Forschungszentrum Karlsruhe
Technik und Umwelt

Interner Bericht
32.21.03

The Test Facility DISCO-H

Melt Dispersion and Direct Containment Heating (DCH)

L. Meyer, M. Greulich, M. Kirstahler
M. Schwall, E. Wachter, G. Wörner

Institut für Kern- und Energietechnik
Programm NUKLEAR

IKET-Nr.: 11/02
NUKLEAR: 3373

März 2002

Forschungszentrum Karlsruhe
Technik und Umwelt

Interner Bericht
32.21.03

The Test Facility DISCO-H

Melt Dispersion and Direct Containment Heating (DCH)

L. Meyer, M. Greulich, M. Kirstahler
M. Schwall, E. Wachter, G. Wörner

Institut für Kern- und Energietechnik
Programm NUKLEAR

IKET-Nr.: 11/02
NUKLEAR: 3373

März 2002

Abstract

The DISCO-H Test Facility at Forschungszentrum Karlsruhe is used to perform scaled experiments that simulate melt ejection scenarios under low system pressure in Severe Accidents in Light Water Reactors (LWR). These experiments are designed to investigate the fluid-dynamic, thermal and chemical processes during melt ejection out of a breach in the lower head of a LWR pressure vessel at pressures below 2 MPa, and various failure modes with an iron-alumina melt and steam.

The test facility models the reactor pressure vessel, the reactor cavity, compartments and the containment. If the melt is dispersed out of the reactor pit, the mechanisms of efficient melt-to-gas heat transfer, exothermic metal/oxygen reactions, and hydrogen combustion produce a rapid increase in pressure and temperature in the cavity, compartments and containment. In the frame of these Direct Containment Heating (DCH) phenomena the following issues are addressed:

1. final location of the melt,
2. loads on the containment in respect to pressure and temperature
3. amount of hydrogen produced and burnt
4. loads on reactor pit and support structures
5. impact on safety components

Main components of the facility are:

1. Containment pressure vessel,		14.0 m³,	rated at 1 MPa,	200°C
2. RPV and RCS pressure vessel,		0.08 m³,	rated at 2 MPa,	220°C
3. 1:18 scaled cavity,				
4. Steam accumulator,		0.08 m³,	rated at 4 MPa,	250°C
5. Steam generator,	capacity	42 kg/h,	32 kW,	1 MPa

Standard results are:

1. pressure and temperature history in the RPV, the cavity, the reactor compartment and the containment,
2. duration of melt ejection,
3. post test melt fractions in all locations with size distribution,
4. if possible, video film in reactor compartment and containment (timing of melt flow and hydrogen burning),
5. pre- and post test gas analysis.

1. Introduction

In a severe accident special pressure relief valves in the primary circuit of German Pressurized Water Reactors (PWR) will transfer a high pressure accident into a low pressure scenario. However, there may be a time window during late in-vessel reflooding scenarios where the pressure is in the order of 1 or 2 MPa at the moment of the reactor vessel rupture. A failure in the bottom head of the reactor pressure vessel, followed by melt expulsion and blowdown of the reactor cooling system, might disperse molten core debris out of the reactor pit, even at such low pressures. The mechanisms of efficient debris-to-gas heat transfer, exothermic metal/oxygen reactions, and hydrogen combustion may cause a rapid increase in pressure and temperature in the reactor containment and may endanger its integrity. This complicated physical and chemical process is known as Direct Containment Heating (DCH). Investigating the DCH-issue a number of problems have to be addressed: (i) final location of corium debris, (ii) loads on the containment in respect to pressure and temperature, (iii) amount of hydrogen produced, (iv) loads on reactor pit and support structures, and (v) impact on safety components. The knowledge of these points can lead to realize additional safety margins for existing or future plants. DCH phenomena have been investigated intensively for cavity designs with large instrument tunnels, high melt ejection pressures and small holes centered at the lower head. Only few works have studied these phenomena and melt ejection scenarios at low pressure with an annular cavity design, where the only large pathway out of the reactor pit is the narrow annular gap between the RPV and the cavity wall [1-3]. Therefore, our experimental program is aimed at low failure pressures, diverse failure modes and larger breach sizes together with an annular cavity design.

At FZK the test facility DISCO-C has been built for performing dispersion experiments with *cold* simulant materials in a scale 1:18 based on a 1200 MW PWR. The fluids employed were water or a bismuth alloy (Wood's metal) instead of corium, and nitrogen or helium instead of steam. Subsequently, selected experiments in the DISCO-H facility in the same scale will be performed with thermite melt, steam and a prototypic atmosphere in the containment. These experiments are designed to investigate the fluid-dynamic, thermal and chemical processes during melt ejection out of a breach in the lower head of a LWR pressure vessel at pressures below 2 MPa, and various failure modes. The test facility models the reactor pressure vessel (RPV), the volume of the reactor cooling system (RCS), the reactor cavity, pump and steam generator compartments and the containment.

2. Description of the experiment

The containment model (Fig.1 and 2) is heated over a time period of approximately 10 hours by filling with steam additional to the atmospheric air until the vessel pressure reaches 0.2 MPa. The condensate water is drained at the bottom of the vessel from time to time. The average gas temperature and the wall temperature inside the vessel is 273 K (100°C) at the end of the heat-up. A metered amount of hydrogen gas (3 mol%) are added to the vessel at the end of heat-up while fans are running inside the vessel. A gas sample is taken just before the start of the experiment.

The pressure vessel modeling the RPV and RCS volume, which is inside the containment vessel, is electrically heated to the saturation temperature of steam at the planned blowdown pressure, e.g. to 453 K (180°C at 1.0 MPa). Before the initiation of the experiment it contains nitrogen at that temperature at 0.1 MPa.

