 in vessel wall temperature difference, *(iv)* 1:1 in membrane stresses, and *(v)* 1:10 in thermal stresses.

3 EXPERIMENTAL FACILITY AND PROCEDURE

The facility employs 1/10-scaled 16MND5-(French)- and 15Mo3-(German)-steel vessels of 400mm diameter, 750mm height and 15mm wall thickness, fig.3d. The auxiliary systems are designed to provide an overpressurization up to 4 MPa in the test vessel. Thus, severe accident scenarios with RCS depressurization are modeled. Up to 20 liters of an oxidic melt with

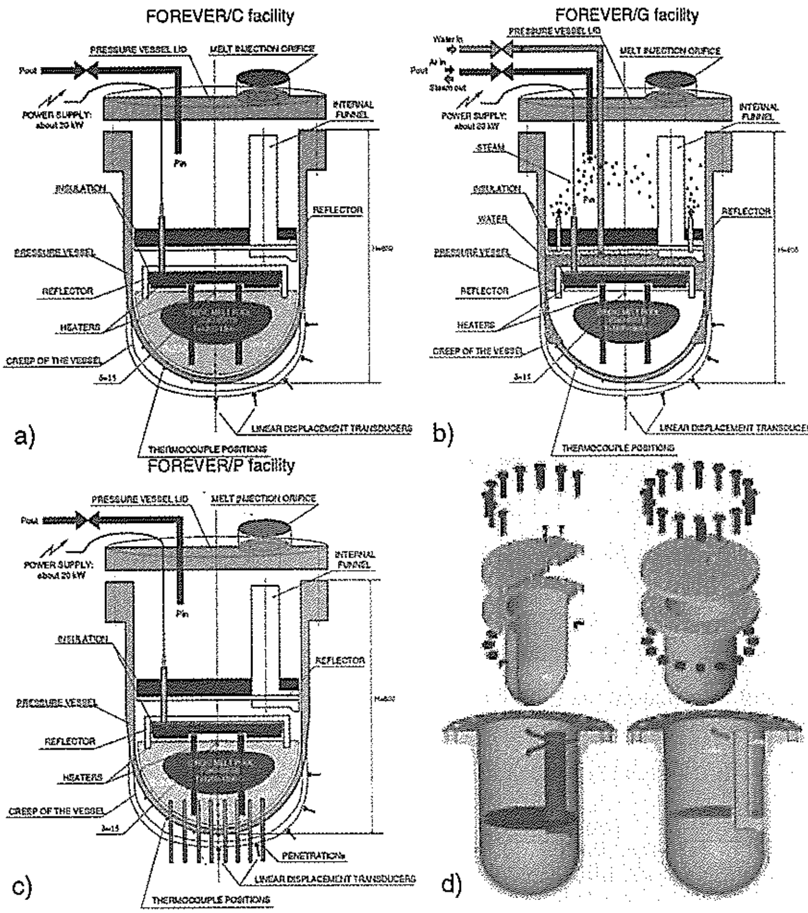


Fig. 3: *Schematic of the FOREVER/C (a), FOREVER/G (b) and FOREVER/P (c) tests. Design of the pressure vessel (d).*

100-300 K superheat are employed, as simulant for the prototypic corium melt. Temperature difference between the melt liquidus and solidus is about 50K and the liquidus point is in the range from 1050 to 1150°C.

The high-temperature (up to 1300°C) oxide melt is prepared in a SiC-crucible placed in a 50kW induction furnace, which is, then, poured into the test section. The $MoSi_2$ 50kW internal heaters are employed to heat and keep the melt pool temperature in the range up to 1500°C. Thus, the vessel wall temperature can be sustained in the range up to 1100°C.

Specified overpressurization is supplied with an inert gas supply, after the vessel wall temperature has achieved steady-state conditions. In order to assure safe test performance all the test equipment is installed inside a concrete containment with 40 cm thick walls; Fig.4.

