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# FUEL OVERFLOW AND TANK DIFFERENTIAL PRESSURE DUE TO AIR RELEASE FROM FUEL AT ALTITUDE

by

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# FUEL OVERFLOW AND TANK DIFFERENTIAL PRESSURE DUE TO AIR RELEASE FROM FUEL AT ALTITUDE

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## SUMMARY

The pressure rise and fuel overflow produced by taking a tank of air saturated fuel to altitude and then switching on a booster pump have been measured. Two tanks (4.6 $m^3$ and 55 litres) were used with different vent arrangements and various pumps. The ullage volume and altitude were varied.

Although some empirical equations for the tank differential pressure and overflow have been derived, it was not possible to obtain general equations for design use. This was due to the large number of parameters involved, especially the rate of air release, which is dependent on the agitation produced by the booster pump.

It is concluded that if operation of any aircraft fuel system is likely to produce rapid de-aeration, for example, by the starting of a fuel booster or transfer pump at altitude, simulated tests are necessary to prove the system.

Departmental Reference: EP 594

## CONTENTS

Page

1 INTRODUCTION 3

2 TEST RIGS AND TEST METHODS 4

- 2.1 Test rigs 4
  - 2.1.1 4.6 $m^3$ tank 4
  - 2.1.2 55 litre tank 4
- 2.2 Test procedures 5
  - 2.2.1 4.6 $m^3$ tank 5
  - 2.2.2 55 litre tank 5

3 PRESSURE RISE 5

- 3.1 Vented tank (4.6 $m^3$) with zero ullage: orifice size and altitude varied 5
- 3.2 Vented tank (4.6 $m^3$): ullage and orifice size varied 6
- 3.3 Closed tank (55 litres): ullage and altitude varied 7
- 3.4 Closed tank (55 litres): agitation varied 8
- 3.5 Vented tank (55 litres): agitation and altitude varied 8

4 FUEL OVERFLOW 9

- 4.1 Vented tank (4.6 $m^3$)with zero ullage: orifice size and altitude varied 9
- 4.2 Vented tank (4.6 $m^3$) with ullage 10

5 FUEL AIR CONTENT 10

6 DE-SUPERSATURATION BY NITROGEN BUBBLING 11

7 DISCUSSION 12

8 CONCLUSIONS 14

Appendix A Description of test rigs 17

Appendix B Method of test 19

Appendix C Theoretical pressure rise in a closed tank 21

Tables 1-5 23

Symbols 28

References 29

Illustrations Figures 1-17

Detachable abstract cards -

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## 1 INTRODUCTION

It is well known that gases are soluble in liquids, the amount being expressed by Henry's law which states that the mass of gas in solution is proportional to the partial pressure of the gas over the liquid. The constant of proportionality, or solubility coefficient, varies with the liquid, the gas and the temperature. Thus aviation kerosene (AVTUR) absorbs about 15% by volume of air (at stp) but due to their constants of proportionality oxygen and nitrogen are absorbed in the fuel at ground level in the percentages, by volume, of about 32 for oxygen and 68 for nitrogen, compared with 21% oxygen and 79% nitrogen in the atmosphere.

A change from the original saturation conditions in either reduced pressure or a change in temperature can lead to the liquid becoming supersaturated. If the liquid is then agitated the gas will be rapidly released. It follows that reduction of fuel tank pressure during an aircraft climb results either in the progressive release of air or in the fuel becoming supersaturated, the degree of supersaturation being influenced by the corresponding changes of the fuel temperature and whether agitation is present.

Air release raises a number of potential problems for the fuel system designer;

(a) Performance of fuel pumps (e.g. transfer, booster or backing) may be affected since the ratio of the volume of air to liquid may be such as to prevent satisfactory starting of the pump or to seriously effect the pump efficiency because of cavitation[1].

(b) Inerting systems may be adversely affected due to the preferential release of oxygen enriched air under altitude conditions[2].

(c) Capacitance fuel gauging systems may be affected by frothing of the fuel caused by gas release.

(d) Transient pressure differentials in the tank may be caused, depending on the rate of release of the gas and the size of the venting system.

(e) Fuel may be lost through the tank vents, because the released gas bubbles raise the fuel level.

This Report describes a series of experiments to investigate the pressure rise and fuel overflow caused by taking fuel, saturated with air, at ground level to various altitudes and then switching on a booster pump to release the supersaturating air. The main work was done with a 4.6 $m^3$ tank (1000 gal) fitted with a simple orifice vent, which was in an altitude chamber. Further experiments were made with a small tank (55 litres) with a vent pipe connecting it to a vacuum pump. The effects of varying the ullage, vent size, and agitation have been investigated.

It was hoped that empirical equations would be developed which would be of use in design work. It was found that the effects were more complex than expected, in particular, the rate of gas release was very dependent on the details of the agitating pump, and it has not proved possible to achieve this objective.

## 2 TEST RIGS AND TEST METHODS

Detailed descriptions are given in Appendices A and B.

### 2.1 Test rigs

Two test tanks were used in this series of experiments. One of 4.6 $m^3$ (1000 gall) capacity and the other 55 litres (12 gal).

### 2.1.1 4.6 $m^3$ (1000 gal) tank

The 4.6 $m^3$ tank was installed in an altitude chamber and vented into a collector tank through a simple orifice plate mounted in the top. The size of this orifice could be varied over a range of sizes from 45-178 mm (1.75-7.00 in). Agitation of the fuel was achieved by running an aircraft booster pump mounted in the bottom of the tank at the opposite end to the vent. Fuel level within the tank was monitored by a calibrated sight glass and a capacitance type probe and tank pressure by pressure transducers and a differential pressure gauge. Prior to each test the fuel was aerated under ground level conditions by bubbling dry air through eight sintered discs positioned along the floor of the tank. The physical layout of the tank-altitude chamber configuration is shown in Figs.1a and 1b.