The steam accumulator is outside of the containment vessel. It is heated electrically to the saturation temperature of twice the planned burst pressure, e.g. 486 K (213°C at 2.0 MPa). The accumulator is filled with a measured amount of water by a high pressure metering pump to reach that pressure. The RCS pressure vessel and the accumulator are connected by a 25 mm diameter pipe with an electro-pneumatically actuated valve.

The model of the RPV, that is directly flanged to the RCS pressure vessel, is filled with aluminum-ironoxide thermite. The experiment is started by igniting the thermite electrochemically (Pyrofuze) at the upper surface of the pressed thermite powder. When a pressure increase in the RPV-RCS pressure vessel verifies that the thermite reaction has started, the valve in the line connected to the accumulator is opened and steam enters the pressure vessel. When the pressure has reached a preset value the valve is automatically closed again. The amount of steam that is initially in the RCS-RPV pressure vessel is determined by the amount of steam originally in the accumulator minus the steam left in the accumulator. The steam flow takes approximately one second. During that time and thereafter the thermite reaction progresses until it reaches the bottom of the RPV vessel. Approximately 10 seconds after ignition the brass plug at the bottom of the RPV vessel is melted by the 2400 K hot iron-alumina mixture. That initiates the melt ejection. By that time the pressure in the RCS-RPV pressure vessel will be higher than the preset value due to radiation heat transfer from the hot melt to the steam. The melt is driven out of the breach by the steam and is dispersed into the cavity and the containment. Due to the melt-to-gas heat transfer, exothermic metal/oxygen reactions, and hydrogen combustion the pressure and temperature in the containment pressure vessel will rise up to an estimated 0.6 MPa and 900 K, for a short time (less than a minute).

3. Components of the test facility

3.1 The containment pressure vessel (CPV)

The containment pressure vessel is a TÜV-approved cylindrical pressure vessel made of 15 mm steel and is rated at 1.0 MPa and 200°C. It has an outer diameter of 2.20 m and a height 4.60 m; with the pedestal and the top port its total height is 5.80 m (see Fig. 1 and 2, for data see Table 1).

The pressure vessel consists of two segments and a lower and an upper head. Each segment has six instrument penetration ports at two levels labeled A through D. One of the level C ports is closed with a safety ruptures disk (diameter 200 mm), with a burst pressure of 1 MPa. The lower head is filled with concrete that forms a level floor. All internal structures are bolted to that floor. At the center of the floor is a large vertical pipe that contains the condensate draining piping and has a connection to the bottom port. The connection of this pipe with the containment volume is via a 10 mm hole in the concrete cavity floor. The entire vessel is insulated against heat loss on the outside by a 100 mm thick fiberglass insulation. The empty volume of the containment vessel is 14.18 m³.

3.2 Subcompartment

The subcompartment is an annular space around the cavity. The flow path from the cavity is along the eight stubs modeling the main cooling lines. The top cover of the subcompartment has three openings with a diameter of 130 mm (Fig. 2 and 3), that are covered by a mesh to prevent melt to enter the containment.

3.3 The pressure vessel modeling the RCS and RPV volume

The RCS-RPV pressure vessel models the volumes of both the reactor cooling system (RCS) and the reactor pressure vessel (RPV) (Fig. 2 ,3 and 5) and has a total volume of 0.076 m³. A disk holding 8 pipes (46 mm I.D., 255 mm length) separates the two partial volumes. This arrangement models the main cooling lines with respect to the flow constriction between RCS and RPV. The cylinders (I.D. 20 mm) modeling the RCS and RPV are heated electrically, and are insulated over the hole length and on the top.

3.4 The RPV model

The RPV model, that serves as crucible for the generation of the melt, is bolted to a plate carrying the RCS-RPV pressure vessel (Figs.1, 6 and 8). An insulation material of magnesium oxide (MagneRam) is filled between the outer shell of the RPV model and an inner steel cylinder, that contains the thermite powder. The hole at the bottom of the melt generator is formed by a graphite annulus. It is closed with a brass plate.

3.5 The reactor pit

The cavity and RPV-holddown were designed to withstand a pressure of 10 MPa with a safety factor of 2 to yield. The reactor pit is made of concrete (Figs. 7 and 8) and is installed inside a strong steel cylinder (30 mm thick walls). This cylinder is clamped by 8 bolts (56 mm diameter) between a base plate and a top plate, both 90 mm thick (see Fig. 2). Besides the flow path along the main cooling lines there is the option of a flow out of the cavity straight up into the containment through eight openings with a total cross section of 0.052 m². Depending on the reactor design that is to be investigated this cross section is a variable (Figs.4 and 8).

3.6 Steam accumulator

The steam accumulator is a TÜV-approved cylindrical pressure vessel placed outside of the containment pressure vessel with approximately the same volume as the RCS-RPV pressure vessel and is rated at 2.0 MPa and 250°C (Fig. 2 and 10). Both vessels are connected by a 25 mm diameter pipe with an electro-pneumatically actuated valve. The vessel is electrically heated from the outside and is insulated by fiberglass. The required amount of steam is generated inside the steam accumulator. A high pressure metering pump is connected to the accumulator that can inject very accurate amounts of water into the heated vessel to reach that required pressure.

3.7 Steam generator

The steam generator serves for heating up the containment vessel and providing the steam for the initial containment atmosphere. It has a capacity of 42 kg/h steam (32 kW) at 1 MPa. The steam generator is also used to vent the steam accumulator of air.