4 INSTRUMENTATION AND DIAGNOSTICS

A number of B- and K-type thermocouples are used to measure temperatures of the melt (debris) at different locations in the hemispherical pool and to measure the temperatures of the vessel wall as a function of azimuthal angle. The distribution of the heat flux along the

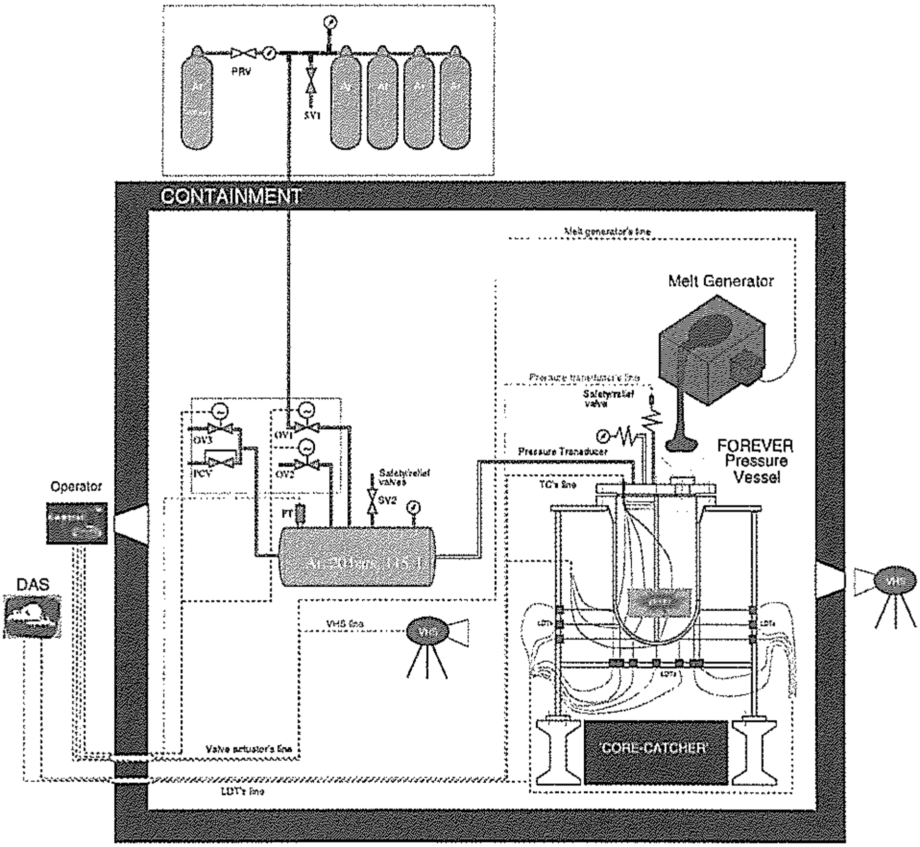


Fig. 4: *Schematic of the FOREVER/C experimental set-up.*

hemispherical bottom and the total heat balance are deduced from the temperature measurements. The vessel deformation and creep are measured by linear displacement transducers. Up to 20 displacement-measuring devices are used to measure the multiaxial creep behavior of the three-dimensional vessel.

5 FOREVER/C1 EXPERIMENTAL RESULTS AND DISCUSSION

The experiment started with melt delivery to the pressure vessel. After the vessel temperature had become steady, 20 min after the melt delivery, the pressurization system was activated. The internal pressure $P_{int} \simeq 25$ bar was kept for 24 hrs, until the maximum creep strain reached 5%. Experimental conditions and parameters of the FOREVER/C1 test are summarized in Table 3.

Figs.5-6 present the measured total vessel wall displacements, as functions of time, for five different measurement points. It is seen, that during the first 20 minutes of the test, due to the thermal expansion, the vessel wall moved radially in the range from 2.5 to 4 mm, depending on the angular position. After the pressurization, which was activated about 20 minutes after the melt delivery, measurable creep deformation started, fig.6. After the primary creep stage, the secondary creep is established, approximately 1/2 hour after the pressurization. During the secondary creep, the creep strain rate was nearly constant, $\bar{\dot{\varepsilon}} \simeq 0.125$ %/hr.

