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EARLY OPERATIONAL EXPERIENCE WITH THE CERN 500 LITRE HEAVY LIQUID BUBBLE CHAMBER

1. Introduction

The operation of a large bubble chamber is rather critical, because it depends on the temporary achievement of an unstable superheated state in a large mass of liquid, without generalized boiling. The instability must be such that bubbles may be enucleated by the passage of a minimum ionizing particle and grow rapidly to a visible size. A series of tests and preliminary experimental runs have allowed to find satisfactory operating conditions for the CERN 500 litre heavy liquid bubble chamber.

Most of the liquids that can be used in the chamber have the common property of relatively high density. Heavy liquids are preferable for experiments which require interaction lengths and radiation lengths much smaller that in liquid hydrogen. Operational studies have been performed with a typical representative of this category: CF_3Br, called commerciall Du Pont Freon 13 B1.

2. The chamber

The chamber [1)] is a polished cylindrical stainless steel vessel, 1.15 m in internal diameter and 0.50 m long, with an horizontal exis, closed at one end by a 0.25 m thick glass window, and at the other by a reinforced rubber diaphragm which rests, in the expanded state, against a perforated plate, supported by a magnetic pole.

The beam enters through a stainless steel spherical window, 4 mm thick, having a diameter of 0.16 m.

The glass window is protected by a pressurized safety tank, having smaller windows in its thick end-plate, which supports the cameras. A gas pressure equal to the chamber static pressure is maintained in the safety

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tank by an electropneumatic "pressure equalizer".

Gas pressure can be applied behind the diaphragm through pneumatic membrane valves from two reservoirs, where pressures are automatically regulated at preset values below and above the equilibrium pressure of the working liquid. The expansion cycle is obtained by programmed operation of the membrane valves by means of auxiliary electropneumatic systems ("Barksdale" system).

The temperature in the chamber and safety tank is controlled by six independent water-circulating loops, each with a pump and a thermostat. Xenor flash tubes are contained in eight pressure-tight glass pipes, inside the chamber, and are cooled by water circulated in finned copper pipes. A central control desk contains the timing system, the monitoring instruments, the pulsed power supplies for the electropneumatic valves and for the flash tubes.

The chamber is mounted inside an 82 ton magnet, which creates a field of 2 Wb/m^2 with 5000 A excitation and > 2.7 Wb/m^2 with 8000 A (4.5 MW dissipation). Fig. 1 is a vertical axial section of the chamber in the magnet. Fig 2 and 3 are photographs of the apparatus during assembling and in operation respectively.

3. Operation with CF_3Br

The experimental activity with the chamber started with an early attempt to detect high energy neutrino interactions. A filling of very high density was essential in a search for such rare events. Trifluorobromomethane (CF_3Br) [2),3),4)] also known as Freon 13 B 1, was the densest suitable fluid available in large quantities at a reasonable price. Its operating density is about 1.5 and its radiation length 0.11 m. It operates just above room temperature and at a convenient pressure; it is stable, and is not corrosive, toxic or inflammable. Table I gives the physical constants of CF_3Br.

Table I

Physical constants of freon CF_3Br

Molecular weight 148.92 $Z_e = 68$

Boiling temperature $- 57.8\,^{\circ}C$

At critical point ; temperature $t_c = 67\,^{\circ}C$; pressure $p_c = 40.5\ kg/cm^2$; density $\rho_c = 0.75$

Temperature	Vapour pressure	Saturated Vapour density	Liquid density	Specific heat of vaporization	Surface tension	Specific heat of liquid	Thermal conductivity of liquid
$^{\circ}C$	kg/cm^2			kcal/kg	$Newton/m \cdot 10^{-3}$	$kcal/kg\,^{\circ}C$	$\frac{kcal}{m\,^{\circ}C\ h}$
- 5	7.15						
0	8.4	0.065	1.70	20.7	7.5	0.187	0.057
5	9.7						
10	11.2	0.085	1.64	19.5	5.9	0.195	0.055
15	12.8						
20	14.5	0.115	1.57	18.5	4.5	0.205	0.053
25	16.5						
30	18.6	0.155	1.49	17.7	3.2	0.217	0.051
35	20.8						
40	23.2	0.205	1.38		2.0	0.237	0.049

Five experimental runs were performed with CF_3Br, with a total of 250'000 expansion cycles (the diaphragm and the rubber membranes of the main valve were replaced after 160'000 cycles). Stable operating conditions could be obtained at temperatures between 27^{o}C and 30^{o}C, at repetition rates of 3 and 2 seconds. Some 150'000 pictures were taken for the neutrino search, 8'000 during tests with cosmic rays, and 12'000 in a 4 $\frac{GeV}{c}$ positive beam (Fig 4).

