D_2-cold moderator system at SINQ

- pressure tests of the moderator vessel -

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Abstract:

The design concept of the liquid D_2-cold moderator system of SINQ is based on the principle of isothermal convection of liquid D_2 between a He/D_2-heat exchanger and phase separator in the vertical leg, and a 22 l liquid D_2-moderator vessel at the tip of a horizontal insert. The moderator vessel is made of pure (99.5 %) aluminium in order to avoid radiation embrittlement. Pressure test with He-gas at 78 K up to 4 bar abs. and with water at room tempearture up to the forced rupture at about 30 bar abs. proved that the presssure resistance of the moderator vessel is sufficient for the safe operation under normal conditions as well as in the case of possible malfunctioning, such as the sudden breakdown of the insulating vacuum. The tests show that the onset of plastic deformation occurs at about 6 bar, sufficiently above the operating pressure (2.8 bar) and the design internal pressure (4.4 bar). The forced rupture of a prototype vessel occured between 30 and 31 bar.

Technical concept and status

At the previous ICANS meeting [1], the technical concept of the liquid D_2-cold moderator for the Swiss spallation source SINQ was presented. Meanwhile, the realization of this project made substantial progress: several man years of engineering work have been invested since then to transform the basic concept into a detailed technical layout suitable for manufacturing and purchase of components. Most of the major plant components have now been ordered and will be delivered successively during the current year. Our goal is to have the entire plant assembled and ready for testing and pre-commissioning at a separate testing emplacement in July 1994, about six months before its planned integration into the target shielding block. Thus we count on having it ready for reliable operation with the first proton beam on target.

Horizontal insert and moderator vessel

The heart of the system is the horizontal insert shown in Figure 1. At its tip it carries the D_2-moderator vessel with a volume capacity of approximately 22 l of liquid D_2. The distance from its front surface to the target surface is approximately 10 cm. The moderator vessel is enclosed by a double walled vacuum jacket consisting of an outer 2 mm thick AlMg3-tube and an inner zircaloy tube, 3 to 4 mm thick, which being the pressure safety tube, is designed to withstand an internal pressure of 30 bar.

Behind the D_2-moderator vessel, the horizontal insert carries a D_2O reflector vessel to minimize neutron losses. The D_2/He-heat exchanger ist not inside the horizontal insert but is mounted in a separate, vertical leg in order to minimize the radiation load and to realize the necessary vertical separation for the natural convection system. This system is driven by the liquid-gas mixture flowing back from the moderator vessel and up to a phase separator below the heat exchanger.

Pressure load of the moderator vessel

Fig. 2 shows a vertical cut through the D_2-moderator vessel and its concentric D_2-flow tubes. Some relevant data are given in Table 1. The vessel will be made of 99.5 % pure aluminium, semi-hard with one welding seam around its cylindrical surface at the far end with respect to the target. Material softening around the weld requires the wall thickness of the vessel to be increased from 3 to 5 mm in this region to obtain the strength necessary to resist an internal pressure of 4.4 bar.

Material	Al 99.5	
Outer diameter	296/300	mm
Length	354	mm
Wall thickness	3 resp. 5	mm
Total volume	22.3	l
Volume filled with liquid D_2	~ 20	l
Total mass of Al	4.375	kg
Total weight of filled vessel	~ 7.6	kg
Design internal pressure	4.4	bar
Max. operating pressure	2.8	bar

Table 1: Some relevant data for the D_2-vessel of the SINQ cold moderator

The choice of pure aluminium for the wall material of the moderator vessel was governed by concerns about radiation embrittlement during long-term source operation. Its disadvantage is a relatively low material strength, and in particular a possible uncontrolled softening by the necessary welding. The **real** strength and pressure resistance of the final vessel or an equivalent prototype is therefore a crucial property to guarantee safe operation and to rate the chances of the system to survive conceivable malfunctioning without fatal damage. It was therefore decided to undertake relevant tests with 1:1 prototype vessels by measuring the real strength at different positions of the vessel after fabrication and by investigating the deformation of the vessels when exposed to excessive internal pressure.