### 2.1.2 55 litre tank

The smaller, 55 litre tank was also fitted with an aircraft booster pump in its base but instead of using a vacuum chamber to simulate altitude conditions, it was connected directly to a vacuum pump via a pipe and isolating valve. Venting of this tank was through the suction pipe, and by closing the isolating valve closed tank tests could be performed.

As in the large tank, pressure was monitored with gauges and a pressure transducer, and aeration of the fuel was by air bubbling through a sintered block. Arrangement of this tank is shown in Figs.2a and 2b.

## 2.2 Test procedures

### 2.2.1 4.6 $m^3$ tank

The large tank was filled to the required level with Avtur and aerated to ensure that the fuel was fully air saturated under ambient conditions. The altitude chamber was evacuated at a rate corresponding to 50 m/s (10000 ft/min) altitude climb rate and, when the desired steady pressure condition existed within the tank, the fuel was violently agitated by switching on the aircraft booster pump.

The resulting sudden release of supersaturated air from solution within the fuel caused the fuel to expand, forcing a mixture of air and fuel through the vent. The tank pressure rise was recorded and after the overflow had ceased, the quantity of fuel expelled from the tank was measured.

### 2.2.2 55 litre tank

The test method for the 55 litre tank was basically the same as that above except that some tests were made with the tank closed.

All tests were made using Avtur (D. Eng R.D. 2494) fuel.

## 3 PRESSURE RISE

## 3.1 Vented tank (4.6 $m^3$) with zero ullage: orifice size and altitude varied

The 4.6 $m^3$ tank was completely filled with Avtur which was then aerated by bubbling dry air through the fuel to ensure air saturation at ambient conditions. The chamber was evacuated to 9150 m (30000 ft), 13700 m (45000 ft) or 19800 m (65000 ft) at a rate of 50 m/s (10000 ft/min) and after a period of 1 minute at the test altitude the booster pump in the tank bottom was switched on. The tank pressure versus time was recorded and the maximum pressure differential measured. The experiment was repeated for various vent sizes, between 45 mm and 178 mm.

The results are given in Table 1 and plotted in Fig.3. There is a scatter of the order of ±10% in the maximum pressure differential which is probably due to ambient temperature variation of about 8°C, variation in the ambient pressure and possibly a small amount of air trapped at the top of the tank (see section 4). It was also noted that during the climb some air was released, particularly from around the pump area, and there is no reason to believe that this was constant.

Plotted on a semi-logarithmic basis, see Fig.4, the maximum differential pressures fall on straight lines. Thus, within the range of test conditions, the following relationships holds between pressure rise and vent size:

$$\Delta P_0 = 28.5e^{-nd} \tag{1}$$

where $\Delta P_0$ is the maximum differential pressure (kN/m$^2$), $d$ is the vent diameter (mm) and $n$ is a constant depending on the altitude. Fig.5 plots the constant $n$ against the altitude pressure and shows the following relationship holds

$$n = 6 \times 10^{-3}e^{0.051P_a} \tag{2}$$

where $P_a$ is the altitude pressure (kN/m$^2$).

The common intercept with the ordinate of the extrapolated lines in Fig.4 is 28.5 kN/m$^2$. This should correspond to a closed tank condition. It is shown in Appendix C (equation (C-8)), and is intuitively obvious, that the pressure differential for zero orifice size and zero ullage is

$$\Delta P_0' = P_G - P_A$$

where $P_G$ is the ground level pressure and $P_A$ the altitude pressure. Since the pressures at the three test altitudes were 30, 15 and 6 kN/m$^2$, the corresponding theoretical pressure differentials for a closed tank are 71, 86 and 95 kN/m$^2$. No firm explanation for the large discrepancies can be advanced, but it is probably due to the fuel remaining oversaturated even after agitation. This was shown in direct measurements, see section 5.

## 3.2 Vented tank (4.6 m$^3$): ullage and orifice size varied

The 4.6 m$^3$ tank was partially filled, leaving an ullage, the air saturated and the chamber taken to 19800 m (65000 ft) as previously described (section 2.2). The booster pump was switched on and the pressure measured versus time. The experiment was repeated for various ullage proportions, up to 15%, and various vent sizes (45-102 mm).

The results are given in Table 2. The ratio of the pressure rise with finite ullage $\Delta P_u$ to the corresponding figure with zero ullage $\Delta P_0$, other conditions being held the same, is plotted in Fig.8, using semi-logarithmic axes. The value of $\Delta P_0$ for each condition is obtained from equation (1) (corresponding to the best fit straight lines in Fig.3). Although there is some scatter of points, the following relationship holds approximately:

$$\Delta P_u = \Delta P_0 e^{-kU} \qquad (3)$$

where U is the ullage fraction and k is a constant, with the numerical value for these conditions of 0.162. Variations of k with altitude and other variables was not determined.

Fig.9 contrasts on linear scales, the actual pressure rise as measured and the empirical curves based on equations (1) and (3), for 63.5 mm dia vent and 19800 m altitude.

## 3.3 Closed tank (55 litres): ullage and altitude varied

In order to check the validity of the expression for the maximum pressure rise developed in a closed tank, viz:-

$$\Delta P = (P_G - P_a)(1/[u/(1 - u)k + 1]) \qquad (4)$$

where $P_G$ = ground level pressure
$P_a$ = altitude pressure
k = constant of proportionality (solubility coefficient)
U = ullage ratio V/c
V = tank ullage volume
c = tank total volume

as derived in Appendix C, tests were made in the 55 litre closed tank. This was partially filled, pumped down to altitude pressure and, when conditions were stable, the externally mounted booster pump was switched on. The pressure rise was measured. The experiment was repeated for a range of altitude pressures (96 down to 6 kN/m$^2$) for each ullage faction (4 to 40%).