4. Instrumentation

4.1 Temperature

Initially, only type-K thermocouples (chromel-alumel) are installed in the facility. They are steel sheathed thermocouples with insulated wires. The outer diameter of the sheath is given in table 3. It is planned to use some high temperature thermocouples at selected positions in later experiments. A large number of thermocouples is installed at the outside of the steam accumulator tank and the RCS-RPV pressure vessel to control the electric heaters. These temperatures are monitored at the heater control board.

The data acquisition system records the signals of the 22 thermocouples that are listed in table 3, at a rate of 2000 samples per second per channel. The steam temperature in the accumulator tank is measured by two thermocouples, one near the top and one near the bottom. There is one thermocouple within the draining pipe at the bottom to measure the water temperature, if water is present. There are two thermocouples within the RCS-RPV pressure vessel, one in each compartment (RCS and RPV). A total of 11 thermocouples are located at different levels in the containment pressure vessel (CPV, level A through D) to measure the bulk gas temperature. Two of them are within the subcompartment, one is at the floor and the rest is either close to the wall or in the space between the RCS-RPV pressure vessel and the containment wall.

Six thermocouples are at two locations near or inside the concrete wall of the cavity. The thermocouple sticking 2 mm out of the wall will measure the arrival of the melt. It will be destroyed by the melt. Later experiments will have a high temperature thermocouple there. The thermocouples placed at two different depths within the concrete will serve to measure the transient heat flux entering the concrete.

4.2 Pressure

A total of 15 strain gauge-type pressure transducers (Kulite) with ranges of 0–1.7 MPa, 0–3.4 MPa and 0–7.0 MPa were used to measure steam and gas pressures (Table 4). The compensated operating temperature range is 27°C – 232°C, with a thermal drift of +/- 5% of full scale output. The transducers are being adjusted at the operating temperature just before the start of the experiment. The data acquisition system records data at a rate of 2000 data points per second per channel. All gages are mounted in tapped holes that are connected gas tight with the outside atmosphere at their backsides. In case of the transducers in the RCS-RPV pressure vessel, the compartment, and the cavity this connection was achieved by flexible steel hoses. The gages in the containment pressure vessel were mounted in the blind flanges of the ports at different levels.

4.3 Gas composition

Ten pre-evacuated 500-cm³ gas grab sample bottles will be used to collect dry-basis gas samples at three positions, in the cavity, in the subcompartment, and in the upper part of the containment. The sample lines and the sample bottles will be cold, thus the bottles will be filled with noncondensible gases only. One pretest sample will collect background information just prior to the start of the melt ejection. One sample at all three stations will be taken during the blow down and one 20 seconds after the blow down. The gas samples will be analyzed at the Engler-Bunte-Institut at the University Karlsruhe.

4.4 Additional measurements

Three video cameras will be used in the experiment. One camera looks down from the dome into the containment, one is installed at the level B port looking at the top of the subcompartment and the openings in the top plate, that represent the direct path from the cavity into the containment. A third camera looks into the compartment from the side by means of an endoscope.

Breakwires are placed across the RPV exit hole (Fig. 9) and at the annular gap exit. The breakwires were intended to give timing information on entry of debris into and out of the cavity.

The total debris mass dispersed into the DISCO vessel and the debris mass in specific locations will be determined by a posttest debris recovery procedure. A posttest sieve analysis of the debris recovered from different locations will be performed for each test.

5. Thermite Burn Scoping Test

Two thermite burn tests were performed outside of the DISCO Test Facility. The goal of the burn tests was to determine the time to melt plug failure (from ignition) and to verify that the melt plug failed as expected [4].

The tests were performed with the RPV-RCS pressure vessel connected to the RPV-model. The vessel contained nitrogen at 1 bar at room temperature prior to ignition. The crucible (RPV-model) contained 11.5 kg of aluminum-ironoxide thermite. In the first test the inner diameter of the crucible was 220 mm and the density of the thermite was 1.17 g/cm^3. The time from ignition to melt plug failure was 4.3 seconds, with a burn rate of 6.5 cm/s. The pressure increased to 0.61 MPa inside the RPV-RCS-vessel. Because the time was too short to safely fill the vessel with steam before melt plug failure, the parameters were changed in the second test. The diameter of the crucible was reduced to 168 mm, and the density was increased to 2.28 g/cm^3 by applying a higher compacting pressure. Although the height of the thermite was approximately the same as in the first test, the time to melt plug failure increased to 10.1 seconds, which meant a burn rate of 2.8 cm/s. The pressure increase was less with 0.460 MPa, compared to the first test, probably because of the smaller surface area of the melt pool.

The melt plug was filmed by a high speed camera (500 frames/s) from below and the side. From these pictures we can infer, that the melt plug is fully open within 2 ms. Posttest inspection of the melt plug exit area determined that the exit hole was round, fully open, and with a diameter of about 55 mm. A 0.5 mm thick film of melt coated the carbon ring that formed the exit hole. A thin film of melt also coated most of the interior steel liner. Some of the steel liner had melted exposing the MgO insulator, particularly at the bottom of the liner.

