Forschungszentrum Karlsruhe

Technik und Umwelt

Wissenschaftliche Berichte

FZKA 6453

Experiments on Concrete Erosion by a Corium Melt in the EPR Reactor Cavity: KAPOOL 6-8

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Forschungszentrum Karlsruhe GmbH, Karlsruhe
2000

Experimente zur Betonerosion durch eine Kernschmelze in der EPR-Reaktorkaverne: KAPOOL 6-8

Zusammenfassung

Für zukünftige Leichtwasserreaktoren werden spezielle Einbauten (Kernfänger) erforderlich sein, um das Containment-Versagen infolge von Erosion des Fundamentes bei einem Kernschmelzunfall zu verhindern. Nach Versagen des Reaktordruckbehälters soll die Kernschmelze zunächst in der Reaktorgrube etwa 1 h zurückgehalten werden, damit auch eventuell später abstürzende Restschmelzen gesammelt werden. Nach Aufschmelzen einer Schicht aus Opferbeton, mit der die Reaktorgrube ausgekleidet ist, und eines Stahltors am Boden der Reaktorgrube soll sich die Kernschmelze gleichmäßig in einem dafür vorgesehenen Ausbreitungsraum verteilen und anschließend mit Wasser von oben geflutet und dadurch gekühlt werden.

Es wurde deshalb eine Serie von Experimenten durchgeführt, um das Erosionsverhalten einer Opferbetonschicht zu untersuchen. Dabei wurde als Simulationsmaterial für die Kernschmelze eine Thermitschmelze aus Aluminiumoxid und Eisen verwendet. Als Opfermaterial wurde ein spezieller Beton benutzt, der vom Industriepartner empfohlen wurde. Er setzt sich zusammen aus 49 Gew% Fe_2O_3, 43 Gew% SiO_2 und 8 Gew% Zement, der Wassergehalt betrug etwa 3%. In zwei Tests (KAPOOL 7 und 8) wurde der Schmelze Zircalloy zugesetzt, um die Oxidation von Zirkonium durch Wasser, Eisenoxide und Silikate zu simulieren. Ergebnisse der Erosionsgeschwindigkeiten im Opferbeton sowie Inhomogenitäten der Schmelzfront werden in diesem Bericht beschrieben.

Abstract

In future Light Water Reactors special devices (core catchers) might be required to prevent containment failure by basement erosion after reactor pressure vessel meltthrough during a core meltdown accident. After failure of the reactor pressure vessel the core melt is retained in the reactor cavity for ~ 1 h to pick up late melts. The reactor cavity is protected by a layer of sacrificial concrete and closed by a steel gate at the bottom. After meltthrough of this gate the core melt should be distributed homogeneously in a special spreading room. The spread melt is cooled by flooding with water from top.

A series of experiments has been performed to investigate the erosion of a sacrificial concrete layer using alumina-iron thermite melts as a simulant for the core melt. The sacrificial material was a special concrete which was recommended by the industrial partner. Its composition is 49 wt% Fe_2O_3, 43 wt% SiO_2 and 8 wt% cement, the water content was about 3%. In two tests (KAPOOL 7 and 8) some zircaloy has been added to the melt to simulate oxidation of zirconium due to the presence of water, ironoxides and silica.

Erosion velocities of the sacrificial concrete and the inhomogeneity of the melt front are presented in this report.

Content

1 Introduction

To exclude significant release of radioactivity to the environment even in the case of a core melt accident, next generation LWR's shall incorporate the ability to retain the core melt within the containment. In the planned European Pressurized Reactor (EPR) this shall be accomplished by spreading the core melt on a large area and cooling the spread melt by flooding with water from top [1, 2], Figure 1.

Various series of experiments are performed at Forschungszentrum Karlsruhe to study core melt behaviour. In all these tests the core melt is simulated by iron and alumina melts produced by the thermite reaction. Thermite melts are excellent simulants of the core melt because

- both, the metallic and the oxidic core melt component, are simulated
- the melt temperatures (~ 2200 °C) are comparable to that of the core melt (this is important to achieve representative high radiation heat losses)
- by admixture of other components (SiO_2, CaO) to the alumina melt, the characteristics of the oxidic corium melt after admixture of concrete components (large difference between solidus and liquidus temperature) can be simulated.

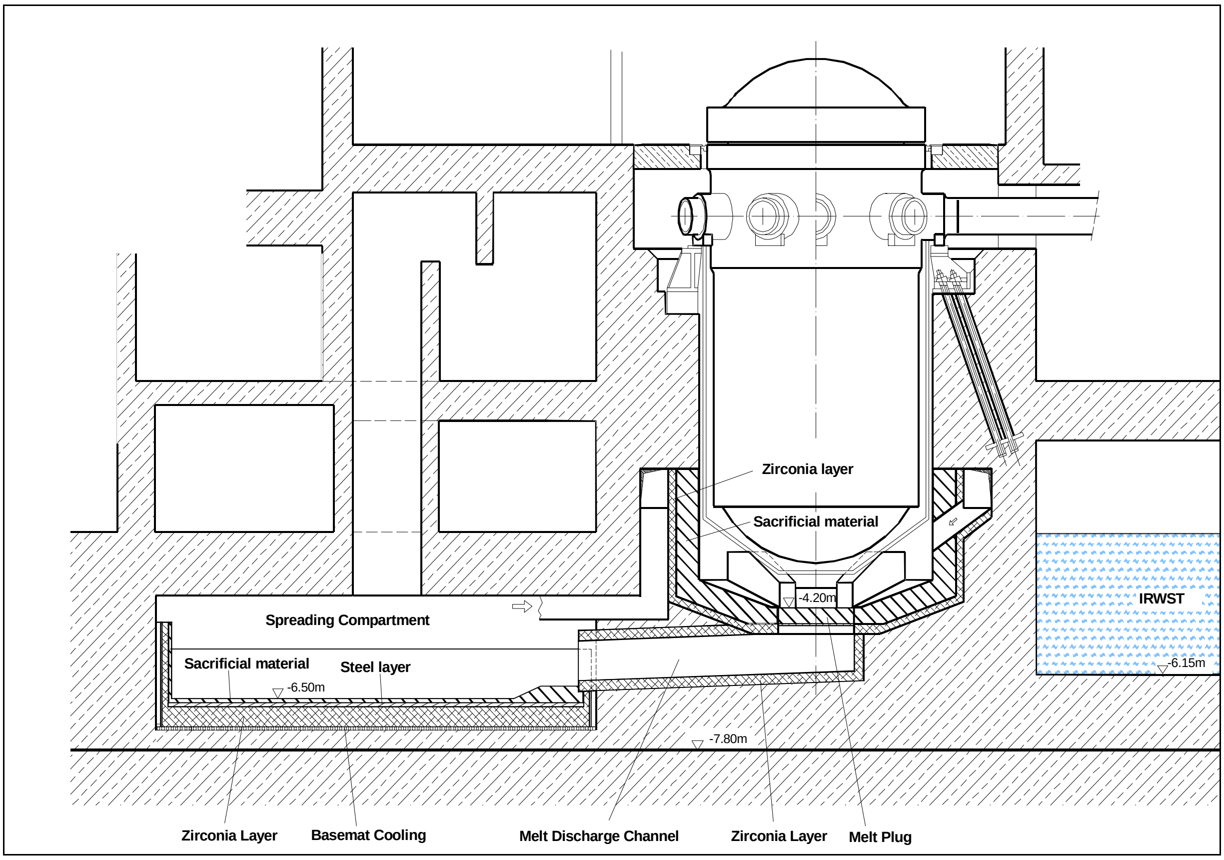


Figure 1: Concept of the EPR core catcher

After meltthrough of the reactor pressure vessel the corium melt is gathered in the cavity below the vessel. It is foreseen to hold the melt there for about one hour. This time interval is long enough to ensure that practically all corium inventory will be gathered in this cavity. The corium melt interacts with the sacrificial concrete of the cavity. This interaction changes the corium material properties drastically: metallic zirconium is oxidized, the admixture of concrete with the oxidic melt lowers the liquidus- and solidus temperatures by several hundred degrees and the density of the oxidic melt, originally up to 9000 kg/m^3 higher than the metallic one (≈ 7000 kg/m^3), is decreasing steadily, and eventually a flipover of the two separated phases, oxidic and metallic melts, will happen. Once the concrete erosion is finished, a steel gate will be eroded by the melt and spreading of the melt into the spreading compartment starts.

The KAPOOL experiments investigate important processes (corium-concrete interaction and gate opening) inside the reactor cavity. In this report especially the interaction of a metallic melt with a specific sacrificial concrete is studied.

2 Objectives of this test series

The corium melt is composed of a metallic (steel, zirconium) and oxidic (UO_2, ZrO_2, FeO) phase. In the KAPOOL experiments these two phases are simulated by an thermitically produced alumina/iron melt. The thermite reaction ($8\ Al + 3\ Fe_2O_3 \rightarrow Al_2O_3 + 9\ Fe$) produces about 50 wt% iron and 50 wt% oxidic melt. The reaction is strongly exothermic, the maximum temperature of the melt is close to 2500 °C. This reaction is performed inside the KAPOOL container. Due to the different densities (iron melt at 6530 kg/m^3, oxide melt close to 3000 kg/m^3) the iron melt segregates at the bottom and therefore is in contact with the sacrificial concrete layer. The tests investigate 1-dim downward erosion by the metallic melt.

These tests are strongly transient because there is no additional heating. The temperature of the melt decreases during the test period. Therefore it has to be recorded periodically with high-temperature thermocouples which are immersed into the melt one after the other. For the detection of the erosion front thermocouples (NiCr-Ni type, 1mm diameter) have been embedded in the concrete layer at different heights. To quantify the amount of inhomogeneity of the erosion front across the test surface thermocouples are installed at several lateral locations in the concrete.

The erosion rate, its amount of inhomogeneity and the temperature of the melt are recorded as a function of time. From these data therefore a correlation between erosion rate and melt temperature can be deducted. Similar results of an earlier test series [3, 4] using glass concrete are compared with these results. In one of these three tests (KAPOOL 6) the height of the concrete layer has been chosen to allow the melt to reach the bottom of the container and erode the steel gate. The concrete layers in KAPOOL 7 and 8 are high enough to stop the erosion front inside these layers.

3 Sacrificial Concrete

The composition of the concrete (type VM281Q) which has been recommended by the industrial partner, contains a high amount of ironoxide, see Table 1. The grain size of the ironoxide and silica was < 1 mm, which is rather small compared to normal concrete. Ironoxide is chosen as an oxidant for metallic zirconium. Water content of the concrete should be kept at a minimum to reduce the production of hydrogen. The decomposition enthalpy of this special concrete has not yet been measured.

Table 1: Composition of the concrete VM281Q

Chemical Composition	Weight %
Fe_2O_3	49
SiO_2	43
Portland Cement	8
	100
Water to mix the cement	10

Samples of concrete have been made together with the concrete layer inside the KAPOOL container and underwent the same history from production until the day of the test. The weight of these samples has been controlled steadily. No mechanical properties like compressive strength have been investigated because this concrete serves only as a sacrificial layer. According to the specifications the KAPOOL container and the samples were kept at room temperature and dry conditions for two days. The water content decreased from 10 wt% to about 7 wt%. Afterwards the container has been heated up to 200 °C for 24 hours. The final water content at the day of the test was at 3 wt%. The density of the concrete was 2200-2300 kg/m^3.