At a working temperature of 29^{o}C, corresponding to an equilibrium pressure of 18.2 kg/cm, a typical expansion pressure was 9.5 kg/cm^2 Since an overpressure of 4 kg/cm^2 was used, the actual pressure change in the chamber at expansion was 13 kg/cm^2. The corresponding variation of liquid volume, is about 2.6 o/o : 13 litre on 500 litre. Specific operational problems and experimental results are discussed in the following sections.

4. The expansion cycle

The use of a heavy filling in the chamber emphasized the problems of hydrostatic pressure on the vertical diaphragm and of inertial effects in the expansion.

The pressure difference between gas and liquid on the two sides of the vertical diaphragm changes with level because of the hydrostatic pressure of the liquid: therefore the forces acting on the diaphragm are not circularly symmetrical. The stresses in the diaphragm balance the pressure gradients and make the diaphragm take different shapes for different liquid volumes: vertical cross sections in the symmetry plane are sketched in Fig. 5. For correct operation, it is essential that the diaphragm is well away from the perforated plate at compression so that it does not hit it during expansion: this requirement fixes the maximum amount of filling in the chamber.

With CF_3Br, the hydrostatic pressure at the membrane bottom is 0.15 kg/cm^2 higher than at the top: for good operating conditions the gas pressure must exceed the freon pressure at the top by about this amount. The maximum tensile stress originated under such conditions depends on the equivalent elastic modulus of the diaphragm. The relation between sagitta and applied pressure on our nylon reinforced, 6mm thick rubber diaphragms, was determined experimentally. The resulting linear tension is about 10 kg/cm at a pressure of 0.15 kg/cm^2. The diaphragms were proved to withstand this load with adequate safety margins *).

Under good operating conditions, this diaphragm has to move back by about 2 cm to expand the chamber. Roughly we may consider that the liquid layer near the diaphragm moves by this amount, and that the displacement decreases linearly along the chamber axis and is zero at the window. At the beginning of the expansion, the liquid is accelerated. The end of the expansion and the following recompression correspond to a negative acceleration, while at the end of the recompression, acceleration is again positive.

The forces involved may be estimated by considering the motion as uniformly accelerated during the first quarter of the expansion, and as uniformily retarded at the bottom of the cycle. The resulting acceleration at the membrane is 180 m/s^2 for a typical expansion time of 30 msec. The average acceleration in the liquid mass in then 90 m/s^2 and the corresponding inertial force is a push of about 7 tons. This internal force is small, compared to the static pressure loads : it is equivalent to a pressure difference of 1 kg/cm^2 between liquid and gas on the two sides of the diaphragm. However, it is clear that a severe shock would be produced if the diaphragm would hit the perforated plate during expansion because of insufficient free-volume.

The expansion speed was limited by the cross-section of the ducts in an adjustable throttle: a total expansion time of 30 ms was obtained with

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*) Note : The nylon reinforced diaphragms had 4 layers of 1 mm^2 mesh, made of 0.25 mm thread. If the nylon would take the whole load, the stress in it would be 3.5 kg/mm^2.

a cross section of 140 cm^2 (50 o/o of the maximum). The mass of air flowing out during expansion corresponded to the active volume of 13 litre plus a dead volume of 46 litre. So the total mass avacuated was 1.15 kg. From the maximum slope of the pressure-time diagrams (Fig.6) it results that the equivalent velocity of flow through the minimum section was 200 m/s, or, assuming that the velocity of sound was actually reached in the contracted vein, that the contraction of the flow made the critical cross section equal to 60 o/o of the total minimum section.

No need was felt for a faster expansion which could be obtained by using the full section of the expansion ducts. The speed limitation represents a precaution against the vibrations that would be produced in the system if, by accident, wrong operating conditions would occur and the membrane would hit the perforated plane during expansion.

5. Optimum operating conditions

An investigation of optimum operating conditions was guided by the application of existing studies on bubble formation and growth to the case of Freon 13 B 1. (see Appendix). Fig. 7 shows the expected trends in bubble density at minimum ionization and in rate of growth, as a function of temperature and pressure drop. For a given temperature, the number of bubbles per cm and the rate of growth would both increase with increasing pressure drop, but for a constant pressure drop, the bubble growth should become slower with increasing temperature.