Table 3: *Experimental conditions and parameters of the FOREVER/C1 test.*

%	*Parameter*	*Value*
1	Average pressure at the steady-state, MPa	2.5
2	Average power at the steady-state, kVA	22
3	Maximum temperature of the external surface of the vessel measured at the steady-state, $^\circ C$	800
4	Position of the maximum temperature, °	60 – 90°
5	Maximum temperature of the melt measured at the steady-state, $^\circ C$	1100
6	Maximum total displacement of the vessel wall measured, mm	10
7	Maximum creep displacement of the vessel wall measured, mm	6
8	Angular Position of the maximum displacement measured, °	45°
9	Estimate of the maximum total strain, calculated as $\varepsilon_{\theta}^{max} = \frac{\Delta r^{max}}{R}$, %	5
10	Estimate of the average creep strain rate, calculated as $\bar{\dot{\varepsilon}} \sim \frac{\Delta r^{max,creep}}{R \cdot t_{exp}}$, %/hr	0.125
11	Total duration of the experiment, hrs	28
12	Duration of the thermal steady-state, hrs	21
13	Duration of the pressurization, hrs	24

The creep deformation of the vessel was observed to be quite symmetrical, which can be deduced from the radial and angular displacement data, presented in figs.7 and 8.

The measured radial creep deformations vary from 1mm (at $\phi \simeq \pm 75^\circ$) to 5mm (at $-45^\circ < \phi < +45^\circ$). At the same time, the maximum of the angular displacement is detected in the region of $\phi \simeq 80^\circ$. As one can see from fig.9, the vessel displacement was oriented downwards, rather than radially. In fact, the vessel wall temperature in the lowest region of the lower head was relatively low (see fig.15) and could hardly cause significant creep deformations. Thus, it is believed that the creep process was taking place only in the corner regions, where the maximum temperature was located. Because the deformation was oriented downwards, it caused equivalent displacement of the bottom part. Therefore, the vessel wall thinning should have occurred in the corner, while the bottom part must be mostly intact.

The temperature in the melt pool was measured by three centerline thermocouples, figs.10 and 11. As can be seen, the temperature inside the liquid melt pool achieved nearly steady-state in 0.5 hr, and stayed at the level of 1050-1100°C until the depressurization. This corresponds to the melt superheat above the liquidus point of $\simeq$ 50°C. The lowest thermocouple was located 3 cm above the vessel wall, in the crust. Due to the crust growth during the first 3-4 hrs (see pre-test calculations by the MVITA code, fig.12), this thermocouple registered slow temperature drop from about 850°C in the begining of the test to about 700°C at the steady-state stage, fig.10.

Figs.13 and 14 show the view of the vessel in the very beginning of the test and after the test. It can be seen, that due to high-temperature-conditions, significant vessel outer wall oxidation took place. Creep displacement of the outer surface of the lower head was also evident, when viewed along with cylindrical part of the vessel.

Temperature of the vessel wall was registered by 21 internal and external thermocouples. Steady-state conditions for the thermocouples at the upper ($\phi > 60^\circ$) parts of the lower head were achieved in 1 hr after the beginning of the test. The thermocouples at the lower parts ($\phi < 60^\circ$) reached approximately steady-state conditions after 3-4 hrs of the test, when the