One of the most severe failures one can imagine and should design for is the sudden complete breakdown of the insulating cryo-vacuum when the system - vessel and transfer tubes - are filled with liquid D_2. The vacuum breakdown leads to boiling and evaporation of the liquid D_2 with the consequence of a sudden pressure increase in the system. Fig. 3 shows the calculated pressure rise in the moderator vessel for the relevant time period after this event for three different assumptions for the heat input into the system [2]. The figure shows that for all three cases the pressures rises quite fast, i.e. within the first two-tenths of a second, and then relaxes due to the onset of backflow into the buffer tank. The highest pressure predicted is at about 3.3 bar, occuring as expected for the shortest time constant of 3 ms. Although this is unrealistically fast, this value together with an appropriate safety factor was used as a basis for the design pressure of 4.4 bar as given in Table 1.

Pressure test with He-gas at 78 K

In order to monitor the deformations during the pressure tests, the prototype vessel was equipped with 18 strain gauges at representative positions, as illustrated in Fig. 4. For safety the vessel was water-loaded at room temperature up to 5 bar abs. prior to the He-gas test at liquid nitrogen temperature. After cooling to liquid nitrogen temperature the vessel was filled with He-gas, increasing the pressure in steps of 0.5 bar to a maximum of 4 bar abs. The results from the strain gauges, read after each pressure run and subsequent relaxation to normal pressure, are shown in Fig. 5. Within the sensitivity of the sensors ($\pm$ 2 μm/m) no indication for a permanent deformation was found. This indicates that all deformations up to a load of 4 bar at 78 K are in the fully elastic range.

Rupture tests with water at room temperature

A second sequence of pressure tests was carried out at room temperature, using water as pressurizing medium, with the aim to exceed the elastic range and to induce plastic deformations up to the forced rupture of the vessel. The deformations remaining after relaxation to normal pressure are plotted in Fig. 6 for the pressure range up to 15 bar. According to these results, at all positions monitored the deformation is in the elastic range up to a pressure of about 6 bar. Between 6 and about 11 bar, considerable plastic deformation occurs but only in the vicinity of the weld. As expected, the material softening due to the welding is the limiting factor for the resistance to plastic deformation of the moderator vessel. Yet, the threshold pressure for the outset of plastic deformations is not less than 6 bar in this region, i.e. well above the required design pressure of 4.4 bar (cf. table 1). Pressure increase above 15 bar led to further considerable plastic defomation and to visible expansion. It finally led to the rupture of the vessel at a pressure between 30 and 31 bar. A photograph of the ruptured vessel is given as Fig. 7. It shows that the rupture occured by a crack of about 10 cm length along the cylinder surface, extending parallel to the cylinder axis. The material around the weld is deformed but unruptured, which is attributed to the higher wall thickness in this region combined with work hardening during the testing and the more favourable position at the edge of the cylinder around the bottom. Generally, the observed rupture behaviour followed the predictions of classical rupture mechanics for the given vessel geometry and the assumption of (almost) equally strengthened material all around.

All tests reported here were repeated with a second prototype vessel. This second test sequence yielded almost identical results as the reported one.

Conclusions

The tests performed on two prototypes of the liquid D_2 moderator vessel at the temperature of liquid nitrogen confirmed that the vessel can withstand any pressure level that might be expected to arise as a consequence of a sudden heat influx into the liquid while the transfer pipes to the expansion tank are open. Room temperature testing revealed that the moderator vessel can withstand a pressure up to 6 bar without any plastic deformation and can withhold a pressure of more than 25 bar when plastic deformation is allowed. Rupture as a consequence of excessively high pressure occurs in the form of a gap opening on the cylindrical circumference and not in a catastrophic way. Operationg of the SINQ D_2 cold moderator is therefore considered to be safe under all circumstances.

References

[1]   H. Spitzer, A. Höchli, G.S. Bauer and W. Wagner: Proc. of ICANS-XI, KEK, Tsukuba, Japan (1990), 430

[2]   K. Skala, H. Spitzer, G.S. Bauer, ibid. p.416

Figure 1: Vertical section through the horizontal insert of the SINQ cold D_2-source.