An operating temperature of 29°C was found to give the best compromise between sensitivity and rate of growth, for a pressure drop of 9 kg/cm^2 under the equilibrium pressure. Under these conditions a flash delay of 5 ms with respect to the beam made the tracks well visible with a total flash energy of 1440 J and an aperture of f/22. Tracks at minimum ionization had an average of 15 bubbles/cm, when the beam entered the chamber at the bottom of the cycle. The sensitive time was about 10 ms.

By reducing the pressure drop to 7 kg/cm^2 under equilibrium, the sensitivity was strongly reduced: the tracks of minimum ionizing particles had 5 to 6 bubbles/cm. Pictures taken with intermediate pressure drops showed a progressive change in sensitivity. The amount of light was 5 to 6 times less, so that the surface growth seems to have been twice slower. Both these findingscheck with the theoretical predictions of the diagram in Fig 7. Pictures taken with variable flash delays showed that the track width of thick tracks was roughly proportional to the square root of the time of growth.

Overall measurements of distortions in the chamber with CF_3Br are made difficult by multiple Coulomb scattering, which would give an r.m.s. radius of curvature of 78 m, i.e. an r.m.s. sagitta of 1.6 mm on 1.00 m tracks of 4 GeV/c particles. A preliminary investigation carried out on simple projection tables has permitted to find occasional tracks of incoming 4 GeV/c particles crossing the whole chamber with no visible sagitta (less than 0.5 mm) in the absence of magnetic field. (A sagitta of 0.5 mm on a 1 m track corresponds to a radius of curvature of 200 m). Random distortion is actually expected to be smaller because the temperature was uniform within 0.3°C throughout the chamber and no displacement of the bubbles was visible when a second set of flash tubes was triggered 5 msec after the first one.

6. Thermodynamic cycle and thermal effects

The heat produced in the chamber by the thermodynamic cycle corresponding to the optimum operating conditions was evaluated from measurements of temperatures in the thermostatic circuits and of heat transmission. For the pressure cycle shown in the picture of Fig. 6 the heat produced was 0.3 kcal/cycle. This means that the total volume of the vapour bubbles formed and recompressed at each cycle was about 1 litre, i.e. of the order of 8 o/o of the liquid volume variation during expansion. At the operation rate of one cycle every 2 seconds the average dissipation was 600 W. Small variations in expansion pressure change heat production appreciably.

The temperature was kept uniform throughout the chamber within 0.3°C. The water temperature on the lower half of the chamber was equal to the liquid freon temperature, and the internally produced heat was extracted by the water circuits on the upper part of the vessel, which were about 10°C cooler. Our experience confirms that thermal balance is delicate in a large chamber because the heat transmission through thicker walls is more difficult and because the ratio of wall surface to total volume decreases with increasing size. For example, instability developes rapidly if a permanent vapour bubble is formed at the top.

Thermal effects involved in operation and in handling liquefied gases present the most serious problems in the case of heavy liquid chambers using thick glass windows, which cannot withstand thermal shocks. The manufacturer of the 25 cm thick glass window of the CERN chamber permits to increase its surface temperature by 10°C/h and to decrease it by 5°C/h. The corresponding situation with freon CF_3Br is illustrated by the following data.

The condensation of 450 litre of CF_3Br vapour at room temperature during the filling process frees about 1000 kcal: it takes more than 2 hours to remove this heat with a temperature drop of 5°C across the walls.

Full expansion of the chamber requires the formation of some 40 litre of CF_3Br vapour. If the heat of evaporation is supplied uniformly by the liquid mass the temperature drops by 0.7°C.

If the chamber is emptied by removing liquid through the bottom valve and the volume left is filled by evaporation, the allowable flow, for a cooling rate of 5°C/h, is about 5 litre/min, so that it takes 90 minutes to get the liquid out. Evacuation speed can be increased by supplying warm vapour from a separate tank to avoid local evaporation: in practice it has been possible to empty the chamber safely in one hour, but it seems difficult to go much faster. This fact would be relevant in case of emergency dumping.

At ordinary operating temperatures and not too far from saturated vapour pressure, the temperature drop due to irreversible adiabatic expansion of freon vapour from a tank into another is the order of 2°C/atm.

The successful achievement of regular operation and the present understanding of chamber control, obtained with operational tests, give now confidence that the CERN 500 litre heavy liquid bubble chamber can be used efficiently as a nuclear physics instrument.

Calculations and practice prove, however, that in this range of dimensions the difficulty of operation increases considerably with size. In this chamber a precise control of operating conditions is essential.

Summary The CERN 500 litre heavy liquid bubble chamber, 1.15 m in diameter and 0.5 m deep, came into operation in Spring 1961. A magnetic field of 2.65 Wb/m^2 has been measured in the chamber, when the magnet was powered with 3.9 MW.