The experimental results are given in Table 3 and plotted in Fig.10 (broken lines), together with the theoretical lines (shown solid) as obtained from the above expression. A solubility coefficient of $k = 0.15$ was used in this analysis.

It can be seen from Fig.10 that a difference ranging from 13% to zero at 4% and 40.0% ullages respectively, occurs between the theoretical and measured values. These differences could be due to an error in the assumption of a value of 0.15 for k, errors in measurement of ullage or a combination of both.

Fig.11 shows the variation of the factor $1/[u/(1 - u)k + 1]$ with ullage using three different values of k and from these curves it can be seen that small absolute errors in ullage value, especially in the region 0-20%, will have a significant effect on the value of the factor and hence on the calculated pressure rise. The increasing differences shown in Fig.10 suggests an error in ullage measurement which tends to be verified by the fact that accurate measurement is extremely difficult due to unknown volumes of air in manometer lines etc., connected to the top of the fuel tank, and which become increasingly significant as the tank is filled.

Tests at zero ullage were impossible as fuel tended to be sucked through the vacuum line during the climb to altitude.

### 3.4 Closed tank (55 litres): agitation varied

In order to examine the possible affects of the size and configuration of the agitator on the rate of air released in a closed tank, the results in section 3.3 using the externally mounted pump (SPE FB11 Mk.9) were supplemented by tests using a much smaller, totally immersed fuel pump (SPE BP14 Mk.3) from which the fine mesh wire debris guard had been removed.

The results in Fig.12 show that the rate of increase in pressure (rate of air release) in the 55 litre closed tank when using the smaller pump was much slower. After several minutes agitation the final pressure was observed to be the same as that generated by the larger pump.

A visual difference in the manner in which the air was liberated from the fuel was also noted. Using the larger externally mounted pump, air bubbles were dispersed throughout the bulk of the fuel almost immediately the pump was started, whereas with the internally mounted pump, air bubbles rose initially in a restricted vertical column only dispersing throughout the bulk of the fuel after a period of several seconds.

### 3.5 Vented tank (55 litres): agitation and altitude varied

As the 55 litre tank was not in an altitude chamber (cf. 4.5 $m^3$ tank), the only convenient way of providing a vent was to keep the vacuum pump running and connected via a fuel trap to the tank during a test. A regulated supply of air was bled into the vacuum line to maintain the required altitude conditions within the tank.

Three different pumps were used for these tests; the two used in the preceding tests (section 3.4) and another totally immersed pump, type SPE 2009 Mk.4, which had a centrifugal impeller preceded by an inducer stage. A further variation of agitation level was achieved by fitting the wire mesh debris guard to the SPE BP14 Mk.3 pump.

In all these tests the tank was 90% full of fuel (i.e. 10% ullage). The experiments were repeated for various altitudes.

Fig.13 shows the results which were intended purely as qualitative as the presence of back pressure in the suction line due to fuel overflow prevented any direct comparison with the 4.6 $m^3$ tank results with a simple orifice vent. They confirm the results of section 3.4 that the pressure rise is a function of the amount of agitation which varies from pump to pump. Even the debris guard has a significant effect.

At very high altitude the pressure rise produced by SPE Type 2009 pump became less than expected from simple extrapolation from lower altitudes. The reason for this was not established.

No allowance was made for the tank volume occupied by the various pumps, for example the SPE 2009 Mk.4 pump reduced the fuel quantity appreciably. In all the tests the absolute ullage volume was the same.

## 4 FUEL OVERFLOW

### 4.1 Vented tank (4.6 $m^3$) with zero ullage: orifice size and altitude varied

The experimental procedure was as outlined in section 2.2. After the air release had ceased the quantity of fuel lost through the orifice vent was determined.

The results are listed in Table 1 and plotted in Fig.14. There was a scatter of about ±10%.

It was observed that higher overflow usually occurred in the first test of the day although conditions were otherwise identical. The circled points in Fig.14 indicate that they were obtained on first runs. At 19800 m (65000 ft), where the majority of tests were made, the difference is so marked that separate curves have been drawn for the first and subsequent tests. Thus the overspill appeared to increase with the length of time the tank stood empty, and may have been due to air adhering to the tank surfaces.

It was also noticed that during a climb to 19800 m (65000 ft) altitude, with no agitation, about 2% fuel overflow occurred. This was probably due to air being trapped during filling against the top surface between the stringers which were 50 mm deep. Also some increase in volume occurs during the climb due to air release prior to agitation (as mentioned in section 3.1). In some earlier tests[8] with the 55 litre tank it was observed that outgassing started at 14600 m (48000 ft), giving 0.75% volumetric expansion at 15000 m and 2-3% at 19800 m (65000 ft).

The vent in the 4.6 $m^3$ tank was a simple orifice and the overflow therefore depended on its size and the pressure difference across it. The latter, of course, was a function of time, vent size and altitude. In Fig.15, the ratio $Q/\sqrt{\Delta P_0}$, where Q is the overflow and $\Delta P_0$ the maximum pressure difference, is plotted against orifice size on log-log scales. Data for the first test of the day has been excluded. At any altitude, the points fall on a straight line indicating the relationships

$$Q = \text{const}\ d^{0.69} \sqrt{\Delta P_0} \tag{4}$$

where the value of the constant is 4.38 $10^{-3}$ for an altitude of 19800 m.

