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THE AAEC BLOWDOWN AND CONTAINMENT RIG

by

P.G. HOLLAND

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ABSTRACT

The arrangement, operation and associated instrumentation of the AAEC blowdown and containment rig up to mid-1980 is described. Details of typical experiments are given to illustrate applications. The rig consists of a 14 L high pressure vessel, rated to operate up to 16 MPa at 340°C, and an 1800 L low pressure vessel having a maximum pressure rating of 450 kPa at 250°C.

The blowdown discharge rate can be controlled in various ways, including flow through an 8 mm bore tube or one of a set of bevelled orifice plates with bores ranging from 2 to 8 mm. The variables usually measured are the pressure and temperature at selected positions as functions of time.

Experimental results show, among other things, the considerable effect of the initial air pressure in the containment vessel on the maximum pressure attained and on the temperature distribution.

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BLOWDOWN; CONTAINMENT; PRESSURE VESSELS; SIMULATION; REACTOR SIMULATORS; LOSS OF COOLANT; HIGH PRESSURE; MEDIUM PRESSURE; HIGH TEMPERATURE; MEDIUM TEMPERATURE; SPATIAL DISTRIBUTION; PRESSURE DEPENDENCE; PRESSURE MEASUREMENT; TEMPERATURE MEASUREMENT; FLUID FLOW

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1. INTRODUCTION

A loss-of-coolant accident (LOCA) is generally held to be a very severe fault condition (formerly called 'maximum credible accident' (MCA)) in a water-cooled nuclear power reactor. The blowdown and containment rig described in this report was built at Lucas Heights to perform experiments which will simulate some aspects of this type of accident and provide experimental data which will enable a better appreciation of the thermohydraulic phenomena occurring during blowdown from a reactor pressure vessel into a containment building. The analysis of such data from even small-scale experiments is of substantial value in assessing the applicability and probable accuracy of computer codes now used in reactor accident analyses.

The maximum ratings of the high pressure vessel (HPV) are similar to the operating pressure and temperature of the primary coolant system of a conventional pressurised water reactor. The low pressure vessel (LPV), into which hot water is discharged from the HPV, simulates the essential features of the thermohydraulic behaviour of a simple containment vessel.

This report provides detailed provide background information relevant to published work [Marshall and Holland, 1976, 1977a, 1977b; Marshall 1979].

2. RIG DESCRIPTION

The blowdown and containment rig is shown schematically in Figure 1 and the main dimensions are set out in Table 1. The rig may be arranged so that the fluid discharge from the high pressure vessel is directed in one of two ways; it is sent either to the outside atmosphere (as in arrangement 1), or to a low pressure containment vessel (as in arrangement 2). The HPV is mounted on a flange which is separated from the lower supporting flange by an insulating spacer assembly holding an electrical heater (Figure 2).

Arrangement 1 was used for an initial series of experiments to gain information on the depressurisation of the HPV containing water under pressure. Vertically below the HPV, a short pipe carrying a thermocouple at its lower end is fitted to the pipe section; further downstream is the bursting disc assembly, a transition piece and ducting connected to the outside atmosphere.

In arrangement 2 the discharged fluid is passed through the curved outlet pipe installed below the HPV, then via the pipe section (or orifice plate), the bursting disc assembly and the expansion pipe (EP) into the LPV.

The rig has been designed, built and tested to conform to the Standards Association of Australia, AS.1210-1977, and ASME Boiler and Pressure Vessel Code, section 8, division 1.

2.1 High Pressure Vessel and Outlet Pipe

The HPV is a class 1 pressure vessel made of type ASTM A312 TP316 (formerly Australian Standard G19-316) stainless steel; it is completely lagged with the glass fibre compound Insulwool. The HPV is shown in the isometric drawing on Figure 1, and in more detail on Figure 2; its maximum pressure rating is 16 MPa at 340°C. Its internal effective volume (13.6 L) was determined from its dimensions and confirmed by water filling.

An outlet pipe, made of stainless steel (Figure 3), joins the HPV to the pipe section in arrangement 2 of the rig by means of Ermeto fittings.

2.2 Electrical Heater

The water contained in the HPV is heated by a low voltage (approx. 30 V), direct current (approx. 300 A), custom-built immersion heater rated at 10 kW and consisting of twelve separate coils, connected in parallel and each wound with 19 B.S.G. (1.07 mm dia.) bare nichrome wire which is in direct contact with the water. Each coil consists of 31 turns and has a resistance of 1.3 ohms; the coils are installed on formers of tubular alumina each 8 mm dia. x 63 mm length. The heater is electrically insulated from the HPV by means of gaskets of phenolic resin asbestos sheet placed between the two spacers that separate the two flanges; it is located, as shown in Figure 2, at the bottom of the HPV and attached to the annular surface of the lower spacer and extending inside the flange on the HPV. It is fully immersed at the beginning of an experiment.

2.3 Flow Restrictions

The discharge flows through either a pipe section or an orifice plate, of which several sizes are available; in the latter case, a length of straight pipe is inserted upstream of the orifice plate.

2.3.1 Pipe section

As shown in Figure 4a, the pipe section has a bell-mouth inlet leading into a parallel-sided section of 8 mm i.d. (nominal) x 173 mm length, and an outlet having a conical divergent passage with an included angle of 7°. The section is made of carbon steel which is plated with nickel to a depth of 75 µm to prevent corrosion. Figure 1 shows the position of the pipe section relative to the other components and Table 1 gives its dimensions.

The small divergence of 7° allows the flow to 'choke' at the throat, and produces an exit pressure distribution which is reasonably characteristic of the free stream [Henry 1968]; this means that the pressure measured at the pipe wall is nearly equal to that anywhere on a diametral plane.

2.3.2 Orifice plate

Bevelled stainless steel orifice plates, of nominal thickness 3 mm, were manufactured with a 90° outlet angle according to the dimensions shown in Figure 4b. This type of flow restriction has a very small L/D ratio, and so produces a very different flow pattern from that in the pipe section. The orifice plate is inserted in the bursting disc assembly, immediately upstream of the bursting disc, as shown in Figure 4c. When this type of flow restriction is used, a pipe of 16 mm i.d. replaces the pipe section described in Section 2.3.1.

2.4 Bursting Disc Assembly

The bursting disc unit serves as a fast-acting valve, which presents minimal flow restriction when it is opened. As shown in Figure 5, the bursting disc assembly comprises essentially a pressure block mounted between two 'holders' with a flow passage through the assembly of 16 mm diameter. Two identical copper bursting discs, initially 0.23 mm thick, are each held between a stainless steel ring and a stainless steel holder; they are made to rupture at approximately three-quarters of the required maximum steady-state pressure in the HPV. The central space between the discs, which is termed the 'buffer zone', is filled with nitrogen gas the pressure of which is continuously adjusted to be at about half of the HPV pressure during warm-up; in this way there is approximately the same pressure difference across each disc when the unit is in service. The discs will burst when gas is released from the buffer zone. The dished centres of both discs (first the upstream disc, then the downstream disc) rupture around their circumference and the fluid held in the HPV and outlet pipe is then discharged through the expansion pipe into the LPV. The burst centres are blown into the LPV and the flow passage is left clear.

2.5 Expansion Pipe

The expansion pipe (EP), shown in Figure 6, is a class 3 pressure vessel, rated for 1.17 MPa at 250°C, and made in accordance with the SAA code, AS.1210-1977. It was fabricated from a 92 mm bore carbon steel pipe of 5 mm wall thickness.

It was originally intended to be used as a test length on which measurements would be made of pressure gradients (both across a diameter and along the pipe axis) and voidage during a transient, so a number of equally pitched tapping positions were welded along the pipe length. However, the tappings have not been used for this purpose.

2.6 Low Pressure Vessel

The low pressure vessel (LPV) is shown in Figure 7; it consists of a cylindrical shell with two domed ends and is made of mild steel. It is rated for 450 kPa internal pressure at 250°C and can withstand an internal vacuum at temperatures up to 120°C.

The vessel is a class 2 unfired pressure vessel and has been built in accordance with SAA Boiler Code CB1, parts I to V. The internal surface was left as bare mild steel for the experiments described by Marshall and Holland [1976, 1977a]. Subsequently, it was painted with an amorphous carbon paint (British Paints Ltd Apexior No.1) to reduce corrosion. This coating is often used to protect 'hot wet' metal surfaces subjected to quite high temperatures; after operating for three years, the surface had deteriorated and required further treatment, so it was subjected to an abrasive blast (to achieve a class 3 condition) to expose the parent metal. The surface was then coated with inorganic zinc to a depth of approximately 75 μm.

3. INSTRUMENTATION AND MEASUREMENT

3.1 Fast Response Instruments

The instrumentation used to determine instantaneous values of physical quantities during an experiment is listed in Table 2 and identified in Figures 8a and 9.

The pressure transducers P_1, P_3 and P_4 are calibrated during each experiment using the Heise Bourdon tube pressure gauge (Section 3.2) which measures the HPV steady-state pressure; transducers P_2 and P_5 are calibrated in situ using a dead-weight tester, so that all the sensors and their associated amplifiers are checked together. Figure 8a shows a rig configuration in which the fluid is discharged through the pipe section; for blowdown tests in which the flow restriction is an orifice plate and not the pipe section, pressure sensors P_3 and P_4 are not fitted.

The liquid level of the HPV is measured by the differential pressure transducer (DP), shown in Figure 8a. One side of the DP cell is connected to the bottom of the HPV, and the other to the top of the vessel via an external cold leg maintained, throughout the blowdown, full of water at ambient temperature. The condenser (Figure 8b), situated at the top of the cold leg and cooled by natural circulation of surrounding air, is a container having a cross-sectional area that is larger than that of the standpipe below it; consequently, a relatively large change in condensate volume, which might be caused by evaporation in the HPV during the blowdown, would produce only a small height difference and hence only a small pressure change on the high pressure side of the DP cell. The transducer is calibrated with a known height of water, measured by the graduated glass tube shown in Figure 2, in the HPV on one side and a column of water in the cold leg on the other; the net output is displayed as a digital voltage and is also available as an analogue voltage for recording. The calibration is repeated over the range of initial water heights needed for the test program.

The internal wall temperatures of the LPV are measured by 1 mm stainless steel sheathed chromel-alumel thermocouples, held tightly to the surface by spotwelded stainless steel straps. Twelve thermocouples, in positions indicated as A1 → A4, B1 → B4, C1 → C4, are dispersed internally at approximately 90° spacings around the circumference of the LPV at each of three levels, as shown in Figure 9.

The atmospheric temperature inside the LPV is measured with a 0.5 mm thermocouple near the centre-line of the vessel and at a height of 600 mm above the base of the cylindrical section (see Figure 9).

The thermocouples are calibrated in a temperature bath before installing them on the rig; the thermocouple amplifiers are regularly calibrated using a precision voltage source. All the thermocouple cold junctions are made inside an insulated box. The temperature inside this enclosure is measured by a resistance thermometer.

The recording instruments used in the initial experiments were a six-channel Hewlett-Packard 7000 series pen recorder and an eighteen-channel Yokogawa type 2916 ultra-violet recorder; a maximum of eight channels on the UV recorder was used to achieve a clear indication of events and enhance signal identification. For convenience, the pressure sensor outputs were displayed on one chart recorder and most of the thermocouple outputs were shown on another; the recorders were synchronised by a common time marker so that all of the quantities could be evaluated at any particular time following the start of blowdown.

Towards the end of 1978, a datalogger based on a DEC LSI-11 computerised system was installed. This instrument can scan up to sixteen differential-input channels and directly digitise the signals, storing the digital information on a high density flexible magnetic disc. There is a high speed serial data link existing between this computer, a DEC PDP11/03 computer, and an IBM3031 computer which may be programmed to analyse and plot the data.

3.2 Slow Response Instruments

Steady-state measurements of initial conditions are made with relatively slow response instrumentation. These are also used for the general operation of the rig. The instrumentation is indicated in Figure 10 and listed in Table 3. The Heise Bourdon tube pressure gauge (P_a) is calibrated with a dead-weight tester; it is used to measure the initial pressure within an accuracy of ± 0.1 per cent. The temperatures are all recorded on a Honeywell-Brown multi-point precision recorder.

Ambient temperatures in the vicinity of the fluid circuit are measured with two resistance thermometers; one is placed 60 cm below the expansion pipe and a second is inside the safety enclosure, described in Section 4.1, approximately 30 cm from the HPV. A third resistance thermometer is fixed to the outside of the LPV, 9 cm below the thermocouple in position A3, to measure the initial temperature at the vessel wall: another thermometer measures the reference temperature inside an insulated box near the low pressure vessel. Other instruments are primarily used to detect possible faults (Section 4.2).

Figure 11 is a typical calibration chart of the water volume contained in the HPV; for a given height of water in the graduated sight glass, the water volume contained in the vessel may be determined. During tests,the sight glass is disengaged by the isolating valve (Figure 2).