Experimental data on chamber operation with CF_3Br is reported. They concern tensile stresses in the diaphragm due to hydrostatic pressure gradients, inertial effects in the expansion, gas flow in the expansion system, heat production in the thermodynamic cycle, thermal effects and precautious against thermal shocks to the glass windows in various operations, and preliminary data on distortion. The influence of temperature and pressure drop on sensitivity and bubble growth is discussed.

Operation is stable and reproducible, but the size of the chamber demands a precise control of operating conditions.

Acknowledgements.

The 500 litre liquid bubble chamber has been built by a team in the N.P.A. division of CERN. The names of its members and their specific contributions are listed in Ref. 1.

Our colleagues F. Bisson, G. Kuhn, D. Neet, M. Nikolic, B. de Raad and R.G.P. Voss have taken part in running the chamber and in improving its performance during these operational studies. The constant support of Dr. C.A. Ramm, division leader, and the help of the whole technical staff of the N.P.A. division are also gratefully acknowledged.

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Appendix

Bubble formation in freon CF_3Br

The mechanism of enucleation of bubbles in a superheated liquid by ionizing particles and the process of bubble growth have been studied in detail by several authors, [5),6),7)]. An elementary approach is adequate to make qualitative predictions on the operation of a bubble chamber with a given filling of known physical properties. Freon CF_3Br is considered in the following calculations.

The equilibrium equation for a spherical bubble of radius R, subject to internal pressure p_f and surface tension σ , is

$$p_i = p_f + \frac{2\sigma}{R}$$

If the radius of the bubble R_1 is larger than the critical radius

$$R_c = \frac{2\sigma}{p_i - p_f}$$

the action of the internal pressure prevails, and the bubble can grow spontaneously by evaporation in the fluid. In a bubble chamber, R_c is very small : for freon CF_3Br under ordinary conditions it is of the order of 10^{-6} cm.

The ionizing particle must supply the energy necessary to the formation of a bubble of radius $R > R_c$: the successive growth to visible size occurs spontaneously.

The minimum formation energy can be evaluated by adding the heat of vaporization, the surface energy and the work against the fluid pressure. The heat of vaporization is

$$E_h = \frac{4}{3} \pi R^3 \rho_v r$$

where ρ_v is the vapour density and r the specific heat of vaporization. Under ordinary operating conditions with CF_3Br, this term is about 10 times bigger than each of the two others.

For $R = R_c = \frac{2\sigma}{p_i - p_f}$, we can write

$$E_h = \frac{32\pi}{3} \rho_v r \frac{\sigma^3}{(p_i - p_f)^3}$$

The cubic law explains the strong dependence of sensitivity on temperature (of which σ is a function) and on pressure drop.

Curves of constant minimum energy, represented in the diagram of Fig. 7. as a function of temperature and pressure drop, have been calculated using the physical constants of CF_3Br given by table 1. The average number of interactions with electrons per unit length, in which an ionizing particle loses more than a given energy E_{min} is inversely proportional to E_{min} and to the square of the velocity β_c. The chamber sensitivity (number of bubbles per cm) for minimum ionizing particles (β=1) should be proportional to $1/E_{min}$: the curves in diagram 1 can therefore be interpreted as a scale of sensitivity.

The rate of growth of the bubbles to visible size is determined by the rate at which heat flows from the surrounding liquid to the surface of the bubble, to provide the heat of vaporization. The temperature inside the bubble will rapidly approach the boiling temperature T_b at the fluid pressure p_f, because the required difference between internal and external pressure

$$p_i - p_f \geqslant \frac{2\sigma}{R}$$

is very small for $R \gg R_c$. The thickness of the layer through which heat flows, at the instant t of the growth, from the fluid at temperature T_W to the bubble at temperature T_b, is of the order of

$$s = \sqrt{2 \frac{\lambda}{\rho c} t}$$

where λ, ρ, c are the thermal conductivity, the density and the specific heat of the liquid.

By writing the balance between the incoming heat in a time dt and the heat of evaporation to increase the radius R by an amount dR, the following relation between radius and time can be obtained:

$$R^2 = \alpha \frac{2\lambda c \rho}{r^2 \rho_v^2} (T_W - T_b)^2 \, t$$

where ρ_v is the vapour density and r the specific heat of vaporization at the temperature T_b, and the coefficient α is of the order of unity. From this formula it results in particular that the amount of light scattered by the bubble is proportional to the time of growth. The rate of surface growth, $\frac{R^2}{t}$, depends on the square of $\frac{T_W - T_b}{r \rho_v}$. This term increases with pressure drop, but for a given pressure drop, is higher at lower working temperatures.