Since $\Delta P_0$ is proportional to exp(-nd), from equation (1), Q tends to zero when d is either very small or very large. The overflow is thus a maximum at some intermediate orifice size, which is found by differentiation to be about 100 mm. No maxima were observed during the tests to the higher altitudes but, on rather limited results, they were present at the lower altitudes.

## 4.2 Vented tank (4.6 $m^3$) with ullage

The experimental procedure was as previously described and the effect on the overflow of varying the ullage was determined for a fixed orifice size (63.5 mm) and altitude (19800 m, 65000 ft).

The results are plotted in Fig.16.

There was a large amount of scatter and no firm conclusions can be drawn. If however equation (4), is used to calculate the overflow, putting $\Delta P_u$ for $\Delta P_0$ and calculating $\Delta P_u$ from equations (1) and (3), a theoretical curve is obtained, which is plotted in Fig.16. It will be seen that the curves lies well above the experimental values. This is probably due to changes in the pressure-time curve with ullage, whereas equation (4) was derived from results at zero ullage.

## 5 FUEL AIR CONTENT

A few samples were taken from the bottom of the 4.6 $m^3$ tank before and after tests at 19800 m (65000 ft). During these sampling tests the pump was operated at altitude for a period of about two minutes until the tank pressure differential was zero. All samples were taken at ground level pressure since it was not possible to obtain samples at altitude owing to the throttling effect of the sampling lines and the consequent de-aeration of the sample when passing through the altitude chamber. The results are given in Table 4.

The fuel air content varied between 15 and 20% by vol at stp before test, after saturation treatment, and 5-7% after test. The initial figure agreed with the typical values for Avtur. If the fuel was reduced to saturation level at 19800 m (65000 ft) by pump agitation the air content, according to Henry's law, would have been expected to be of the order of 1%. Since descent after a test was rapid, it was assumed that insufficient time would be available for any significant amounts of air to go back into solution. The fuel therefore appeared still to be in a supersaturated state at altitude after evolution had apparently ceased. The samples were taken from only one point in the tank and it is probable that there were saturation gradients within the bulk of the fuel.

## 6 DE-SUPERSATURATION BY NITROGEN BUBBLING

Some tests were made to investigate the removal of supersaturation by bubbling gas through the fuel during the climb, in a full tank. The pressure rise produced by switching on the booster pump was then measured. It was not intended to investigate this method in detail, but to obtain some idea of its efficiency. De-supersaturation by means of jets of recirculated fuel has already been tested by BAC and found acceptable. For safety reasons the gas used was nitrogen which was supplied through the sintered metal aeration discs situated at the bottom of the 4.6 $m^3$ tank. Only one vent size 63.5 mm was used. The altitude and nitrogen flow rate were varied.

The results are given in Table 5 and the maximum tank pressure rise against nitrogen flow, at NTP, is plotted in Fig.17.

Although there is scatter in the results, especially at 16700 m (55000 ft), it can be seen that the effect of a small flow of nitrogen on the tank pressure is very marked. A flow of $3 \times 10^{-5}$ $m^3/s$ limiting the pressure rise to less than 5 $kN/m^2$ up to test altitudes of 19800 m (65000 ft). The curves of maximum pressure rise against flow rate will be affected by vent diameter and probably by the layout of the bubbling discs and vent position. It is significant that the maximum pressure differential decreases with increased altitude, (see Fig.17) which is the reverse of the results without agitation during the climb (see Fig.3). However the pressure differential at altitude after nitrogen bubbling was low, all less than 6.0 $kN/m^2$.

The amount of fuel overflow was in the range 0.17-0.23 $m^3$ (37-50 gal) with most results falling within the range 0.18-0.20 (40-43 gal) compared with values up to 0.48 $m^3$ (see Table 1) for the non-bubbled situation. Over the range of flow rates tested there was no detectable influence of either nitrogen flow rate or altitude upon the amount of fuel overflow.

## 7 DISCUSSION

Most of the experiments have been made with the 4.6 $m^3$ (1000 gal) tank venting directly through an orifice into a collector tank, without any restrictions due to pipework or such items as air/no fuel valves. It was hoped that the pressure rise could be predicted for other tank configurations, with particular vent and ducting arrangements. However the tests in the 55 litre tank with different pumps have shown (Figs.12 and 13) that the agitation and air release varies widely from one pump to another even the debris guard having a marked effect. Thus, correlation of all parameters is made difficult.

For the particular 4.6 $m^3$ tank and booster pump investigated, the pressure rise and fuel overflow are given by simple empirical functions of the orifice diameter, altitude pressure and ullage (see equations (2), (3) and (4)). Similar functions, with different values of the constants, have been obtained for previous work[4] using two different tanks. One of these tanks was of 640 litre capacity with a fuel depth of 1.5 m while the other was of 450 litre capacity with a fuel depth of 0.5 m. Both tanks were fitted with simple vents directly over the pump position.

The change in the values of the empirical equation constants appears to be largely influenced by the fuel depth.

The volume of fuel that is agitated is a critical factor and this is dependent upon the design of pump, pump position in relation to the tank walls, tank geometry, position of vents and, possibly, pump speed. For example, air released at the pump, if not confined, spreads in a conical fashion disturbing more fuel as it rises to the free surface. The head of fuel above the agitator is therefore important since the higher the head the greater the air released by a given agitator. In a horizontal shallow tank the position of the vent has an important effect since gas rising to a vent directly above the source of agitation disturbs less fuel.

In some BAC tests[5] recirculated fuel acted as the agitator in closed tanks of different sizes, with various numbers of recirculating jets. Different values of equilibrium pressures were obtained for similar values of ullage proportion. As shown in Appendix C, in a closed system the equilibrium pressure at a given ullage fraction should be independent of total tank volume. In the BAC tests the lower equilibrium pressures were associated with the lower number of recirculating jets, suggesting that the whole of the fuel was not being agitated.