References

1. M. L. de Bertodano, A. Becker, A. Sharon, R. Schnider, “DCH Dispersal and Entrainment Experiment in a Scaled Annular Cavity,” *Nucl. Eng. Des*., **164**, 271-285, (1996).
2. T. K. Blanchat, M.M. Pilch, R.Y. Lee, L. Meyer, and M. Petit, “Direct Containment Heating Experiments at Low Reactor Coolant System Pressure in the Surtsey Test Facility,” *NUREG/CR-5746, SAND99-1634*, Sandia National Laboratories, Albuquerque, N.M., (1999).
3. S.B Kim, R.J. Park, H.D. Kim, Chevall and M.Petit, “Reactor Cavity Debris Dispersal Experiment with Simulant at Intermediate System Pressure,” *SMiRT15 Post Conference Seminar on Containment of Nuclear Reactors,* Seoul, Korea, August 23-24, (1999).
4. L. Meyer, M. Greulich, M. Kirstahler, M. Schwall, E. Wachter, G. Wörner, “DISCO-H Thermit Brenntest”, Interner Bericht 32.21.03, Forschungszentrum Karlsruhe, IKET-Nr. 7/01, NUKLEAR: 3358, (2001)

Table 1: Geometric parameters of the test facility

Containment Pressure Vessel		
Diameter (inner)	m	2.170
Height of a segment	m	1.650
Height of upper head	m	0.640
Total inner height	m	3.940
Diameter of portholes (DN 200)	m	0.199
Length of ports	m	0.215
Length of lower port (vertical pipe)	m	1.601
Volume of lower port (vertical pipe)	m³	0.050
Total empty volume of containment	m³	14.180
Volume of internal structures (RPV, cavity, etc)	m³	0.300
Total freeboard volume (incl. subcompartment)	m³	13.880
Subcompartment		
Outer diameter (inside)	m	1.810
Inner diameter	m	0.600
Height	m	0.785
Volume	m³	1.740
RCS and RPV pressure vessel		
Inner diameter	m	0.200
Height of RCS	m	1.586
Volume of RCS	m³	0.0498
Volume of the line connecting to accumulator	m³	0.0013
Height of upper RPV (same diameter as RCS)	m	0.430
Volume of upper RPV	m³	0.0135
Inner diameter of lower RPV (crucible)	m	0.168
Height of lower RPV (crucible)	m	0.514
Volume of lower RPV (crucible)	m³	0.0114
Total volume of RCS and RPV	m³	0.0760
Volume of the steam accumulator	m³	0.0820

Table 2 Geometrical flow parameters in the cavity

Height of cavity	m	0.612
Diameter of cavity (lower part, concrete wall)	m	0.342
Height of lower part (concrete wall)	m	0.462
Diameter of cavity (upper part, steel wall)	m	0.540
Height of upper part (steel wall)	m	0.150
Length from RPV bottom (lower head) to cavity floor	m	0.066
Length of annular cross section	m	0.316
Gap width between RPV and cavity wall	m	0.021
Cut out diameter at nozzles (around main cooling lines)	m	0.086
Cold/hot leg diameter (main cooling lines)	m	0.050
Flow area of annulus	m^2	0.0212
Flow area in upper part of cavity	m^2	0.1583
Flow area at nozzles (8 $\times$ cut out area – 8 $\times$ cold/hot leg area)	m^2	0.0308
Flow area into containment (where existing, 8 holes)	m^2	0.0520
Empty volume of cavity (without RPV)	m^3	0.0748
Free volume of cavity	m^3	0.0365

Table 3 Thermocouple Summary

No. T	Channel	Location	Type diameter mm	Range (0 - 5 Volt) °C	Position Height cm	Position from wall cm	Position angular degree
1	03	accumulator low	K 1.0	0 - 500			
2	04	accumulator high	K 1.0	0 - 500			
3	05	RCS high (10 cm)	K 0.5	-100 -1350			
4	06	RCS low (170 cm)	K 0.5	-100 -1350			
5	07	accumulator (bottom)	K 1.0	0 - 500			
6	08	CPV A1	K 0.35	0 - 500	0	3	45
7	09	CPV-A2 (subcomp.)	K 0.35	0 - 1000	45	50	135
8	10	CPV-A3 (subcomp.)	K 0.35	0 - 500	46	61	225
9	11	CPV-B1	K 0.35	0 - 1000	116	56	45
10	12	CPV-B2	K 0.35	0 - 1000	109	56	135
11	13	CPV-B3	K 0.35	0 - 500	116	52	225
12	14	CPV-C1	K 0.35	0 - 1000	211	9	45
13	15	CPV-C2	K 0.35	0 - 1000	212	71	135
14	16	CPV-D2	K 0.35	0 - 500	283	5	135
15	17	CPV-D3	K 0.35	0 - 500	277	8	225
16	18	CPV-D3	K 0.35	0 - 1000	280	61	225
17	19	Cavity	K 0.35	0 - 1000	362	-3	0
18	20	Cavity	K 0.35	0 - 1000	362	2	0
19	21	Cavity	K 0.35	0 - 1000	362	-1	0
20	22	Cavity	K 0.35	0 - 1000	62	-3	0
21	23	Cavity	K 0.35	0 - 1000	62	2	0
22	24	Cavity	K 0.35	0 - 1000	62	-1	0

Table 4 Pressure transducer Summary

No. P	Position	Channel	Line No.	Transducer No.	Pressure [bar]	Type	Position [cm/degree] Height	angular
1	Accumulator flange	33	D1	614	35	HEM-375-35 BAR A		
2	Accumulator flange	34	D2	228	70	HEM-375-70 BAR SG		
3	RCS flange	35	101	101	17	HEM-375-17 BAR A		
4	RCS flange	36	102	102	17	HEM-375-17 BAR A		
5	CPV A1	37	92	92	17	HEM-375-17 BAR A		
6	CPV A2	38	93	93	17	HEM-375-17 BAR A		
7	CPV B1	39	94	94	17	HEM-375-17 BAR A		
8	CPV C2	40	98	98	17	HEM-375-17 BAR A		
9	CPV B3	41	99	99	17	HEM-375-17 BAR A		
10	cavity – 1	42	86	86	17	HEM-375-17 BAR A	162	0
11	cavity – 2	43	87	87	17	HEM-375-17 BAR A	412	0
12	cavity – 3	44	88	88	17	HEM-375-17 BAR A	162	180
13	cavity – 4	45	89	89	17	HEM-375-17 BAR A	412	180
14	compartment - 1	46	90	90	17	HEM-375-17 BAR A		
15	compartment - 2	47	91	91	17	HEM-375-17 BAR A		