3.3 Error Estimates

The steady-state instruments are used to determine the initial conditions of the rig, with overall estimates of experimental errors as follows:

Pressure in the HPV	± 0.3% fsd
Pressure in the LPV	± 1% fsd
Temperature in the LPV	± 1°C
Water volume in the HPV	± 0.08 L

4. SAFETY FEATURES

4.1 Intrinsic Safety

Intrinsic safety is provided by hardware which is designed to include built-in safety features. The five or six pressure vessels used in the rig (the HPV, condenser, double bursting disc assembly, expansion pipe and LPV, the pipe section, if used, being the sixth pressure vessel) have each been subjected to a hydrostatic test, in accordance with section 5.10 of the SAA Code, AS.1210-1977.

The high pressure section of the rig as far as the expansion pipe is surrounded by a timber-lined steel safety enclosure which stands approximately 3.6 m high around the HPV and 2.4 m high around the pipework up to the expansion pipe.

4.2 Engineered Safety Systems

Safe operation is ensured by instruments which are fitted to the rig or are connected to electrical relays that actuate trips and/or energise lamps and bells. Measures were incorporated to correct faults, the most important of which are as follows:

(i) If the pressure in the HPV rises above the expected blowdown pressure by a given margin, a warning lamp is illuminated. If no action is taken and the pressure continues to rise, the heater is tripped.

(ii) If the temperature in the HPV rises above the saturation temperature for the expected blowdown pressure by a given margin, a warning lamp is energised and a further rise will trip the heater.

(iii) If the HPV leaks through the bursting disc assembly before the expected blowdown pressure is reached, the signal from a thermocouple fitted at the upstream end of the expansion pipe will cause the heater power to be tripped.

(iv) If the electrical supply fails before the expected blowdown pressure is reached, the hot steam/water mixture in the HPV may be manually dumped through an emergency valve, which bypasses the bursting disc assembly.

(v) The positions of eight thermocouples on or near the HPV have been selected such that if any region near the vessel were to experience an unexpected temperature excursion during the course of an experiment, indicating a possible leak, it would be recorded by the multi-point recorder, and corrective action could then be taken.

5. EXPERIMENTAL PROCEDURE

To minimise the effect of air being present in the system, a vacuum pump is connected to the vent pipe, which extends inside the HPV (Figure 2). The pump is operated before each experiment to remove air from the vessel and the pipework to avoid trapping air bubbles. Demineralised water is injected into the vessel via the water inlet valve and the isolating valve. The vacuum pump is operated again after the completed filling procedure to remove air from the ullage space of the vessel and air dissolved in the water; the pump is switched off when the vessel pressure is 40 torr (5.2 kPa) which is usually reached within ten minutes.

During the filling procedure, when the vessel holds the required volume of water for the blowdown, the cold leg of the differential pressure transducer and the condenser are filled with water through the standpipe valve, situated above the condensate pot at the top of the cold leg of the differential pressure transducer, as shown in Figure 8a. The isolating valve is then opened and the water level in the HPV will be indicated in the graduated sight glass. The height of the water column in the sight glass corresponding to a predetermined quantity of water is given in the calibration plot of Figure 11. Fine adjustment of the level can be obtained using either the drain valve or the water inlet valve.

The electrical heater is energised to heat the water in the HPV and so raise its pressure. When the pressure in the HPV reaches 3 MPa, nitrogen gas is admitted to the central space within the bursting disc assembly until its pressure reaches 1.5 MPa, so that the pressure differences across the bursting discs are approximately equal. Further heating causes the pressure and temperature to rise; the gas pressure in the central space is increased such that its value remains continuously at about half of the pressure in the HPV, until the predetermined pressure is reached. In this way, the pressure difference across each of the two bursting discs always tends to burst them from the concave side of each disc.

The power input to the heater is then adjusted to keep the pressure of the steam-water mixture about 2 per cent higher than the predetermined blowdown pressure. After a period of 'soaking' at this elevated temperature, the HPV has reached a steady thermodynamic state as indicated on the multi-point precision recorder. The difference in temperature between the vessel wall and the fluid is small throughout the heating period: this may be seen in Figure 12 which is a typical multi-point recorder chart of some rig temperatures during an experiment.

The heater is then switched off and the HPV pressure starts to decrease. Blowdown through the flow restriction is initiated at the predetermined pressure by releasing to atmosphere the gas in the buffer zone.

For blowdown tests into a containment the containment vessel usually contains air at atmospheric pressure, but if a different initial condition is required, it may be partly evacuated by a pump connected as shown in Figure 10.

While the high pressure vessel is 'soaking' at the elevated temperature before blowdown, the instrumentation system is checked to ensure that the chart recorders or datalogger capture the pressure and temperature signals during the depressurisation of the HPV and the subsequent pressurisation of the LPV.

6. EXPERIMENTAL RESULTS

Several experiments have been reported [Marshall and Holland 1976, 1977a, 1977b; Marshall 1979]. Additional results are given here to expand that information.

(a) Temperature Transients

Temperature/time plots for the containment vessel during a blowdown are given in Figures 13 and 14. In the first of these, the initial air pressure in the containment vessel was one atmosphere and in the second at near vacuum, i.e. about 2.3 kPa. In these experiments the thermocouple at position A1 was faulty. The plots show the way in which the temperatures varied in different regions of the containment. When the pressure was initially at one atmosphere, there was a substantial spread among the temperatures at each level - except at the lower level (see Figure 13c) - which persisted for a considerable time.

Initially, the HPV contained a water mass of 6.7 kg at 7 MPa saturated pressure; the discharge into the low pressure vessel produced at the upper level a temperature increase which, on achieving maximum, was followed by a decrease to an equilibrium value (see Figure 13a). It appears that both conduction and convection effects contribute to the temperature increase. The thermocouple at position A2 was placed on the LPV wall nearly opposite the pipe through which the fluid enters the LPV from the HPV, so its output rose rapidly owing to the direct impact of the hot fluid; the thermocouple placed at A3, which is mainly influenced by convection, had a temperature smaller than A2. The thermocouple placed at A4, which was possibly influenced mainly by conduction from the expansion pipe, recorded the highest temperature of all the thermocouples nine seconds after blowdown was initiated. The middle level temperatures (see Figure 13b) followed similar curves at each of the four positions B1, B2, B3 and B4; their maximum generally occurred much later than those shown in Figure 13a, and the spread of their temperatures was fairly wide.

The temperature pattern indicated by the thermocouples B1, B3 and C1, C3 was approximately symmetrical about the vertical plane through the expansion pipe and LPV.

The information contained in Figure 14 is generally similar to that in Figure 13, but refers to different experimental conditions; the LPV was initially at a low pressure (2300 Pa). The temperature contours are within three degrees of each other after fifteen seconds; this applies to those around the circumference at the same level and those at different levels. The lower space temperature in Figure 14 approximates the wall temperature measured in the upper level at the front - see A4; apparently the steam/water mixture is carried rapidly down into the lower region.

(b) Pressure Transients

The second set of results is given in Figures 15-18 and consists of pressure/time plots. The influence of many factors on the pressure transients of both pressure vessels is shown; the type of restriction in the flow (i.e. whether flow occurs in a pipe section or an orifice), the size of the orifice plate used and the initial air content of the LPV are all investigated.

Figure 15 shows two pressure transients obtained by discharging a water mass of 6.9 kg, initially at a pressure of 10.4 MPa, through an 8 mm diameter pipe section into the LPV: Figures 16 and 17 show similar graphs for flow though a 4 mm diameter and a 2 mm diameter orifice respectively. After a rapid pressure drop and partial recovery, the pressure in the HPV fell somewhat slowly until most of the water had been ejected; at this point the discharge became predominantly vaporous and the pressure decrease was rapid. As Figures 15-17 indicate, the duration of the liquid phase increased as the outflow area was reduced. At the same time, the value of the peak pressure in the LPV also decreased, since the energy loss from the fluid to the vessel walls increased with increased time available for heat transfer.

Figure 18 [from Marshall and Holland 1977a] shows how the initial air content in the LPV affected the pressure rise following depressurisation of the HPV. The resulting pressure rose until the bulk of hot water had left the HPV, then it began to fall as negligible further energy was transferred. The presence of air increased the pressure rise markedly owing both to the rise in partial pressure of air with increasing temperature and to its inhibiting effect on the steam condensation. In these very early experiments, the walls of the LPV were not painted but had been left as bare metal.

7. PROPOSED MODIFICATIONS TO THE RIG

The following developments of the rig are planned:

(a) Improvement to the measurement systems, particularly in relation to the mass outflow rate from the high pressure vessel; a drag disc and turbine flowmeter will be used to measure this quantity. The experimental information will therefore be increased.

(b) A facility to recirculate the hot water in the HPV and outlet pipe, thereby ensuring uniform temperature throughout the water.

(c) Provision for the performance of blowdown tests in which the outlet from the high pressure vessel is at different heights; by this means the dependence of the depressurisation rate and the mass flowrate on rupture position can be investigated.

(d) Division of the low pressure vessel into two compartments either by a diaphragm within the existing vessel or by fitting an extension chamber to the vessel. It is intended to develop a method of measuring the flow of the air/steam/water mixture between the two compartments, and also to measure the wall heat transfer in both volumes.

(e) Adaptation of a two-compartment arrangement of the low pressure vessel so that it may be used to investigate the 'pressure suppression' system, in which a water pool is used to assist in reducing the pressure rise.

8. CONCLUSIONS

A detailed description has been given of the AAEC blowdown and containment rig, together with some typical experimental results obtained using this facility. The rig has been useful in gaining insight into some thermohydraulic transients which would occur during a loss-of-coolant accident in a water-cooled nuclear power reactor system. Information can be obtained both on the depressurisation of a pressure vessel containing water at appropriate reactor coolant conditions and on the pressure rise in a simple containment vessel. Arrangements are in hand to improve the scope of the measurements and to modify the rig for other relevant configurations.

9. ACKNOWLEDGEMENTS

J. Marshall, Leader of the Thermohydraulics and Measurements Section, has generally supervised the work. C. Campbell was responsible for the building and operation of the rig, and also for the subsequent development of the bursting discs. My appreciation is also extended to those who had charge of the earlier work, particularly to A. Payne for his development and design of the heater element and to K. Innes for initial development work on the bursting discs. A.G. Cassar and the late H.N. Harvey also made substantial contributions to the construction of this experimental facility.

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TABLE 1

MAIN DIMENSIONS

Component	Volume	Diameter (internal)	Length	Wall Thickness	Wall Surface Area
	m^3	mm	m	mm	m^2
High pressure vessel	0.0136	97.2	1.867	8.56	0.571
Outlet pipe -					
Arrangement 1	1.75×10^{-4}	15.0	0.825	2.03	0.0402
Arrangement 2	1.11×10^{-4}	15.9	0.308	1.6	0.0204
Pipe test section (choking part)	8.56×10^{-6}	7.94	0.173	5.55	4.31×10^{-3}
Discharge pipe -					
Arrangement 1	8.0×10^{-5}	15.9	0.402	-	0.0200
Arrangement 2	8.5×10^{-5}	15.9	0.428	-	0.0214
Expansion pipe	0.0142	92.0	2.132	5.0	0.650
Low pressure vessel	1.842	914.4	3.05	6.35	8.76

TABLE 2

INSTRUMENTATION FOR TRANSIENT MEASUREMENTS

	Identification	Sensor: Description	Sensor: Application	Sensor: Type	Sensor: Range
PRESSURES	P_1	Pressure transducer M.B. Alinco. 500S	Pressure in high pressure vessel (HPV)	Strain gauge/ bridge	0→2500 psig (~17 MPa)
	P_2	Pressure transducer Bell and Howell Ltd. 4-366-0001-01M0	Pressure in low pressure vessel (LPV)	Strain gauge/ bridge	0→10 bar absolute
	P_3	Pressure transducer M.B. Alinco. 500S	Pressure at expected plane of choking in test section	Strain gauge/ bridge	0→2500 psig (~17 MPa)
	P_4	Pressure transducer M.B. Alinco. 500S	Pressure at position one diameter up-stream of position of P_3	Strain gauge/ bridge	0→2500 psig (~17 MPa)
	P_5	Pressure transducer Bell and Howell Ltd. 4-366-0001-01M0	Pressure in expansion pipe (EP)	Strain gauge/ bridge	0→250 psig (~1.8 MPa)
	DP	Differential pressure transmitter. Rosemount 1151 DP	Water/steam interface displayed instantaneously: mass flow rate estimate during blowdown	Variable capacitance, temperature compensation with thermistor in module	0→150 inches (water) (~37 kPa)
TEMPERATURES	T_1	0.5 mm dia. thermocouple of stainless steel sheathed Cr-Al type	Temperature of steam/water mixture entering low pressure vessel	Thermocouple mounted inside last tapping of expansion pipe	0→1100°C
	T_2→T_9	1 mm dia. thermocouple of stainless steel sheathed Cr-Al type	Surface temperatures of the inside wall of the low pressure vessel	Thermocouple	0→1100°C

