THERMAL-HYDRAULIC CHARACTERISTICS DURING INGRESS-OF-COOLANT AND LOSS-OF-VACUUM EVENTS IN FUSION REACTORS

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ABSTRACT

The thermal-hydraulic characteristics in a vacuum vessel (VV) of a fusion reactor under an ingress-of-coolant event (ICE) and loss-of-vacuum event (LOVA) were investigated quantitatively using preliminary experimental apparatuses.

In the ICE experiments, pressure rise characteristics in the VV were clarified for experimental parameters of the wall temperature, water temperature and with/without a blowdown tank. Furthermore, the functional performance of a blowdown with/without a water cooling system was examined and it was confirmed that the blowdown tank with the water cooling system is effective to suppress the pressure rise during the ICE event.

In the LOVA experiments, the saturation time in the VV from vacuum to atmosphere was investigated for various breach sizes and it was found that the saturation time is in inverse proportion to the breach size. In addition, the exchange flow characteristics through breaches were clarified for the different breach positions on the VV. It was proven from the experimental results that the exchange flow becomes a counter-current flow when the breach was positioned at the roof on the VV and a stratified flow when it is formed at the side of the VV, and then the flow exchange under the stratified flow condition is smoother than that under the counter-current flow. Based on these, the severest breach condition in ITER was changed from the top-break case to the side-break case.

In addition, to predict with high accuracy the thermal-hydraulic characteristics during the ICE and LOVA events under the ITER condition, the necessity of a large-scale test facility was mentioned. The current conceptual design of the combined ICE/LOVA test facility with a scaling factor of 1/1000 in comparison with the ITER volume was expressed.

1. INTRODUCTION

Two experimental studies on an ingress-of-coolant event (ICE) and loss-of-vacuum event (LOVA) have been carried out as International Thermonuclear Experimental Reactor (ITER) [1] safety R&D subtasks so as to obtain verifying data for the fusion safety analysis codes during transient events [2].

A scenario of the ICE and LOVA events in the fusion reactor can be seen in Fig. 1. If cooling tubes installed into plasma-facing components (PFCs) in a Tokamak vacuum vessel (VV) are broken due to some damage, water under high temperature and pressure in the cooling tubes will be discharged into the VV. Then, the discharged water will impinge on the hot surface of the

PFCs and evaporate. As a result, the VV will be filled with steam and the pressure in the VV will increase rapidly. The rapid pressure rise will make a shock wave and lead to high pressurization. Moreover, chemical reactions between the steam and PFC materials could occur. This is called the ICE event.

On the other hand, if the pressurization speed in the VV after the ICE event is faster than operating speeds of some safety devices (i.e., rupture disks and safety valves), the VV and some penetration ducts may be broken as a results of the rapid pressure rise. If the penetration duct is broken as can be seen in Fig. 1, buoyancy-driven exchange flows caused by the temperature difference between the inside and outside of the VV will take place through breaches. In addition, the activated dust accumulated inside the VV and the tritium retained in the PFCs may be entrained by the exchange flows through the breaches to the outside of the VV. This is called the LOVA event.

Some studies [3]-[6] regarding the thermofluid safety for nuclear reactors have been performed at more than atmospheric pressure, however, thermal-hydraulic characteristics during the ICE and LOVA events have not been reported yet because those events occur under a vacuum condition. Then, the ICE and LOVA experiments were carried out using the preliminary test apparatuses to understand the physical phenomena in the VV during ICE and LOVA events and obtain the verifying data for the fusion safety analysis codes. Furthermore, a combined ICE/LOVA test facility was planned to extrapolate the ITER condition with respect to the ICE/LOVA events and its necessity was requested from the code analysts. The volume of the combined ICE/LOVA test facility is around 10 times larger than the preliminary ICE/LOVA apparatuses and corresponds to 1/1000 of the ITER volume. This paper describes the ICE and LOVA experimental results and a conceptual design of the combined ICE/LOVA test.

2. ICE EXPERIMENT

2.1 Experimental Apparatus

A schematic of the preliminary ICE apparatus [7] is shown in Fig. 2. It mainly consists of a VV, boiler, water injector, isolation valve, vacuum pump and blowdown tank.

The VV of stainless steel is a cylindrical enclosure and its diameter and height are 900 and 600 mm. Heating walls, consisting of brass plates and sheath heaters, are set to the inner surface of the VV to control the wall temperature. The VV can be heated to a maximum of 400°C by the heating walls. The target plate, which was made of brass, is a circular plate and its diameter and thickness are 900 and 12 mm. The target plate is installed on the opposite side of the water injector in the VV. The water under high temperature and pressure impinges on the front surface of the target plate. The VV is covered with fibrous insulation with a thickness of 0.2 m. A pressure transducer of a strain-gage type was set to the inside wall of the VV to measure the pressure transients during the ICE event, as shown in Fig. 2.

The boiler consists of a cylinder, electric heaters and piping. The cylinder volume is 0.1 m^3. In the boiler, water is heated to 250°C in maximum by the electric heaters and pressurized to 3.5 MPa in maximum by pressurized N_2 gas. The piping connects the boiler with the VV through the water injector.

The water injector consists of a pneumatic cylinder and water nozzle. The water under high temperature and pressure made by the boiler is injected into the VV through the water nozzle. The water nozzle is set to the edge of the VV.

The blowdown tank is connected to the VV with piping through an isolation valve. The piping diameter is 50 mm. The objective of this tank is to relieve high pressure in the VV during the ICE event. The following two types of the blowdown tanks were used:

- A type is a large circular cylinder and the volume (0.57 m^3) is 150% larger than the VV volume, and its outside is atmosphere;
- B type is a small chamber and the volume (0.045 m^3) corresponds to around 12% of the VV volume, and it is enclosed with a water cooling system as can be seen in Fig. 3.

The objective of the water cooling system for the B type is to reduce the saturation pressure inside the blowdown tank by decreasing the water and vapor temperatures and enhancing the condensation.

2.2. Experimental Procedure and Conditions

The ICE experiments were carried out in the following ways: First, the water in the boiler was set to the values of the experimental conditions; Second, the wall inside the VV was heated to the desired temperature by the heating walls and at the same time the inside of the VV was exhausted to the desired pressure using the vacuum pump; Third, the high temperature and pressure water was injected into the inside of the VV through the water injector at a constant flow rate; Fourth, the injected water impinged on the target plate; Fifth, the injected water boiled and evaporated; and sixth, as this result the inside pressure increased rapidly.

The ICE experimental conditions were as follows: the initial wall temperature, T_v, varied from 100 to 250°C; the initial pressure in the VV was less than 10 Pa; the diameter of the water nozzle was 2 mm; the injection time was 10 s; the initial water pressure was 3.5 MPa; and the initial water temperature, T_w, varied from 100 to 200°C. According to the current ITER design, the wall temperature inside the VV is 230°C and the coolant temperature and pressure in the PFCs are 160°C and 3.5 MPa, respectively. In addition, the isolation valve was opened when the pressure inside the VV became 0.2 MPa. Here, this operating pressure corresponds to the pressure set value of the engineering safety device (i.e., a double-rapture disk system) in ITER. The present experimental conditions were considered based on these ITER conditions.

2.3. ICE Experimental Results and Discussion

Figure 4 shows the pressure transients in the VV during the ICE conditions. Here, T_v and T_w represent the initial wall temperatures inside the VV and the initial water temperature, respectively, and t denotes the time from the start of the experiment. In the figure, the solid line shows the experimental results under the condition of T_v=250 and T_w=200°C. Similarly, the dashed and dotted lines show the experimental results under the conditions of T_v=250 and T_w=100°C, and then, T_v=100 and T_w=200°C, respectively.

For the solid and dashed lines (i.e., the case in which T_v is the same but T_w is different), the pressure transients increase rapidly with the water injection and those pressures at t=10 s reach around 0.42 MPa at the solid line and 0.2 MPa at the dashed line.