Mayer[6] carried out a series of experiments with different sized fuel tanks using JP4 fuel with the object of studying fuel overflow. Two fuel tanks and two different booster pumps were used. No difference in the amount of fuel overflow with the two different pumps was recorded but the overflow from the tall narrow tank (270 litres) was larger than from the shallow tank (730 litres). Unfortunately no tank pressure rises were recorded and it is difficult to say what effective vent size was being used. However successful attempts were made to reduce the fuel overflow by fitting screens around the pumps, again suggesting that the volume of fuel disturbed is important. This agrees with the effects noted above using the SPE BP14 Mk.3 pump with and without a debris guard[2]. Mayer expressed some doubts as to the practicability of pump screening from a pump removal and servicing aspect.

A further factor is that some visible outgassing from the fuel occurs after reaching high altitude (over 14500 m, 48000 ft), before the pump is started, so the amount of supersaturation will decrease with time, and hence the pressure rise on agitation.

All the above evidence of the dependence of the pressure rise on the degree of agitation makes it extremely difficult to derive generalised equations. If the problems of tank pressure rise and fuel overflow are thought to be of significance with a fuel system the only solution at present would appear to be an altitude test on a representative system.

Considering specific types of aircraft, the fuel tanks of fighter aircraft are often pressurised and are generally designed to withstand high g loadings. They are therefore capable of accepting significant tank pressure differentials such as may be produced by air release. In the collector tanks where the booster pumps are operating continuously, there is not likely to be a sudden air release. Large civil subsonic aircraft do not operate at altitudes where the sudden release of air is of significance, that is above about 12100 m (40000 ft). The only type of aircraft that might encounter difficulty from a tank differential pressure would therefore appear to be the high flying supersonic. Methods of alleviating the problem are already known, such as fuel recirculation, gas bubbling (this could be arranged from the tank pressurisation supply) and the use of pump shields. These methods are likely to be affected by the particular installation layout, hence a further general test programme is unlikely to yield relevant design criteria.

There are however certain particular aspects of the problem which do merit further investigation. The testing of the 4.6 $m^3$ fuel tank with a relatively small percentage of the fuel agitated, suggested that the bulk of the fuel remains in a supersaturated condition. It is already known[1] that pump performance is influenced by the amount of 'air' in solution and that difficulties are encountered if pumps have to be started at high altitude[6]. As there may be a high air to liquid volume ratio at the pump entrance, pump starting may be difficult and further investigation to improve pump performance from this aspect is required.

It is also possible that difficulties might arise in the transfer of fuel to collector tanks by pressurisation methods due to 'air' being released within the transfer piping.

Inerting system design will also be affected by the fact that the bulk of the fuel in a large tank is not reduced to saturation level upon agitation and that air release will continue over a prolonged period after altitude is reached. A laboratory scale investigation of the solubility coefficients of fuels and the quality of the 'air' released, has recently been made by Shell[7].

Some recent tests[8] have shown that the presence of plastics foam in tanks for the purpose of explosion protection can trap 'air' and is likely to effect gauging system and possibly pump performance and there is need for further investigation in this area.

The effects of vibration upon the rate of release of 'air' from fuel are at present somewhat obscure and some information as to the likely effects of this is required.

## 8 CONCLUSIONS

(1) The pressure rise and fuel overflow due to the release of air from supersaturated fuel at altitude has been shown to be a complex function of several parameters, including the vent diameter, ullage, tank geometry, including pump and vent positions, the degree of agitation and the altitude.

(2) For the particular 4.6 $m^3$ tank and booster pump investigated empirical equations have been derived relating the pressure rise and fuel overflow to the orifice diameter, ullage proportion and altitude.

(3) It has not been possible to derive general equations for design use, largely owing to the different agitation and air release rates produced by different pumps.

(4) If tank pressure rise and fuel overflow are considered to be a problem in a particular installation, it will be necessary to conduct simulated altitude tests to prove the system.

(5) Information on the effect of vibration on air release is required.

## Appendix A

## DESCRIPTION OF TEST RIGS

(see section 2)

### A.1 4.6 $m^3$ (1000 gal) tank rig

The test tank, which was representative of a large transport aircraft fuel tank, was fitted above a collector tank of equal capacity, within the altitude chamber of the R157 Fuels Laboratory, see Fig.1 and Ref.4. The test tank which was stressed for a differential pressure of 20.7 $kN/m^2$ (3 psi) was open vented with the vent at the opposite end of the tank to the agitating pump. The vent discharged into a large rectangular duct connected to the collector tank.

A calibrated sight glass was fitted to measure tank contents in conjunction with an internal fuel gauge and a pressure transducer to record pressure changes. A differential pressure gauge was also fitted to the tank to indicate pressure. Eight sintered discs were fitted at the base of the tank connected to a dry air supply via a flowmeter and pressure gauge for aeration[3]. Tappings of 6.3 mm dia (¼ in) were fitted for fuel sampling. Chamber altitude was read on an aircraft altimeter.

The behaviour of the fuel around the agitating pump was monitored by a television camera viewing through an observation port in the tank wall. Tank dimensions and details of the agitating pump are given below.

| | | | |
|---|---|---|---|
| Tank dimensions: | height | 0.736 m | (29 in) |
| | width | 1.805 m | (71 in) |
| | length | 2.92 m | (138 in) |
| Vent range | 44.5 to 177.8 mm | | (1.75 to 7.0 in) |
| Internal finish | Viton spray | | |
| Agitator | 28 V dc Thompson pump without debris guard<br>Type B-17 A<br>power input ≈ 1.5 kW. | | |

The air content of the fuel samples taken before and after some tests was measured by an apparatus, made in RAE, of similar principle to that described in Ref.9. The major difference in the apparatus being that the RAE apparatus used a bellows to alter the volume over the sample where as the NEL design used a piston.