Figure 2: The D_2-moderator vessel and its concentric flow tubes (vertical section).

Figure 3: Pressure rise in the moderator vessel for the three different assumptions on heat input
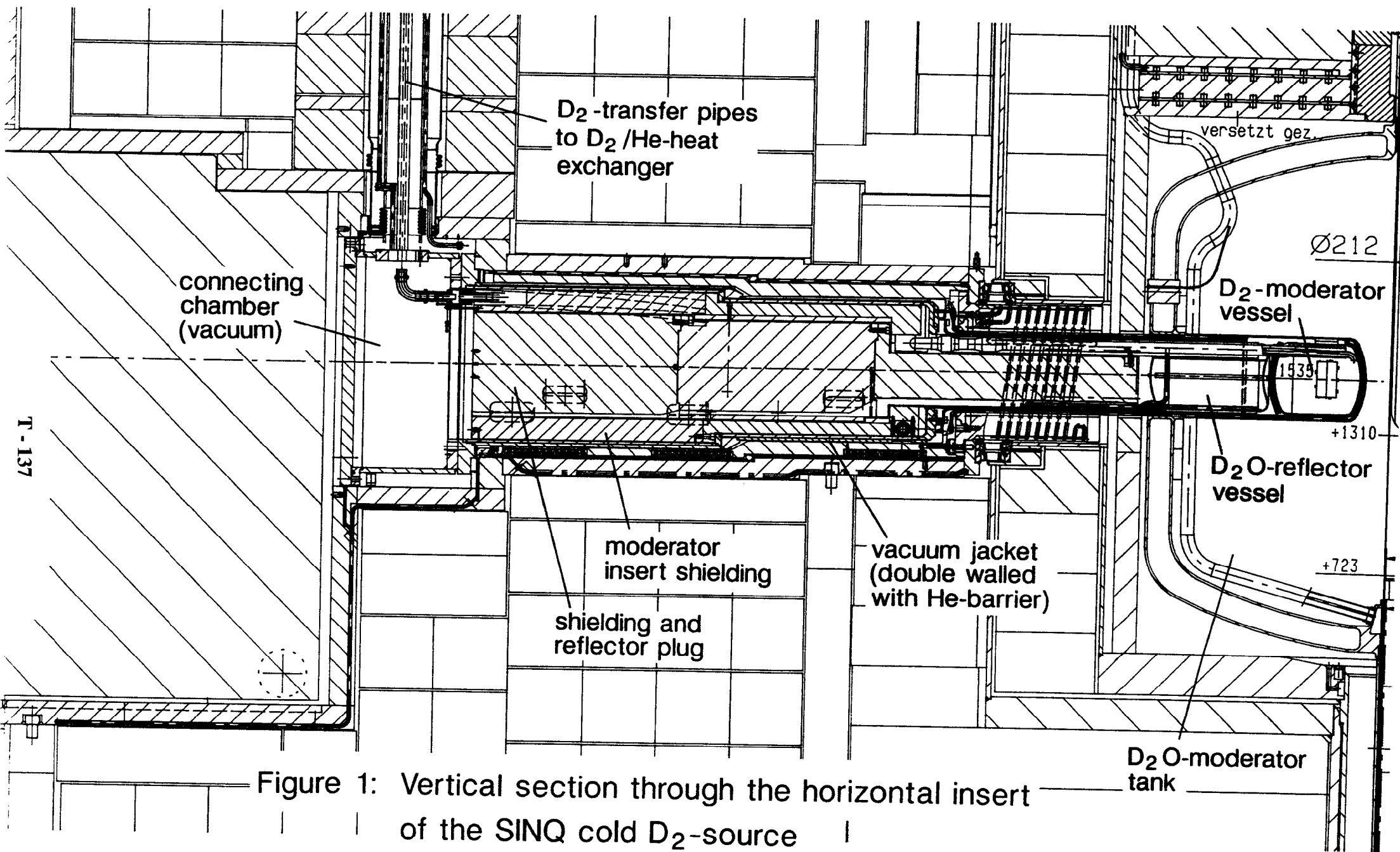a) heat input along the whole D_2-system with 3.6 W/cm^2 of surface, heat flux
b) Heat input concentrated on moderator and phase separator volumes but matching the total heat input of curve a)
c) as b) but time constant of power rise reduced from 300 ms to 3 ms.