The heat transfer rate, Q, from the wall in the VV to the injected water is generally defined as $Q=\alpha(T_v-T_w)$. Here, α denotes the heat transfer coefficient. Just after the break of vacuum due to the water injection, the water temperature accumulated in the VV decreases down to the saturation temperature that is determined by the pressure inside the VV. Therefore, T_v-T_w will be almost similar for each T_w when T_v is constant. This reason was derived from the measured temperature distributions inside the VV. Thus, it can be presumed that the pressure difference between the solid and dashed lines depends on flashing which is specified by T_w. Here, the flashing means that water changes from liquid to vapor under vacuum because the water can not maintain the liquid.

For the solid and dotted lines (i.e., the case that T_w is the same but T_v is different), an effect of the flashing will be similar for both cases because T_w is constant. Therefore, it can be expected that a pressure difference between both lines depends on T_v. That is, the effect of the heat transferred from the wall to the water becomes remarkable in these cases.

Figure 5 shows the pressure transients in the VV at T_v=250 and T_W=200°C. Here, the solid line represents the experimental results without the use of any blowdown tanks. The dashed and dotted lines represent the experimental results with type A and B blowdown tanks, respectively.

For the solid line, the pressure increases as a straight line during the water injection, and then, the pressure rise slows down, and the pressure saturates gradually after 40 s. The saturation pressure at Tv=250°C is 3.77 MPa, however, the measured pressure saturated about 0.67 MPa. The reason why the saturation pressure decreased was that the inside temperature at the penetrations on the VV was lower than 250°C because the temperature control at the surroundings of the penetrations was not sufficient.

For the dashed line, the pressure increases during the water injection, but it decreases suddenly after the isolation valve was opened and the VV was connected to the A type blowdown tank. Since this tank volume is 1.5 times higher than the VV volume, the pressure inside the VV falls down drastically. There was also a lot of condensation on the tank wall, since the initial wall temperature of the blowdown tank was about 18°C.

For the dotted line, which is the same as the dashed line, the pressure increases during the water injection and decreases suddenly after the isolation valve is opened. However, the B type blowdown tank volume is so small that the pressure decrease is not large. Moreover, the pressure slightly increases again because the water injection still continues to 10 s. After the completion of the water injection, the pressure decreases gradually. Here, the pressure decrease after 10 s depends on the condensation of vapor and the reduction of the water temperature due to the water cooling system. From these results, it can be expected that the possibility on the volume reduction in the blowdown tank in the fusion reactor will be high if adequate active cooling systems are provided and assembled into the fusion reactor safety systems.

3. LOVA EXPERIMENT

3.1. Experimental Apparatus

The preliminary LOVA apparatus [8] mainly consists of a toroidal-shaped test section and weight measuring system.

The toroidal-shaped test section consists of a VV, pneumatic vacuum valves and compensation heaters. The VV, which is made of stainless steel, is an annular enclosure with 6 simulated breaches. The pneumatic vacuum valve is set to the outside of the breach. A breach hole on the VV can be simulated by opening a pneumatic vacuum valve. Compensation heaters are installed on the outer surface on the VV to control the wall temperature.

The weight measuring system consists of an electronic balance and a data acquisition system. The electric balance has an accuracy of 1 g with a full measuring range of 600 kg. In the present experiments, the change in the gross weight of the VV including an internal gas weight with respect to time is measured by the electronic balance, and then, the exchange rate in the VV is obtained quantitatively by subtracting the initial weight of the VV before the start of the experiment from the measured weight of the VV during the experiment.

3.2. Vacuum Vessel

A cross-sectional view of the VV is shown in Fig. 6. The inner and outer diameters of the VV are 263 and 838 mm and its height is 832 mm. The outer surface of the VV is covered with compensation heaters and fibrous insulation with a thickness of 90 mm. The compensation heaters consist of micro-heaters sheathed with stainless steel tubes having a diameter of 3.2 mm. These heaters can raise the wall temperature of the VV to a maximum of 200°C. In Fig. 6, T1, T2, S1, S2, S3 and B show the simulated breaches: T1 and T2 are positioned on the roof of the VV; S1, S2 and S3 are at the side wall; and B is on the floor. Each breach diameter is around 100 mm.

3.3. Experimental Ways and Conditions

Two kinds of the LOVA experiments, vacuum test and atmospheric pressure test, were carried out to investigate thermal-hydraulic characteristics during a short and long time after the LOVA event occurred.

In the vacuum test, the T1 breach was opened after the VV was evacuated to less than 10 Pa, and the pressure transients inside the VV were measured for various breach sizes. The objective of the test was to obtain a saturation time in the VV from vacuum to atmosphere.

The atmospheric pressure test was performed to study the exchange flow behavior after the pressure in the VV was equal to the atmospheric pressure under the LOVA conditions. The experiment was carried out in the following way: First, the VV was evacuated to less than 10 Pa; Second, helium gas was supplied the VV; Third, the wall temperature of the VV was set to the experimental conditions; Fourth, the pressure in the VV was adjusted until it was equal to the outside pressure; and Fifth, one or two breaches were opened. As a result, the buoyancy-driven exchange flows through the breaches take place. Namely, helium gas goes out of the VV through the breaches to the outside, and simultaneously, air comes into the inside from the outside. Finally, the exchange mass in the VV is calculated from the change in the gross weight of the VV.

Helium gas and air were used in the present experiments. As conservative estimation, it can be considered that: air flowing from the outside of the VV through the breaches into the inside will reach 1000°C during a short time after the LOVA event occurs because the maximum temperature of the PFCs in ITER is 1000°C at the divertor. But, it is difficult to heat up the air to 1000°C using only electric heaters. The buoyancy-driven exchange flow strongly receives the effect of the fluid density. Fortunately, the density of helium gas at a room temperature condition was nearly equal to that of air at the temperature range of more than 1000°C. Therefore, helium gas was chosen as the working fluid of the present experimental study.

3.4. LOVA Experimental Results and Discussion

Figure 7 shows the pressure transients in the VV under the vacuum test condition when the T1 breach was opened. Here, a solid line represents the experimental results when breach diameter, d, is 100 mm, and Δt denotes the time until the VV is filled with air and the inside of the VV reaches atmospheric pressure, and then, t shows the time since the experiment started. In this figure, Δt was around 0.5 s.

Figure 8 shows the relationship between Δt and d at the vacuum tests. Δt is in inverse proportion to the breach size. Namely, the VV is exchanged immediately to atmosphere when d is large, and Δt becomes very long when d is small. In the figure, Δt at d=1 mm needs about an hour. The VV volume excluding penetration volume in ITER is around 3800 m^3 and it corresponds to approximately 9,200 times larger than that of the present LOVA apparatus. Therefore, it can be estimated that: if the LOVA event occurs in ITER and the breach size is very small, finding the breach position will be very difficult because the pressure rise in the VV is very slow.

Figure 9 shows the changes in exchange flow rates through the breaches at the atmospheric pressure tests. In this figure, T1-S1 means the double breach case in which T1 and S1 breaches are opened simultaneously, and T1 means the single breach case in which T1 breach is only opened, and also S1 means the case in which the S1 breach is only opened. Here, the exchange flow rates were calculated from the exchange mass inside the VV measured by the electronic balance, and t is the time from the start of the experiments.

From these results, it can be concluded that: the flow exchange at the double-breach case is almost completed in a short time in comparison with that at the single-breach case because a two-way flow occurs through both breaches. On the other hand, the flow exchange at the single breach case takes lots of time until its completion. The flow exchange at the T1 breach case is suppressed because the exchange flow through the T1 breach becomes a counter-current flow. Moreover, the flow exchange at the S1 breach case is carried out smoothly in comparison with the T1 breach case because the exchange flow through the S1 breach becomes a stratified flow. These flow patterns through breaches as can be seen in Fig. 9 were visualized and confirmed using the smoke. Based on the above, the severest breach condition in ITER was changed from the top-break case (i.e., T1 breach case) to the side-break case (i.e., S1 breach case).