Fig. 1. The DISCO-H Test Facility

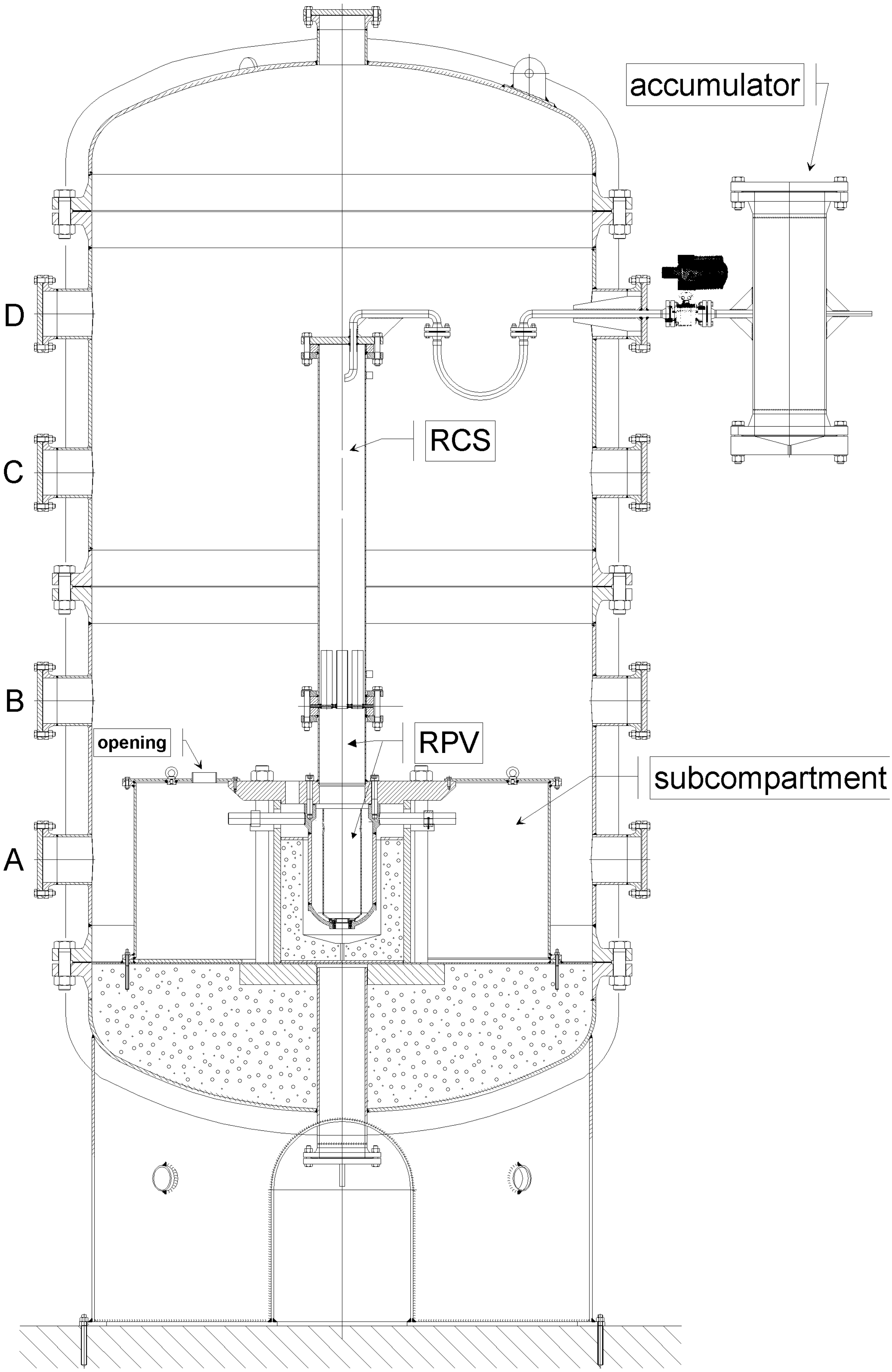

Fig. 2. The Containment pressure vessel with internal structures

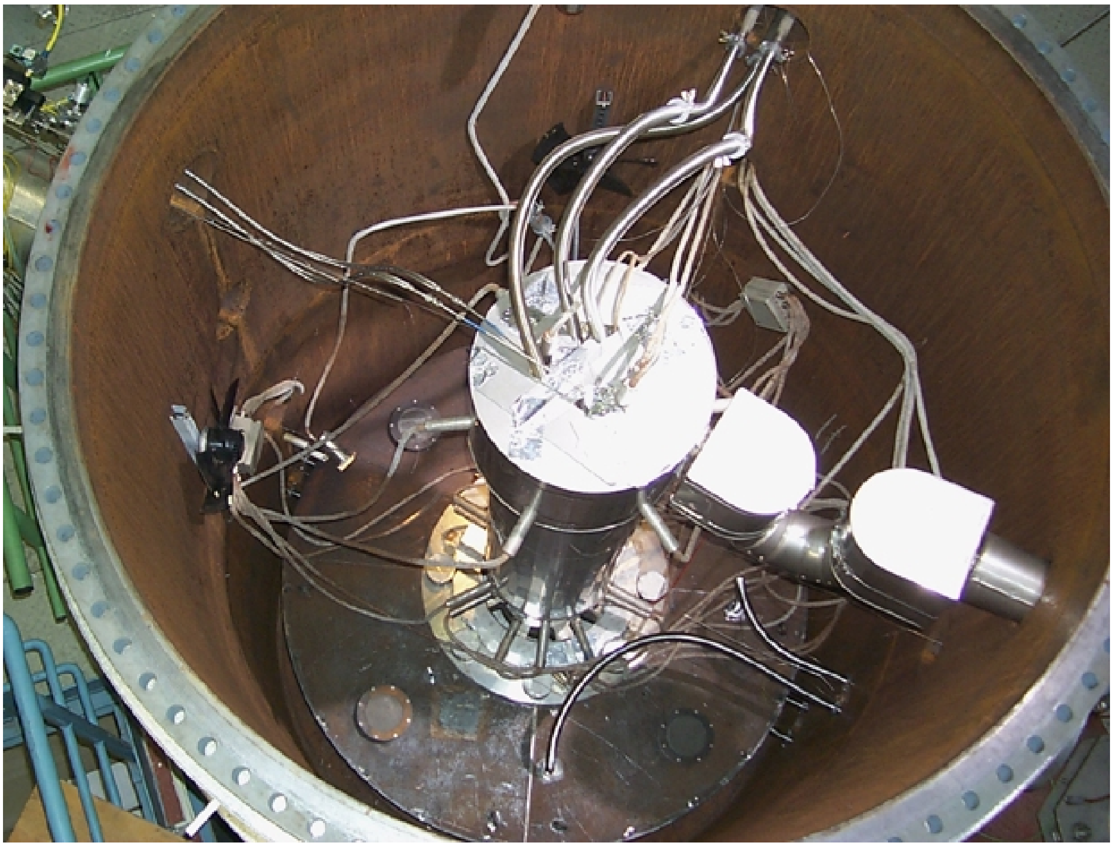

Fig. 3. View into Containment pressure vessel, with RCS-RPV pressure vessel