4 KAPOOL container

All three KAPOOL tests have been performed using the same container geometry: it is of conical shape, the base and rim inner diameters of the steel container are 475 mm and 600 mm, Figure 3. The cone angle is 5 degrees, the height of the container is 710 mm. The wall thickness of the steel was 3 mm. The thickness of the bottom steel plate was 10 mm. A 44 mm thick layer of high temperature ceramics insulates the side steel wall against the melt. The composition of the ceramic material (Plicast Petrolite 39) is mainly Al_2O_3. The heat conductivity is reduced substantially by the presence of hollow spheres of this material, at room temperature it is a factor of two below the value of normal alumina. For best performance of this insulation material it has to be heated up according to a procedure given by the manufacturer, Figure 2 shows the required heating procedure. To prevent melt splashing out of the container during the thermite reaction an additional steel blanket has been mounted above the container.

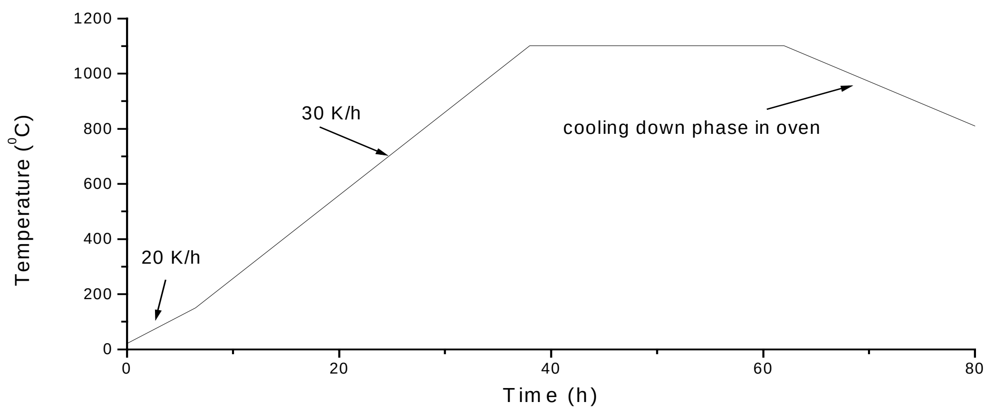


Figure 2: Required temperature treatment of insulating ceramics

5 Thermocouples

K-type thermocouples (NiCr-Ni) have been used to record the erosion front in the concrete layer. They are of the sheathed type with a 1 mm outer diameter stainless steel cylinder. All thermocouples are inserted from below through small holes (1.1 mm dia) in the 10 mm bottom plate, they are fed through and fixed by tapping at the bottom of the steel plate. During concrete pouring they had to be carefully positioned to the desired locations.

Immersion type W-Re thermocouples [Fa. Hereaus-Electro-Nite] have been applied to record the melt temperature. The junction is positioned inside a small u-shaped tube of quartzglass. It is necessary to shield the junction against early chemical reactions. A 0.1 mm thin sheath of steel surrounds the tube to shield against mechanical shocks during handling. In some cases a thin crust of oxide may exist at the top of the melt in the crucible, also for this case the thin steel sheath shields against damage. For iron melts, the response time of this thermocouple is ca. 3 s. In the case of oxidic melts the response time is longer, for typical applications it is around 6 s. The leads of the W-Re thermocouples are protected by a tube made of dense impregnated cardboard. In contact with the melt the outer surface of the cardboard is transformed into a thin layer of charcoal which itself serves as a good insulation against further damage. During the immersion period large amounts of gases are produced due to the interaction of the melt with the cardboard. This, in turn, gives rise to intense turbulent movements in the melt. All thermocouples are fixed above the KAPOOL container and can be remotely lowered into the melt. In these KAPOOL- tests two W-Re thermocouples have been immersed into the thermite melt at the same time. They were arranged to measure the temperatures of the iron- and oxide melts simultaneously.

6 Tests and results

6.1 KAPOOL 6

Figure 3 shows schematically the setup of the container. In this test the thickness of the concrete layer was 100 mm. The diameter of this layer was 387 mm at the bottom and 405 mm at the top. The thermocouples inside the concrete layer are shown schematically. To estimate lateral heat losses into the ceramic insulation four additional NiCr-Ni thermocouples have been installed into the side wall: two thermocouples in the region of the iron melt and two in the oxide melt region. They have been positioned in a distance of 10 mm and 30 mm from the inside wall.

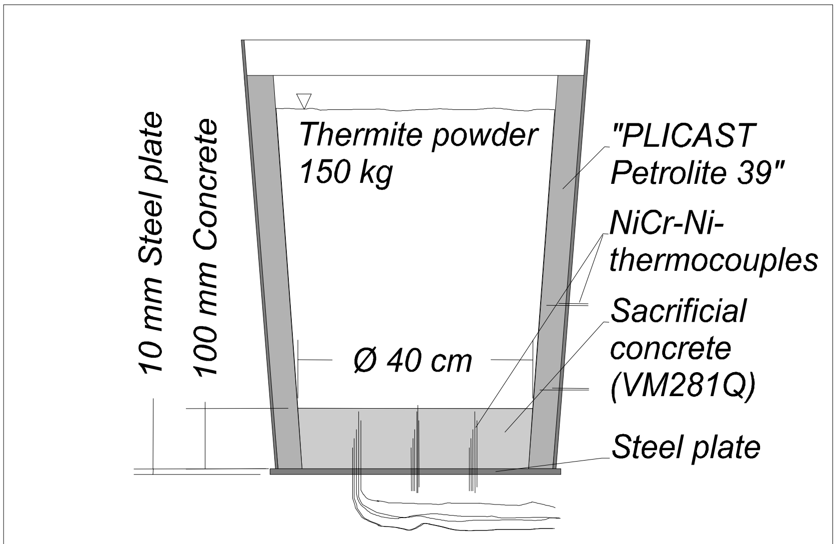


Figure 3: Setup of the KAPOOL 6 container

The positions of all thermocouples is shown in Table 2. 25 thermocouples are used to detect the concrete erosion front, there are five individual groups at five different lateral positions, each group consisting of five thermocouples. One group was located at the center (c) and four groups were located at a radius of 113 mm in each quarter (nw,ne,se,sw). The axial distance of the five thermocouples in each group was 5 mm, 20 mm, 35 mm, 50 mm and 65 mm from the upper concrete surface. An additional thermocouple (#26) is fixed at 5 mm distance above the concrete close to the center and defines the beginning of the concrete erosion.

Table 2: Detection time of thermocouples in KAPOOL 6

Thermocouple #	Position (distance from concrete surface), mm	Time of detection (s) (destruction of T/C)
26	-5 (T/C above the surface, center)	14.0
1	5 center (c)	18.3
2	5 northwest (nw)	14.8
3	5 northeast (ne)	19.5
4	5 southeast (se)	19.4
5	5 southwest (sw)	17.9
6	20 c	32.2
7	20 nw	28.4
8	20 ne	32.6
9	20 se	33.5
10	20 sw	30.3
11	35 c	50.8
12	35 nw	42.2
13	35 ne	49.4
14	35 se	51.7
15	35 sw	47.5
16	50 c	65.4
17	50 nw	62.0
18	50 ne	72.8
19	50 se	79.1
20	50 sw	68.8
21	65 c	97.8
22	65 nw	88.3
23	65 ne	98.7
24	65 se	107.2
25	65 sw	97.9

150 kg of thermite powder have been ignited in the test container at time zero. The reaction produces 48 wt% of iron and 52 wt% of oxidic melt. The calculated height of the iron melt at the end of the reaction time is 86 mm. The chosen iron melt density of 6300 kg/m^3 for this estimate was less than the theoretical one of 6530 kg/m^3 (at 2100 °C), a recommendation of results from former tests, probably due to the existence of gas bubbles in the melt. The calculated height of the 78 kg of oxide melt was 185 mm (density 2800 kg/m^3).

14 s after ignition thermocouple #26 registered the arrival of the melt. The five upper thermocouples registered the erosion front shortly afterwards, Table 2 shows for all thermocouples the time of destruction which happens near 1300 °C. This time is close to the arrival time of the melt at the thermocouple junction. Thermocouples near the surface (5 mm distance) do not show a leveling at 100 °C during which time the physically bonded water vaporizes. At these early times, because of the very high erosion velocity, the 100 °C temperature front is nearly identical with the erosion front. At later times the 100 °C temperature front decouples from the erosion front and proceeds faster into the concrete, which can be seen clearly in the readings of thermocouples deeper inside the concrete. The erosion front eventually gets to a halt while the 100 °C front is still further progressing. Appendix A shows these transient temperatures recordings of the thermocouples in the concrete layer at different vertical locations.

The thermocouples #27 – #30 recorded the transient temperatures inside the ceramic side wall, see Appendix A. The inner ones at 10 mm distance from the surface have been destroyed within a short time while the outer ones (at 30 mm) showed a relatively long rise in temperature. Post experiment inspection of the container wall showed a certain amount of wall erosion, therefore an evaluation of the lateral heat transfer from the melt to the wall cannot be done with these temperature recordings.

During the melt–concrete interaction time, several measurements with the W-Re thermocouples have been conducted to record the temperatures of the iron and oxide melts. Table 3 shows the results together with the time of measurement. The recording of the thermocouples must show an asymptotic behaviour for a reasonable evaluation of the temperature. This was the case with all W-Re thermocouple readings except the first data at 24 s after ignition. The thermocouple recordings show that at the time of first contact between the iron melt and the concrete surface the initial temperature has been between 2400 °C and 2500 °C which is in accordance with results of former tests [4]. The recordings of these temperature measurements are shown in Appendix B.

Table 3: Transient melt temperatures of the metallic and oxidic melts in KAPOOL 6

	Oxide melt		**Iron melt**	
W-Re T/C #	Time (s)	Temp. (°C)	Time (s)	Temp. (°C)
1	24.6	(>2400)	24.3	(2250)
2	52.8	2009	52.5	1995
3	83.1	1888	81.5	1867
4	114.0	1834	115.0	1794
5	142.0	1778	140.4	1738
6	171.8	1740	170.2	1723
7	203.6	1694	199.0	1649

Figure 4 shows the iron and oxide melt temperatures as a function of time. At 24 s there is a relative large uncertainty due to the fact that the asymptotic behaviour can only be estimated.