TABLE 3

INSTRUMENTATION FOR STEADY-STATE MEASUREMENTS

Group	Identification	Sensor: Description and Application	Sensor: Type	Range
PRESSURES	P_a	Large dial Heise gauge mounted on the high pressure vessel	Heise Bourdon tube	0→3000 psig (~21 MPa)
	P_b	Gauge mounted on top plate of the low pressure vessel	Budenberg Bourdon tube	0→60 psig (~500 kPa)
	P_c	Buffer line pressure gauge for measuring nitrogen pressure between supply bottle and buffer zone	National Instrument Company Pty. Ltd. Bourdon tube	0→3000 psig (~21 MPa)
	P_d	Buffer zone pressure gauge for measuring pressure in buffer zone between the two bursting discs	National Instrument Company Pty. Ltd. Bourdon tube	0→1000 psig (~7.0 MPa)
	P_e	Vacuum gauge to indicate degree of vacuum in high pressure vessel before the start of pressurisation	Speedivac Bourdon tube	100→0 torr
	P_f	Vacuum gauge to indicate degree of vacuum in low pressure vessel before blowdown occurs	Speedivac Bourdon tube	100→0 torr
TEMPERATURES	T_a	1.6 mm dia. thermocouple of the stainless steel sheathed Cr-Al type: upper thermocouple inside the high pressure vessel	Thermocouple connected to Shinko temperature controller	0→400°C on controller
	T_b	Thermocouple welded on the outside wall of the high pressure vessel approx. at the mid-height		
	T_c	1.6 mm dia. thermocouple of the stainless steel sheathed Cr-Al type-mounted at the mid-height position inside the high pressure vessel	Thermocouple connected to an Ether Transitrol temperature indicator-controller	0→400°C on controller
	T_d	1 mm dia. thermocouple of the stainless steel sheathed Cr-Al type in the flow core at the pipe block	T_a→T_h are all recorded on the Honeywell-Brown Multi-point Recorder. The actual locations may be changed at will. The eight selected thermocouples are useful in giving information or in detecting potential faults	The operational limit of the Cr-Al thermocouples is 1100°C, but the range of the recorder is 0→500°C
	T_e	Thermocouple welded on the outside wall of the outlet pipe close to T_d		
	T_f	Thermocouple in flow core at second post of EP		
	T_g	Thermocouple welded on the out-surface of the EP halfway along it		
	T_h	Thermocouple welded on the condensate pot body		