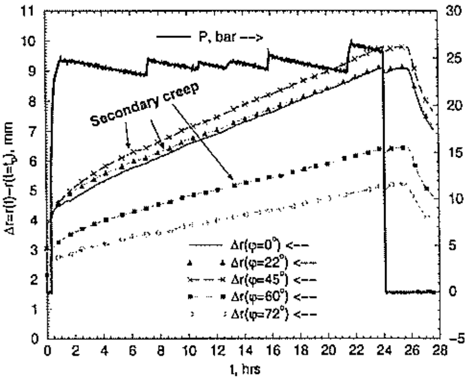


Fig. 5: *History of the vessel wall displacements and internal pressure.*

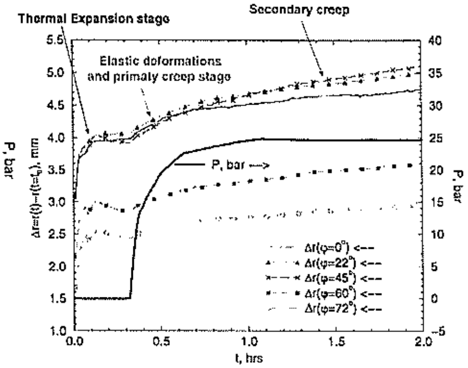


Fig. 6: *History of the vessel wall displacements and internal pressure, in the beginning of the test, (t from 0 to 2 hrs).*

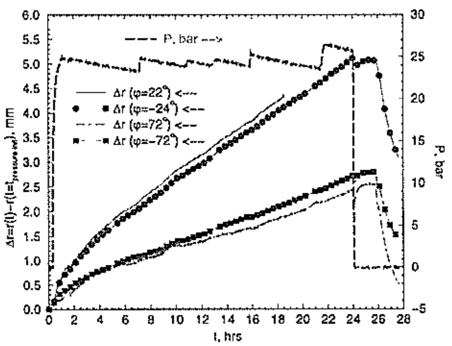


Fig. 7: *Creep displacement at the position ($\phi \simeq \pm 24°$) and ($\phi = \pm 72°$) of the vessel, and internal pressure as a function of time.*

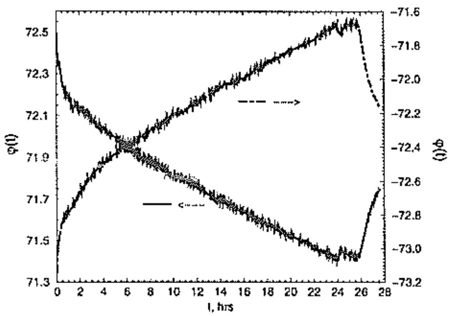


Fig. 8: *History of the angular displacement, measured at the angular position $\phi \simeq \pm 72$.*

bottom crust was fully established and achieved steady-state thickness.

In fig.15, the local distribution of the temperature is presented for hemispherical and cylindrical part of the vessel. The evaluated heat flux distribution is plotted as functions of angle (in the hemispherical part) and of axial coordinate (in the cylindrical part), in fig.16. As can be seen, the maximum wall heat flux is located in the hemispherical part, $\phi \simeq 75°$, exactly where the maximum wall temperature is measured. The local distribution fig.16 is typical for natural convection in the hemispherical melt pool, with minimum heat flux at the very bottom. From these data, the total heat balance is evaluated to be about 90%, at the steady-state stage of the experiment.

After the test, the vessel was cut and the melt-vessel interface was examined, fig.17. It was found that no measurable gap was created in the FOREVER/C1 test. This indicates that the crust adhered to the wall and crept together with the vessel. Similar phenomenon might occur in the prototypic reactor situation, however, this test did not employ any water in the vessel before the melt was poured. This preliminary observation will be subjected to confirmation in the future FOREVER tests.