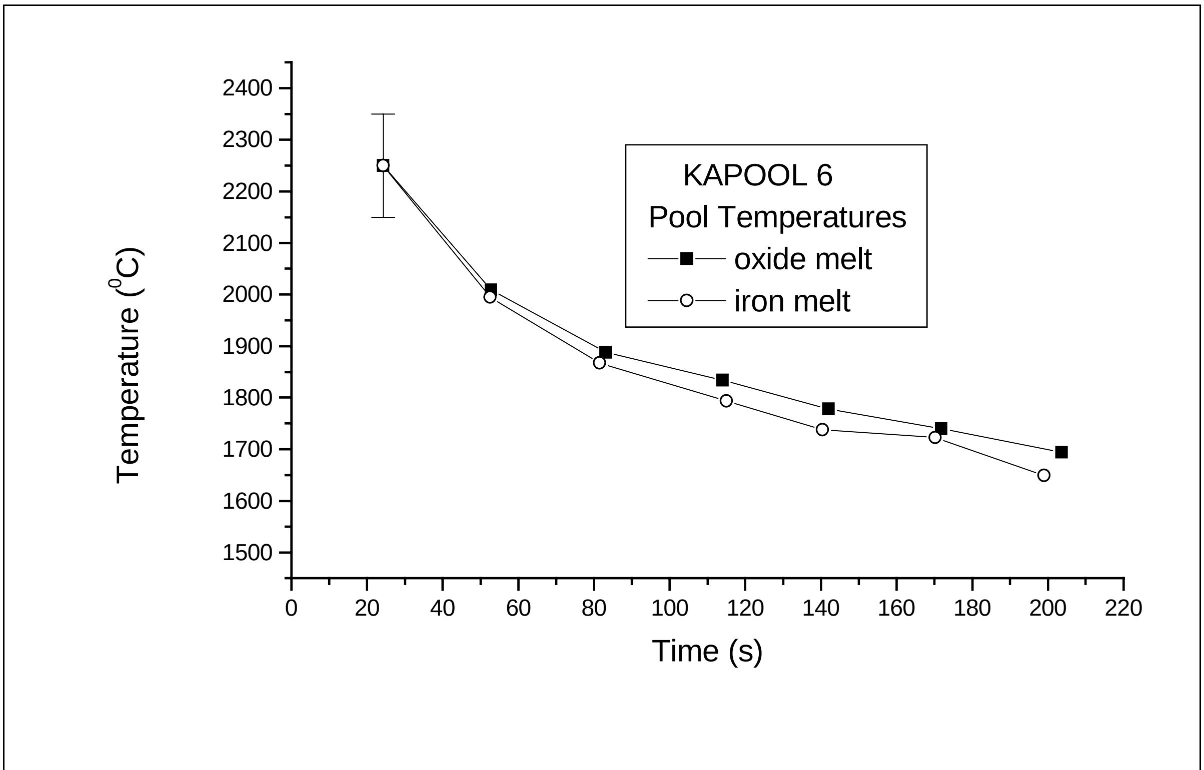


Figure 4: Transient iron– and oxide melt temperatures in KAPOOL 6

The liquidus temperature of the original thermitic oxide melt is around 1900 °C. The temperature of the metal layer is lower than the oxidic layer throughout the test because of the high heat transfer from the iron to the decomposing concrete. The mixing of oxide melt with concrete lowers this value to temperatures below 1700 °C: after 200 s of erosion time the 100 mm concrete layer and also the bottom steel plate were fully eroded and the whole amount of melt poured through the hole within a short time, which is only possible if the oxide melt temperature was still above the liquidus temperature.

Figure 5 shows the transient erosion front in the concrete measured with thermocouples at five different locations. Included is also the curve which results from averaging the data points. The thermocouple #26 5 mm above the concrete surface is used to record the begin of interaction at 14 s. As can be seen from these five recordings, there is an early inhomogeneity in concrete erosion from the very beginning of melt-concrete interaction. This may partly be due to the fact that the thermite reaction is not homogeneous across the surface of the container, partly due to the inhomogeneous structure of the concrete. This inhomogeneity of 5 mm at 20 s increases to about ±10 mm at an erosion depth of 65 mm.

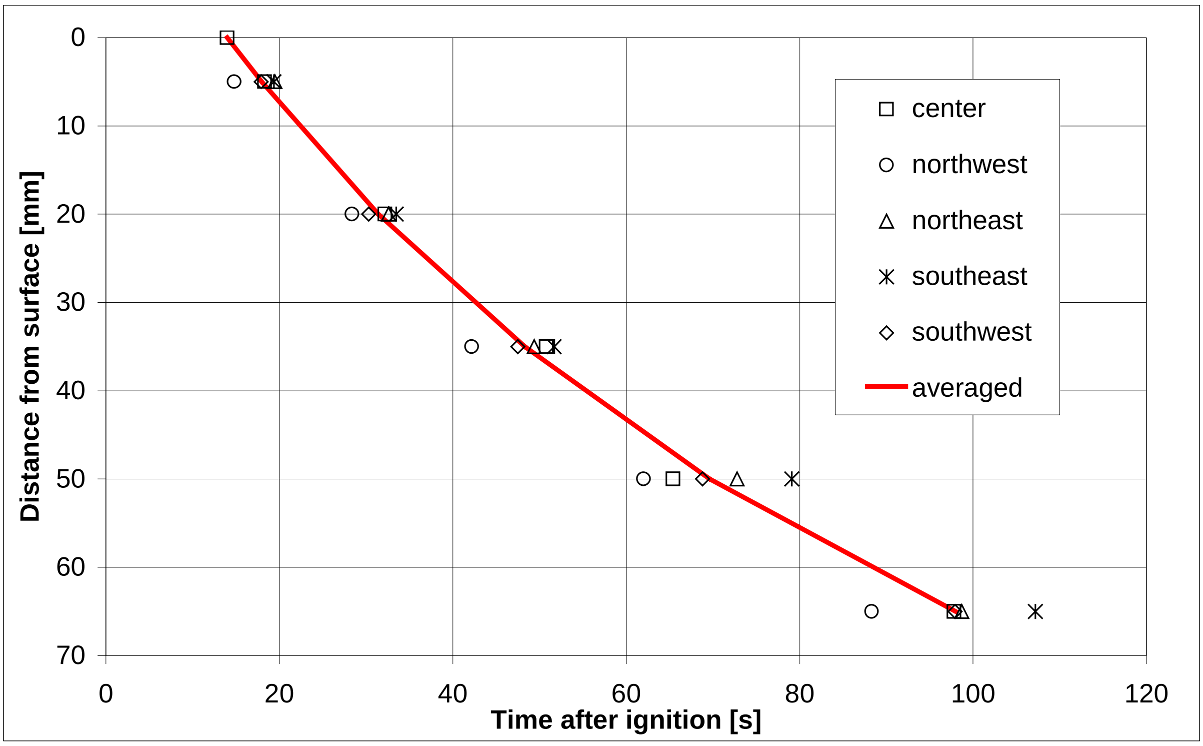


Figure 5: Erosion front in the sacrificial concrete of KAPOOL 6

The thickness of the sacrificial concrete layer in KAPOOL 6 (100 mm) was chosen that the melt will eventually erode the concrete fully, and attack the 10 mm steel plate at the bottom. This happened 202 s after ignition. The pouring time for the two melt phases was 9 s in total. Post test examination of the gate has been done, the final size of the hole was about 100 cm^2 compared to the total gate area of 1256 cm^2.

6.2 *KAPOOL 7*

The layout of the container in KAPOOL 7 was identical to the KAPOOL 6 one, but the thickness of the concrete layer has been increased to 200 mm, Figure 6. The objective of this test was to study the erosion of the sacrificial concrete, yet the erosion front should stop within the concrete layer.

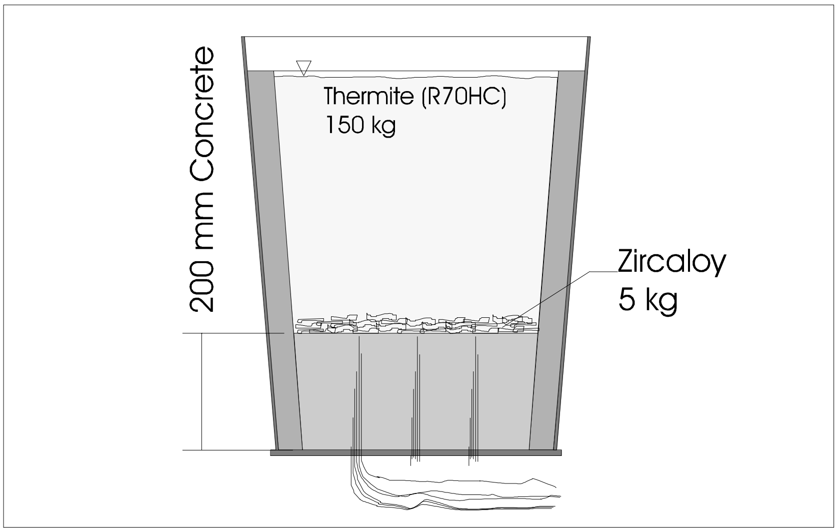


Figure 6: Setup of the KAPOOL 7 container

New in this test has been the addition of 5 kg of zircaloy in the form of small sheet (scrap material from the production of fuel rods). These sheets have been piled up in a layer on top of the concrete surface and covered with the thermite powder. It was assumed that the zirconium will energetically react with the water and ironoxides of the concrete to form ZrO_2. This additional energetic reaction would counteract a fast temperature drop of the melt (compared to KAPOOL 6 for instance). As in KAPOOL 6 W-Re thermocouples have been used to measure the transient temperatures of the iron and oxidic melts.

The positioning of the NiCr-Ni thermocouples inside the sacrificial concrete layer was similar to the one in KAPOOL 6: Here are again five groups of thermocouples (c, nw, ne, se, sw), each group containing 6 thermocouples at different vertical locations: 5 mm, 35 mm, 65 mm, 95 mm,145 mm and 195 mm from the top surface. The positions of all thermocouples are shown in Table 4 together with the time of thermocouple destruction (1300 °C front). An additional thermocouple (#26) has been installed at the bottom center of the 10 mm steel plate which was located below the sacrificial concrete. No thermocouples have been installed in the ceramic wall.

Table 4: Detection time of thermocouples in KAPOOL 7

Thermocouple #	Position (distance from concrete surface), mm	Time of detection (s) (destruction of T/C)
1	5 center (c)	15.8
2	5 northwest (nw)	16.6
3	5 southwest (sw)	18.3
4	5 southeast (se)	18.0
5	5 northeast (ne)	13.0
6	35 c	47.1
7	35 nw	43.2
8	35 sw	54.9
9	35 se	46.6
10	35 ne	43.9
11	65 c	98.3
12	65 nw	96.4
13	65 sw	97.0
14	65 se	100.6
15	65 ne	87.3
16	95 c	140.5
17	95 nw	144.6
18	95 sw	147.2
19	95 se	138.4
20	95 ne	139.6
21	145 c	350.2
22	145 nw	309.5
23	145 sw	345.5
24	145 se	369.7
25	145 ne	337.9
26	At bottom of steel plate	
27	195 nw	Melt stops at 170 mm
28	195 sw	“
29	195 se	“
30	195 ne	“

As in KAPOOL 6 150 kg of thermite have been ignited in the container. The transient erosion front is shown in Figure 7, see also Table 4. As in KAPOOL 6 the inhomogeneity of the erosion front is about 5 mm starting from the very beginning. These inhomogeneities increased up to about ±10 mm towards the end of melt-concrete interaction. Also shown is the curve of the averaged erosion data. Post experiment evaluation showed that the erosion front ended between 170 mm and 180 mm. There the surface of the concrete is rather wavy with height differences between valleys and tops of about ±10 mm.