### A.2 55 litre tank test rig (12 gal)

The test tank which was capable of withstanding a differential pressure of 101.3 $kN/m^2$ (14.7 psi) was connected directly to a suction pump via a

12.7 mm (0.5 in) pipe containing a 6.35 mm isolating valve fitted close to the tank. A controllable atmospheric bleed was fitted to the suction line between the suction isolating valve and the tank. The test tank had viewing ports to enable visual observation of the pump and was fitted with a pressure transducer, vacuum/pressure gauge and a mercury manometer. A single sintered disc was fitted for aeration of the fuel. The tank dimensions and details of the agitators are given below;

| | | | |
|---|---|---|---|
| Approx. tank dimensions: | height | 43.8 cm | (17.25 in) |
| | width | 27.3 cm | (10.75 in) |
| | length | 43.2 cm | (17.0 in) |
| Internal finish | rough paint | | |
| Agitators | SPE | Type BP14, Mk.3 with and without debris guard.<br>Power input ≈ 0.042 kW<br>Immersed pump. | |
| | SPE | Type FB11, Mk.9.<br>Power input ≈ 0.04 kW.<br>Externally mounted on tank base, impeller inlet facing upward. | |
| | SPE | Type 2009 Mk.4 without debris guard.<br>Power input ≈ 0.52 kW.<br>Internally mounted on base. | |

# Appendix B

(see section 2)

## B.1 Method of test 4.6 $m^3$ tank tests

The fuel was drawn from the main underground storage tanks and the test tank filled to the ullage required, the appropriate safety instructions[3] being followed. The altitude chamber pressure was then lowered to about 27.5 $kN/m^2$ and the chamber back filled with nitrogen until the oxygen sensors were recording below 9% oxygen.

The television camera was then switched on and the chamber altitude raised to that required for the test at a rate of approximately 50 m/s (10000 ft/min). After the test altitude had been stabilised, by admitting a small flow of nitrogen into the chamber, conditions were held for 1 minute, the pressure recorder switched on and the pump operated.

Shortly after the start of the fuel pump a drop in altitude, as measured by the chamber altimeter, normally occurred. The fuel pump was kept running until either the initial altitude was recovered or until the altitude was stable after the oxygen sensor in the chamber extraction duct had passed the peak value and returned to its initial reading. The tank pressure recorder was not necessarily operated for the complete time for the above conditions to be met, which depending upon vent size and ullage could be several minutes, but only until the peak tank pressure had passed.

After the fuel pump had been stopped the main suction line was closed and the pressure transducer calibrated by admitting nitrogen to the chamber and stabilising the chamber altitude at 1640 m (5000 ft) intervals over an altitude range of 6500 m (20000 ft). Descent was then carried out by admitting air to the chamber by means of a bleed valve, the chamber door opened and the change in test tank contents measured on the calibrated sight glass.

For subsequent tests the fuel was aerated by bubbling air at a rate of $7.08 \times 10^{-4}$ m/s (1.5 cfm) at a pressure of 207 $kN/m^2$ through sintered discs mounted at the base of the test tank for a period of 40 minutes. The aeration lines were then bled with fuel and the booster pump operated for 45 seconds for priming. Fuel temperature was obtained by measuring the temperature of the fuel returned from the overspill tank between tests.

For the tests where the effects of nitrogen gas bubbling were being examined the nitrogen was admitted to the tank through the aeration discs during the climb.

A few closed tank tests were made, for these the vent was fitted with a pressure relief valve designed to operate at a pressure differential of 10 $kN/m^2$. The pressure relief valve could be remotely operated from the control room to avoid differential pressures on the test tank during climb and descent.

## B.2 55 litre tank (12 gal)

The tests done in this tank were to supplement the large tank results and the procedure was basically the same except that aeration was carried out at a pressure of about 35 $kN/m^2$ in the tank. This was to enable the aeration line to be bled with fuel from the tank before giving the altitude. The pump was then operated at ground level with the tank open to atmosphere until supersaturation at ground level was removed, the pressure rise shown on the manometer falling to zero. For the closed tests the suction isolating valve was closed when the test altitude was reached, for the open vent tests the altitude was controlled by means of air bleed on the suction line downstream of the isolating valve to the test tank which was always left in the open condition to act as the vent.

# Appendix C

## THEORETICAL PRESSURE RISE IN A CLOSED TANK

(see section 3)

Henry's law states that the volume of gas dissolved in a liquid is proportional to the partial pressure of the gas over the liquid, this may be expressed as follows;

$$S = kP \tag{C-1}$$

where $S$ = % volume of gas dissolved in liquid (at stp)
$P$ = partial pressure of gas over liquid
$k$ = a constant of proportionality measured at the temperature conditions of solution.

Let $m_R$ = mass of 'air' released at altitude, neglecting the effects of fuel vapour pressure which for Avtur are small (0.13 kN/m$^2$).

Then

$$m_R = Lk(P_G - P_e)/RT \tag{C-2}$$

where $L$ = liquid volume
$k$ = constant of proportionality
$P_G$ = ground level pressure
$P_e$ = pressure at equilibrium
$R$ = gas constant
$T$ = temperature.

Let tank ullage volume = $V$.

Therefore intial mass of 'air' in ullage at altitude

$$m_a = \frac{P_a V}{RT} \quad . \tag{C-3}$$

After agitation mass of 'air' in ullage

$$m_e = \frac{P_e V}{RT} \quad . \tag{C-4}$$

assuming that $R$ remains constant.