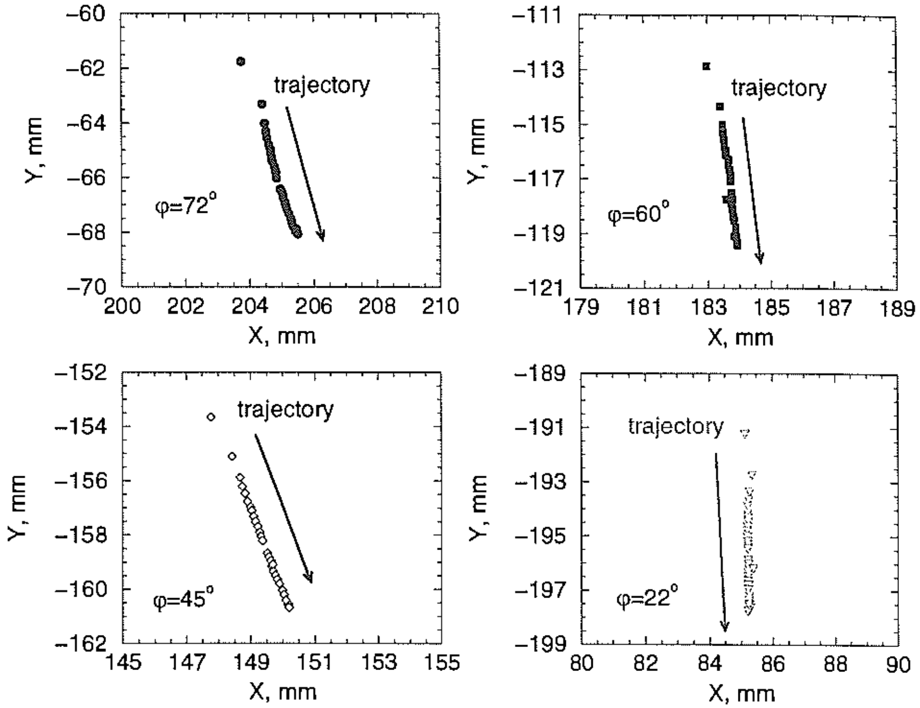
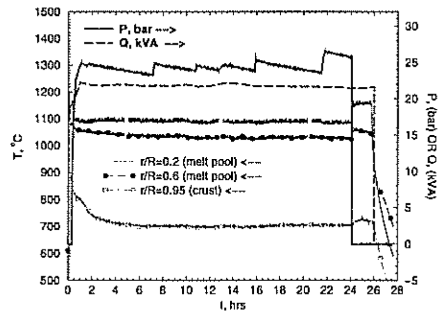


Fig. 9: *Displacements of the LDT measurement points in cartesian coordinates.*



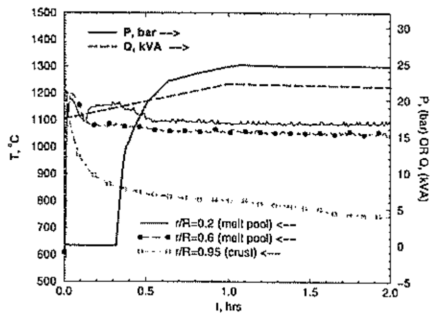


Fig. 10: *Temperature of the melt as a function of time, measured at the centerline, at different radial locations. History of the pressure and power supply.*

Fig. 11: *Temperature of the melt as a function of time, measured at the centerline, at different radial locations. History of the pressure and power supply. Begining of the test (t from 0 to 2 hrs).*