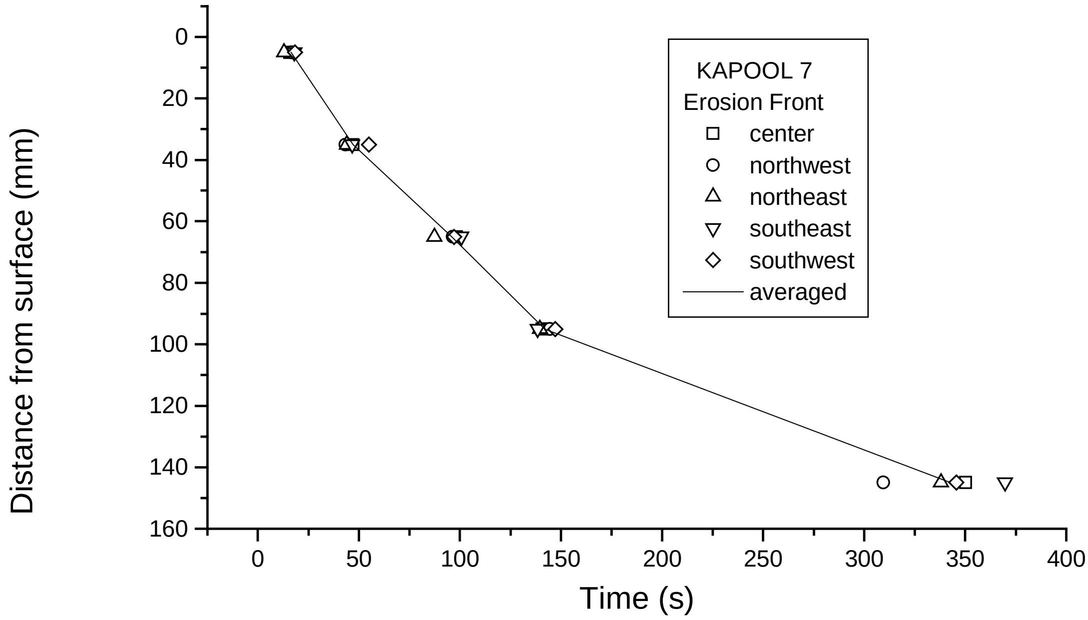


Figure 7: Erosion front in the sacrificial concrete of KAPOOL 7

Figure 8 and Table 5 show both, the iron and oxide melt temperatures, as a function of time. Also here exists a relative large error in the first temperature reading at 22.6 s because the asymptotic behaviour has not been reached before the two thermocouples were destroyed. During conduct of this test the iron melt and oxide melt temperatures have been very similar, which is related to the intense pool agitation during the melt-concrete interaction.

An enthalpy balance has been done to estimate the effect of zircaloy oxidation on the melt temperature and erosion rate. After the end of the thermite reaction 5 kg zircaloy mixes with the iron melt resulting in a temperature drop of about 100 K in the iron and oxide melts. The erosion front at 100 mm depth in the concrete is detected at about 150 s in KAPOOL 7 compared to 200 s in KAPOOL 6. Despite the higher initial melt temperature in KAPOOL 6 at the onset of erosion it drops at a faster rate than in KAPOOL 7 and falls below the value of the former one which is due to the oxidation of zircaloy during the erosion phase.

Table 5: Transient melt temperatures of the metallic and oxidic melts in KAPOOL 7

	Oxide melt		Iron melt	
W-Re T/C #	Time (s)	Temp. (°C)	Time (s)	Temp. (°C)
1	22.6	(>2250)	22.6	(>2200)
2	55.4	1991	55.3	1991
3	87.0	1868	86.2	1861
4	117.2	1810	116.9	1810
5	146.4	1766	145.3	1744
6	180.8	1721	177.0	1707
7	208.6	1668	208.7	1646
8	239.6	1605	238.7	1616
9	301.5	1580	295.5	1560
10	381.4	1536	379.3	1499

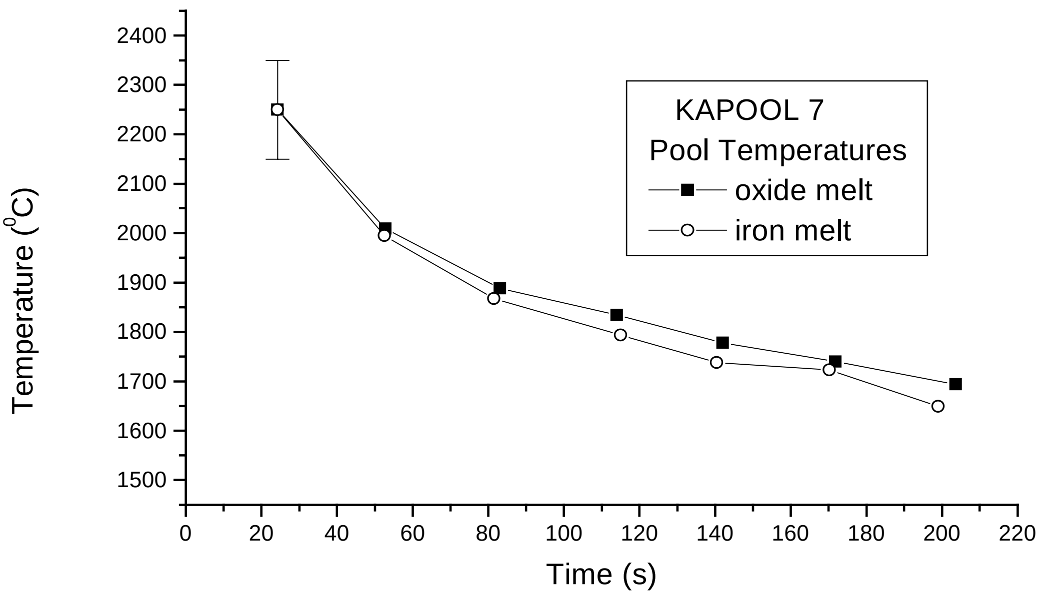


Figure 8: Transient melt temperatures in the iron- and oxide pools of KAPOOL 7

6.3 KAPOOL 8

KAPOOL 8 has been practically a repetition of KAPOOL 7 with one difference: 10 kg of zircaloy have been added instead of 5 kg in KAPOOL 7. The zircaloy has been covered by a sacrificial concrete layer of 10 mm, Figure 9, to assure that the thermite reaction is over before the melt comes into contact with zircaloy and to exclude eventual chemical interaction of melt and zircaloy before onset of concrete erosion.

The thermocouple positions inside the sacrificial concrete are identical to those in test KAPOOL 7, also two W-Re thermocouples have been immersed simultaneously into the melts to record both iron and oxide melt temperatures.

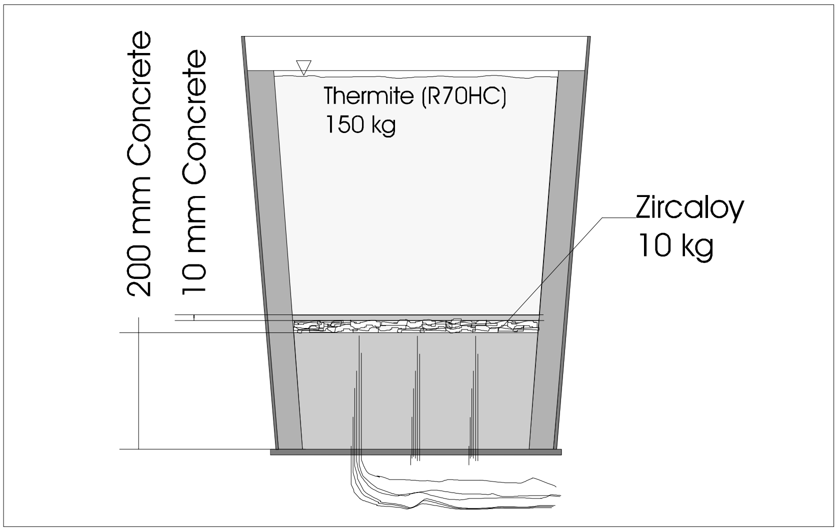


Figure 9: Setup of the KAPOOL 8 container

Table 6 lists the arrival times at the NiCr-Ni thermocouples in the sacrificial concrete, Figure 10 shows the transient erosion fronts at five different locations (c, nw, ne, se, sw). Also included in Figure 10 is the averaged erosion front. The axial thermocouple positions are counted from the top of the 200 mm concrete layer. For comparison with the two former tests, the 10 mm top concrete layer has to be accounted for. The inhomogeneity of the erosion front across the concrete surface is similar to those in KAPOOL 6 and 7. The delay of the erosion front in KAPOOL 8 compared to KAPOOL 7 is connected with the additional 10 mm layer of concrete above the zircaloy. The erosion front in KAPOOL 8 stopped at 160 mm.

Table 6: Detection time of thermocouples in KAPOOL 8

Thermocouple #	Position (distance from concrete surface), mm	Time of detection (s) (destruction of T/C)
1	5 center (c)	31.2
2	5 northwest (nw)	26.6
3	5 southwest (sw)	30.8
4	5 southeast (se)	31.6
5	5 northeast (ne)	29.7
6	35 c	70.5
7	35 nw	74.0
8	35 sw	70.8
9	35 se	80.2
10	35 ne	72.6
11	65 c	126.1
12	65 nw	128.1
13	65 sw	132.6
14	65 se	135.4
15	65 ne	136.0
16	95 c	176.3
17	95 nw	190.9
18	95 sw	184.2
19	95 se	197.6
20	95 ne	192.3
21	145 c	571.0
22	145 nw	454.1
23	145 sw	529.8
24	145 se	533.3
25	145 ne	505.4
26	At bottom of 10 mm steel plate	Stays at 100 ^{0}C from 810 s–1050s, then increases to 320 ^{0}C at 1638 s
27	195 nw	No signal, defect
28	195 sw	Stays at 100 ^{0}C from 685s-950s, then increases to 270 ^{0}C at 1638 s
29	195 se	Stays at 100 ^{0}C from 800s-1040s, then increases to 250 ^{0}C at 1638s
30	195 ne	Stays at 100 ^{0}C from 675s-980s, then increases to 250 ^{0}C at 1638s

The remaining thermocouples, located at 195 mm depth which is 5 mm above the bottom steel plate, recorded a temperature of 100 °C for a relative long time, between 200 s and 300 s. Also thermocouple #26 at the bottom of the steel plate remained at 100 °C for a long time before there was a further temperature rise to 250–320 °C. Some of the water in the sacrificial concrete has been driven down, away from the temperature and erosion front and gathered near the bottom because it could not escape through the bottom plate.