The dotted lines in the diagram of fig. 7 have been calculated from the above formula, assuming $\alpha = 1$. They give a scale of the times needed for bubbles in CF_3Br to grow diameter under different operating conditions. Results of operational tests in the 500 litres H.L.B.C. are in agreement with the predictions of this diagram.

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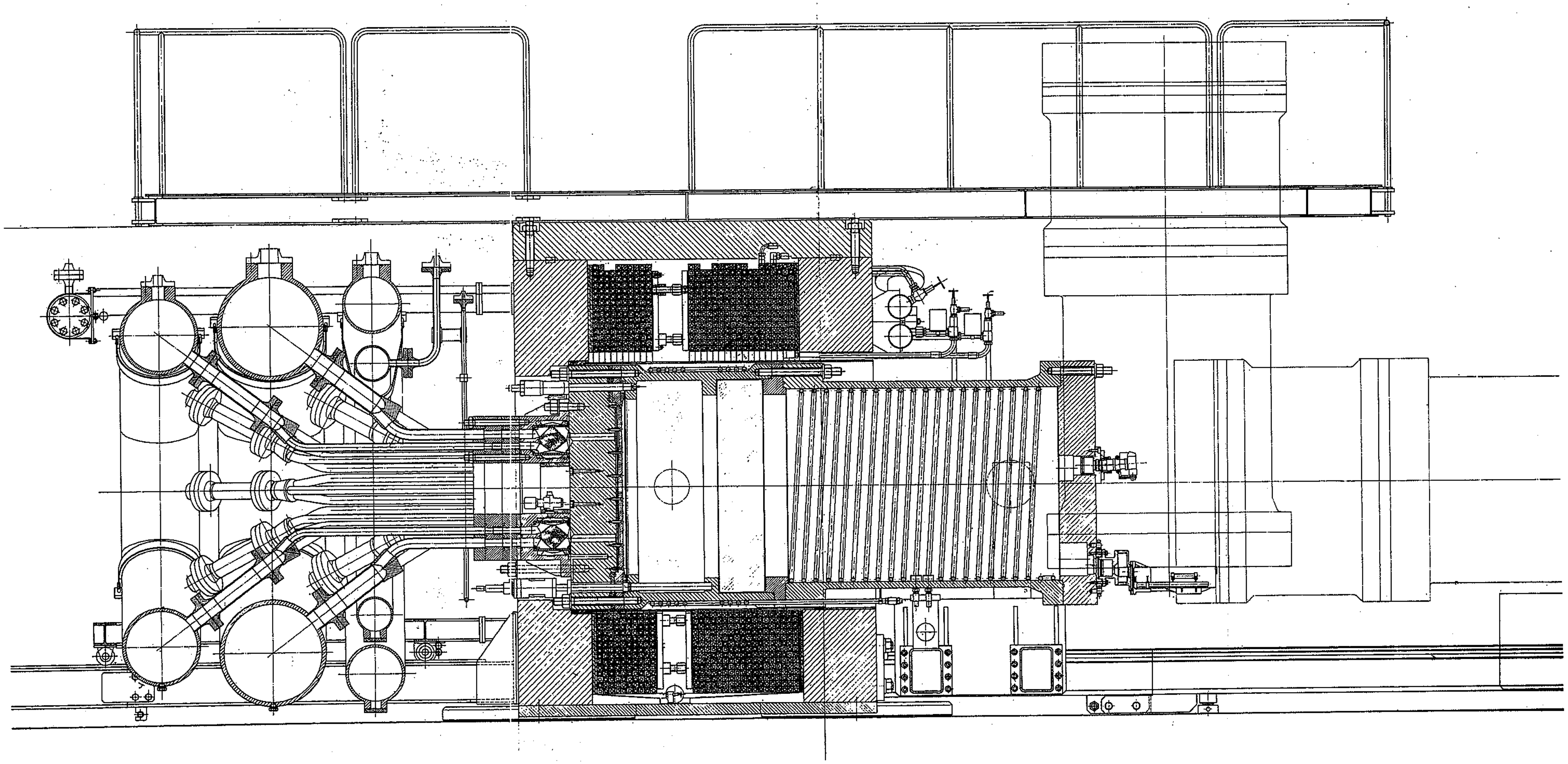