Figure 5: Remaining deformation at various positions of the moderator vessel after pressurizing to different levels and returning to normal pressure at 78 K. The precision of the calibration is ± 0.2 µm/m.

Figure 6: Deformations measured in the room temperature pressure tests. Clearly the limit of elastic deformation (zero after return to normal pressure) is given by the softening around the weld.
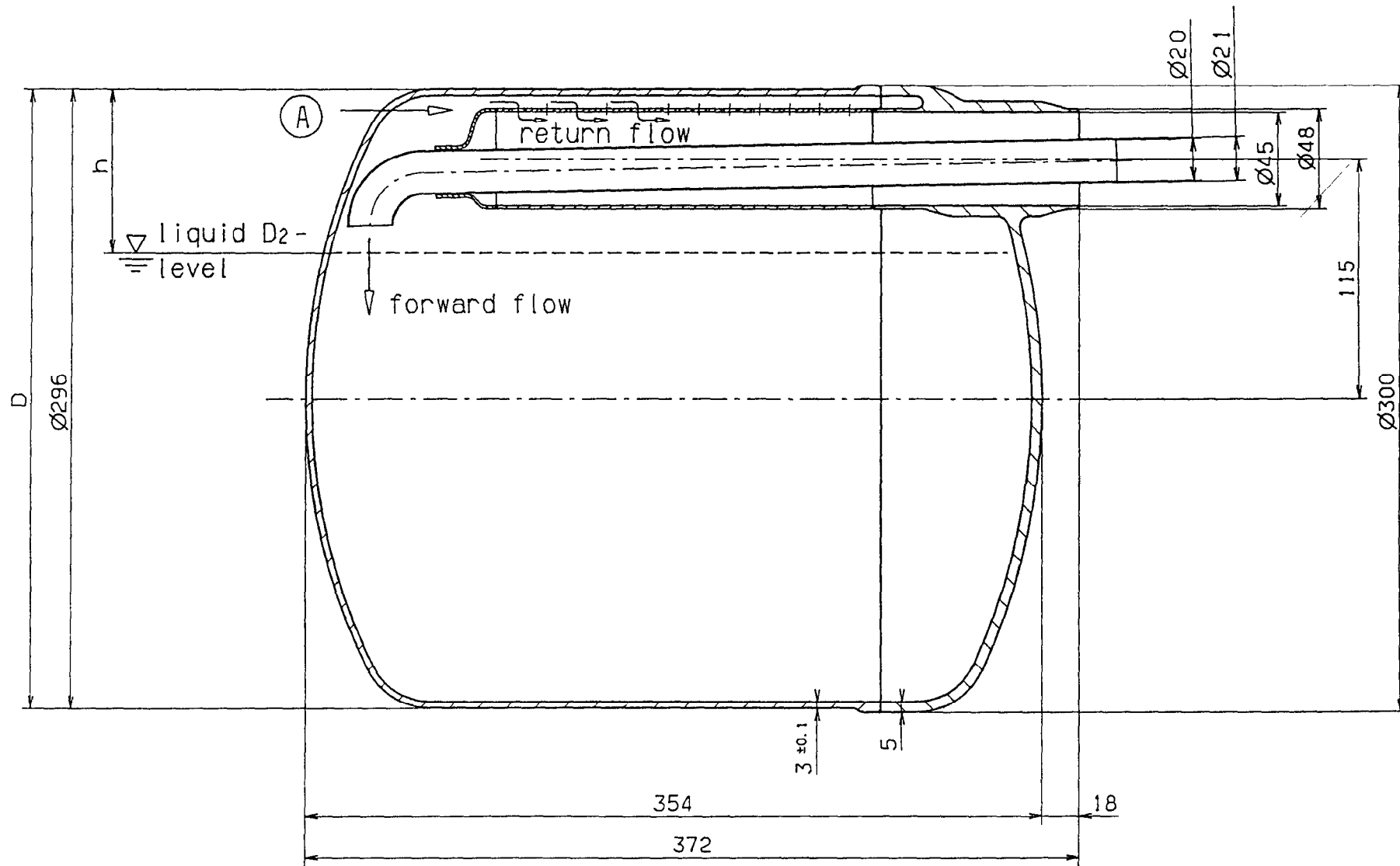
D$_2$-transfer pipes
to D$_2$/He-heat
exchanger

connecting
chamber
(vacuum)

versetzt gez.