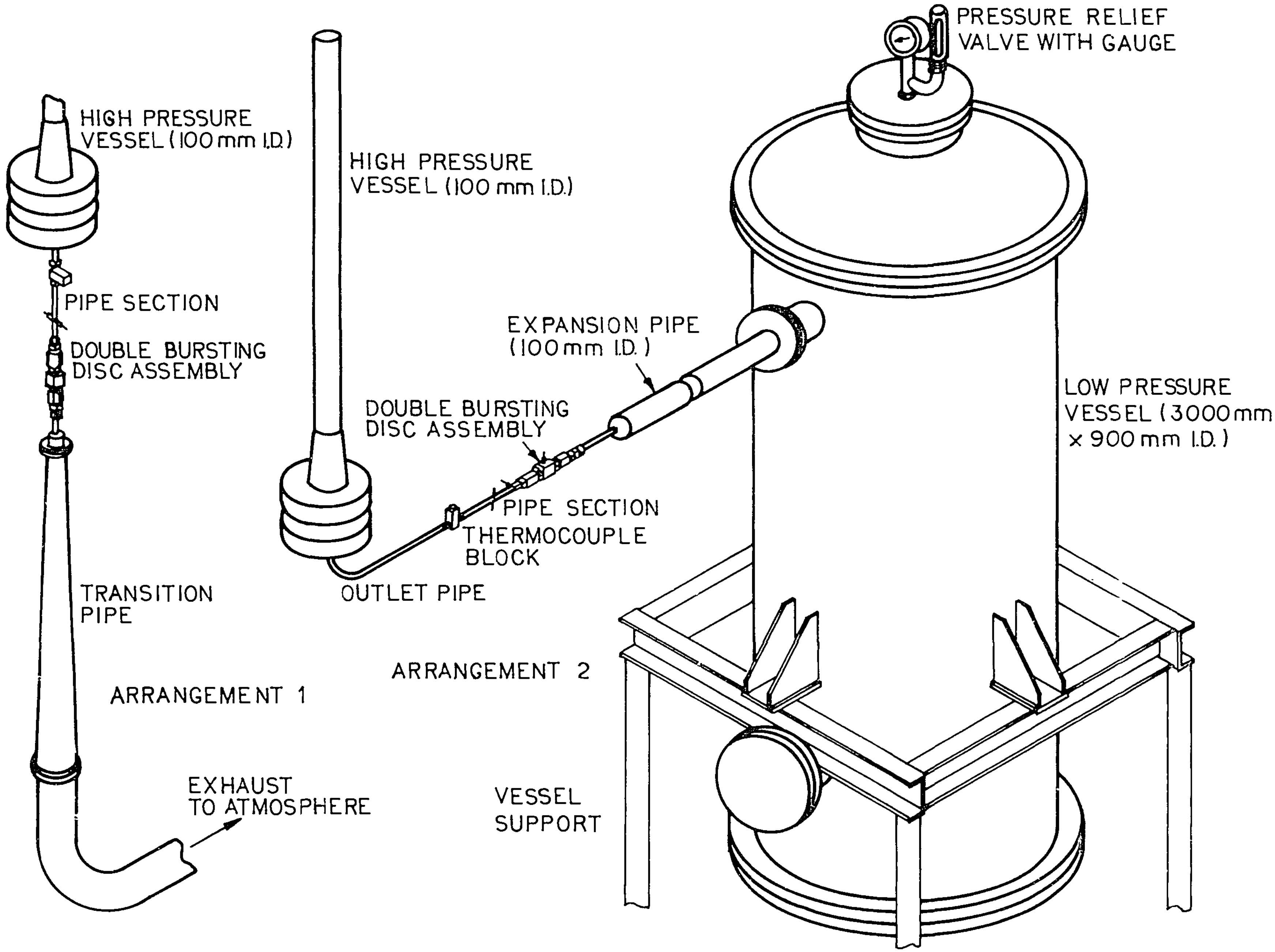


FIGURE 1. GENERAL ARRANGEMENT OF RIG

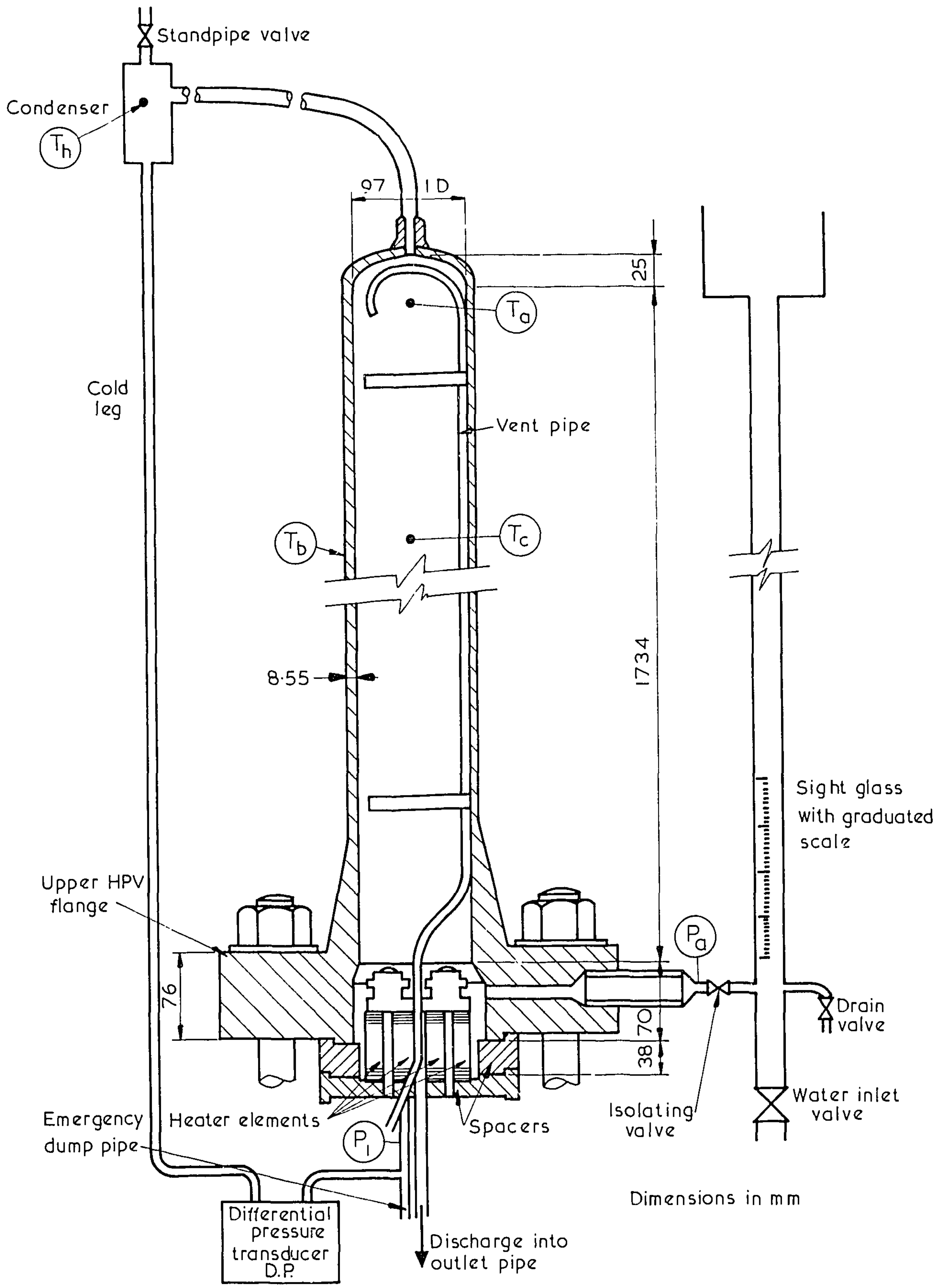


FIGURE 2. HIGH PRESSURE VESSEL

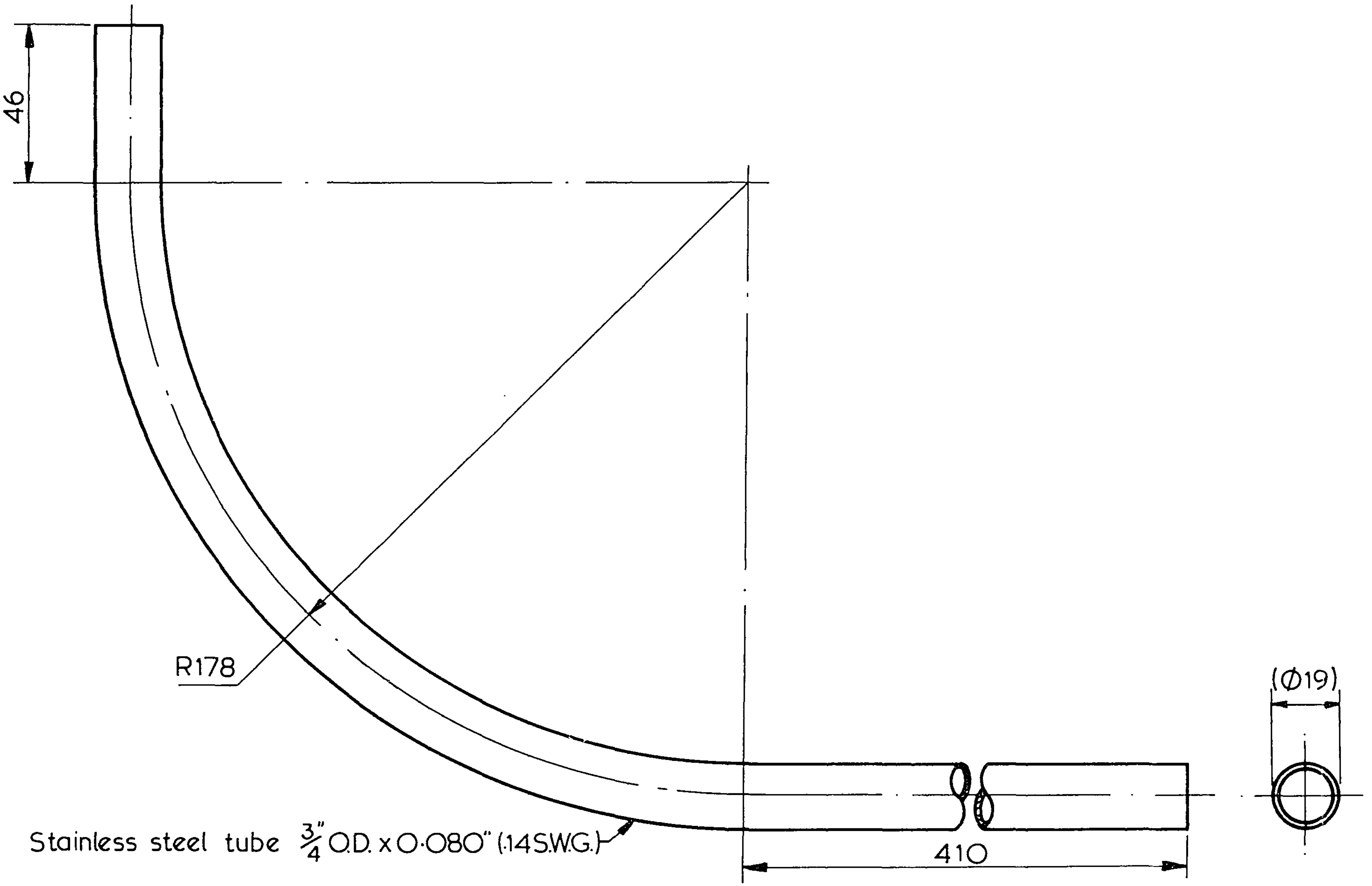


FIGURE 3. OUTLET PIPE

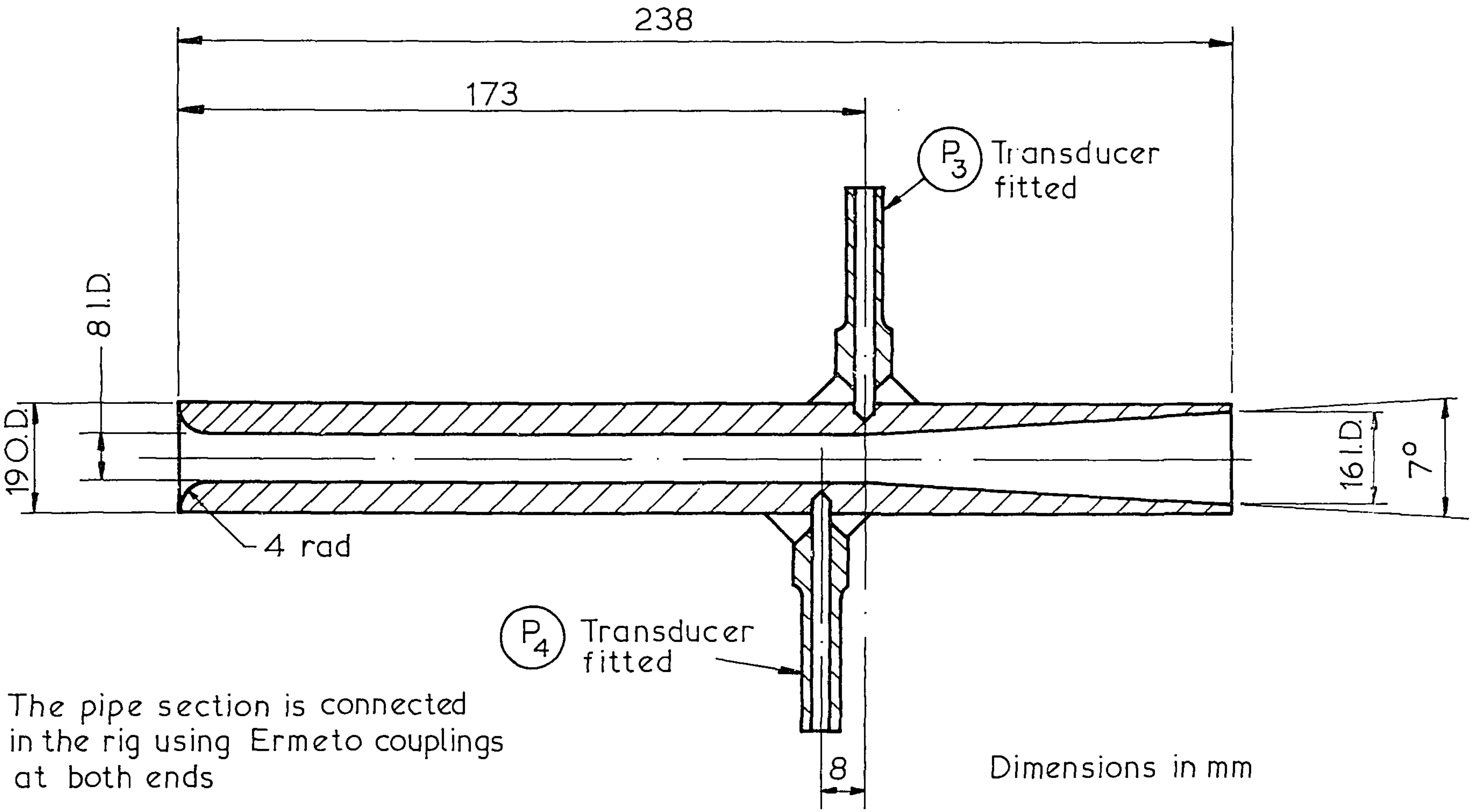
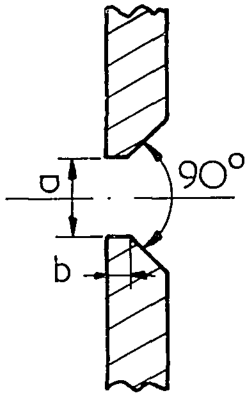


FIGURE 4a. PIPE SECTION



Diameter a	Land b
1·99 mm	0·35 mm
4·03 mm	0·25 mm
8·35 mm	0·37 mm

FIGURE 4b. DIMENSIONS OF BEVELLED ORIFICE PLATES

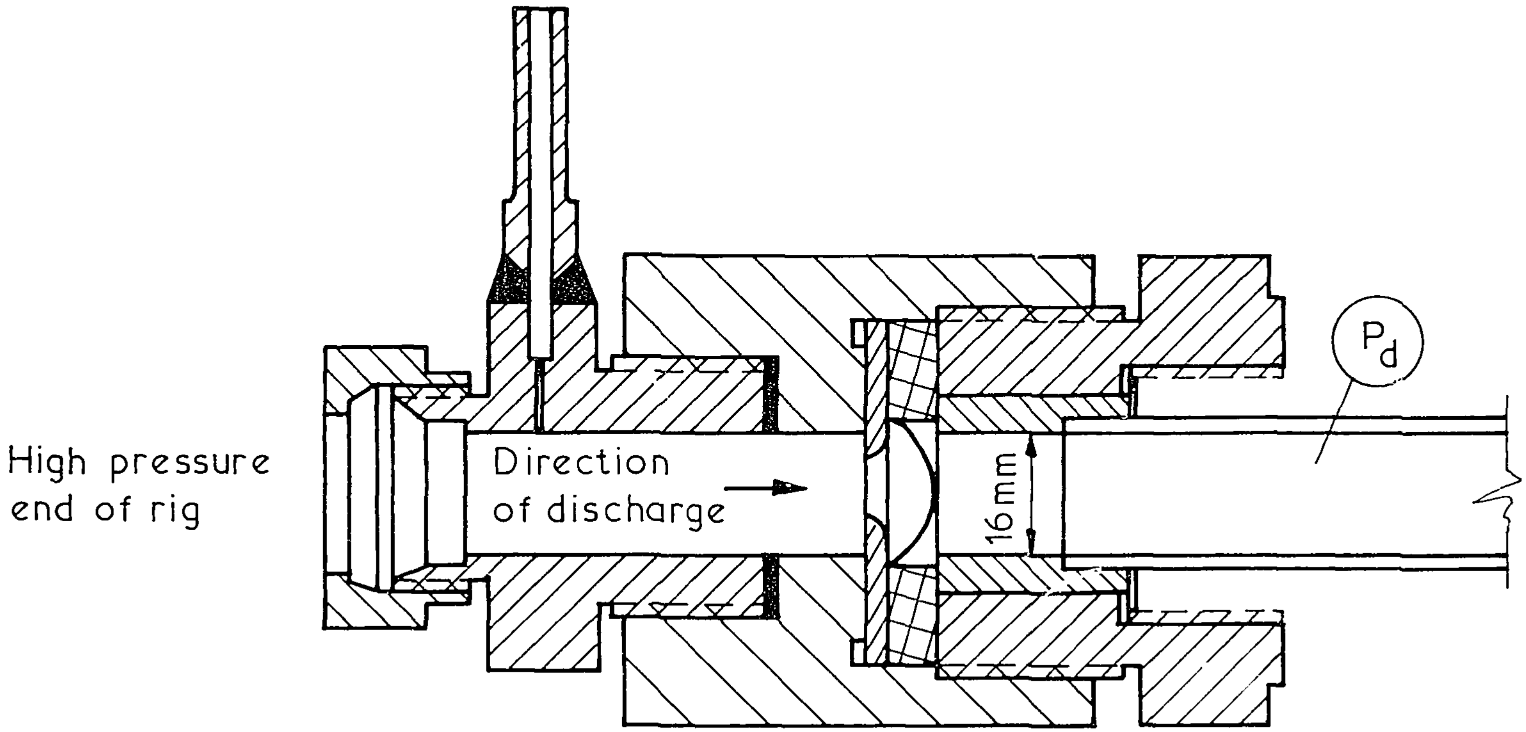
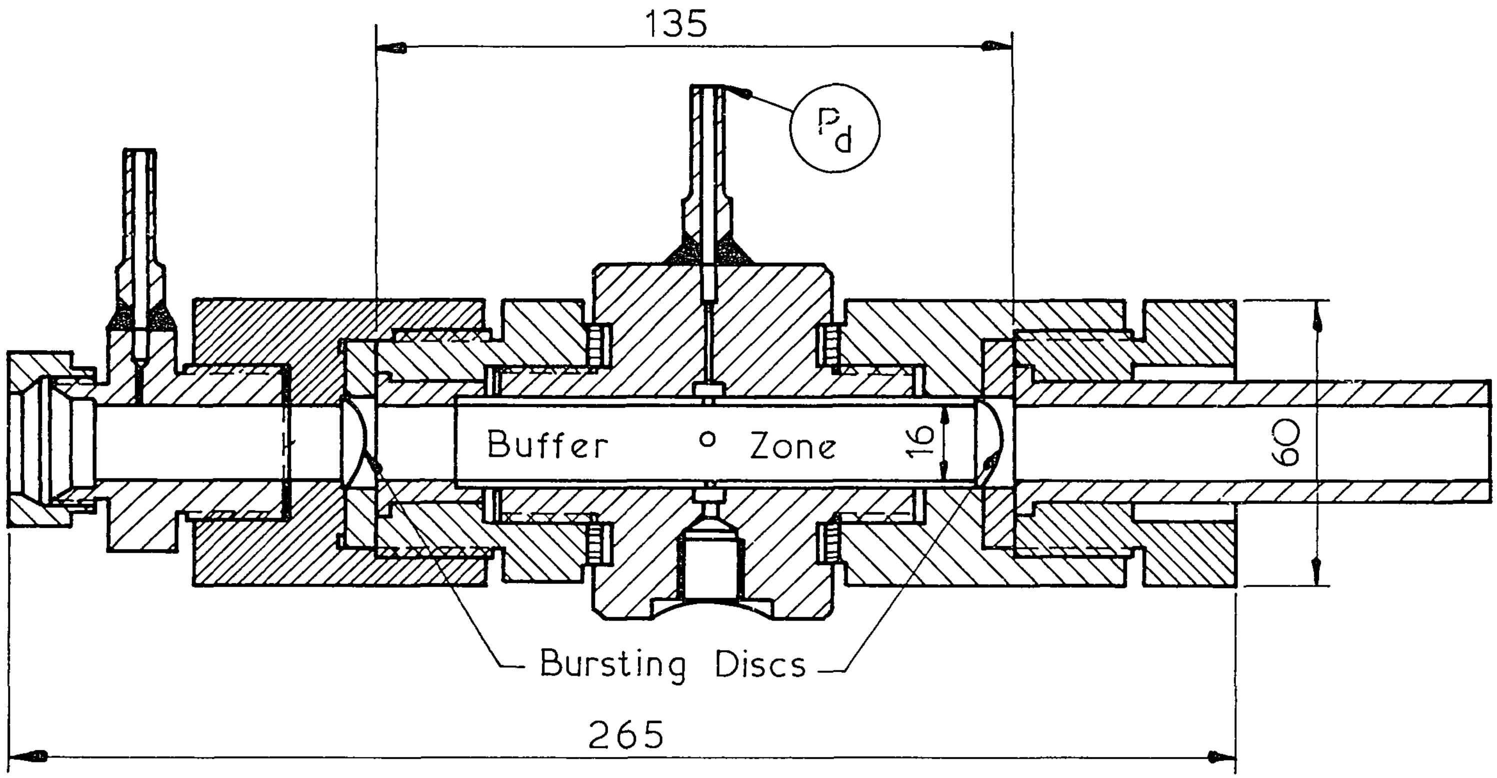