Fig. 1

Vertical - Axial Section of
the Chamber in the Magnet

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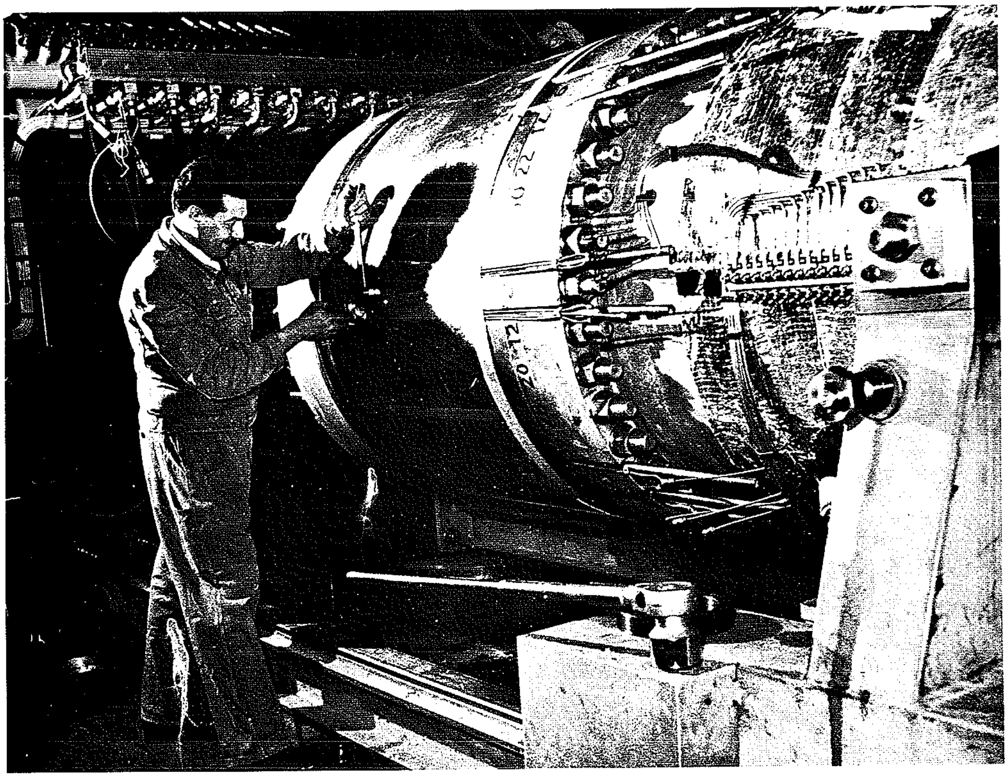