4. FUTURE PLANS OF ICE/LOVA EXPERIMENTS

4.1. Overall Objectives

The thermal-hydraulic characteristics during the ICE and LOVA events could be understood quantitatively from the preliminary ICE and LOVA experiments. However, since each size of those apparatuses was very small in comparison with ITER, it is not easy to extrapolate the ICE and LOVA behavior under the ITER conditions from the preliminary experimental results. Therefore, combined ICE/LOVA tests were needed.

The overall objectives for the combined ICE/LOVA test facility are:

- To demonstrate that the ITER safety design approach and design parameters are adequate for mitigation of the ICE and LOVA events; and
- To provide experimental data for validation of safety analysis codes and methodologies that will be used for regulatory quality analyses.

For demonstration of the adequacy of safety design approach and design parameters, the simulation test was focussed on the Category IV multiple FW pipes break event, where is the highest pressure of the plasma chamber is predicted in the NSSR-2 analyses [2]. More detailed experimental objectives are to get integrated test data to make sure that the code-predicted accidental over-pressure is correct including the effect of steam generation in plasma and vacuum chambers, two-phase pressure drop through the divertor and the divertor ports, and the condensation in the suppression tank.

The following thermal-hydraulic phenomena have been investigated for the code validation:

- steam generation due to flashing in the plasma chamber;
- steam generation due to boiling on the superheated wall surface;
- two-phase flow pressure drop through the divertor; and
- direct-contact condensation effect in the suppression tank.

4.2. Sizing of the Combined ICE/LOVA Test Facility

The scaling factor of main components is around 1/1000 (test facility/ITER). Table 1 shows the design parameters of the combined ICE/LOVA test facility. The basic policy of the scaling is to functionally simulate the ICE/LOVA phenomena, such as by scaling based on volume and mass, without modeling the actual shape of ITER machine. The proposed basic scaling laws between the test facility and ITER are: the volume size is 1/1000; and flow velocity, pressure and temperature are simulated by the scaling factor of 1/1, respectively.

4.3. Design Descriptions

Figure 10 shows a schematic of the conceptual design of the combined ICE/LOVA test facility. The test facility mainly consists of a plasma chamber, simulated divertor, simplified vacuum vessel, divertor port, relief pipe and suppression tank.

The plasma chamber is a cylinder with a diameter of 1200 mm and length of 2500 mm. It can be heated up to 270°C using electrical heaters, which are enclosed around the chamber. Some water injection mechanisms are put into the plasma chamber to simulate the primary pipe break conditions. Here, the direction of the water injection nozzle can be changed to investigate the effect of the wall-impingement jet heat transfer.

The simulated divertor has an orifice plate with multiple holes as can be seen in Fig. 10. The orifice plate simulates open holes (i.e., gaps between the plasma chamber and VV) at the divertor cassette. By changing the orifice plates, the effects of hole size and pitch on the two-phase flow behavior through the divertor can be investigated. The overall pressure drop characteristics through the divertor can be obtained.

A generic bypass line is also connected to the plasma chamber and the other end is atmosphere. This line consists of a window, gap adjuster, valves and piping. The window is set up to measure exchange flow velocities under the LOVA conditions using a laser technique. The gap adjuster simulates the choking effect by the gas baffle plate.

Figure 11 shows the elevation of a plasma chamber, simulated divertor, simplified VV, divertor port and suppression tank. The simplified vacuum vessel is set up the bottom of the plasma chamber through the simulated divertor. The simplified vacuum vessel simulates the bottom small part of the VV in ITER. The wall temperature is controlled separately from the plasma chamber to make test conditions. Three observation windows are set to the simplified vacuum vessel to understand visually the two-phase flow behavior.

The divertor port is connected to the simplified vacuum vessel as can be seen in Fig. 11. This is a cylinder with a diameter of 300 mm and length of 2000 mm. This divertor port is connected to a suppression tank through the relief pipe as same as the ITER design.

The suppression tank consists of a cylindrical tank, plenum distributor and many organ pipes. This tank is set up just under the divertor port through the relief pipe. A magnetic valve is set up to the relief pipe. The suppression tank is connected to the divertor port by opening the magnetic valve. Using this suppression tank, direct-contact condensation characteristics during the ICE event can be investigated.

The boiler consists of a cylindrical tank and electric heaters. Water is pressurized by nitrogen gas and heated up by the electric heaters. Its volume and maximum water holdup will be around 1 and 0.8 m^3, and those values were determined to satisfy the coolant inventory of Category IV multiple in-vessel leakage case based on a scaling factor of 1/1000. The pressurized water in the boiler circulates the circulation loop to prevent from a temperature decrease at the tip of the water nozzle in the water injection mechanism. The water circulation is stopped before the experiment and then the pressurized water is injected into the plasma chamber.

5. CONCLUSIONS

The thermal-hydraulic characteristics in the VV of a fusion reactor under the ICE and LOVA events were investigated quantitatively. In the preliminary ICE experiments, the pressure rise characteristics in the VV were clarified and the performance of the blowdown tank was confirmed. In the preliminary LOVA experiments, the relationship between the saturation time and breach size in the VV was obtained from the results of the vacuum tests and the exchange flow characteristics through the breaches were understood from the results of the atmospheric pressure tests. The present experimental data were very useful to validate the thermofluid safety analysis codes for fusion reactors. In addition, to predict with high accuracy the thermal-hydraulic characteristics during the ICE and LOVA events under the ITER condition, the necessity of a large-scale test facility was mentioned. The current conceptual design of the combined ICE/LOVA test facility with a scaling factor of 1/1000 in comparison with the ITER volume was expressed. The authors are planning on performing numerical simulations regarding the ICE and LOVA phenomena after the combined ICE/LOVA test facility has been set up.

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Table 1 Comparison of design parameters between ITER and test facility

ITER design parameters	Test facility design parameters
- Plasma chamber Volume (including divertor pocket volume) : 2640 m^3 Coolant outlet temp.(normal): 191°C Coolant outlet temp.(baking): 240°C	**- Plasma chamber** Diameter: 1200 mm Length: 2500 mm Volume: 2.9 m^3 Maximum temperature: 270°C Resisting pressure: 1 MPa
- Vacuum vessel Volume (including penetration volume): 4592 m^3 Volume (excluding penetration volume): 3800 m^3 Coolant temp.(normal): 111°C Coolant temp.(normal): 200°C	**- Simplified vacuum vessel** Diameter: 300 mm Length: 2500 mm Volume: 0.2 m^3 Maximum temperature: 270°C Resisting pressure: 1 MPa
- Divertor port Height: 2545 mm Width: 1544 mm(upper) 810 mm(lower)	**- Divertor port** Diameter: 300 mm Length: 2000 mm Volume: 0.15 m^3 Maximum temperature: 270°C Resisting pressure: 1 MPa
- Primary water cooling system Design pressure: 5.8 MPa Operating pressure: 4.7 MPa Design temperature: 270°C Coolant inventory at Categort IV event: 757 m^3 Maximum breach area at Category IV event: 0.6 m^2	**- Boiler** Diameter: 800 mm Length: 2000 mm Volume: 1.0 m^3 Maximum water holdup: 0.8 m^3 Maximum water temperature: 270°C Maximum water pressure: 5 MPa Water nozzle diameter: changeable
- Suppression tank Internal volume: 2246 m^3 Water volume: 1055 m^3 Expansion volume: Max. 75 m^3 Total organ pipe flow area: 8.3 m^2	**- Suppression volume** Diameter: 900 mm Length: 2500 mm Volume: 1.6 m^3 Resisting pressure: 1 MPa Relief pipe diameter: 100 mm