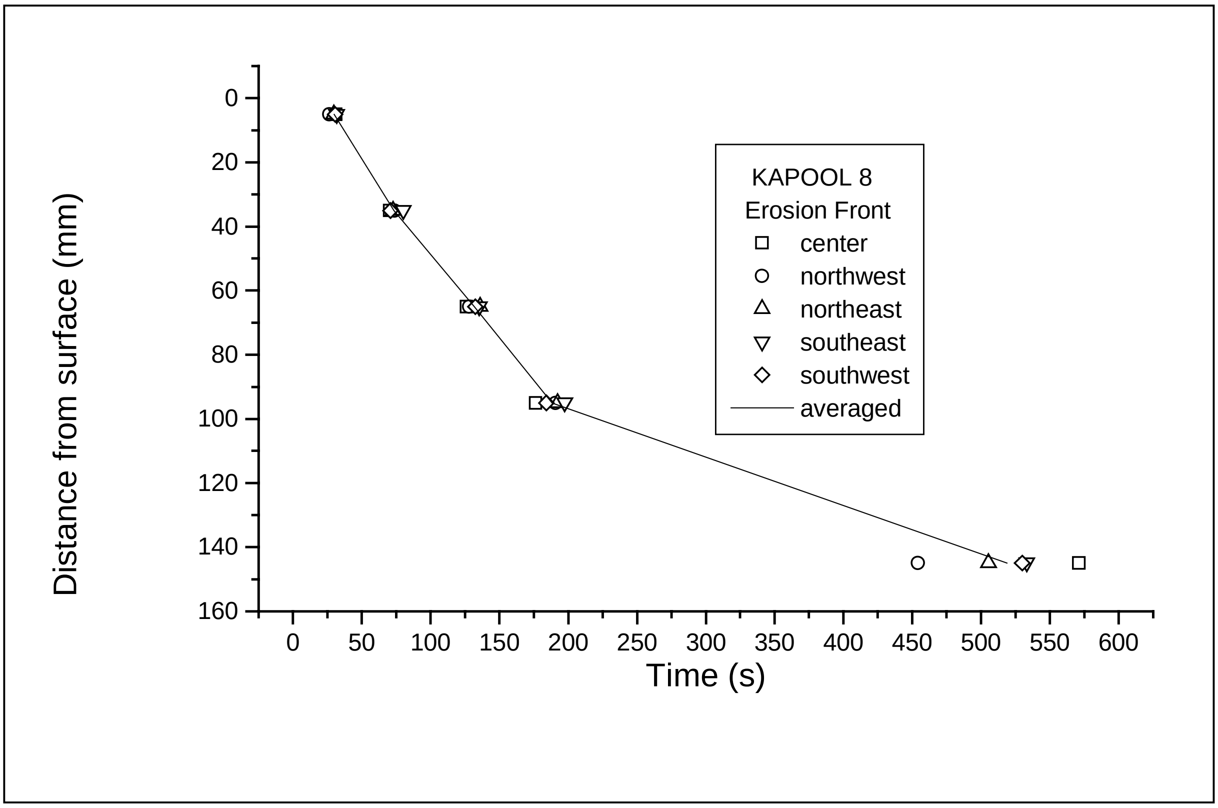


Figure 10: Erosion front in the sacrificial concrete of KAPOOL 8

The results of the temperature measurements in the iron and oxide layers are given in Table 7 and Figure 11. The initial melt temperature was below the value of KAPOOL 6 and 7 at the beginning of concrete erosion which is due to the heating up and melting of 10 kg of zircaloy. As in KAPOOL 7 the enthalpy balance showed that the temperature drop in the melt is around 200 K. Later during the erosion process the melt temperature dropped more slowly than in the two former tests due to the oxidation of zircaloy. The readings for both iron and oxide melts up to thermocouples #7 at 270 s are very similar. Above 270 s the temperature measurements in the oxide melt cannot be evaluated, the readings did not show an asymptotic behaviour anymore which is a hint that the liquidus temperature of the oxide melt at that time is reached (around 1600 °C).

Table 7: Transient melt temperatures of the metallic and oxidic melts in KAPOOL 8

	Oxide melt		Iron melt	
W-Re T/C #	Time (s)	Temp. (°C)	Time (s)	Temp. (°C)
1	35.1	(>2145)	34.4	(>2143)
2	64.3	1957	65.2	1957
3	97.4	1852	97.1	1839
4	126.7	1825	126.7	1812
5	177.4	1746	173.4	1726
6	229.7	1665	227.0	1647
7	280.4	1616	276.7	1594
8	331.6	(1540) *)	327.4	1560
9	400.0	(1508)*)	395.1	1493
10	501.7	(1147)*)	491.6	1474

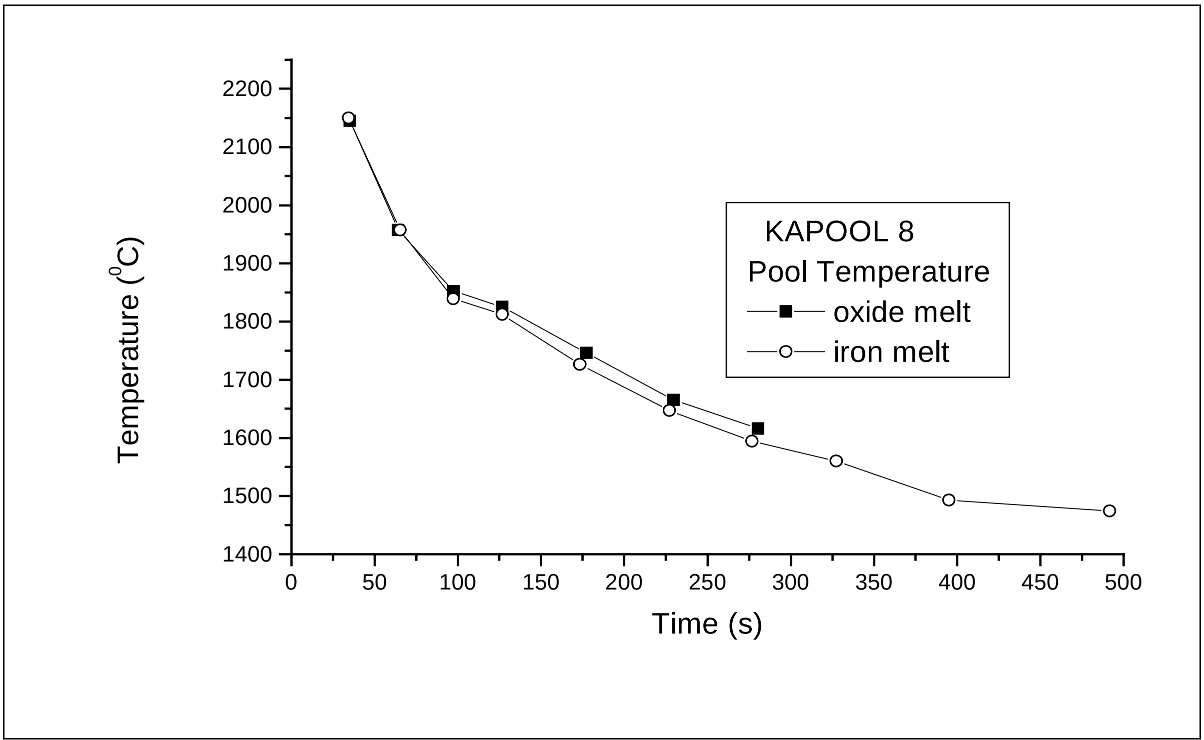


Figure 11: Transient melt temperatures in the iron- and oxide pools of KAPOOL 8

7 Comparison between different tests

7.1 Pool temperatures

Figure 12 shows the transient temperatures of the iron pool in all three individual tests. For further evaluation, analytical curves had to be fitted to these individual temperatures recordings, Figures 13, 14 and 15.

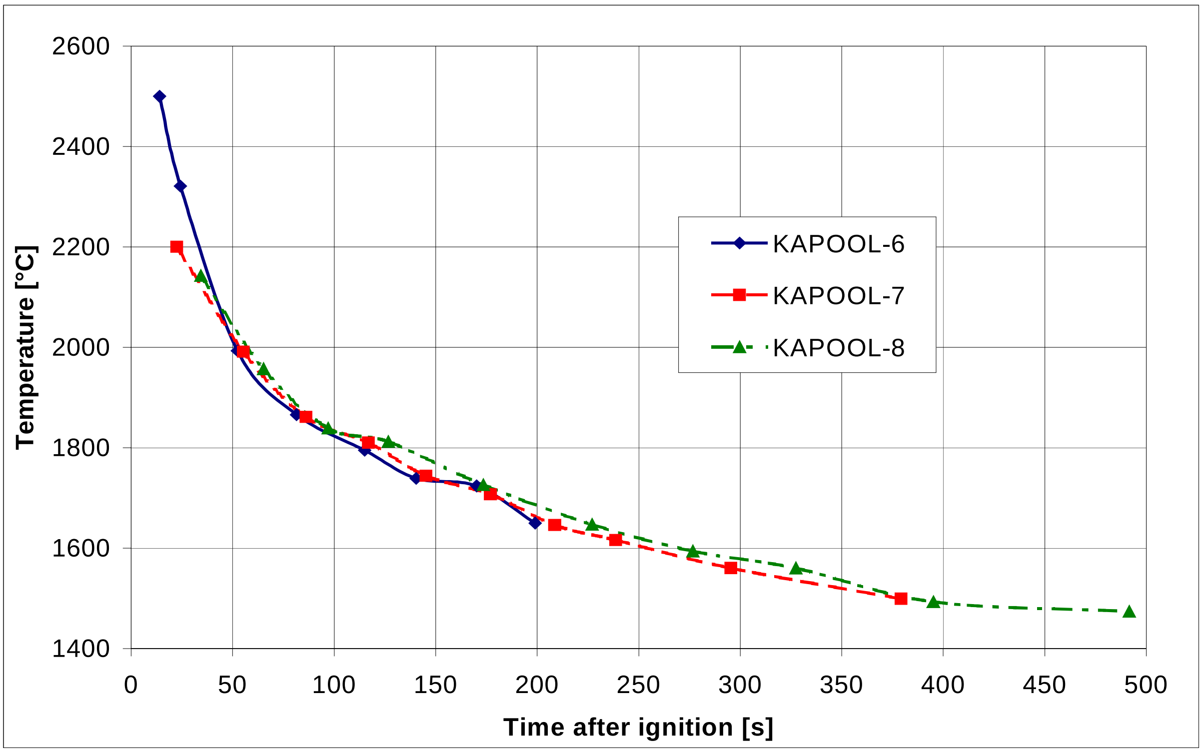


Figure 12: Comparison of the iron pool temperatures in all three KAPOOL tests

The influence of adding zircaloy (0 kg in KAPOOL 6, 5 kg in KAPOOL 7 and 10 kg in KAPOOL 8) onto the transient melt temperatures is as follows: In KAPOOL 6 the temperature of the iron melt 14 s after ignition (first contact with the concrete surface) is about 2500 °C. This value is from extrapolation of the analytical temperature curve in Figure 13. The first temperature measurement, T=2321± 70 °C, was done 10.3 s after contact with the concrete. Shortly before this first recording (22.2 s after ignition = 8.2 s after contact) the erosion depth was 10 mm and the corresponding analytical temperature was 2340 °C.