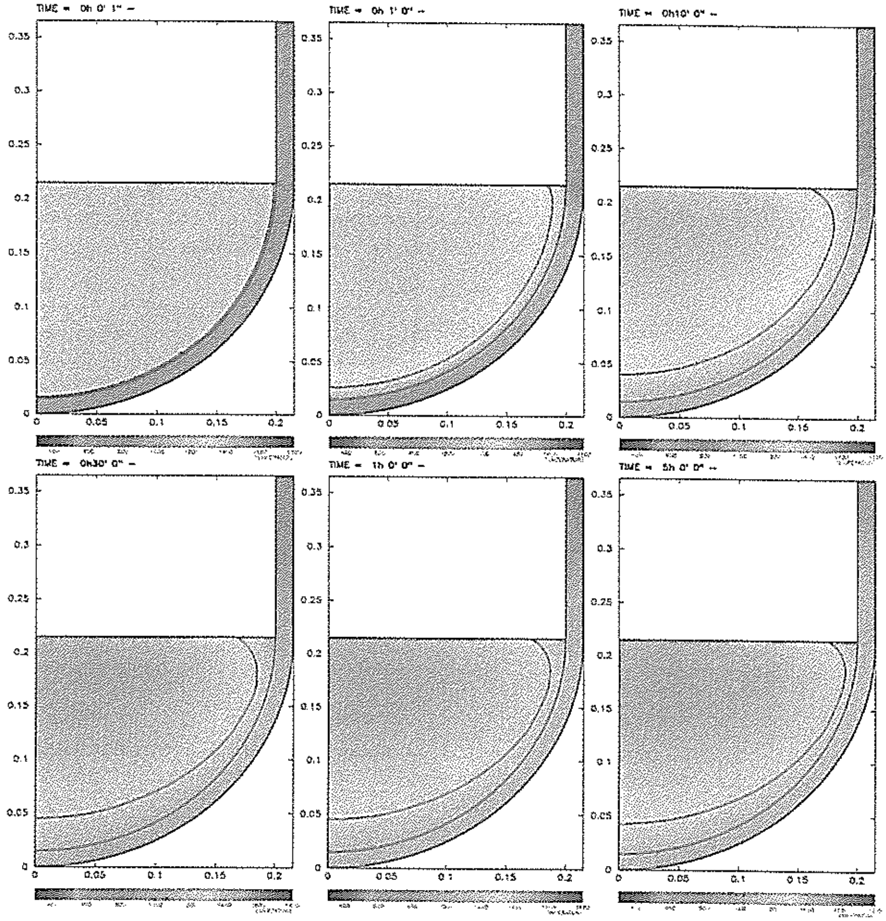


Fig. 12: *Evolution of crust formation and melt pool temperature. Pre-test calculation by the MVITA code.*

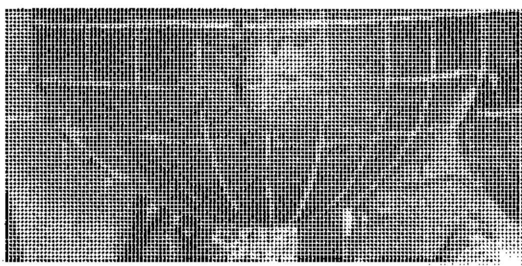


Fig. 13: *View of the hot pressure vessel in the beginning of the test.*

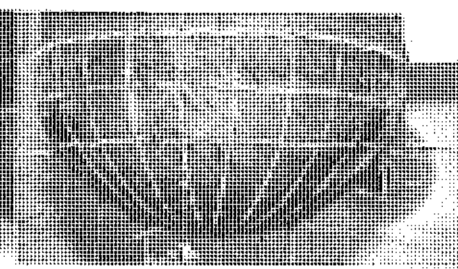


Fig. 14: *View of the cold pressure vessel after the test.*

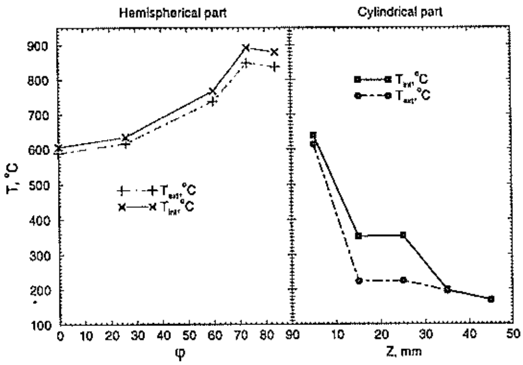


Fig. 15: *Local temperature distribution on the inner and outer surface of the vessel wall, at the steady-state stage of experiment (t=8 hrs.).*

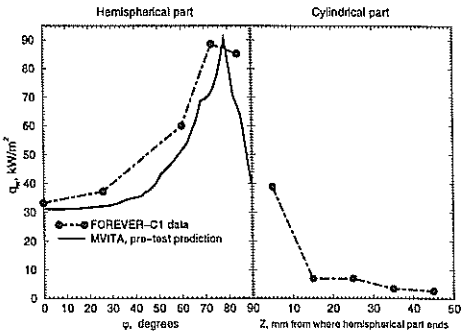


Fig. 16: *Evaluation of the local heat flux distribution on the vessel wall, the steady-state stage of experiment (t=8 hrs.).*