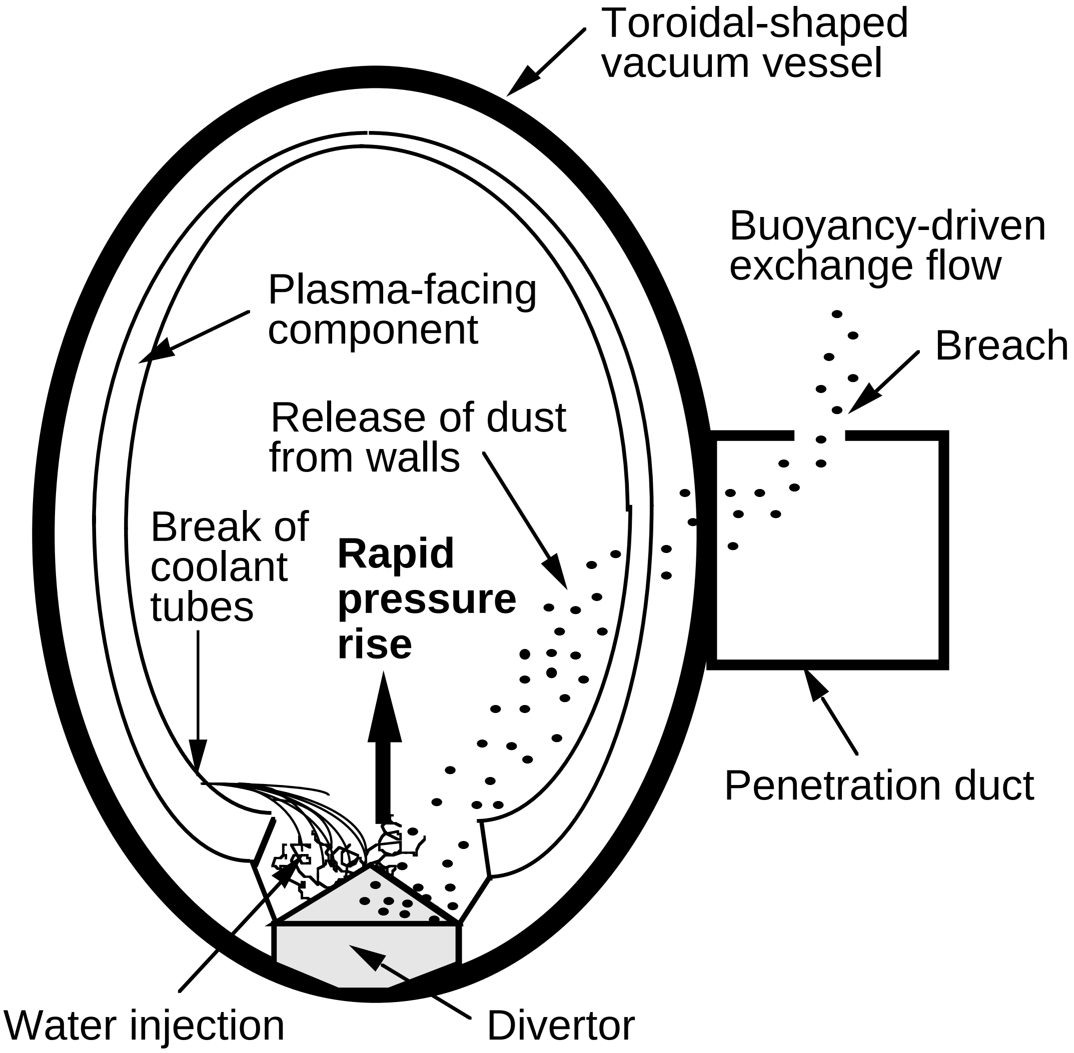

Fig. 1 Scenario of the ICE and LOVA events in fusion reactors

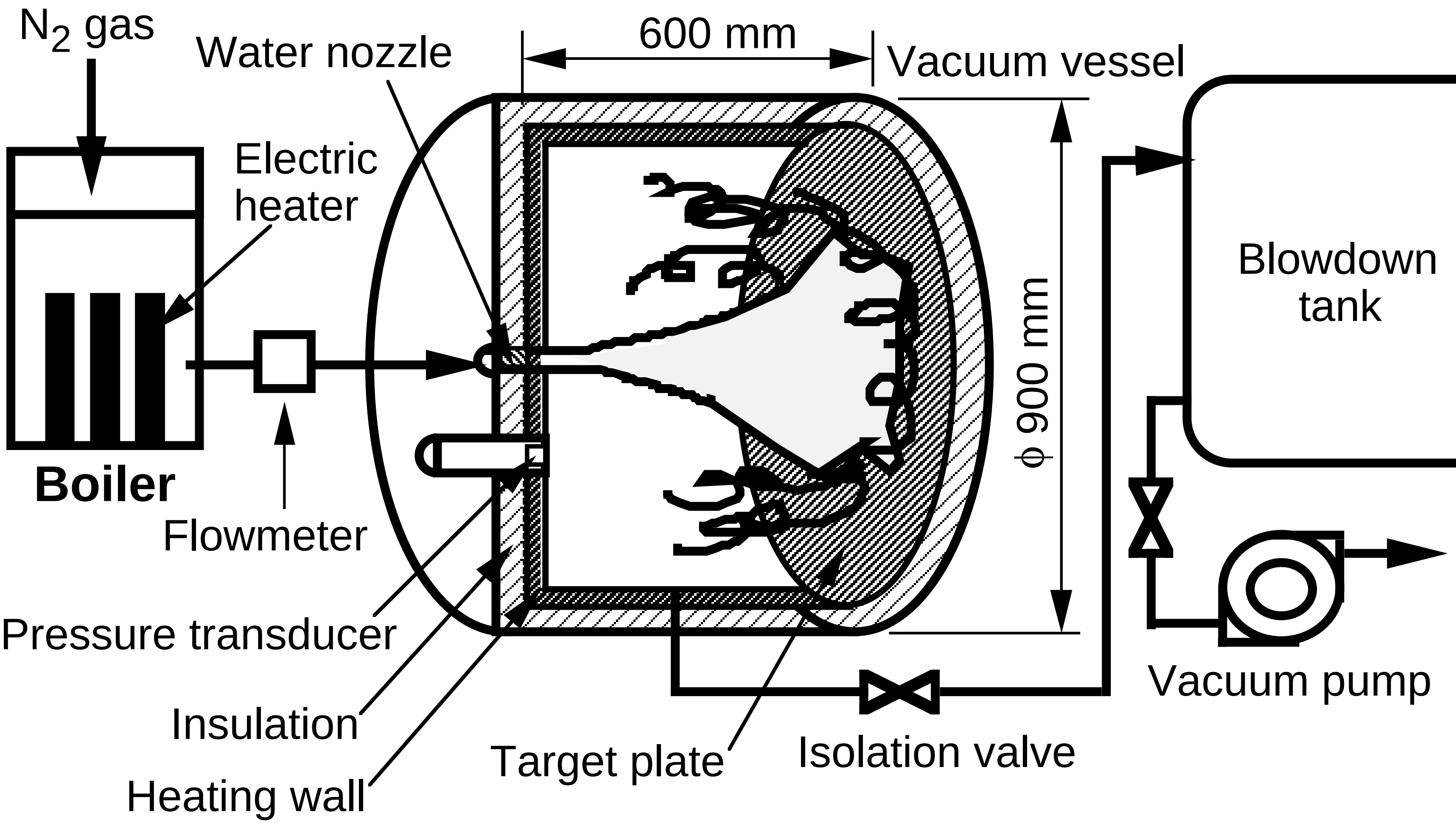

Fig. 2 Schematic of the preliminary ICE apparatus

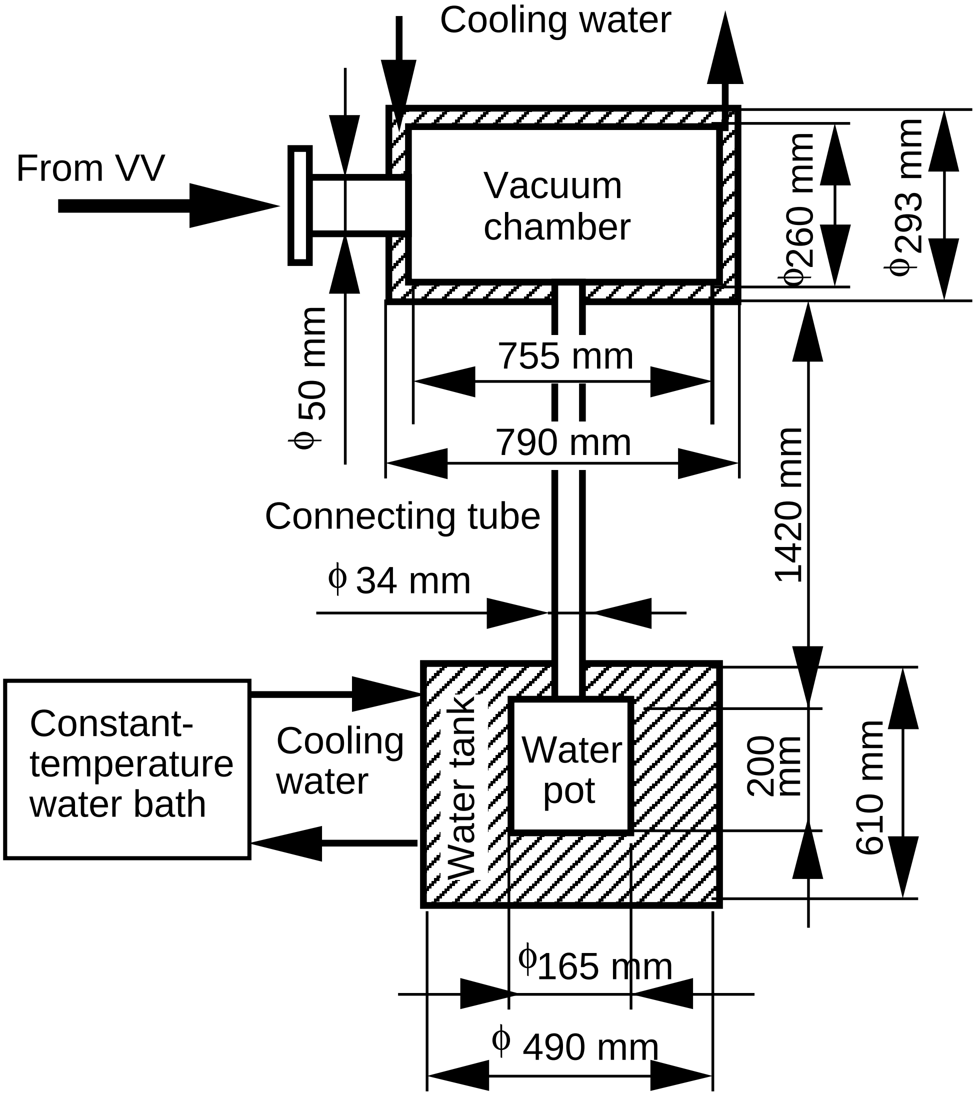