FIGURE 4c. POSITION OF ORIFICE PLATE IN BURSTING DISC ASSEMBLY



Ermeto couplings are used to connect the assembly in the rig

Dimensions in mm

FIGURE 5. DOUBLE BURSTING DISC ASSEMBLY

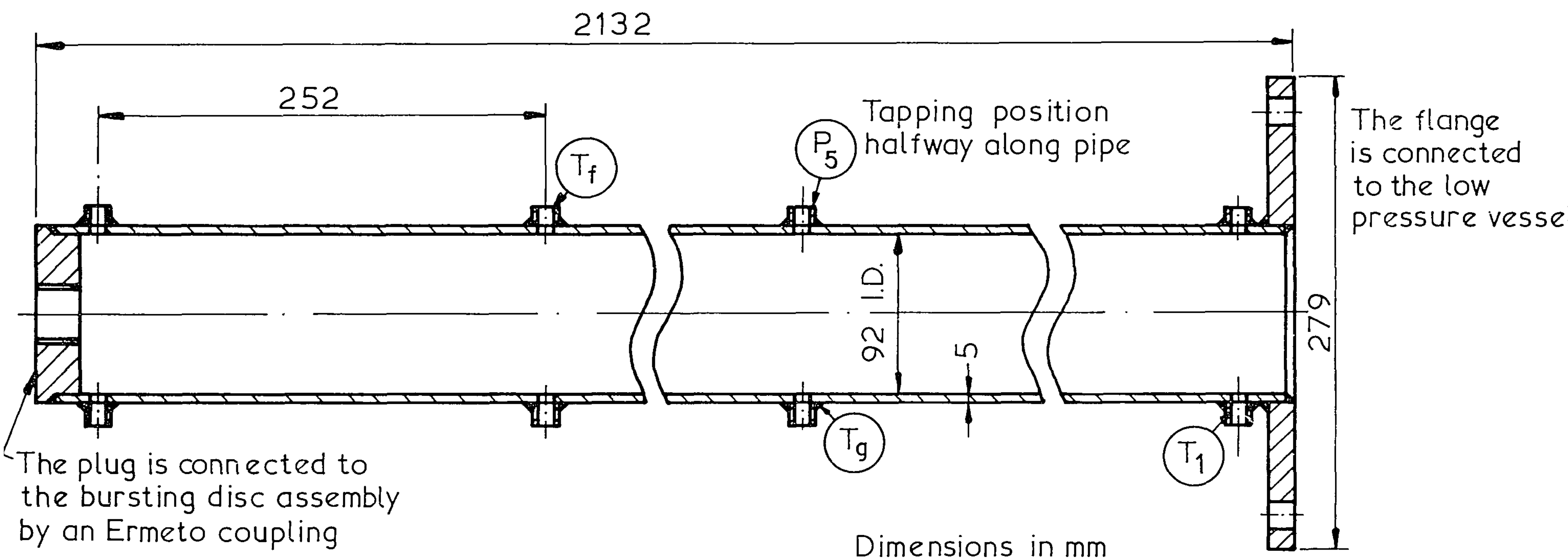


FIGURE 6. EXPANSION PIPE

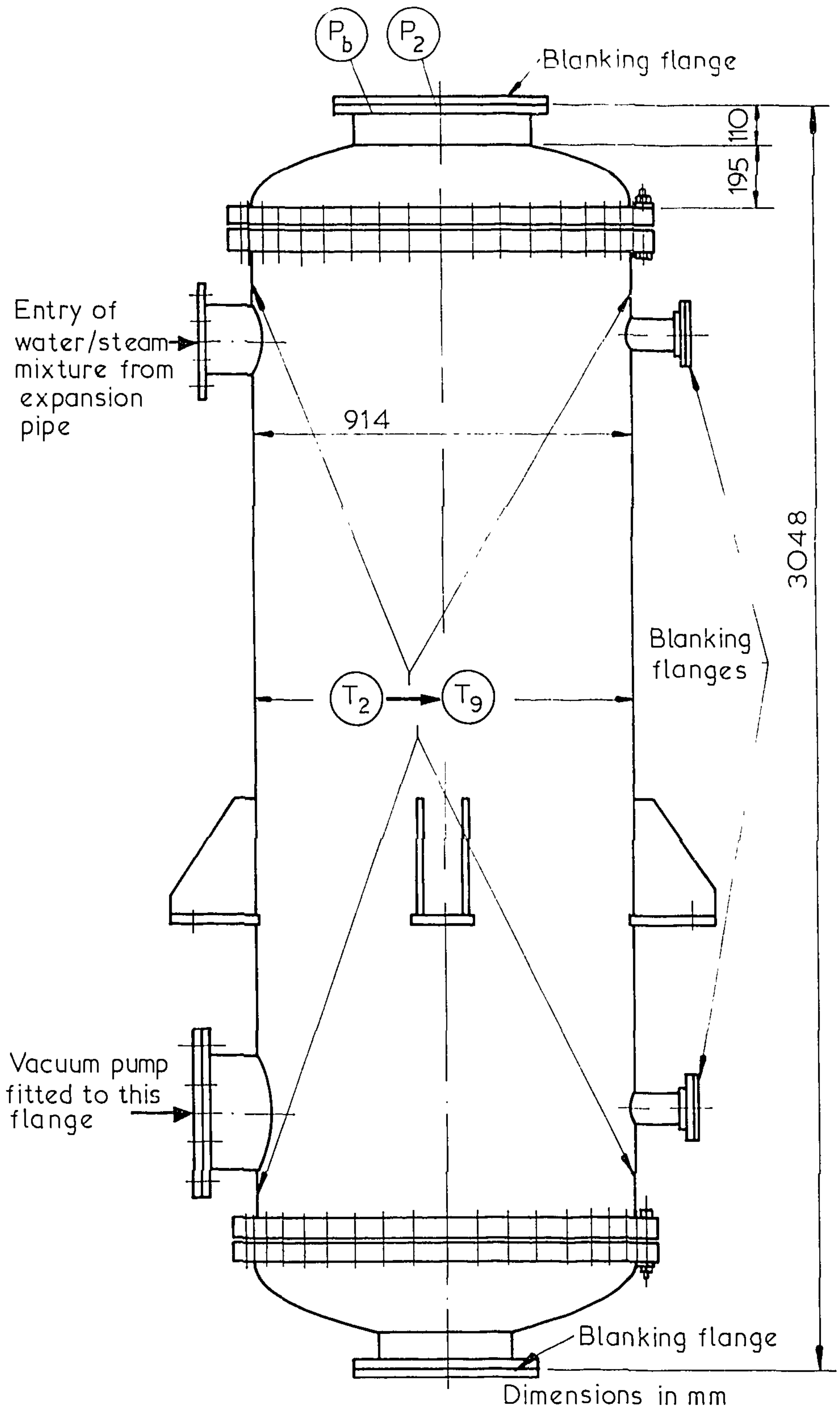


FIGURE 7. LOW PRESSURE VESSEL

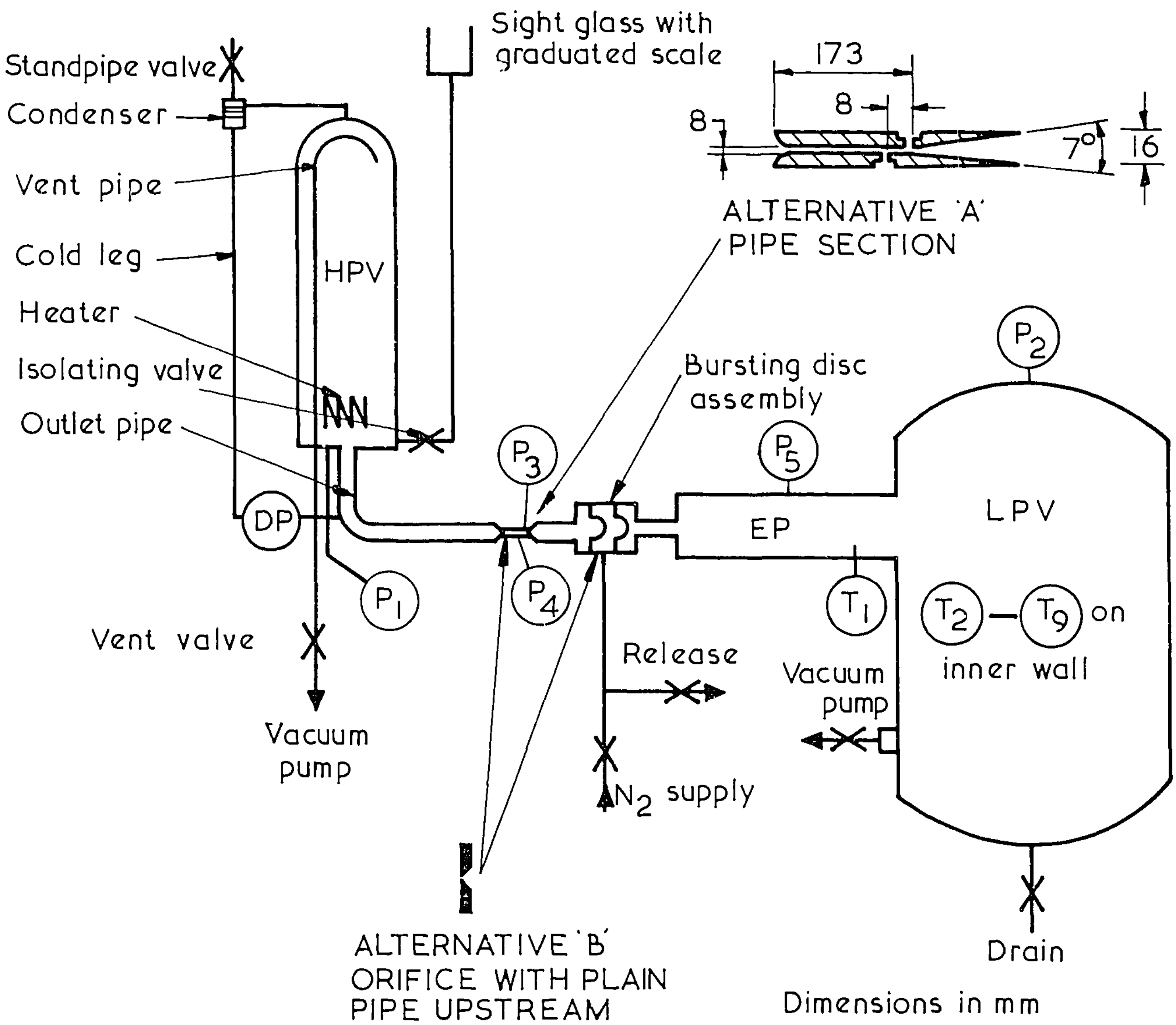


FIGURE 8a. LOCATION OF INSTRUMENTATION FOR TRANSIENT MEASUREMENTS