Ø212

D$_2$-moderator
vessel

1535

+1310

D$_2$O-reflector
vessel

moderator
insert shielding

vacuum jacket
(double walled
with He-barrier)

shielding and
reflector plug

+723

D$_2$O-moderator
tank

Figure 1: Vertical section through the horizontal insert
of the SINQ cold D$_2$-source

Figure 2: The D$_2$-moderator vessel and its concentric
flow tubes (vertical section)

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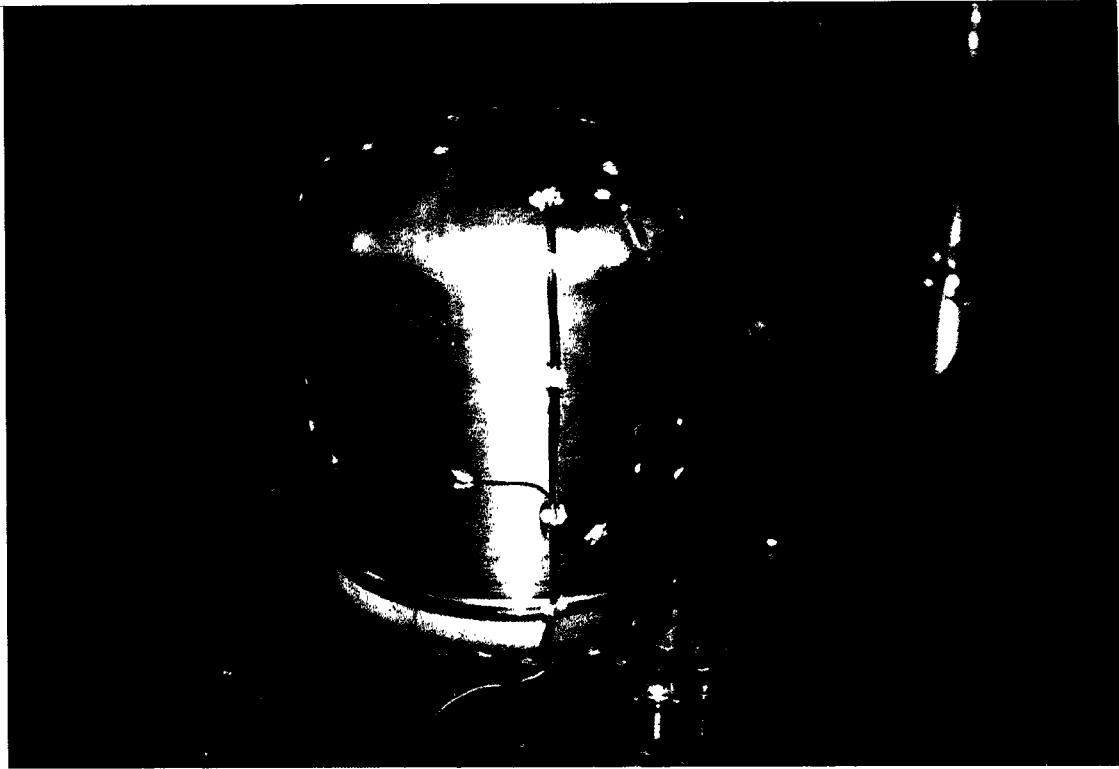