Fig. 4. Top view of the cavity top plate with exit holes leading into containment

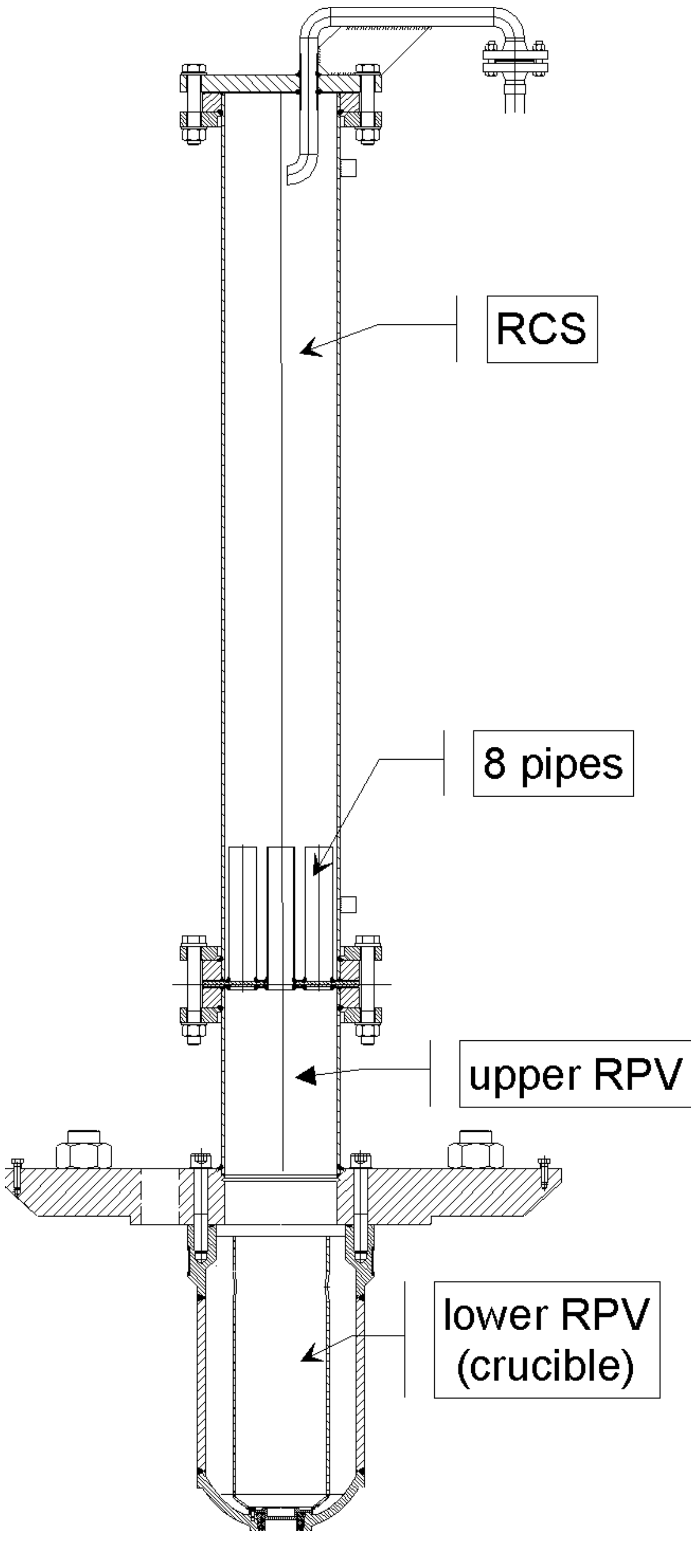

Fig. 5. The model of the Reactor Cooling System (RCS) vessel and Reactor Pressure Vessel (RPV)