Therefore

$$m_R = (m_e - m_a) = V(P_e - P_a)/RT \tag{C-5}$$

therefore

$$\frac{V}{RT}(P_e - P_a) = \frac{Lk}{RT}(P_G - P_e) \qquad \text{(C-6)}$$

but $(P_e - P_a) = \Delta P$ (tank pressure rise).

If tank volume = C then $L = (1 - u)C$ and $V = uC$

$$L = (1 - u)C \quad \text{and} \quad V = uC$$

where $u$ = ullage proportion.

Therefore substituting in equation (b) and rearranging

$$\Delta P = (1 - u)Ck\,[P_G - (P_a + \Delta P)]/uC$$

therefore

$$\Delta P = \frac{(1 - u)k}{u}\left[P_G - P_a\right]\Big/\left[1 + \frac{(1 - u)k}{u}\right] \quad . \qquad \text{(C-7)}$$

Multiplying the right hand side top and bottom by u and dividing top and bottom by (1 - u)k then;

$$\Delta P = (P_G - P_a)(1/[u/(1 - u)k + 1]) \quad . \qquad \text{(C-8)}$$

Therefore the pressure rise in the tank is independent of tank volume and depends upon altitude, the constant of proportionality of solution and the tank ullage.

## Table 1

## RESULTS FOR FULL 4.6 m$^3$ TANK

| Vent dia mm | Altitude m (ft) | Altitude pressure kN/m$^2$ | Aeration time min | Fuel temp °C | Tank max. differential pressure kN/m$^2$ | Fuel overflow m$^3$ | Remarks |
|---|---|---|---|---|---|---|---|
| 44.5 | 19800 | 5.72 | 0 | 15 | - | 0.318 | Pressure recorder failed |
| | (65000) | 5.72 | 40 | 15 | 20.62 | 0.30 | |
| | | 5.72 | 40 | 15 | 21.37 | 0.286 | |
| | | 5.72 | 0 | 16 | 20.96 | 0.30 | |
| | | 5.72 | 40 | 16 | 20.27 | 0.273 | |
| | | 5.72 | 40 | 16 | 20.35 | 0.273 | |
| | | 5.72 | 40 | 16 | 20.35 | 0.286 | |
| | 13700<br>(45000) | 14.76 | 0 | 11.2 | 15.5 | 0.232 | |
| | 9100 | 30.06 | 40 | 11.2 | 8.0 | 0.155 | |
| | (30000) | 30.06 | 40 | 11.2 | 7.8 | 0.146 | |
| 63.5 | 19800 | 5.72 | 0 | 16 | 16.82 | 0.372 | |
| | (65000) | 5.72 | 40 | 16 | 18.0 | 0.346 | |
| | | 5.72 | 40 | 16 | 17.89 | 0.341 | |
| | | 5.72 | 40 | 16 | 17.31 | 0.309 | |
| | | 5.72 | 0 | 12.5 | 16.41 | 0.373 | |
| | 22800<br>(75000) | 3.45 | 40 | 12.5 | 17.44 | 0.391 | |
| | 9100 | 30.06 | 40 | 13 | 4.76 | 0.136 | |
| | (30000) | 30.06 | 40 | 13 | 3.86 | 0.136 | |
| | 6100 | 46.6 | 40 | 16 | 0.4 | 0.055 | |
| | (20000) | 46.6 | 40 | 16 | 1.0 | 0.059 | |
| | 19800 | 5.72 | 40 | 23.5 | 14.68 | 0.264 | Suction valve fully open |
| | (65000) | 5.72 | 40 | 23.5 | 15.58 | 0.254 | Suction valve 40% open |
| | | 5.72 | 40 | 23.5 | 14.43 | 0.236 | Suction valve shut |
| | | 5.72 | 40 | 16 | 18.28 | 0.309 | Extra altitude chamber in line |
| 76.2 | 19800 | 5.72 | 0 | 15 | 14.07 | 0.391 | |
| | (65000) | 5.72 | 40 | 15 | 14.86 | 0.396 | |
| 101.6 | 19800 | 5.72 | 0 | 15 | 12.2 | 0.455 | |
| | (65000) | 5.72 | 40 | 15 | 12.69 | 0.411 | |
| | | 5.72 | 40 | 15 | 12.89 | 0.411 | |
| | | 5.72 | 40 | 15 | 9.46 | 0.396 | Pump failed to start at once |
| | 13700 | 14.76 | 0 | 16.5 | 7.88 | 0.259 | |
| | (45000) | 14.76 | 40 | 16.5 | 7.99 | 0.236 | |
| | | 14.76 | 0 | 16 | 8.89 | 0.273 | |
| | | 14.76 | 40 | 16 | 7.44 | 0.255 | |
| | 9100<br>(30000) | 30.06 | 0 | 15 | 1.77 | 0.136 | |
| | 8100<br>(26500) | 30.52 | 40 | 15 | 0.41 | 0.136 | |
| 127 | 19800 | 5.72 | 0 | 14 | 11.45 | 0.455 | |
| | (65000) | 5.72 | 40 | 14 | 11.45 | 0.455 | |
| | | 5.72 | 0 | 15.8 | 10.48 | 0.464 | |
| | | 5.72 | 40 | 15.8 | 11.10 | 0.455 | |
| | | 5.72 | 40 | 15.8 | 10.76 | 0.423 | |
| | | 5.72 | 40 | 15.8 | 10.76 | 0.456 | |
| | 13700 | 14.76 | 40 | 15.8 | 6.61 | 0.239 | |
| | (45000) | 14.76 | 40 | 15.8 | 5.51 | 0.216 | |
| 152.4 | 9100<br>(30000) | 30.52 | 40 | 15.8 | 0.84 | 0.127 | |
| | 19800 | 5.72 | 0 | 9.3 | 7.24 | 0.45 | Fuel sampled, see Table 4 |
| | (65000) | 5.72 | 0 | 9.3 | 9.61 | 0.477 | Fuel sampled, see Table 4 |
| | | 5.72 | 40 | 9.3 | 8.96 | 0.432 | Fuel sampled, see Table 4 |
| | | 5.72 | 40 | 9.3 | 8.89 | 0.432 | Fuel sampled, see Table 4 |
| | | 5.72 | 40 | 9.3 | 8.08 | 0.434 | Fuel sampled, see Table 4 |
| | | 5.72 | 40 | 15 | 8.18 | 0.491 | |
| | | 5.72 | 0 | 13.5 | 7.93 | 0.468 | Number of extraction pumps halved |
| | | 5.72 | 0 | 13.5 | 8.76 | 0.441 | Number of extraction pumps halved |
| | | 5.72 | 40 | 12.5 | 7.35 | 0.446 | Number of extraction pumps halved |
| | 13700 | 14.76 | 0 | 12.5 | 4.27 | 0.241 | |
| | (45000) | 14.76 | 40 | 12.5 | 4.27 | 0.218 | |
| | | 14.76 | 40 | 12.5 | 4.56 | 0.253 | |
| 177.8 | 19800 | 5.72 | 0 | 15 | 7.79 | 0.50 | Fuel sampled, see Table 4 |
| | (65000) | 5.72 | 40 | 15 | 7.93 | 0.455 | Fuel sampled, see Table 4 |
| | | | 0 | 15 | 8.0 | 0.491 | |
| | | | 40 | 15 | 8.83 | 0.455 | Fuel sampled, see Table 4 |
| | | | 40 | 15 | 7.79 | 0.409 | Fuel sampled, see Table 4 |
| | | | 40 | 15 | 8.89 | 0.436 | |
| | | | 0 | 15 | 8.0 | 0.482 | |