Fig. 2

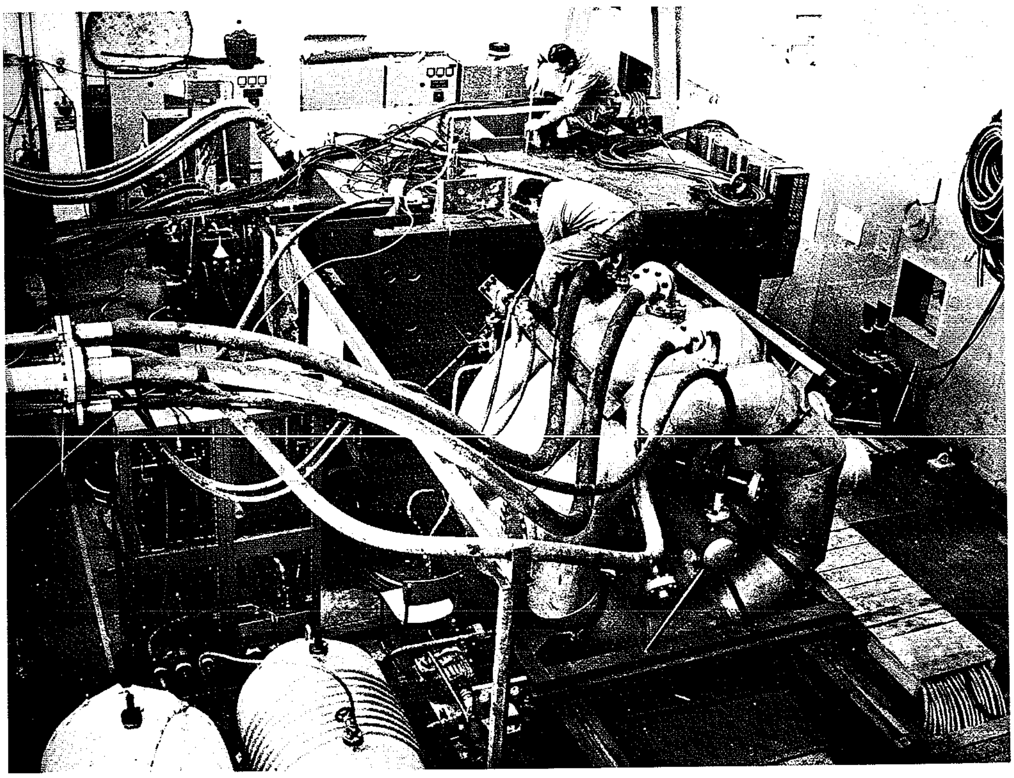

Fig. 3

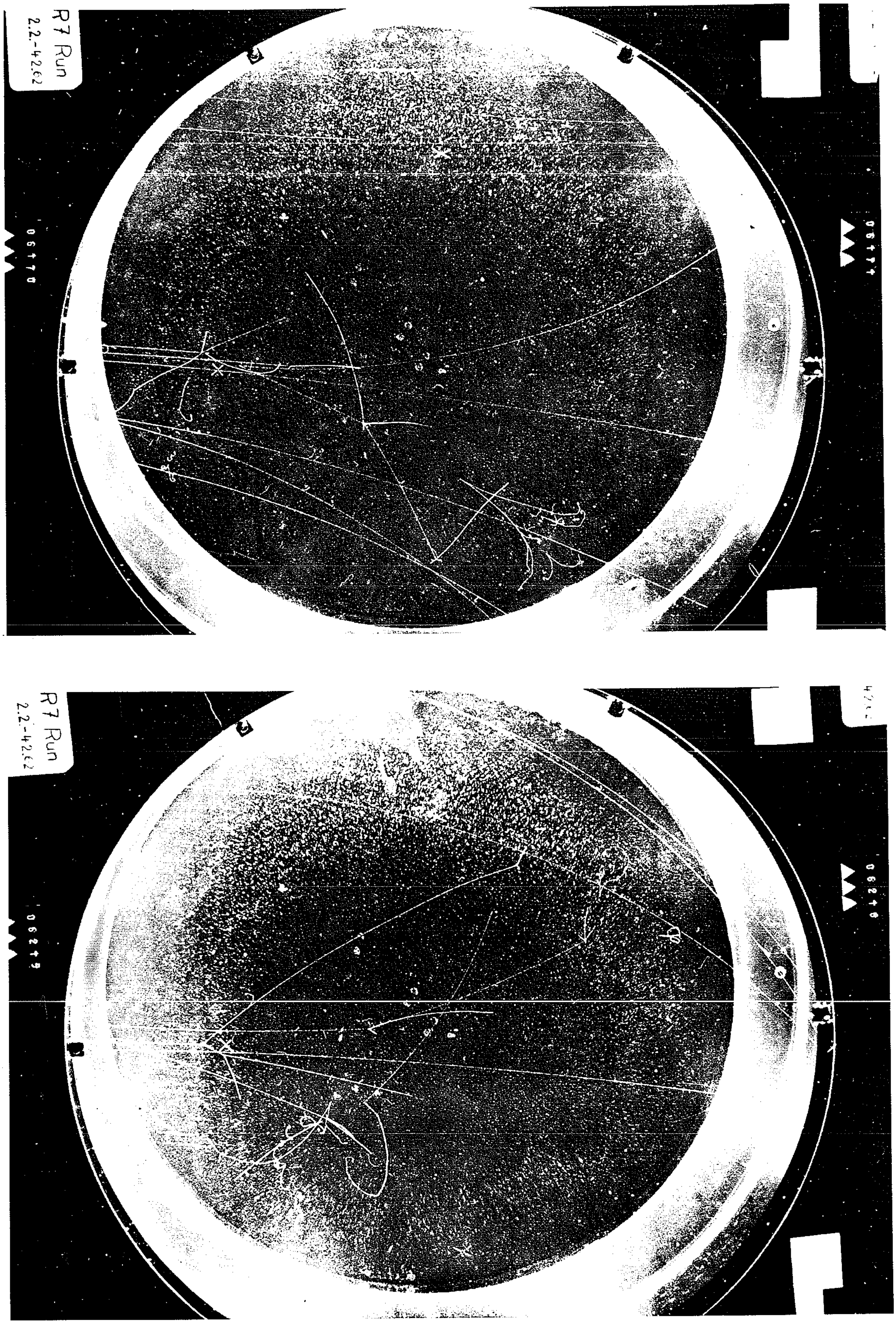

Fig. 4

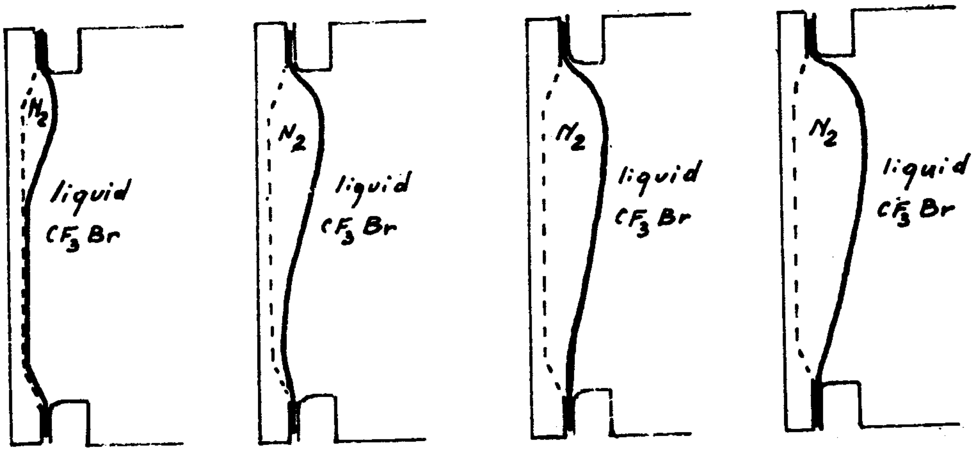

Fig 5 Shapes of the diaphragm at different liquid volumes

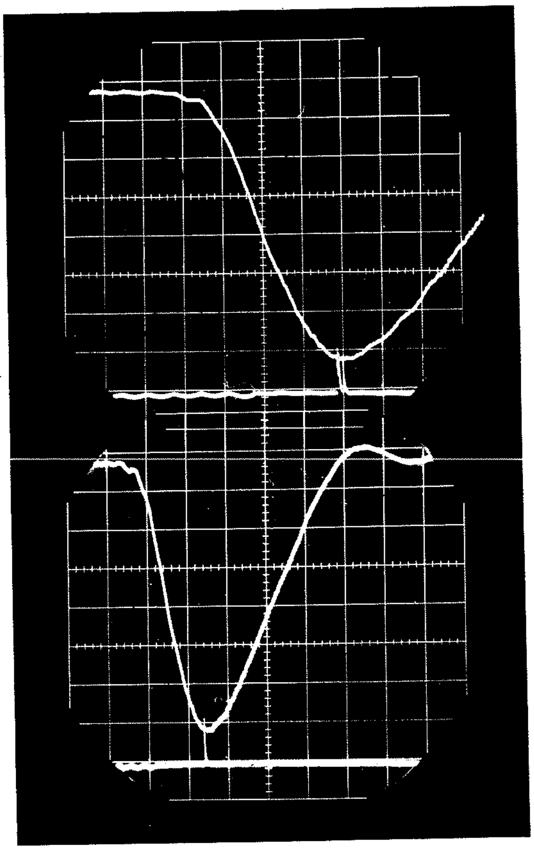

Fig. 6