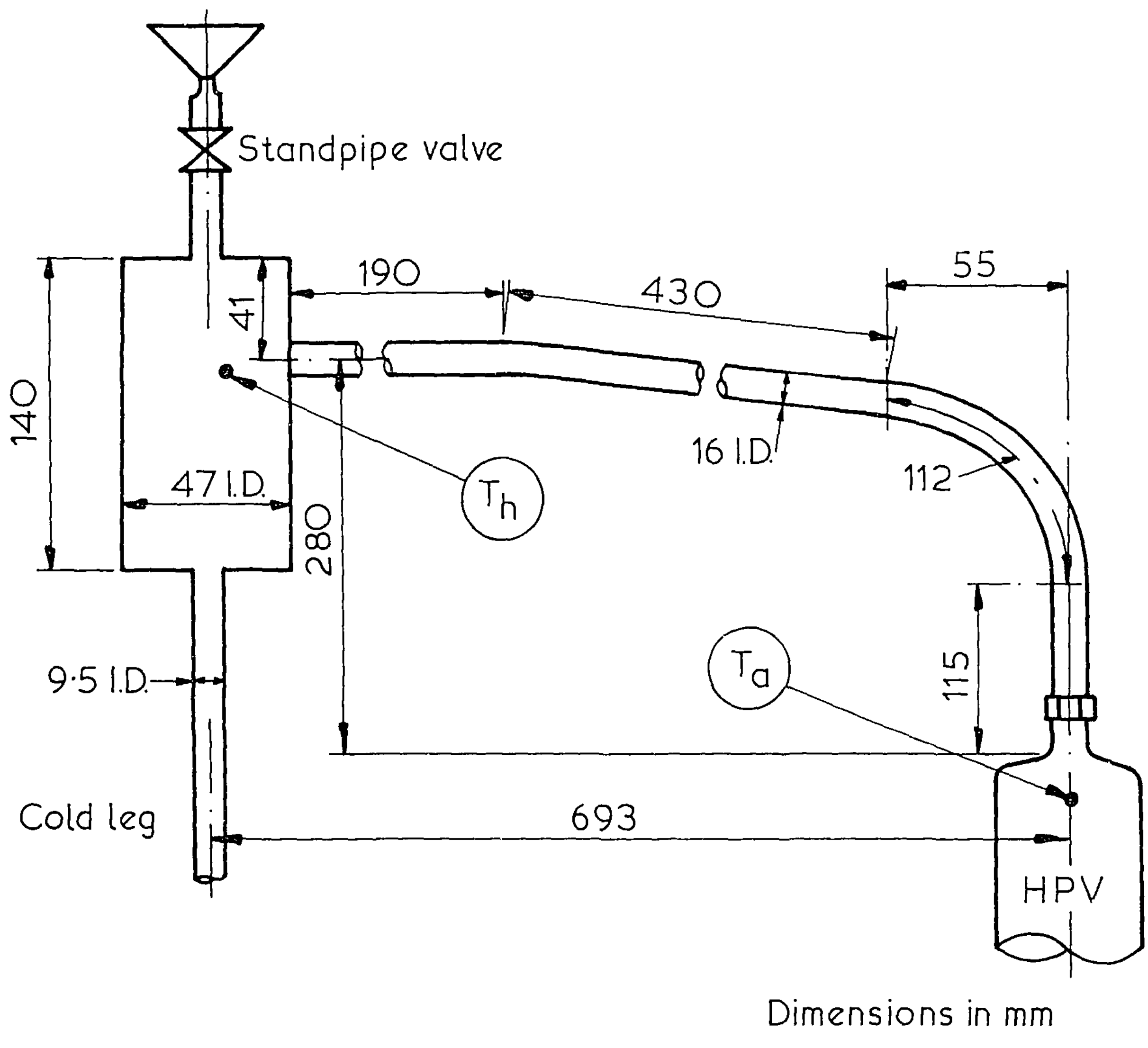


FIGURE 8b. GEOMETRY OF THE CONDENSER AND ITS FITTINGS

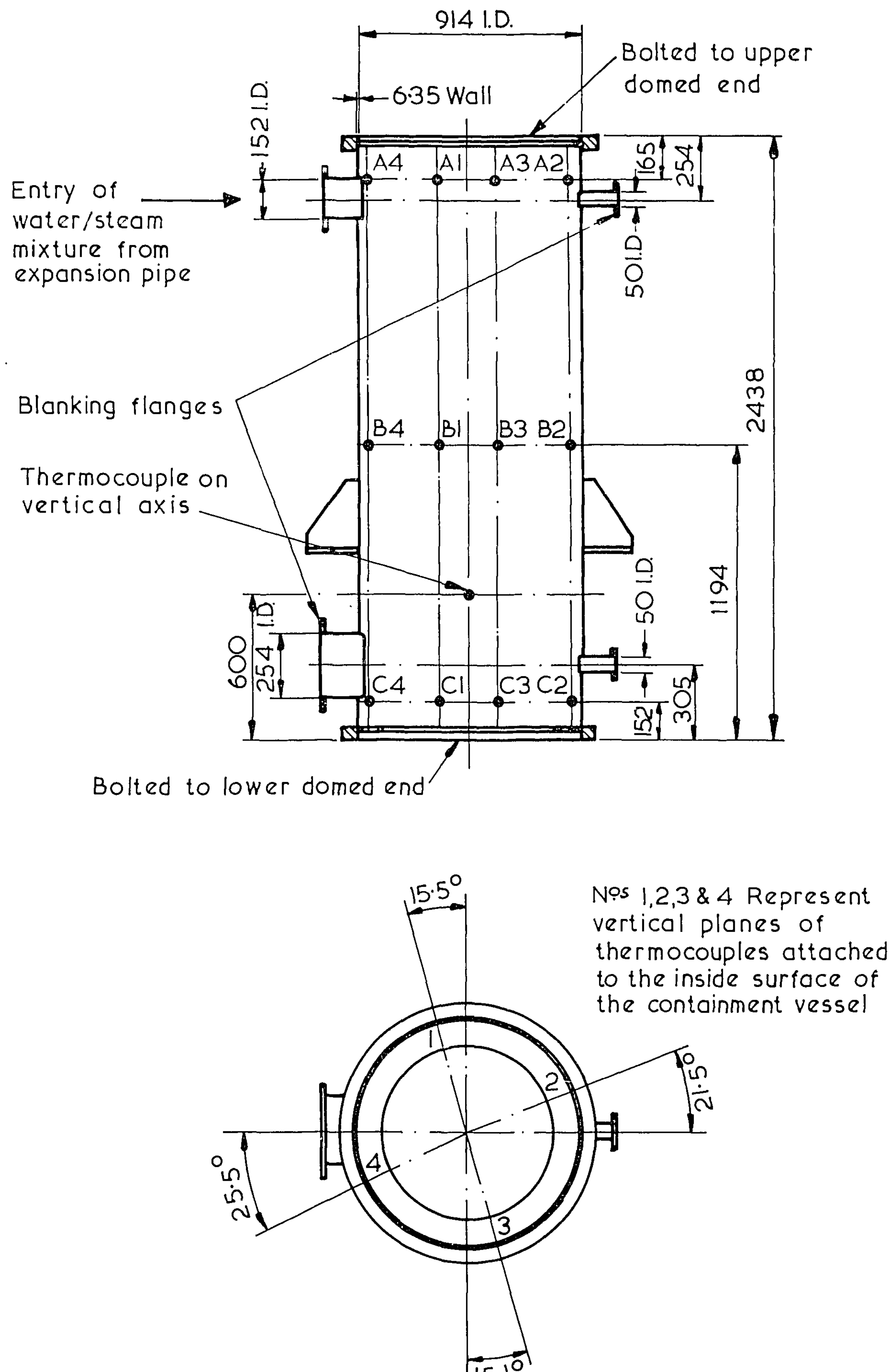


FIGURE 9. POSITION OF THERMOCOUPLES MOUNTED ON THE INNER WALL OF THE LOW PRESSURE VESSEL

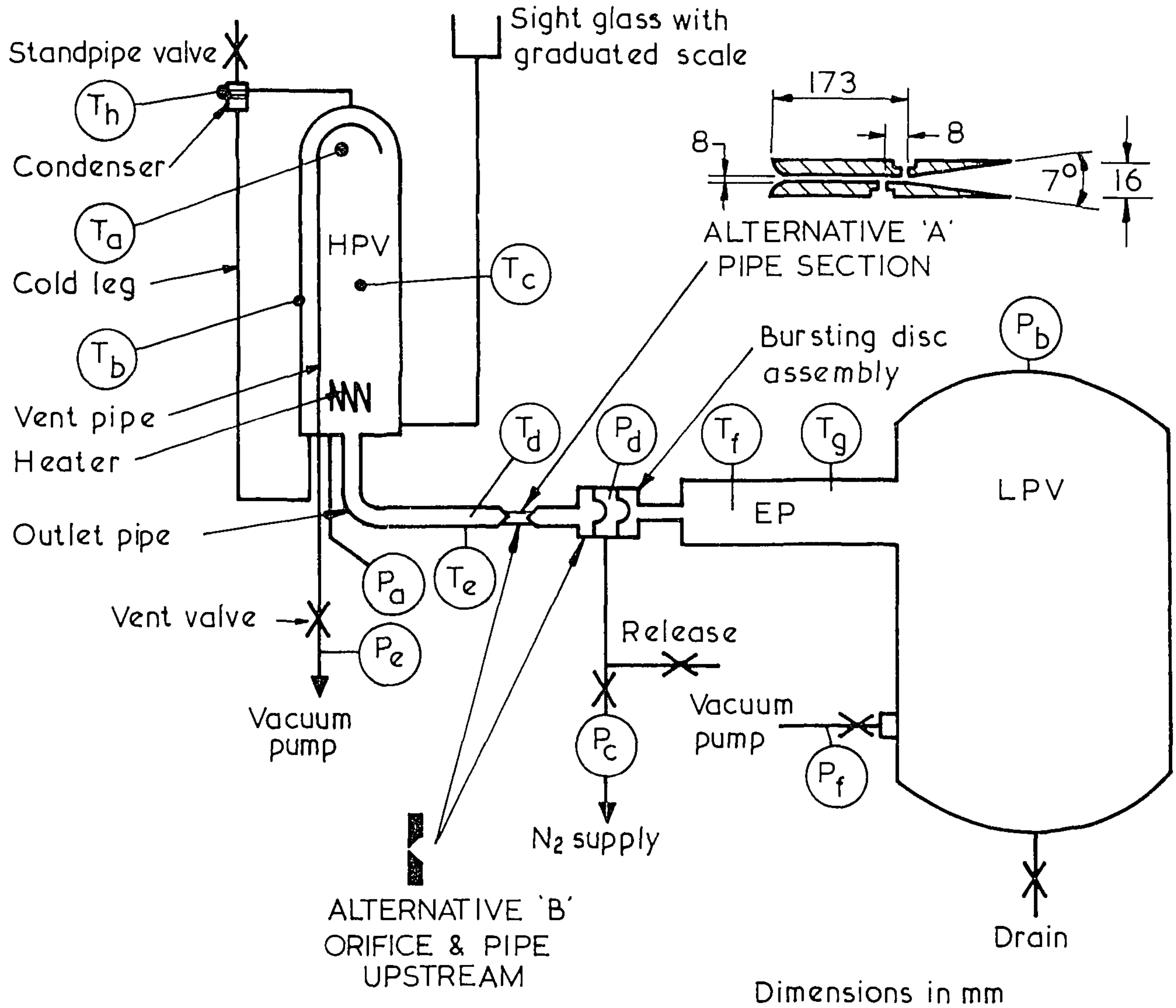


FIGURE 10. LOCATION OF INSTRUMENTATION FOR STEADY-STATE MEASUREMENTS

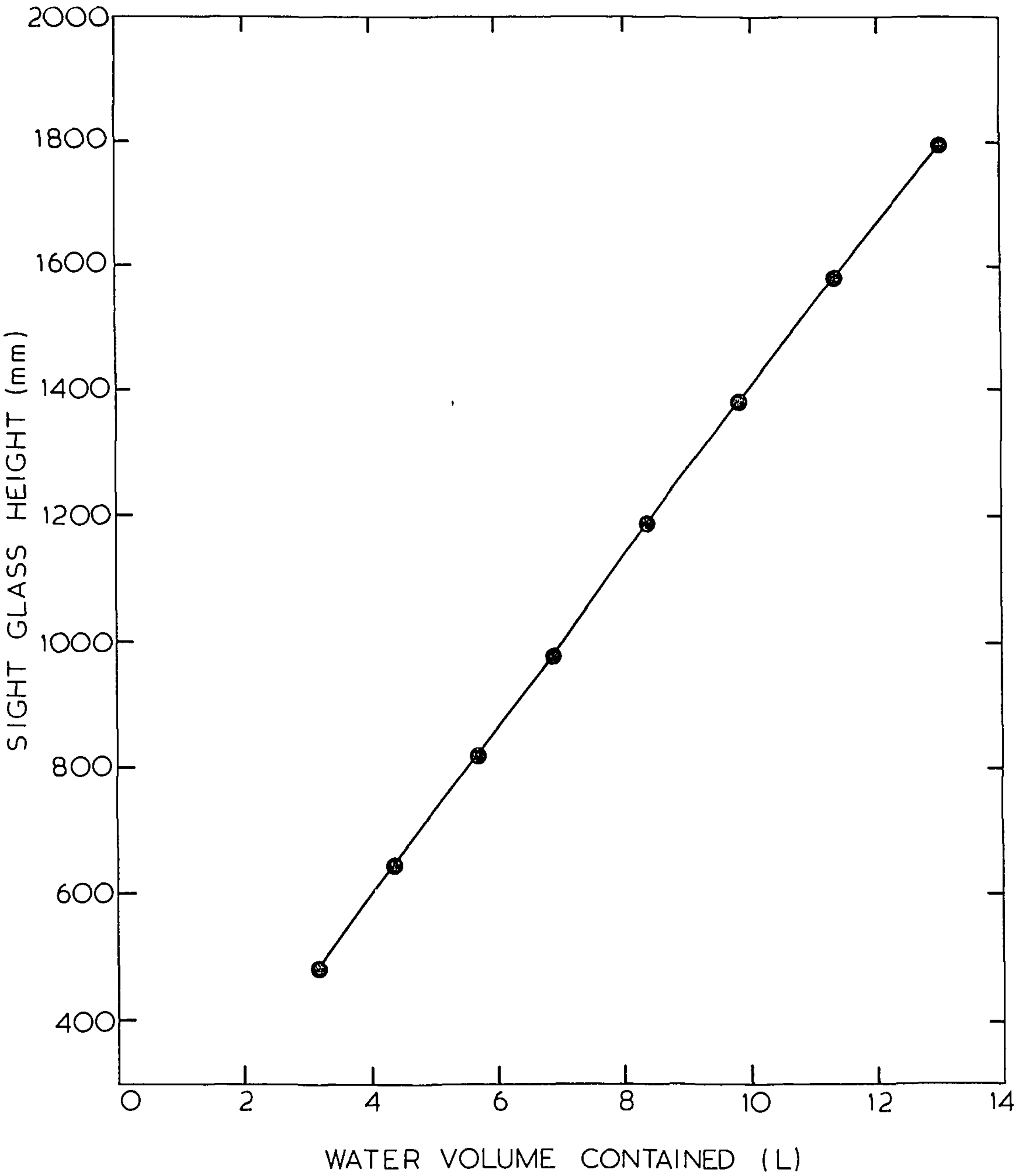