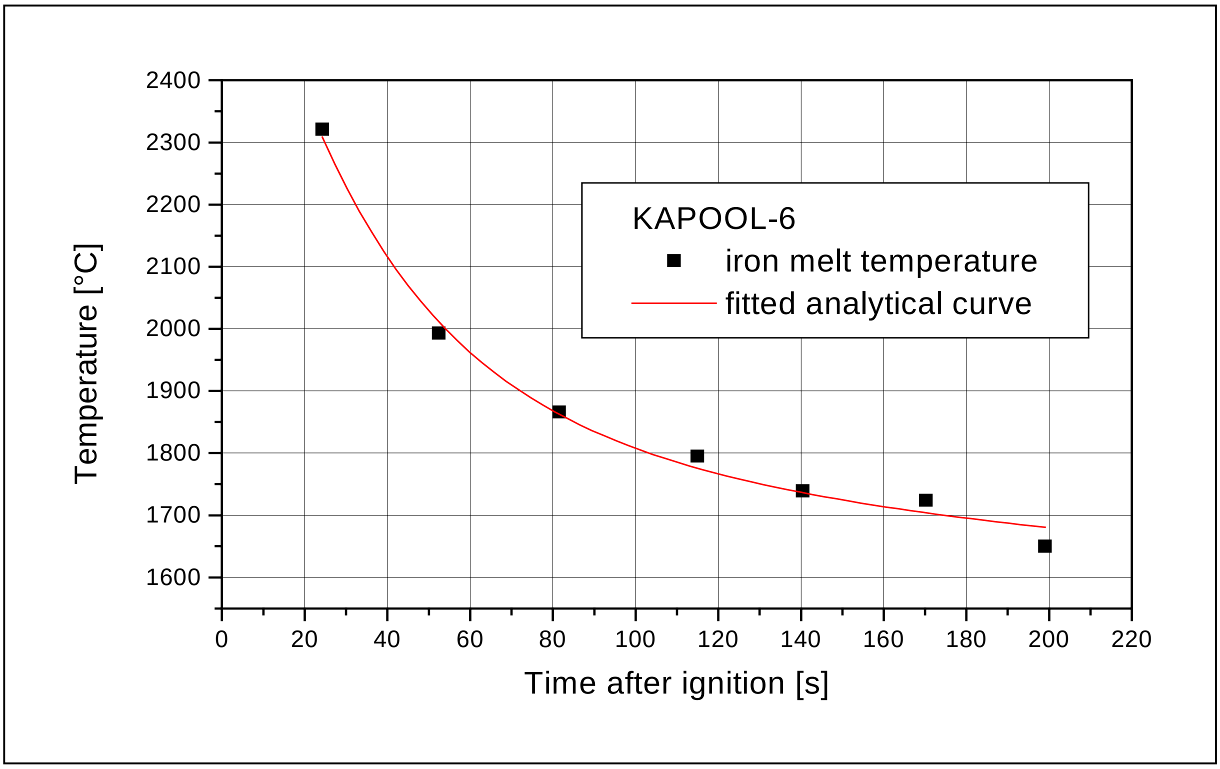


Figure 13: Transient iron melt temperature, included is the fitted analytical curve

In KAPOOL 7 the iron melt temperature at the beginning of concrete was about 100 K lower than in KAPOOL 6 due to heating up and melting of zircaloy, Figure 14.

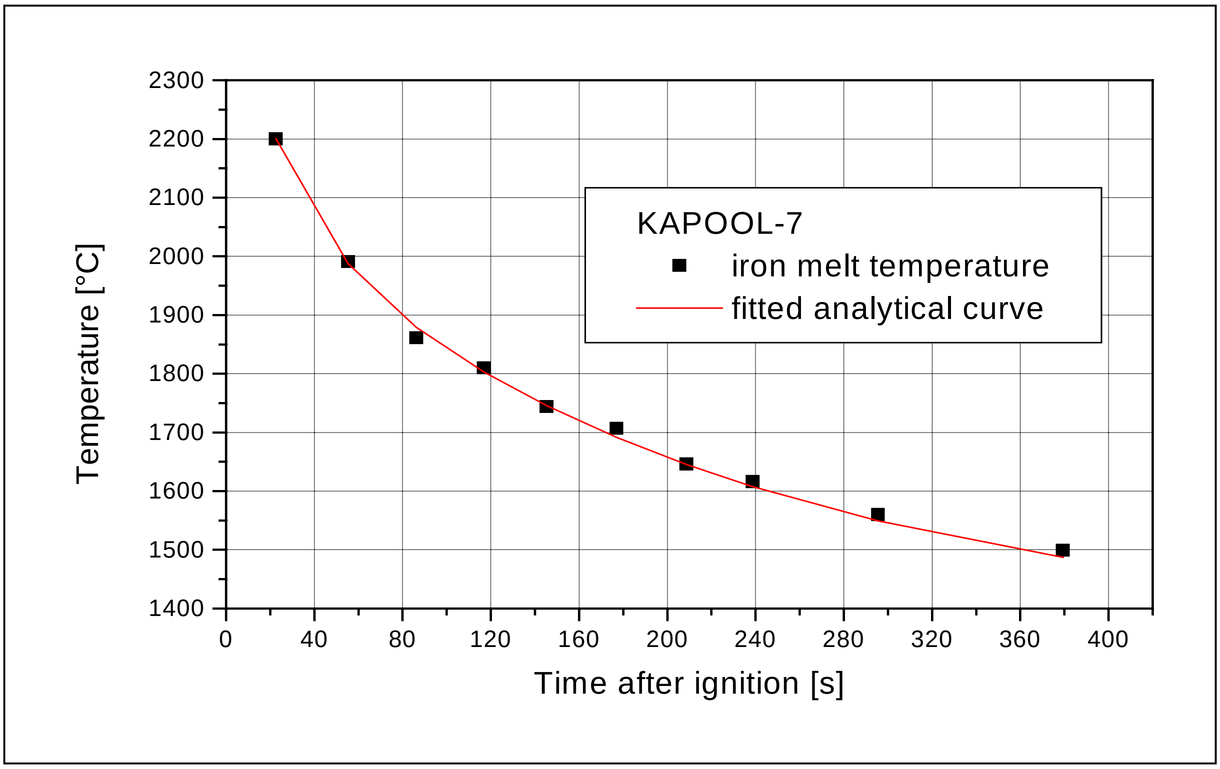


Figure 14: Transient iron melt temperature, included is the fitted analytical curve

In KAPOOL 8 a layer of 10 mm of sacrificial concrete had to be eroded first before getting the melt into contact with zircaloy.

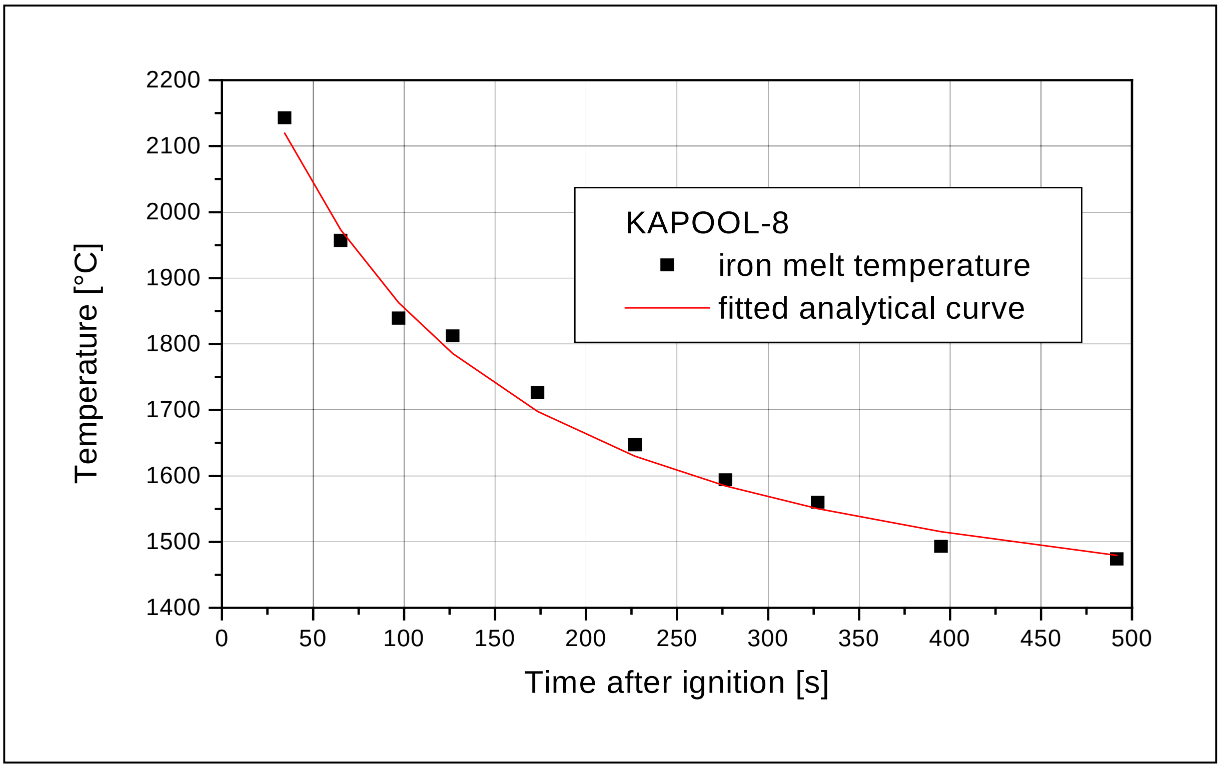


Figure 15: Transient iron melt temperature, included is the fitted analytical curve

From KAPOOL 6, for 10 mm erosion depth a temperature drop of 160 K is calculated for a melt temperature between 2400 °C and 2500 °C. In addition, the heating up and melting phase of zircaloy reduced the melt temperature by another 200 K. Taking these two factors into account, the initial temperature of the melt is calculated to be 2140 °C when it came into contact with the 200 mm thick concrete layer. In reality, the fitted curve in Figure 15 shows a value of 2155 °C at this time of contact of the melt with the concrete.

Later in time, the melt temperature drops more slowly with increasing amount of zircaloy: the melt temperature in KAPOOL 6 drops below those in KAPOOL 7 and 8.

7.2 *Erosion and erosion rates*

For all three tests, the time dependant erosion fronts have been averaged over the five lateral positions and analytical curves fitted to these experimental data, Figs 16, 17 and 18. Erosion rates (mm/s), also shown in these figures, are deducted from these analytical curves by differentiation.