Fig. 3 Schematic of B type suppression tank

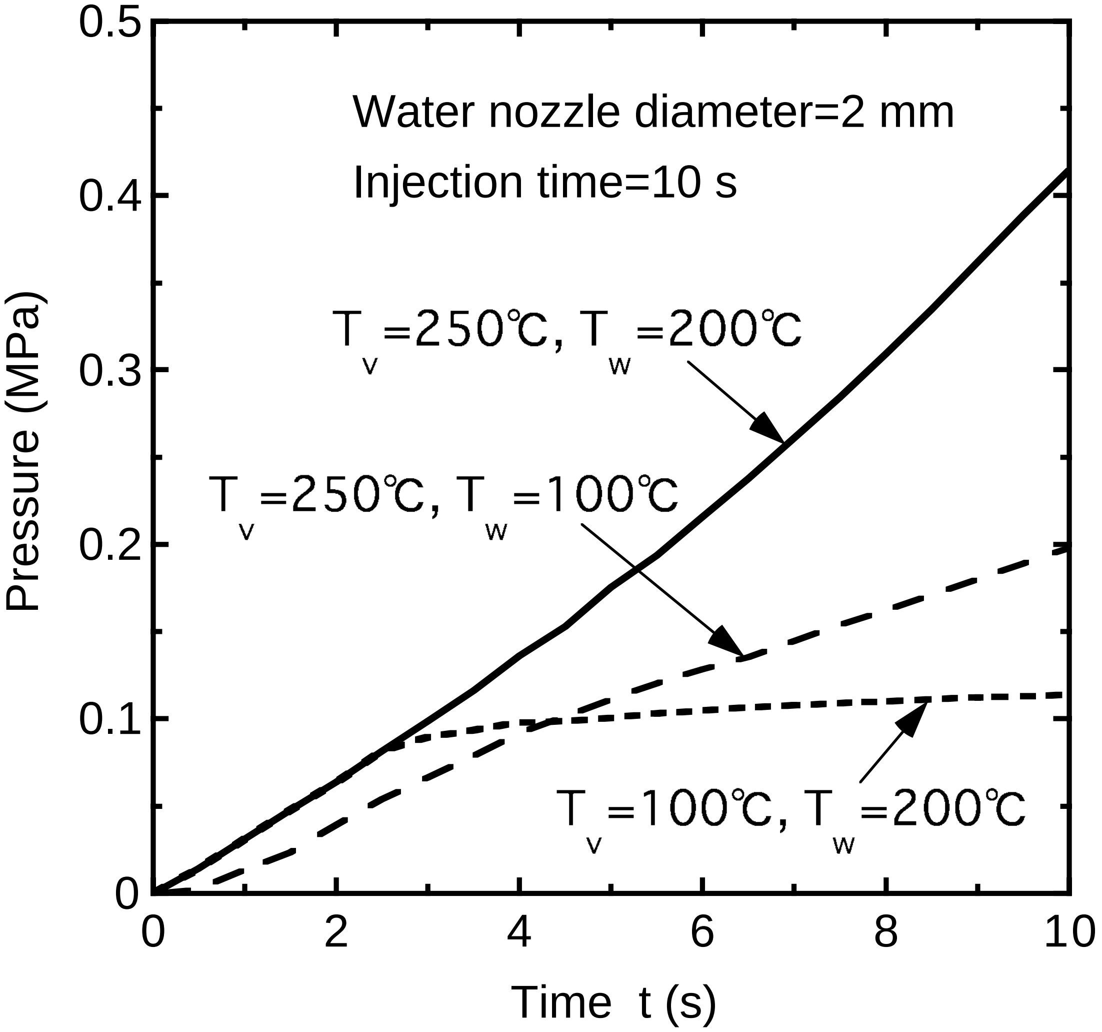

Fig. 4   Effects of water and wall temperatures on pressure rise

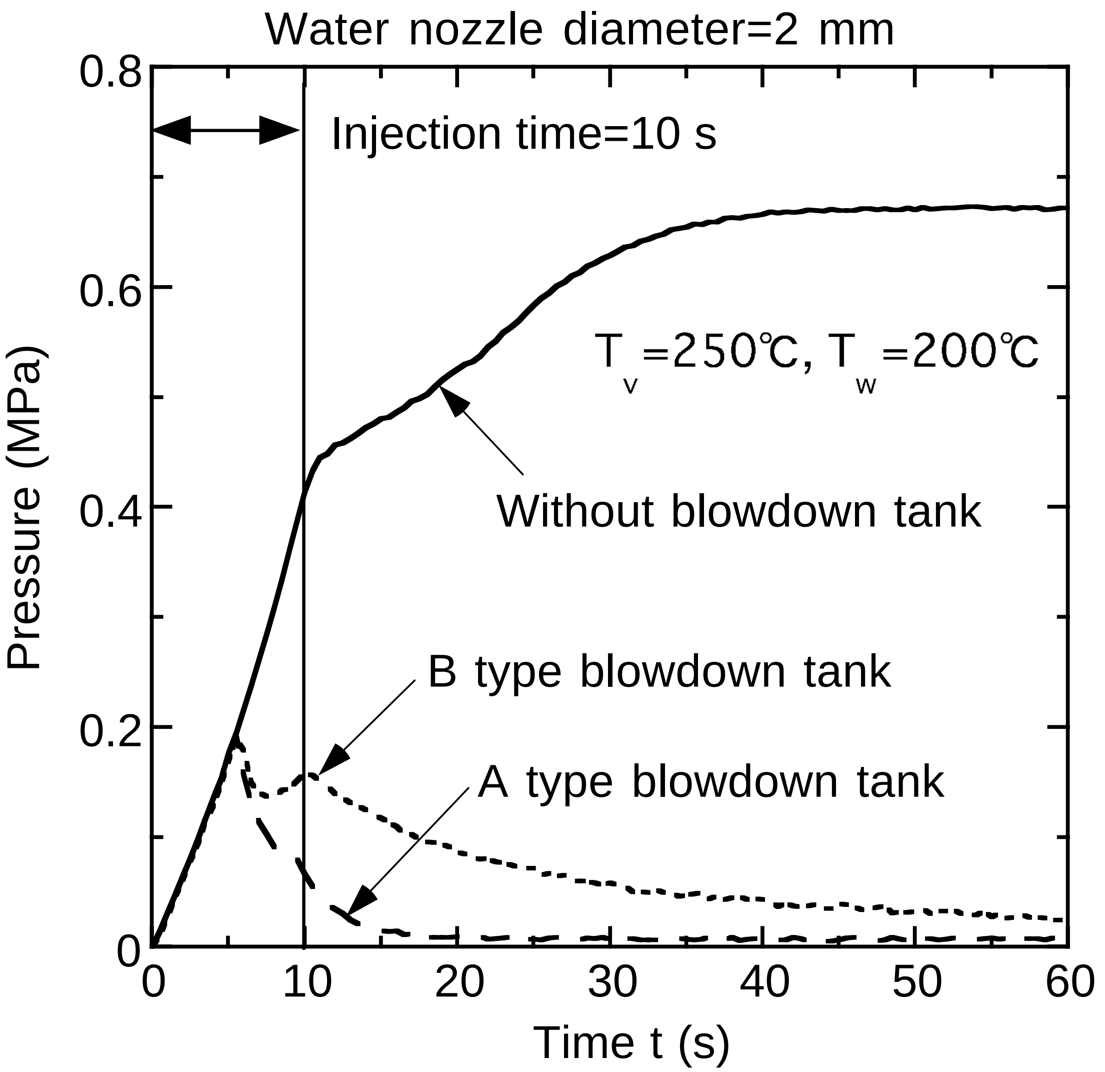

Fig. 5 Pressure transients with/without a blowdown tank