FIGURE 11. CALIBRATION OF WATER VOLUME CONTAINED IN THE HIGH PRESSURE VESSEL

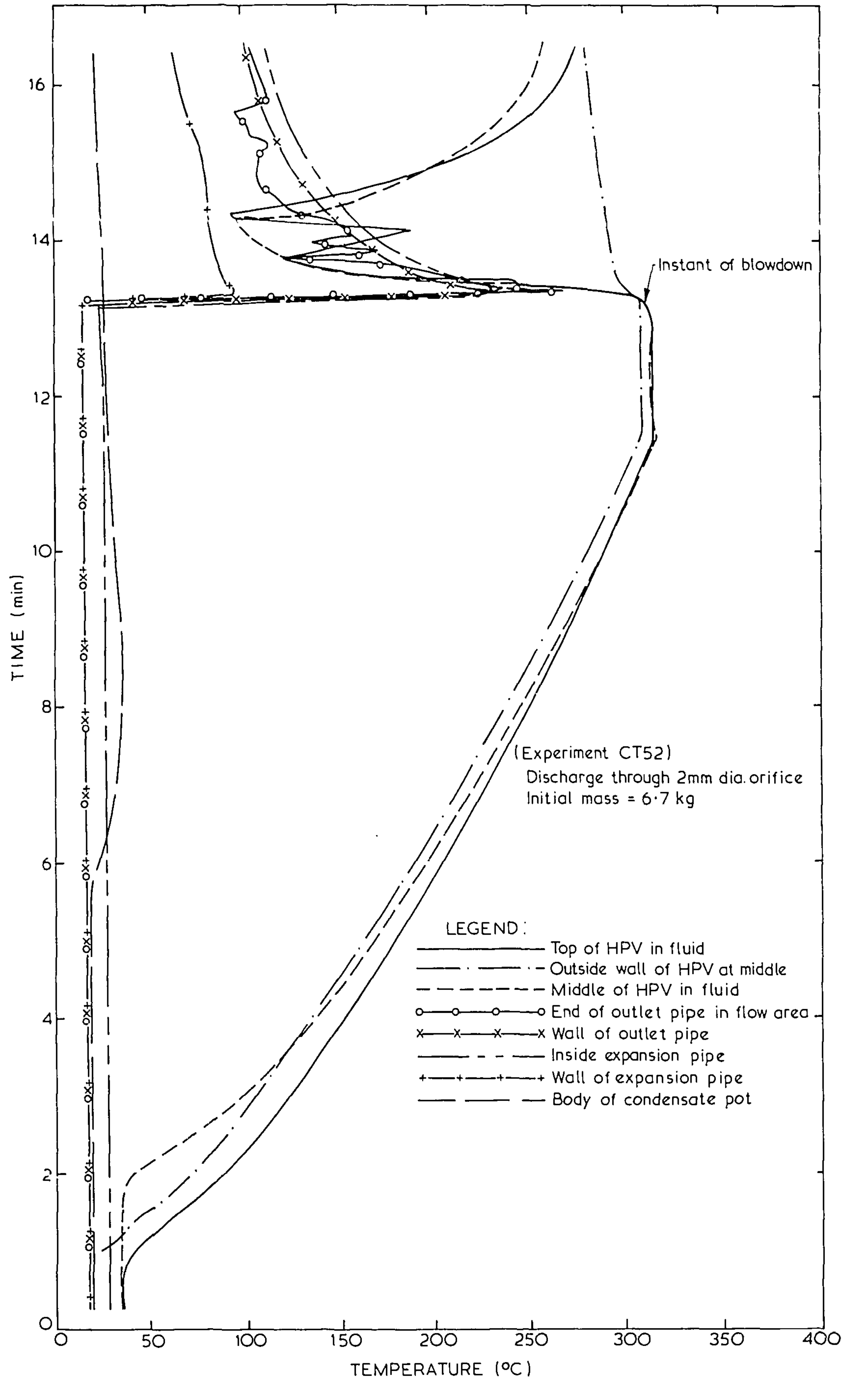


FIGURE 12. TYPICAL RECORD OF RIG TEMPERATURES DURING AN EXPERIMENT

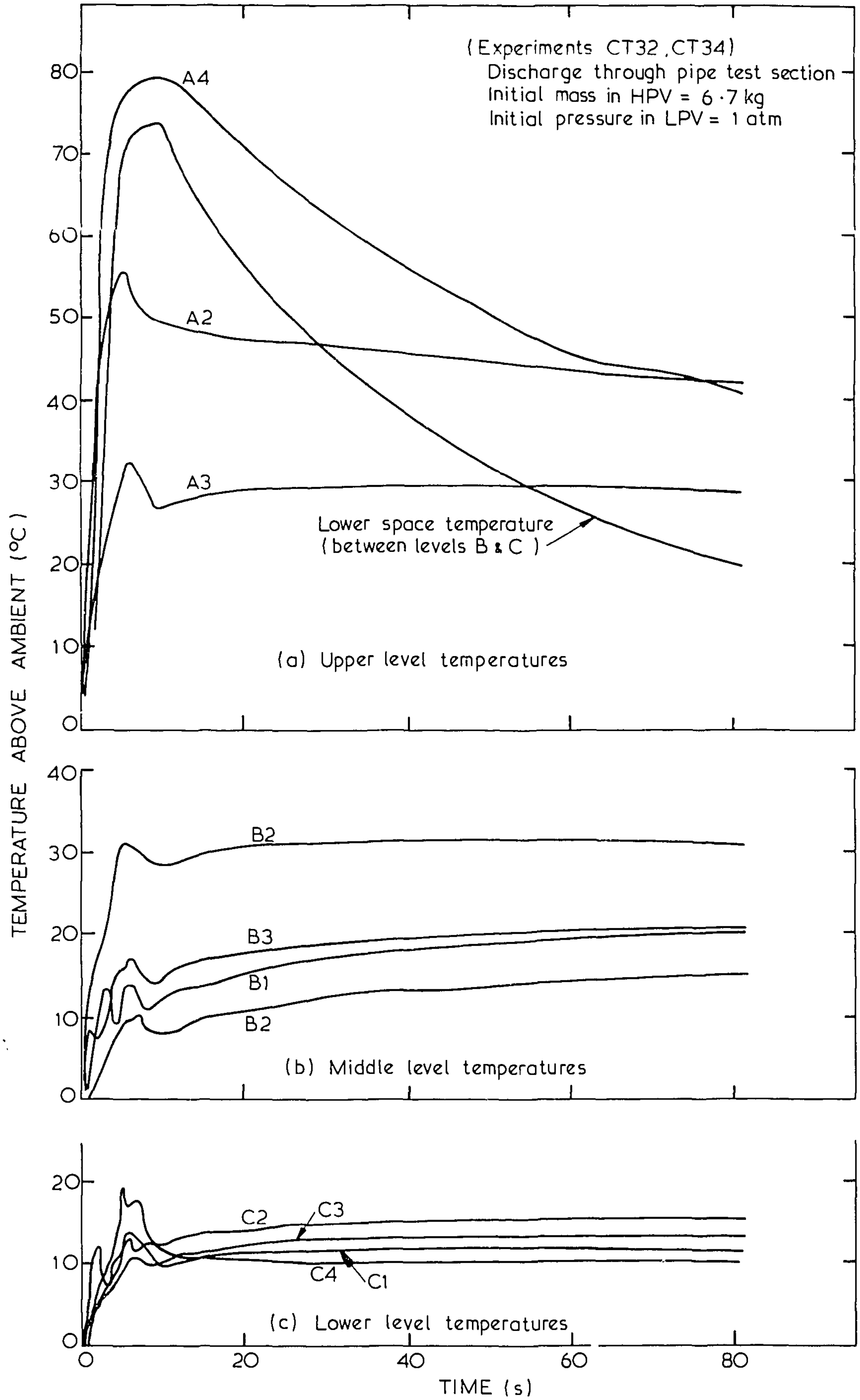


FIGURE 13. LPV TEMPERATURE DISTRIBUTION INITIALLY AT ATMOSPHERIC PRESSURE

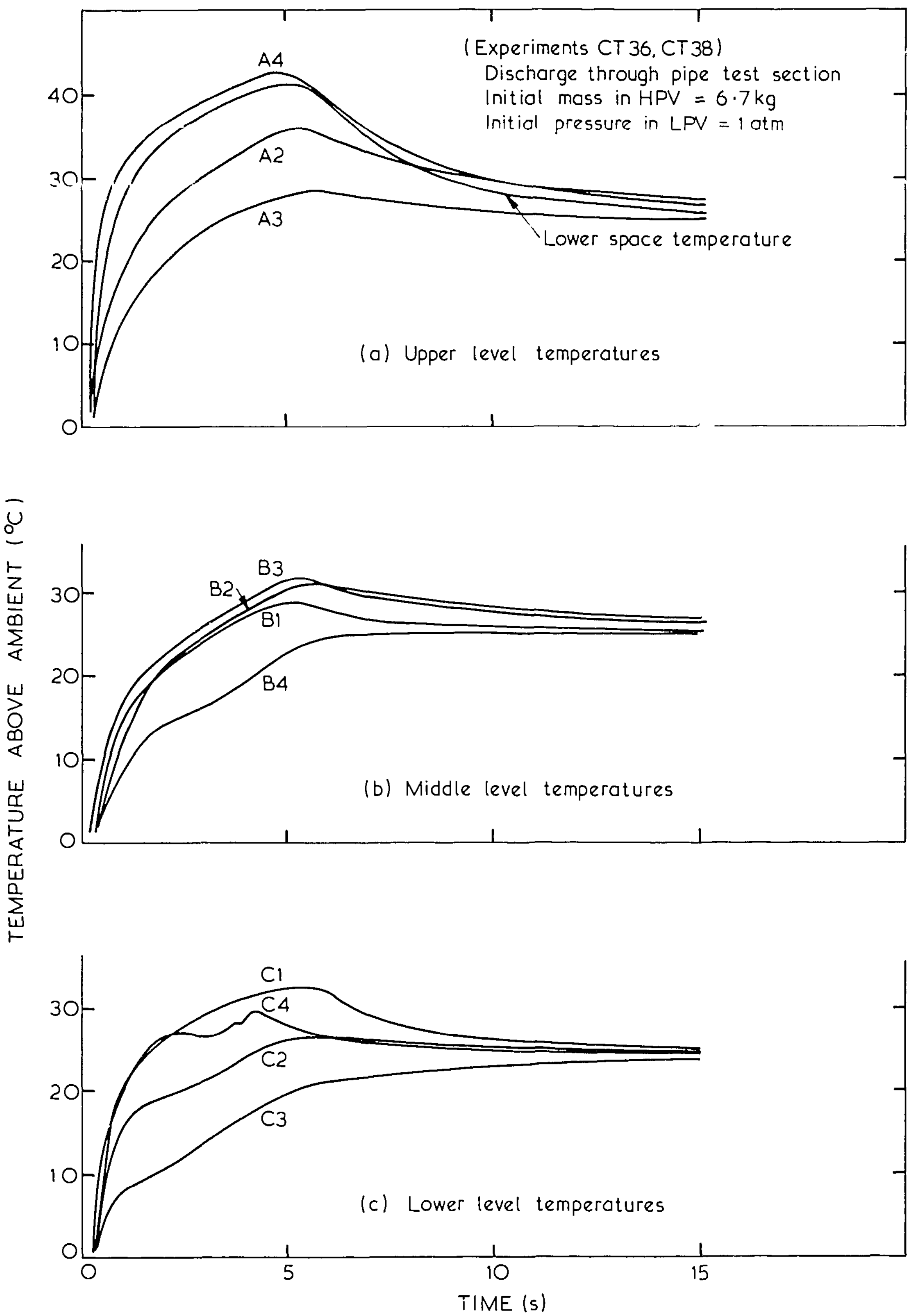


FIGURE 14. LPV TEMPERATURE DISTRIBUTION INITIALLY AT NEAR VACUUM

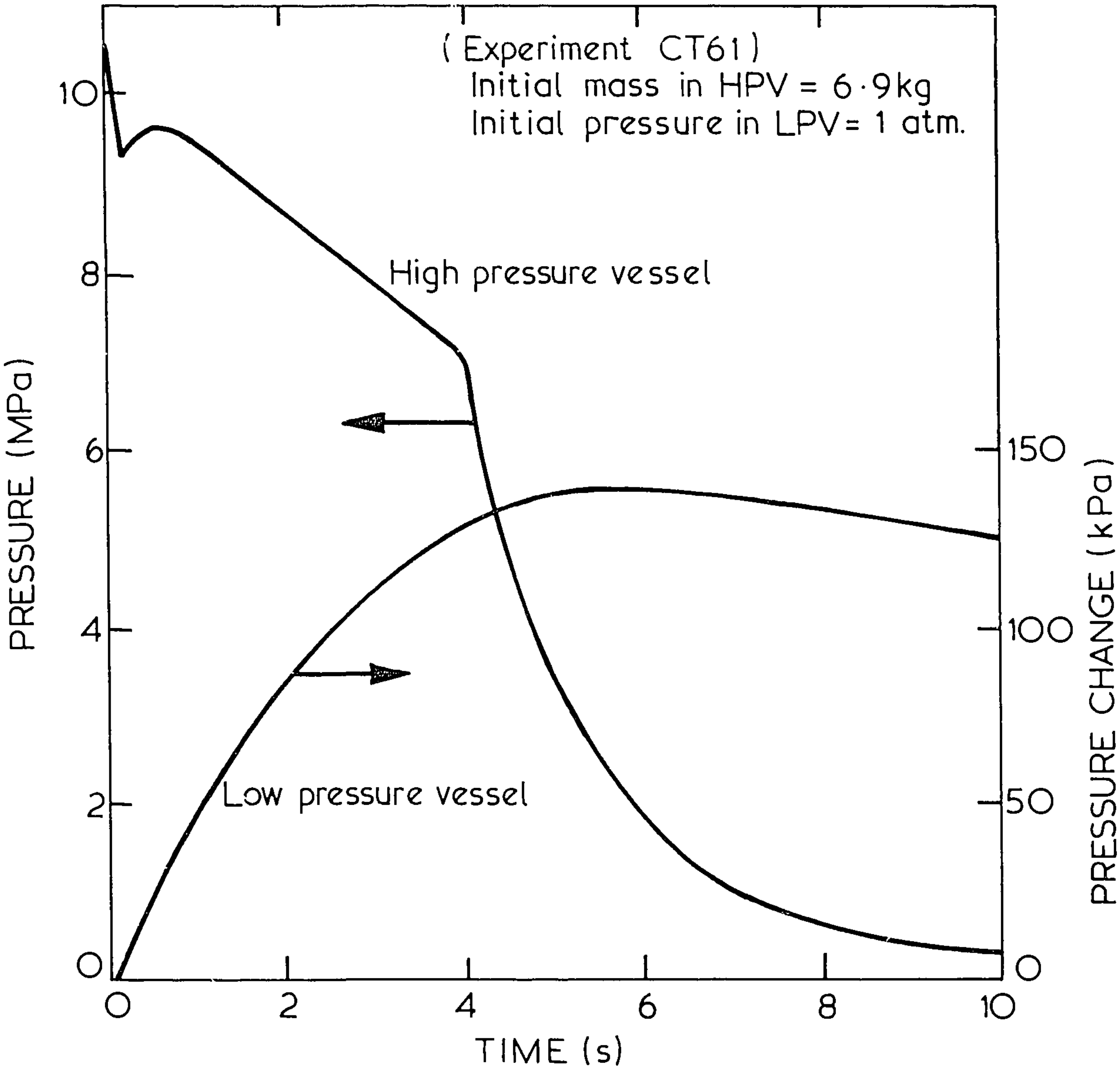