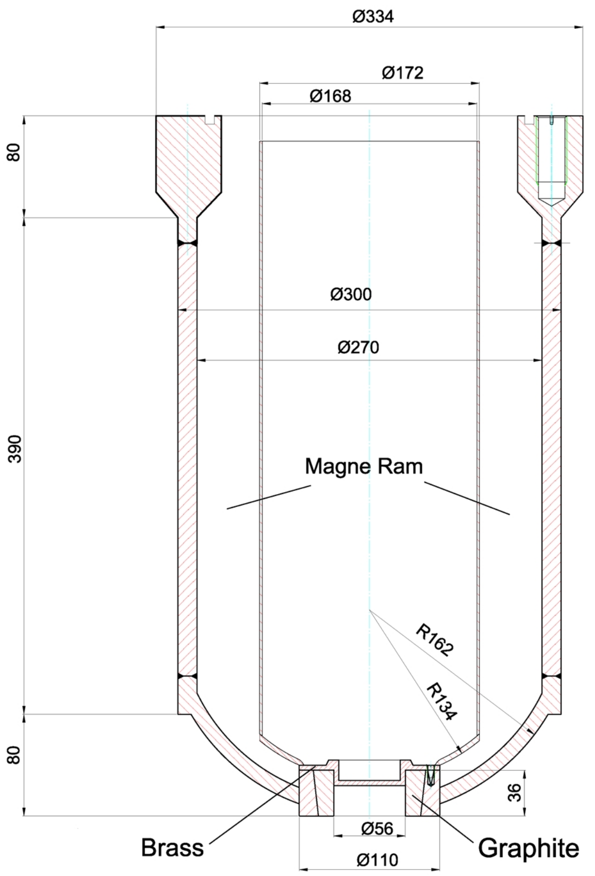

Fig. 6. The RPV model, crucible for the thermite melt

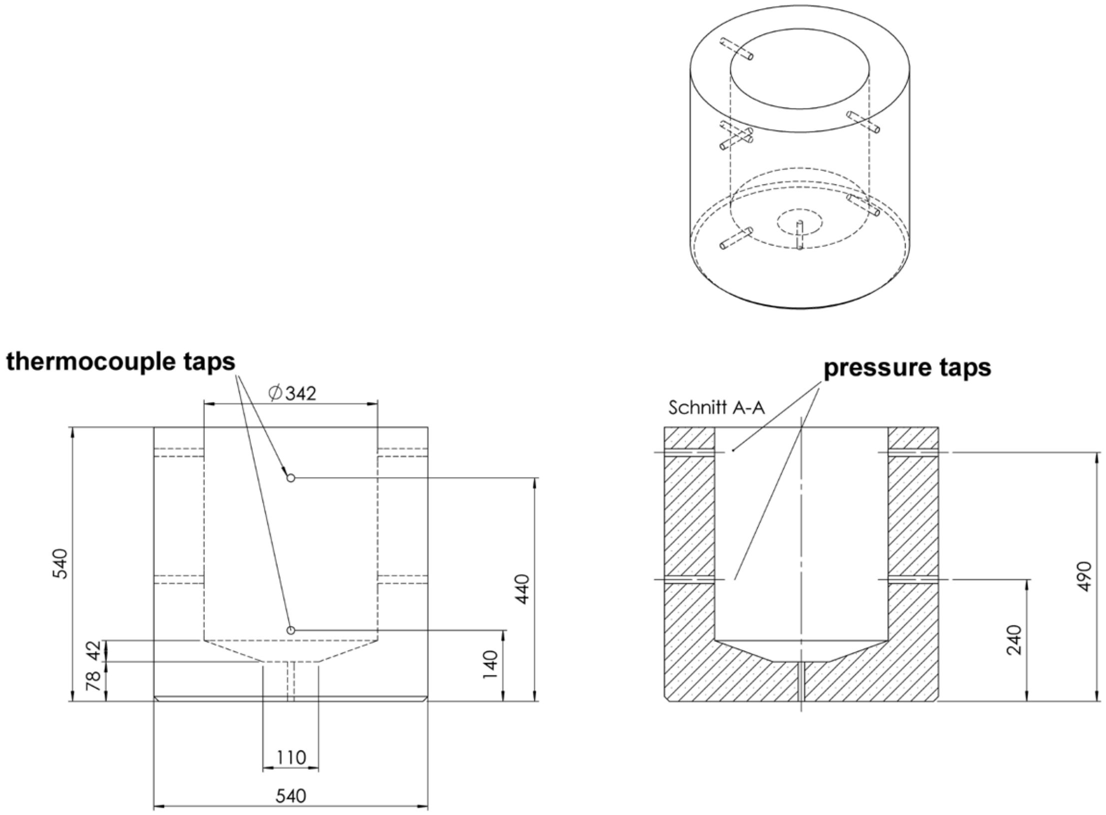

Fig. 7. The reactor pit made of concrete

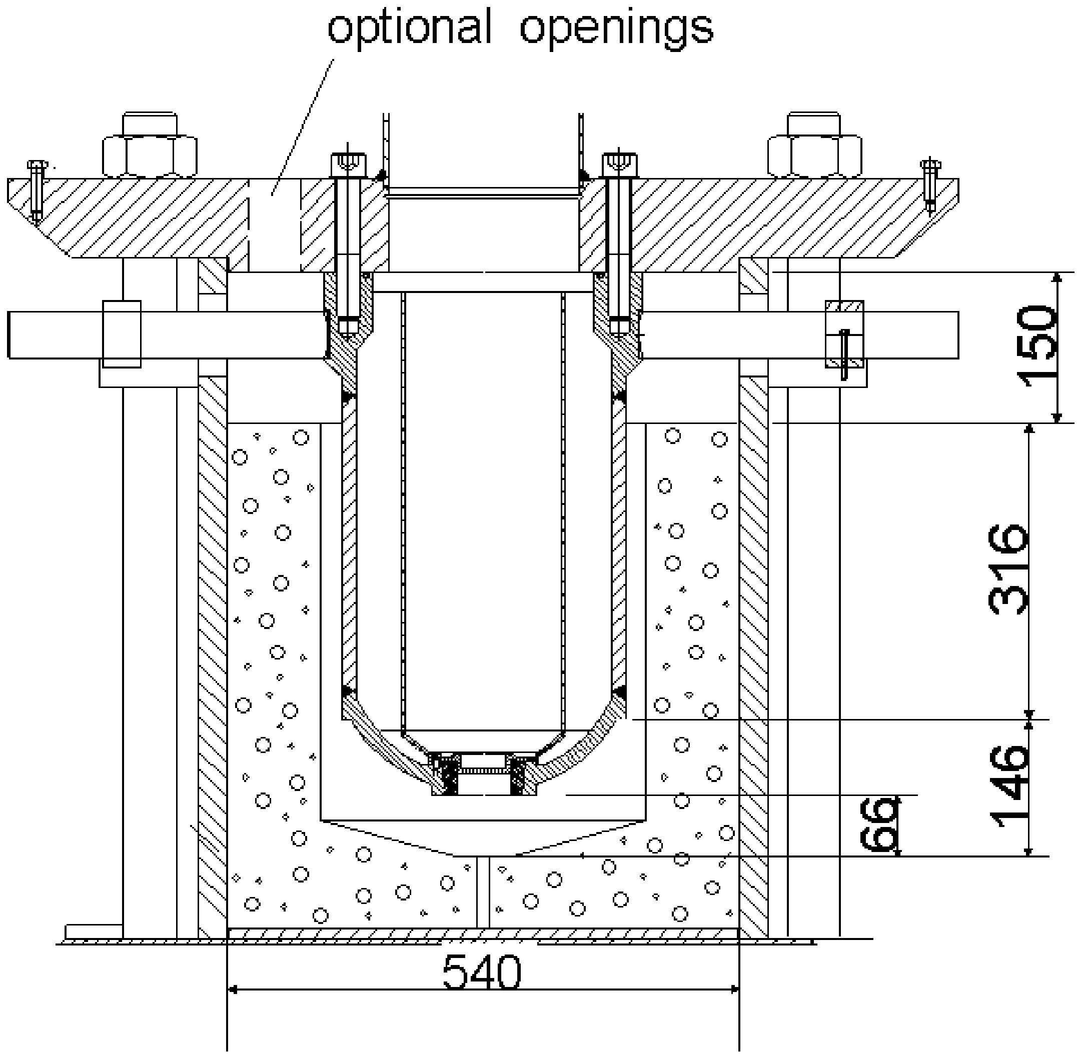