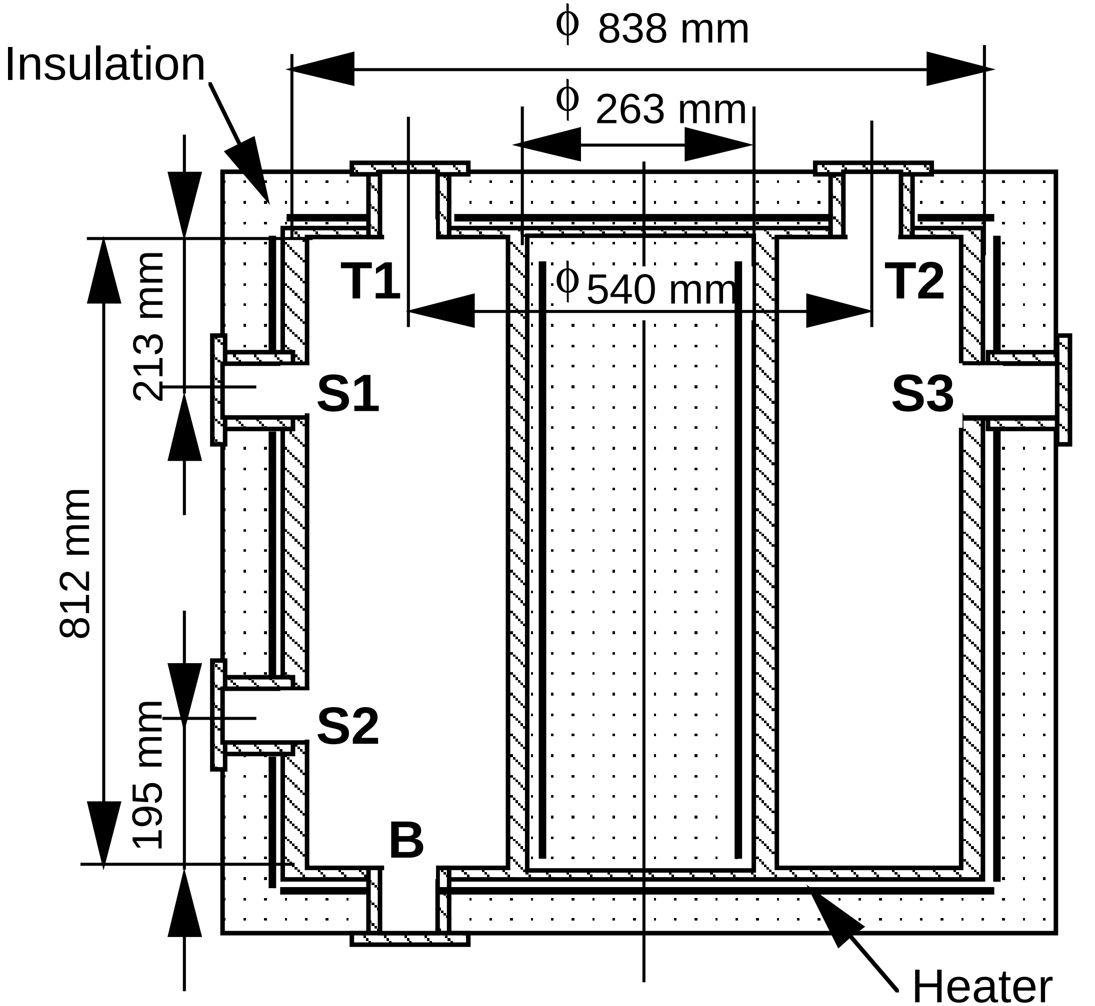

Fig. 6 Schematic of the toroidal-shaped vacuum vessel in the LOVA apparatus

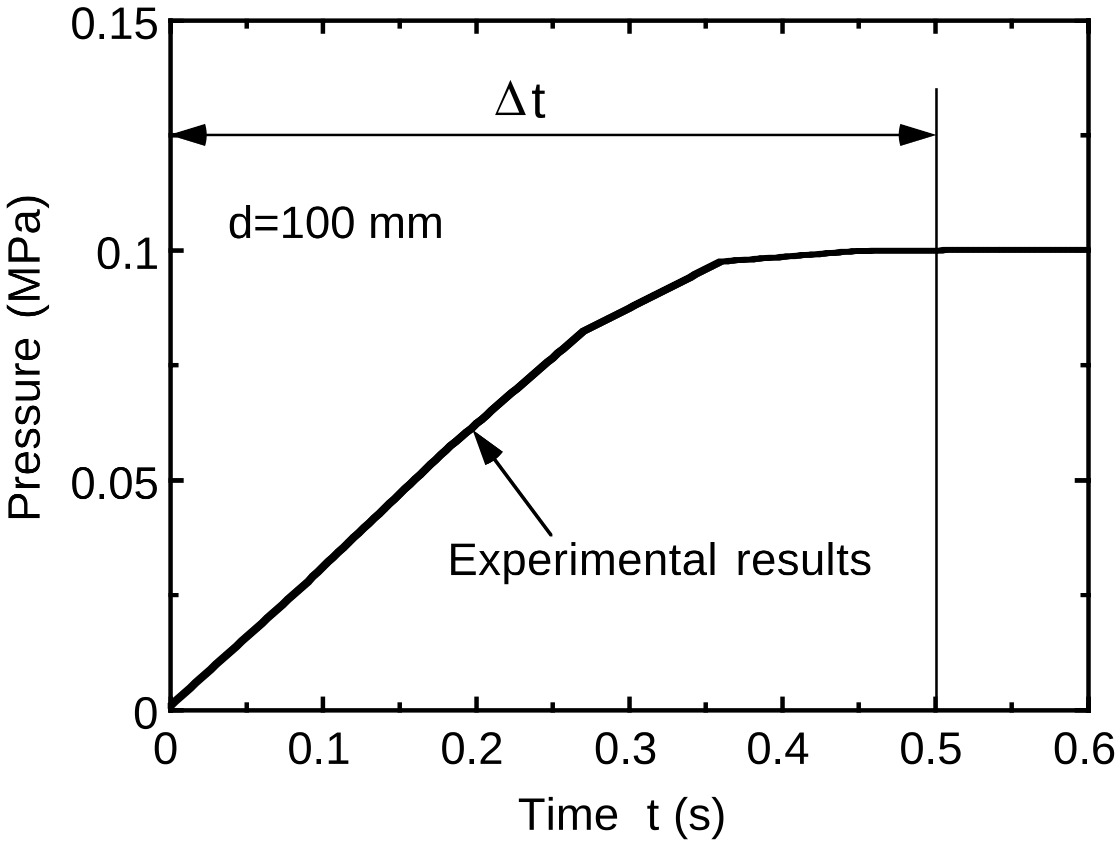

Fig. 7 Pressure transients in the VV during vacuum test under T1 breaching condition