FIGURE 15. PRESSURE TRANSIENTS FOR THE 8 mm dia. PIPE SECTION

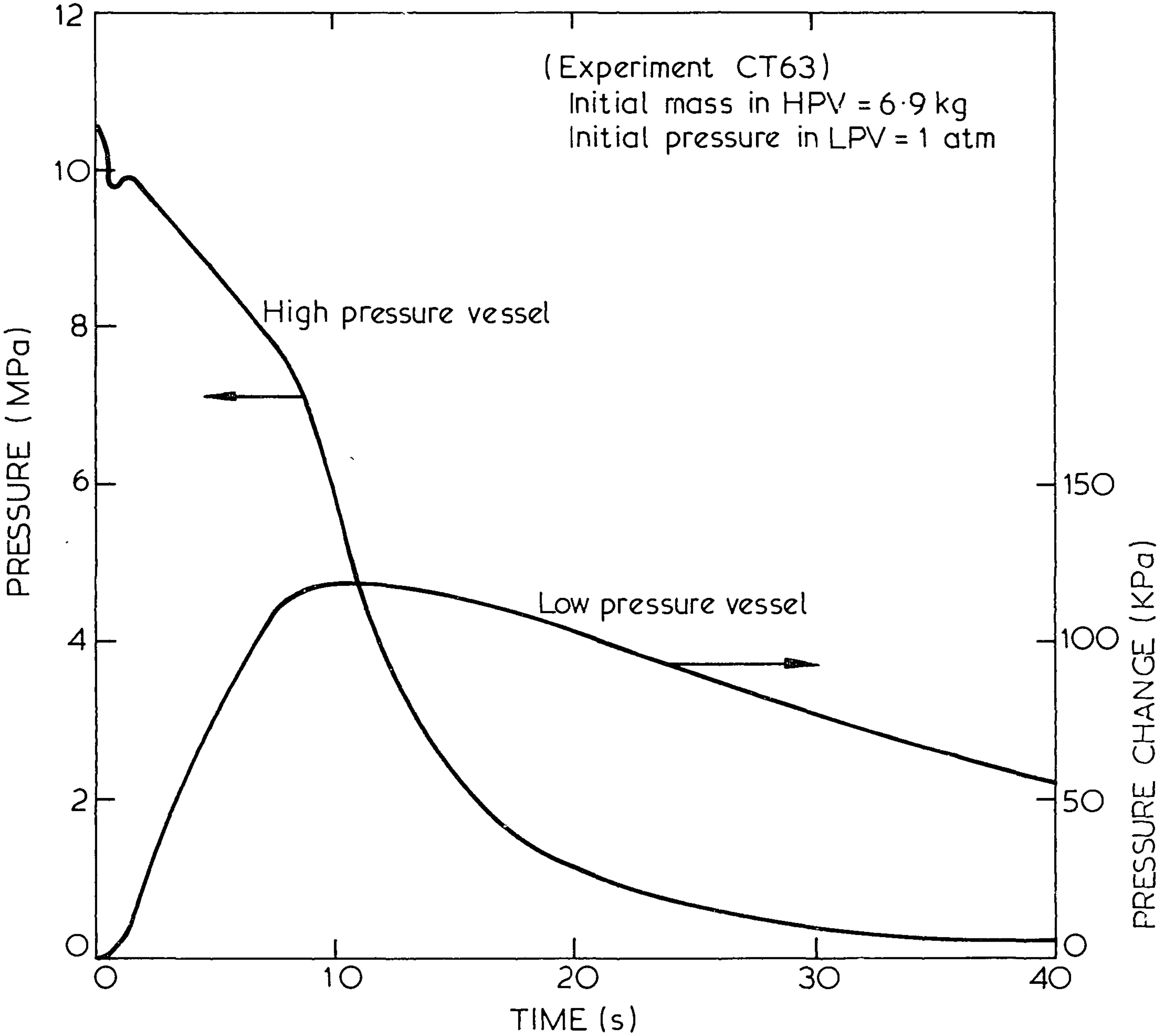


FIGURE 16. PRESSURE TRANSIENTS FOR THE 4 mm dia. ORIFICE

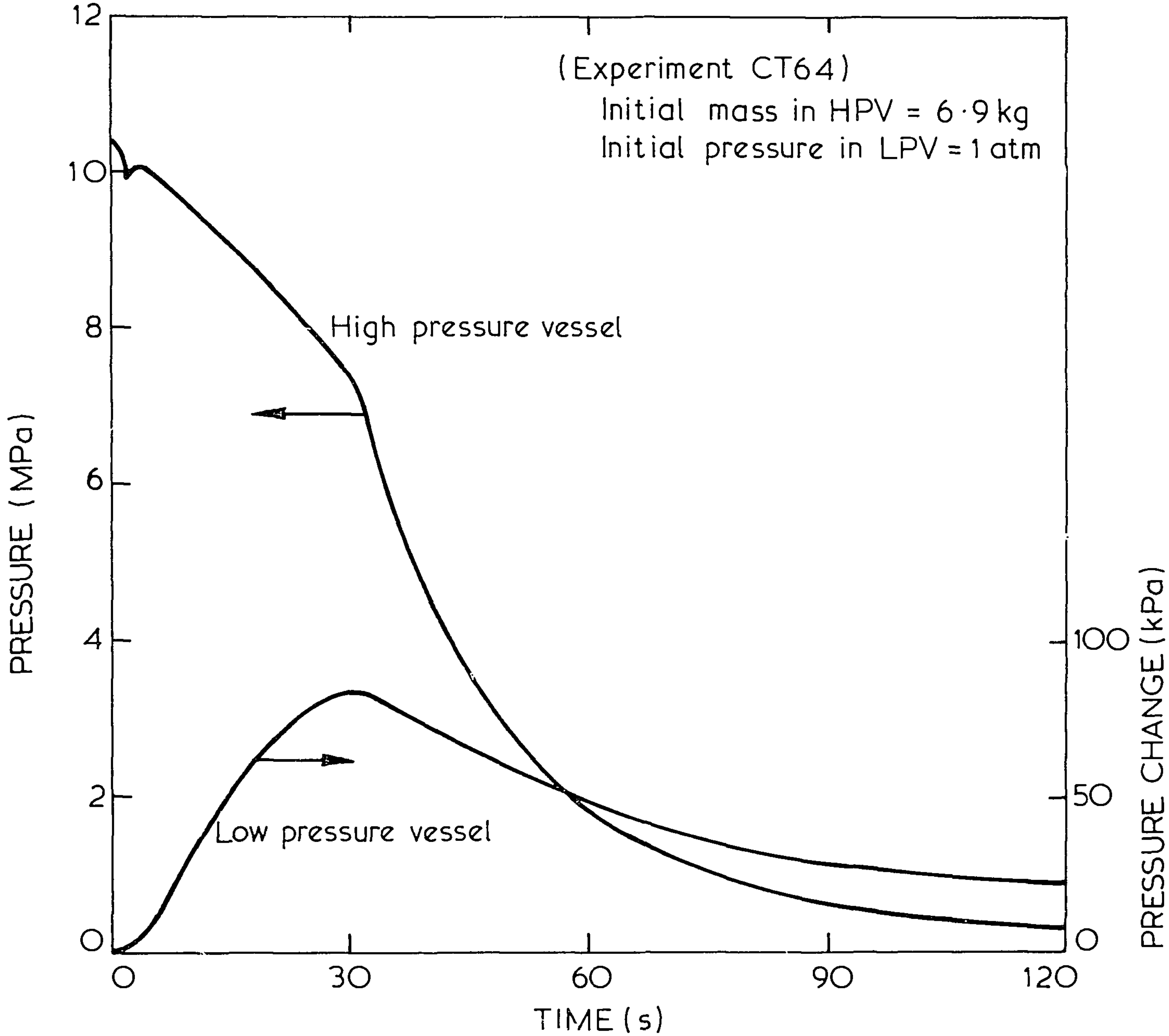


FIGURE 17. PRESSURE TRANSIENTS FOR THE 2 mm dia. ORIFICE

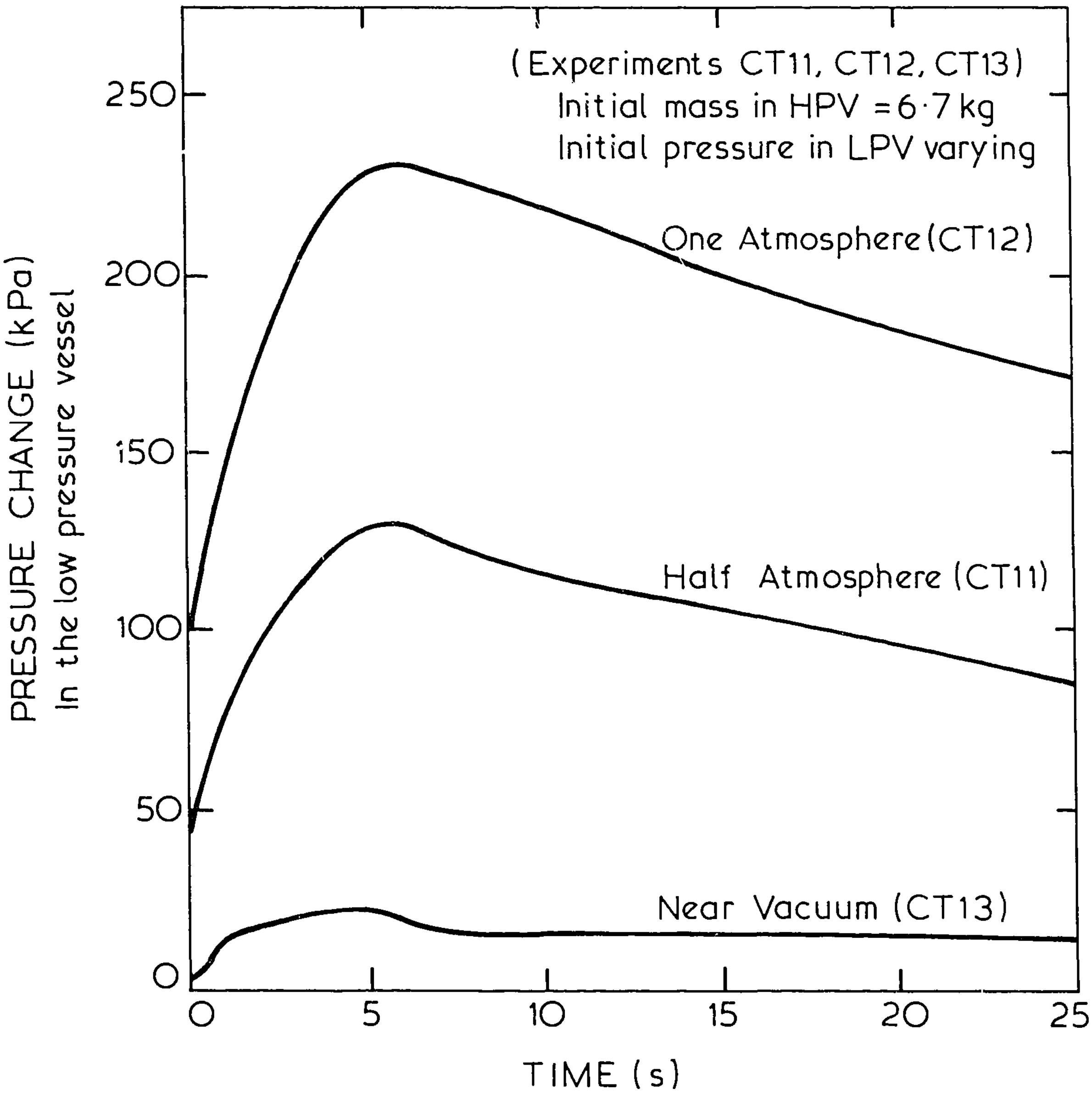


FIGURE 18. EFFECT OF INITIAL AIR CONTENT ON THE PRESSURE TRANSIENT IN THE LOW PRESSURE VESSEL