Fig. 8. The RPV-model (crucible) and cavity

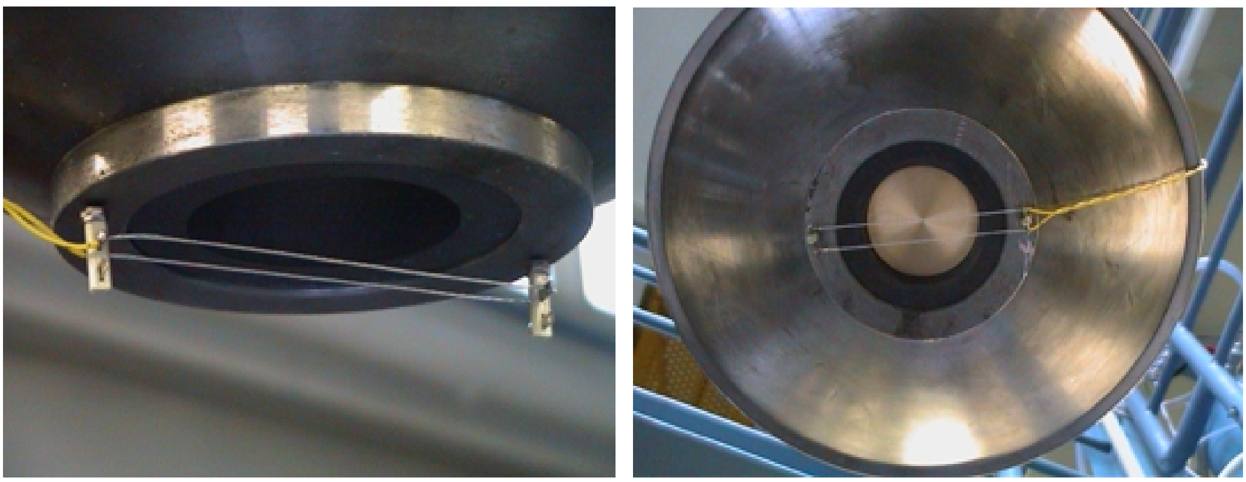

Fig. 9. Breakwires at the RPV exit hole

Fig. 10. The steam accumulator (left) and the steam generator (right)