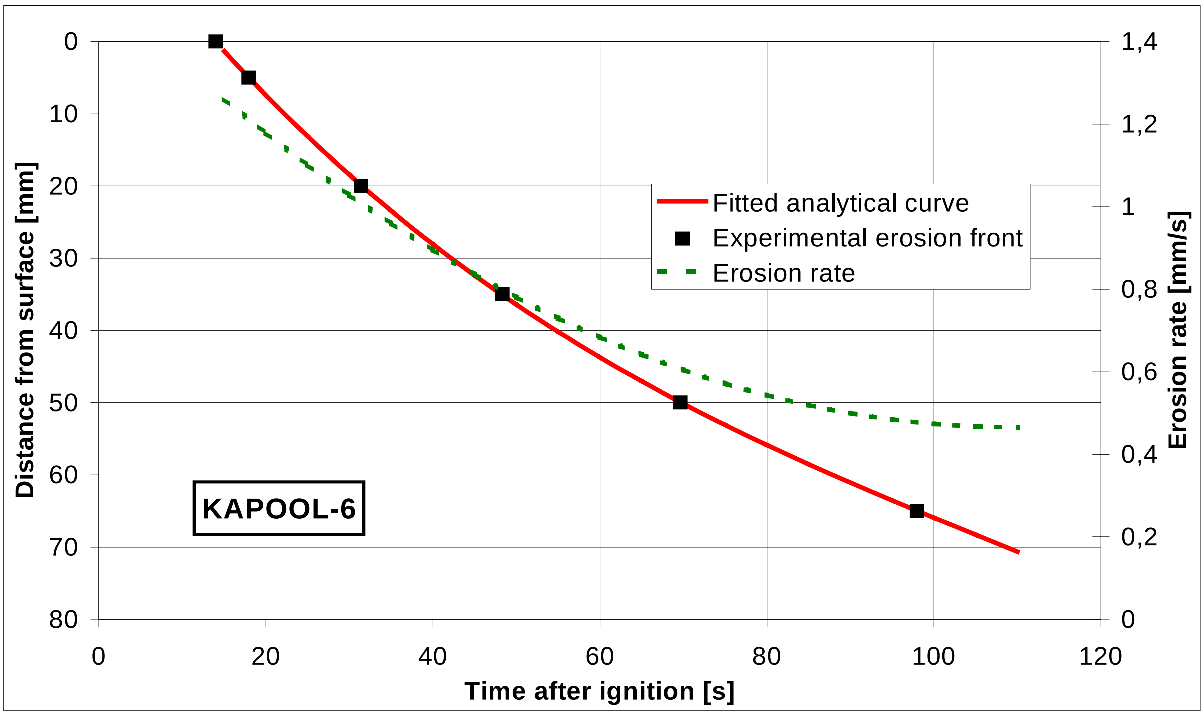


Figure 16: Erosion front with fitted analytical curve and erosion rate

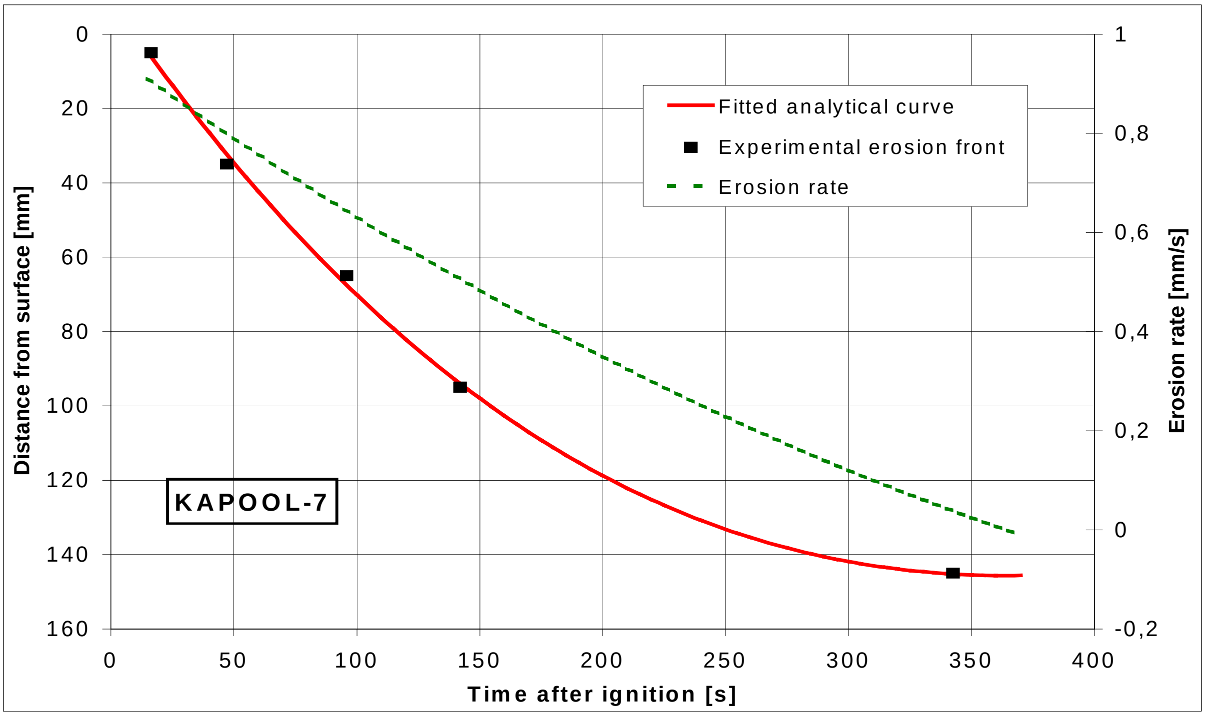


Figure 17: Erosion front with fitted analytical curve and erosion rate

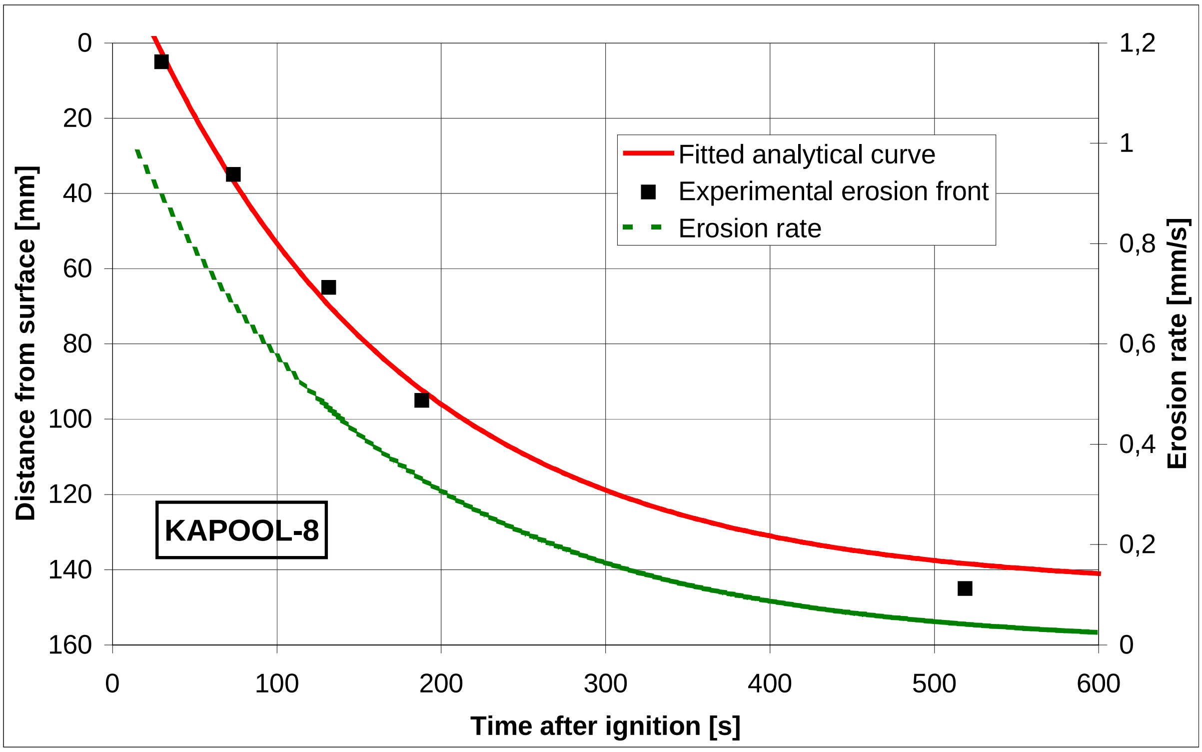


Figure 18: Erosion front with fitted analytical curve and erosion rate

Afterwards these analytical erosion rates are plotted versus the corresponding iron pool temperatures by coupling the transient temperature measurements together with the erosion rates, Figure 19.

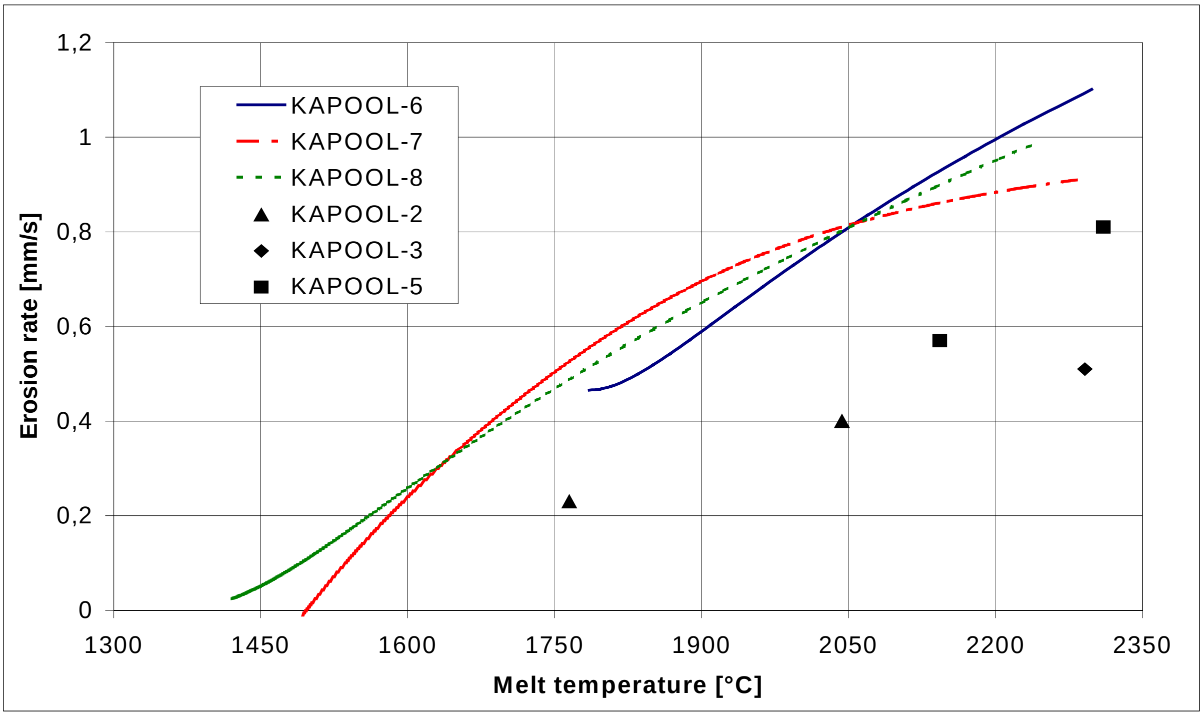


Figure 19: Erosion rates for the glass-concrete (KAPOOL 2/3/5) and the sacrificial concrete VM281Q (KAPOOL 6/7/8) as a function of the iron melt temperature

For comparison, the temperature dependant erosion rates for the glass-concrete experiments KAPOOL 2,3 and 5 [4] are also included in this figure. The erosion rates for the VM281Q sacrificial concrete are about twice as high as for the glass-concrete case. The reason for this difference is partly to be found in the different particle distributions: The size of the glass particles was: 30% in the range 0 – 1 mm, 70% in the range 1 – 8 mm, whereas the particle size in the VM281Q concrete was below 1 mm.