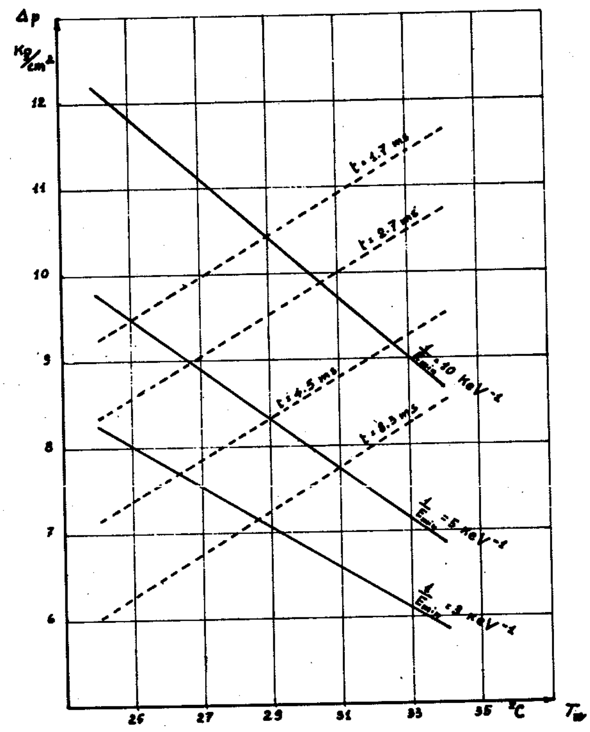

Fig 7 Temperature and pressure dependance of enucleation energy and of bubble growth in CF_3Br

Δp = pressure drop under equilibrium T_w = operating temperature

E_{min} = minimum enucleation energy

t = time of growth to 0.1 mm radius