Figure 4: Moderator vessel equipment with strain gauges. Temperature compensation was accomplished by two monitoring positions visible at the lower right.
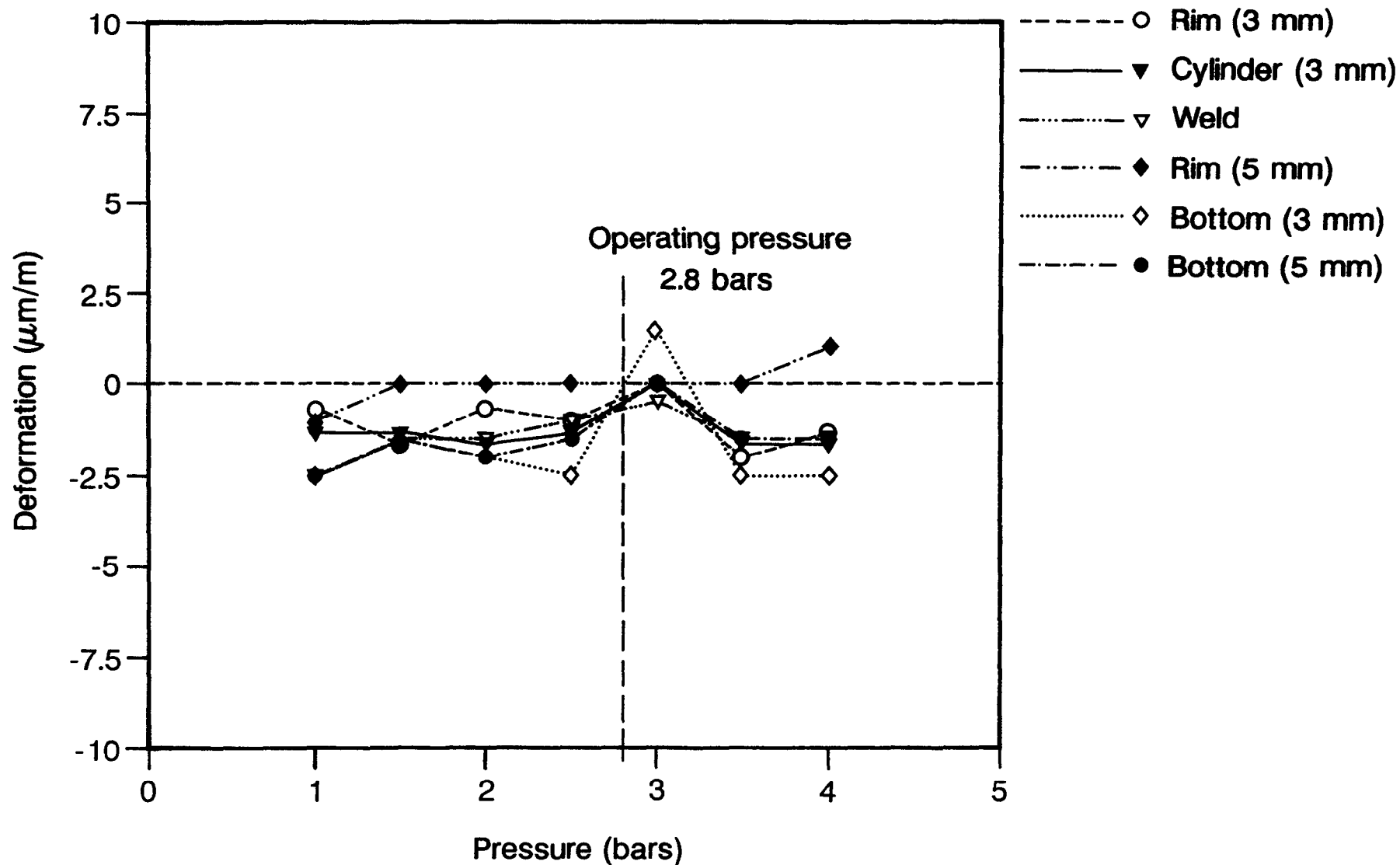
Figure 5: Remaining deformation at various positions of the moderator vessel after pressurizing to different levels and returning to normal pressure at 78K. The precision of the calibration is ±0.2 μm/m