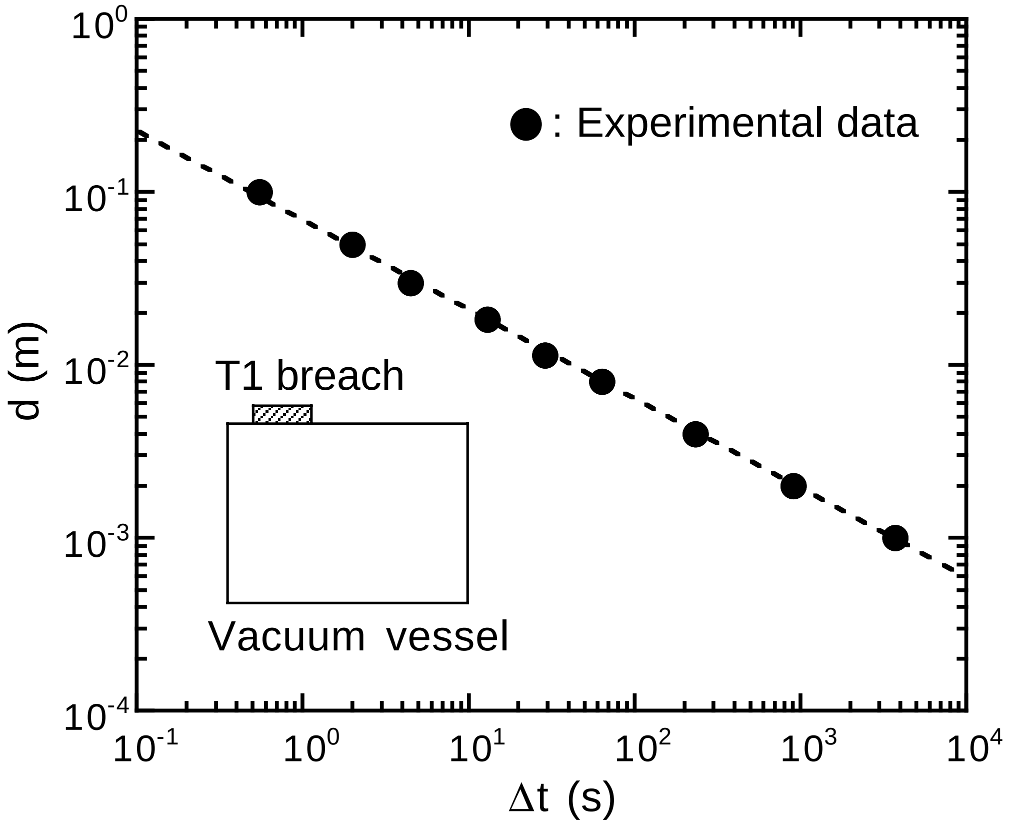

Fig. 8 Relationship between d and Δt during vacuum tests under T1 breaching condition

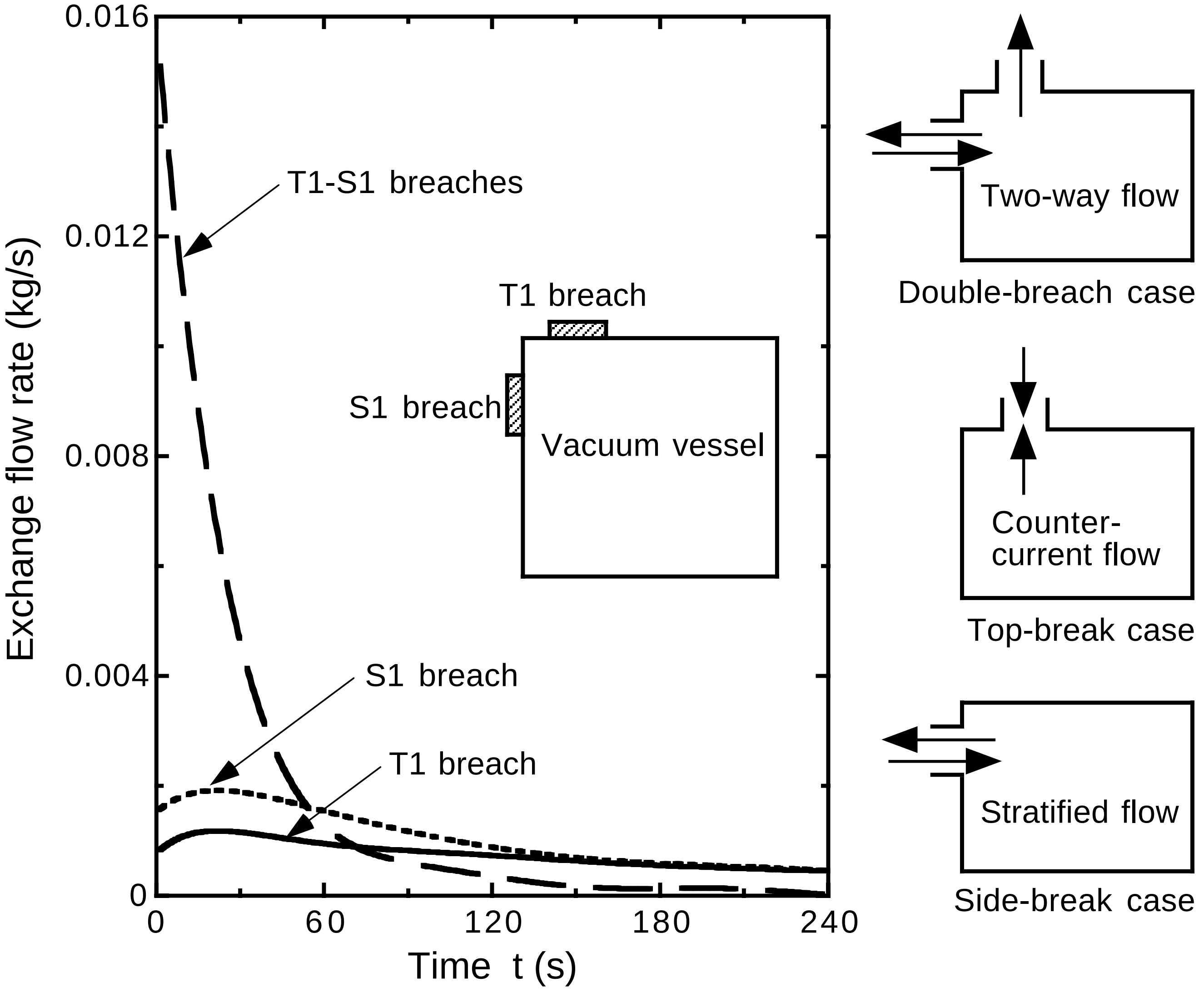

Fig. 9 Exchange flow rates through different breach positions under atmospheric pressure conditions