8 Summary

For a sacrificial concrete based on Fe_2O_3/SiO_2 the temperature dependant erosion rates have been evaluated and compared with the results for a sacrificial concrete based on borosilicate glass. The results differ by about a factor two: the Fe_2O_3/SiO_2 concrete erosion rate is higher than for the glass concrete which is be due to the different grain sizes and possibly also to different times for the concretes to react chemically. The addition of zircaloy to the thermite melt did not show significant results compared to the test without zircaloy.

9 References

[1] H. Alsmeyer et al., “Ex-vessel Melt Behaviour in the EPR”, Proc. KTG/SFEN Conf. On the EPR Project, Cologne, October 1997, S.161

[2] H. Alsmeyer et al., „Beherrschung und Kühlung von Kernschmelzen außerhalb des Druckbehälters“, Nachrichten Forschungszentrum Karlsruhe, Jahrgang 29, 4/97, S. 327-335, also English Version:“Core Meltdown as a Design Basis Accident”, Nachrichten Forschungszentrum, Jahrgang 29, 4/97, pp. 53-61

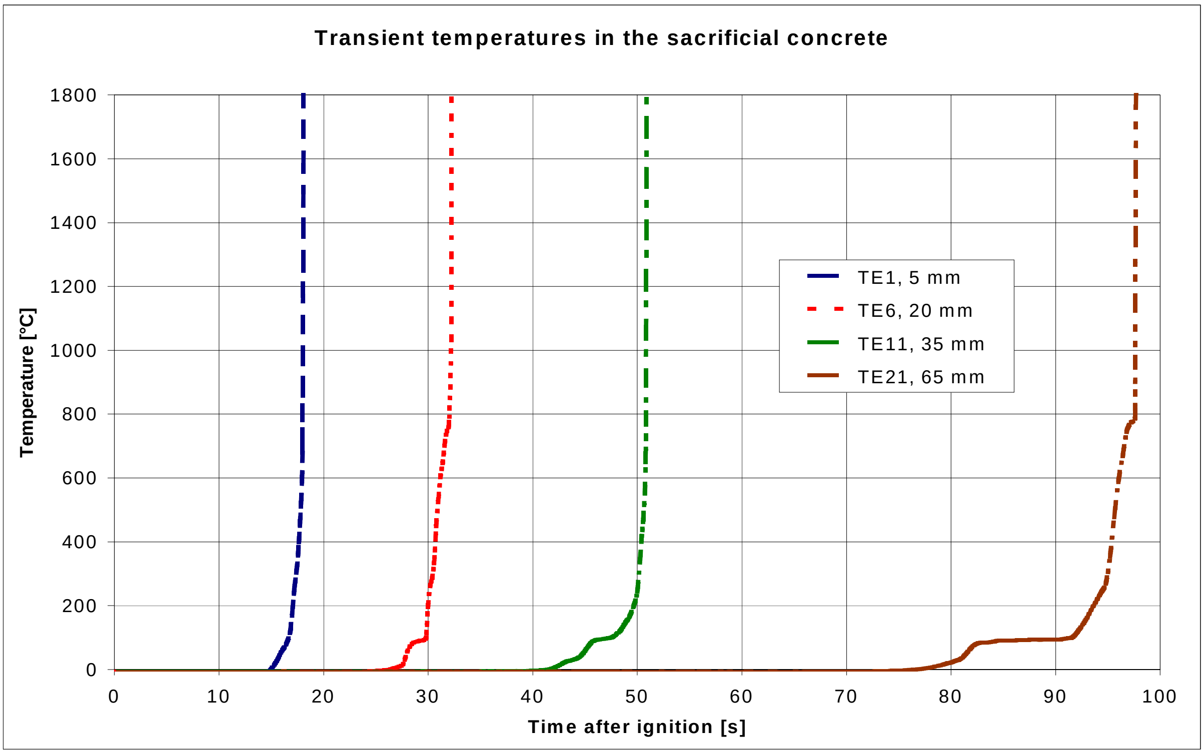
[3] F. Fellmoser, G. Fieg, H. Massier, H. Werle, „Simulation Experiments on the Corium Behaviour in the EPR Cavity: KAPOOL-Tests”, Proc. Jahrestagung Kerntechnik 1998, München, Mai 1998, S. 141

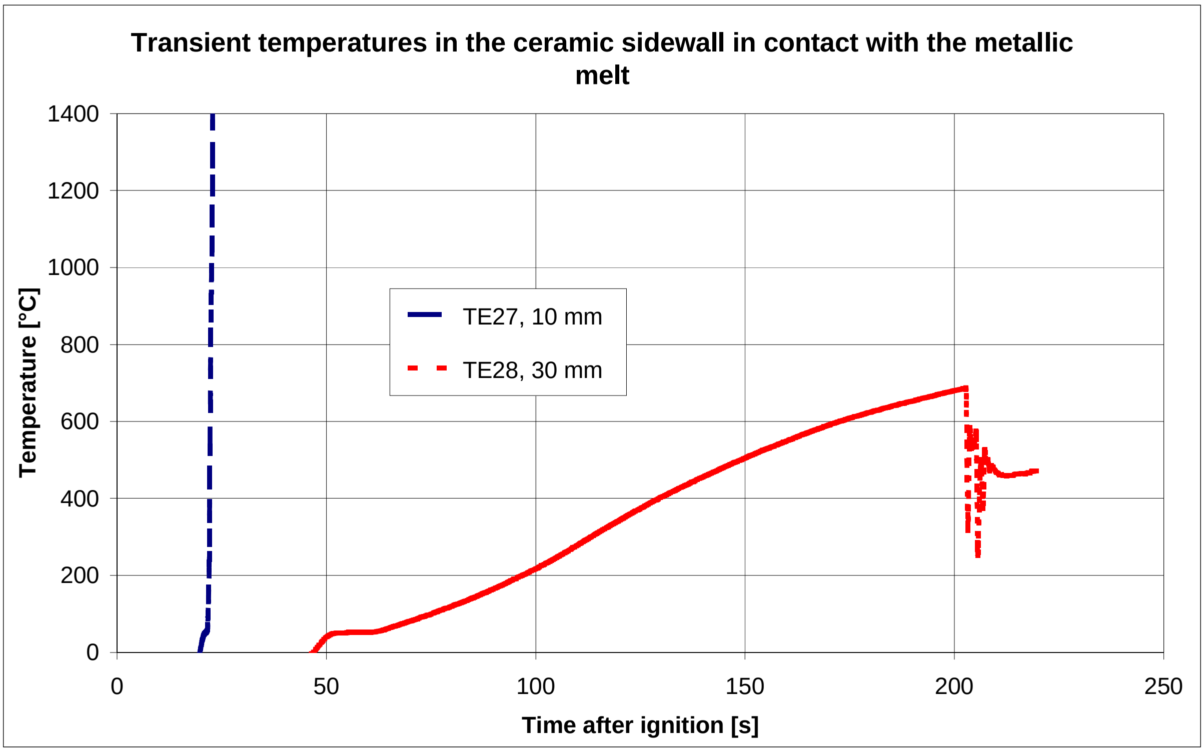
[4] F. Fellmoser, G. Engel, G. Fieg, H. Massier, H. Werle, „Simulationsexperimente zum Verhalten von Kernschmelzen in der Reaktorgrube des EPR: KAPOOL 1-5“, Forschungszentrum Karlsruhe, FZKA-Bericht 6212, Mai 1999

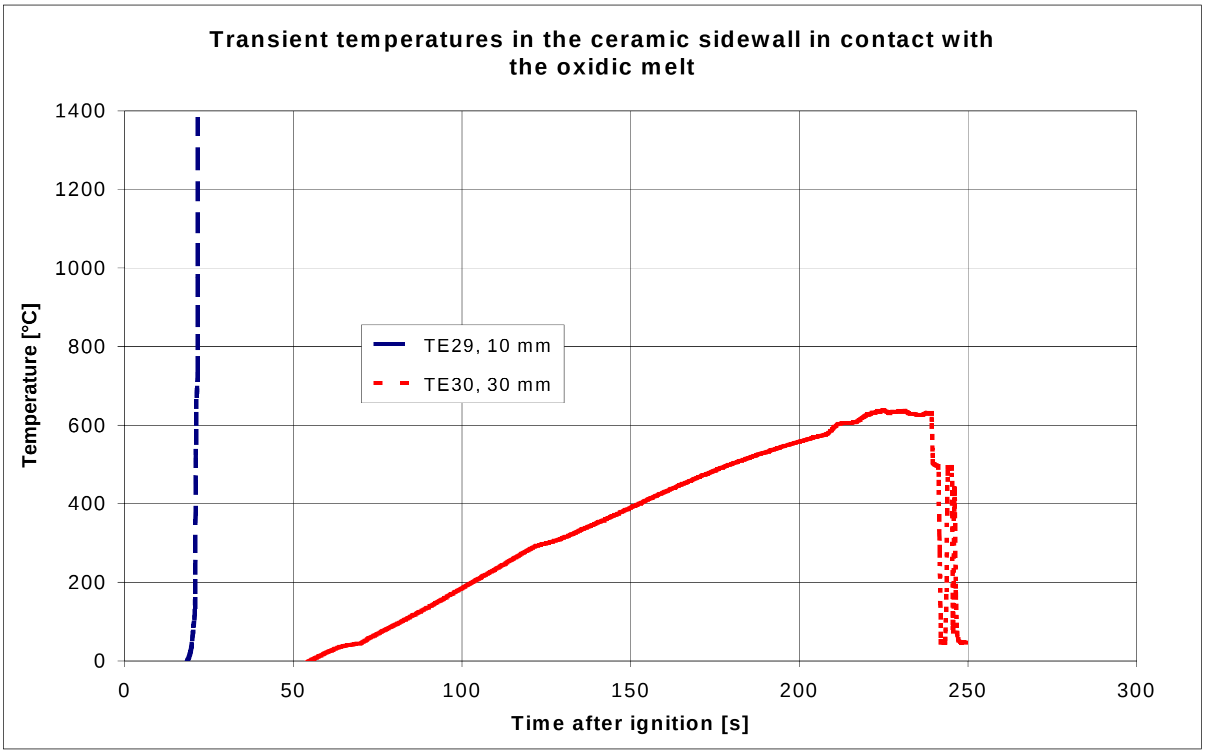
10 Appendix

10.1 Appendix A:

NiCr-Ni Thermocouple Readings inside the Sacrificial Concrete and the Ceramic Sidewall in Test KAPOOL 6







Transient temperatures in the ceramic sidewall in contact with the oxidic melt
Temperature [°C]
1400
1200
1000
800
600
400
200
0
0
50
100
150
200
250
300
Time after ignition [s]
TE29, 10 mm
TE30, 30 mm

10.2 *Appendix B*

Iron- and Oxide Melt Temperatures measured with W/Re Immersion Thermocouples in Test KAPOOL 6