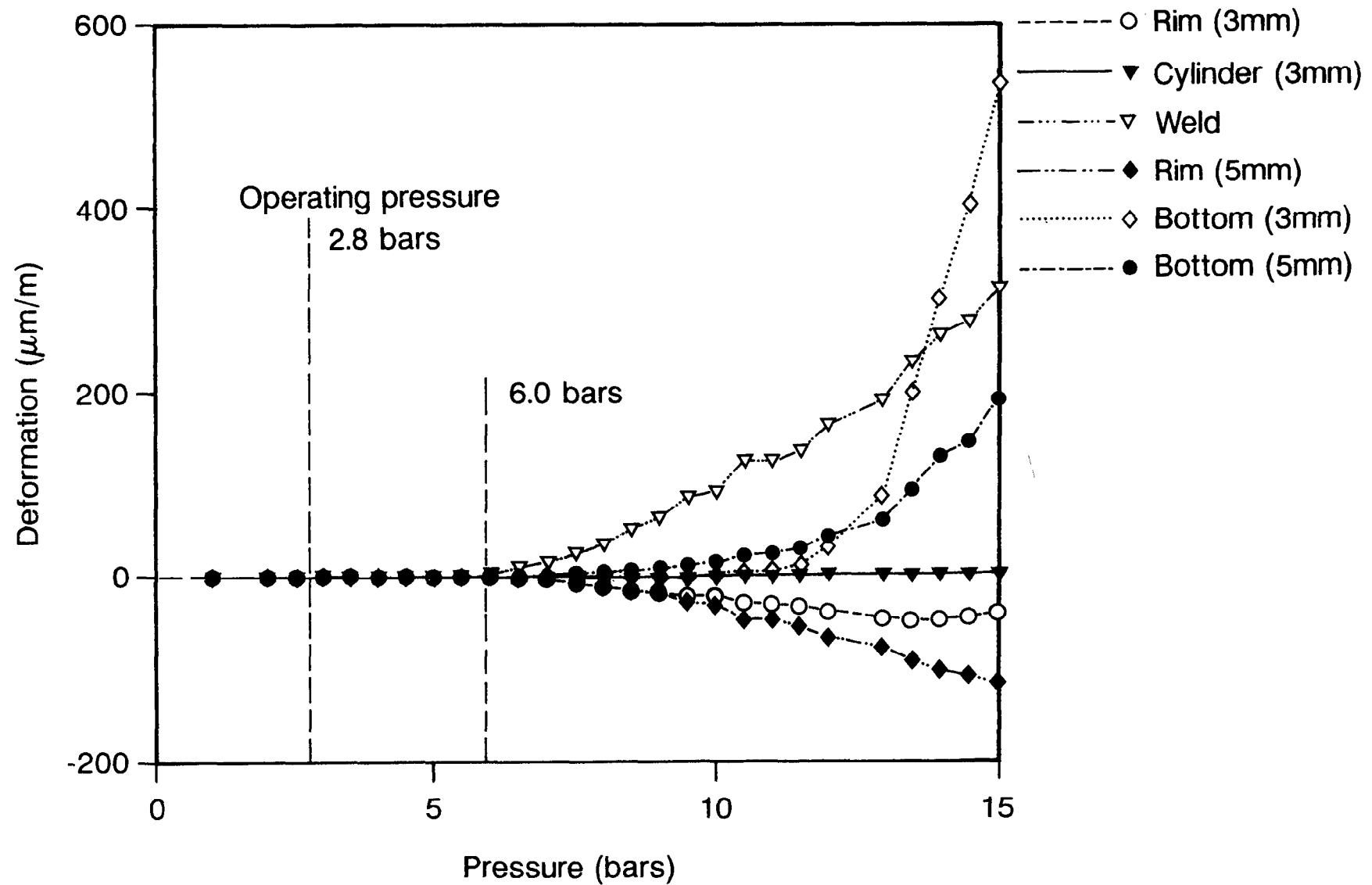
Figure 6: Deformations measured in the room temperature pressure tests. Clearly the limit of elastic deformation is given at around 6 bar by the softening around the weld.

Figure 7: Moderator vessel after rupturing at its cylindrical surface at a pressure around 30 bar. The whole vessel is seen to be plastically deformed (Cylindrical surface as well as the caps).