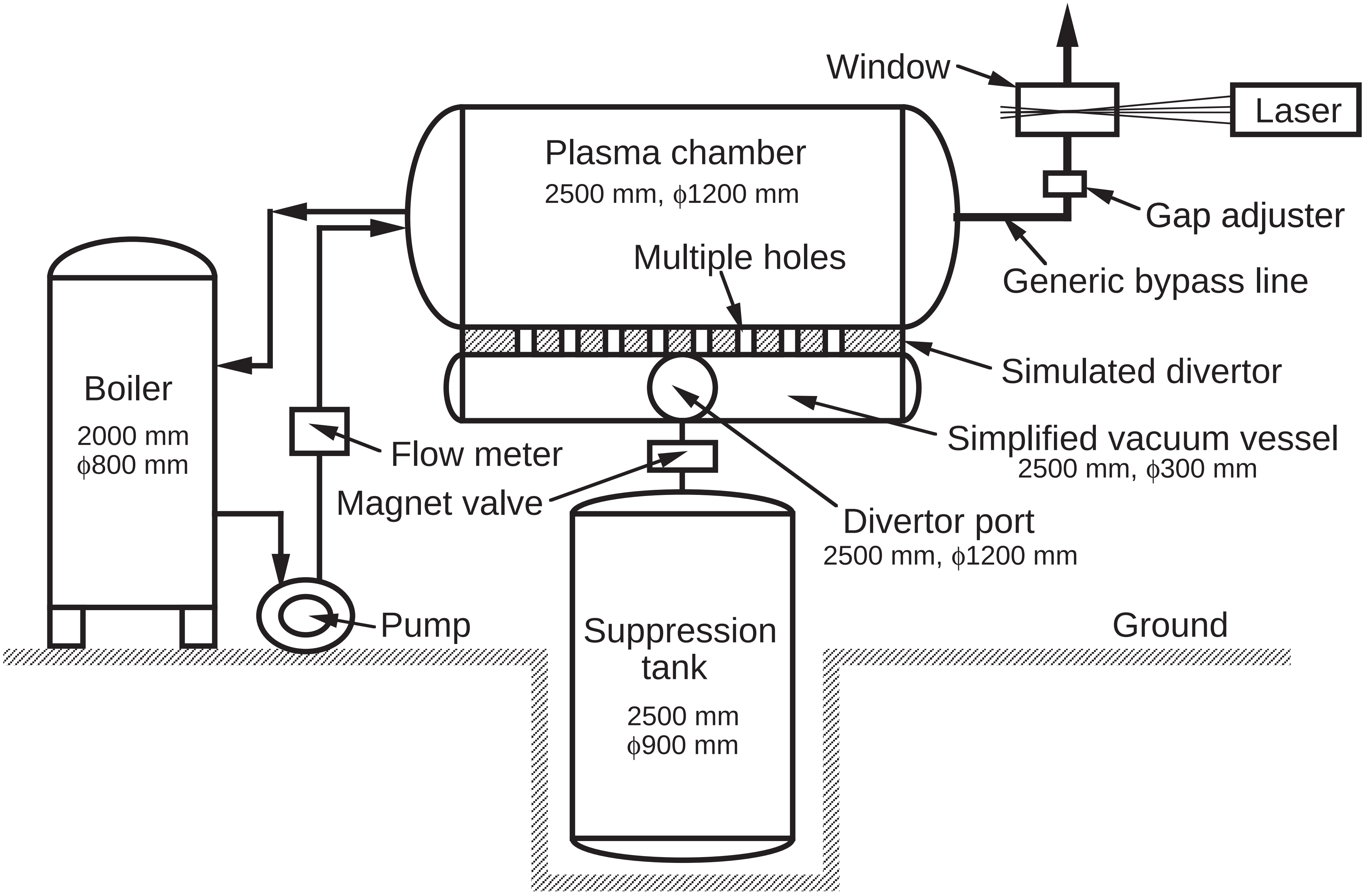

Fig. 10 Schematic of the combined ICE/LOVA test facility

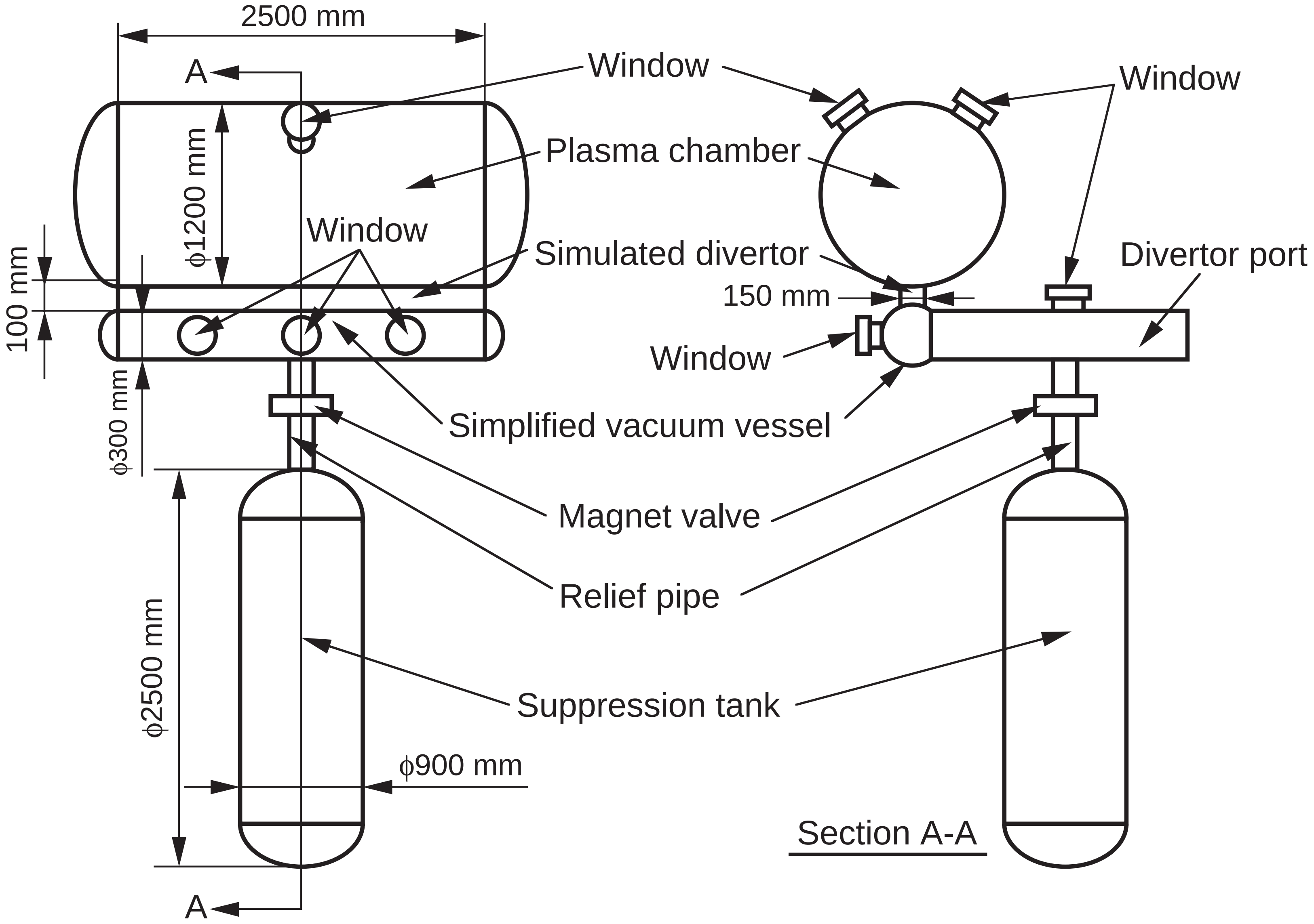

Fig. 11 Elevation of plasma chamber, simulated divertor, simplified vacuum vessel, divertor port and suppression tank in the combined ICE/LOVA test facility