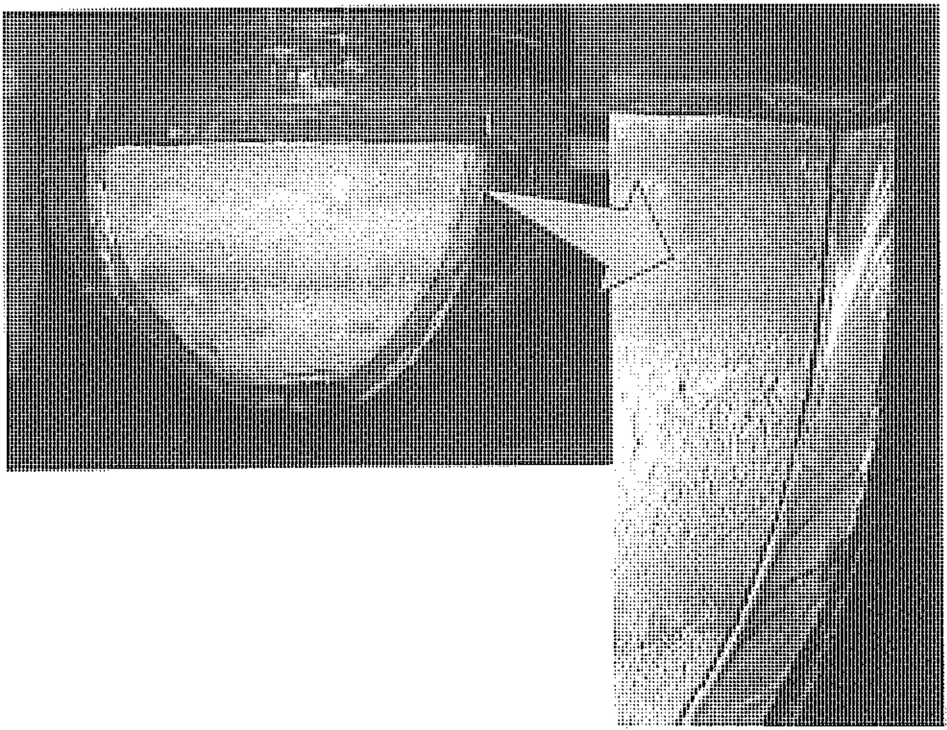


Fig. 17: *View of the solidified melt after the test.*

6 SUMMARY

Interactions between a high-temperature oxidic melt and the hemispherical carbon steel vessels are being experimentally investigated in the 1/10th scale FOREVER facility. The FOREVER/C1 test is the first integral experiment, in which a decay-heated oxidic melt pool was maintained in long-term contact with the hemispherical lower head of a pressurized, creeping, steel vessel. The experiment was successful. A sizeable database was obtained on melt pool temperature, melt pool energy transfer, heat transfer rates, heat flux distribution on the melt (crust)-vessel contact surface, vessel temperatures, and the time-dependent multiaxial vessel wall creep deformation. The multiaxial three-dimensional creep deformation data obtained at high-temperatures, for prototypic reactor vessel material, could be employed for validation of structural mechanics codes, and for investigation of the models of creep deformation. We believe that the FOREVER tests will provide crucial data and knowledge-base to advance the current understanding of the in-vessel melt stabilization and of the vessel creep behavior.

NOMENCLATURE

Q	heat
q	heat flux
P	pressure
R	radius
t	time
T	temperature
x, y, z	cartesian coordinates
ε	strain
φ	angle

Abbreviations

FOREVER	'Failure of reactor vessel retention'
LDT	'Linear Displacement Transducers'

ACKNOWLEDGMENTS

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