## Table 2

## RESULTS FOR 4.6 $m^3$ TANK WITH ULLAGE

Altitude 19800 m (65000 ft) pressure 5.7 $kN/m^2$

| Vent dia mm | Ullage % | Aeration time min | Fuel temp $^oC$ | Tank maximum differential pressure $kN/m^2$ | Fuel overflow $m^3$ |
|---|---|---|---|---|---|
| 44.5 | 2 | 40 | 17 | 15.42 | 0.17 |
| | 2 | 40 | 17 | 16.92 | 0.159 |
| | 5 | 40 | 17 | 9.24 | 0.068 |
| 63.5 | 2 | 40 | 17 | 14.5 | 0.205 |
| | 2 | 40 | 17 | 13.5 | 0.182 |
| | 4 | 40 | 18 | 3.0 | 0.091 |
| | 5 | 40 | 18 | 6.75 | 0.091 |
| | 5 | 0 | 11.2 | 9.1 | 0.177 |
| | 5 | 40 | 11.2 | 9.86 | 0.155 |
| | 5 | 40 | 11.2 | 9.17 | 0.114 |
| | 5 | 40 | 14 | 8.1 | 0.109 |
| | 7.5 | 0 | 13.7 | 4.14 | 0.064 |
| | 7.5 | 40 | 13.7 | 5.32 | 0.055 |
| | 10 | 40 | 13.7 | 3.03 | 0.082 |
| | 10 | 40 | 14 | 3.45 | 0.091 |
| | 10 | 0 | 14 | 3.4 | 0.048 |
| | 10 | 40 | 14 | 3.45 | 0.027 |
| | 15 | 40 | 14 | 2.88 | 0.077 |
| | 15 | 40 | 14 | 0.62 | 0.065 |
| 101.6 | 5 | 0 | 15 | 6.1 | 0.152 |
| | 5 | 40 | 15 | 6.2 | 0.159 |
| | 10 | 40 | 17 | 2.22 | 0.014 |
| | 10 | 40 | 17 | 2.76 | 0.039 |
| | 10 | 40 | 17 | 2.76 | 0.04 |
| | 15 | 40 | 17 | 0.10 | 0.036 |
| | 15 | 40 | 17 | 0.10 | 0.036 |

## Table 3

## RESULTS WITH CLOSED 55 LITRE TANK

| Ullage % | Altitude pressure kN/m$^2$ | Pressure rise kN/m$^2$ |
|---|---|---|
| 4 | 95.77 | 4.57 |
| | 83.08 | 12.7 |
| | 64.46 | 23.87 |
| | 49.9 | 35.04 |
| | 30.33 | 48.41 |
| | 17.17 | 55.35 |
| | 6.06 | 62.63 |
| 13 | 94.62 | 3.05 |
| | 80.4 | 10.16 |
| | 66.35 | 16.76 |
| | 44.79 | 26.14 |
| | 33.01 | 30.13 |
| | 8.13 | 40.79 |
| | 7.62 | 41.64 |
| 20 | 84.87 | 5.92 |
| | 67.1 | 12.19 |
| | 49.33 | 18.62 |
| | 31.5 | 24.78 |
| | 14.56 | 31.04 |
| | 3.11 | 33.85 |
| 39.7 | 67.37 | 6.6 |
| | 45.6 | 10.13 |
| | 38.75 | 11.72 |
| | 28.61 | 13.74 |
| | 22.0 | 14.2 |

## Table 4

## 'AIR' CONTENTS MEASUREMENTS

Thompson B-17A pump started at altitude

| Vent dia mm | Altitude m (ft) | Altitude pressure kN/m$^2$ | Aeration time min | Fuel temp $^oC$ | Tank max. differential pressure kN/m$^2$ | Fuel overflow m$^3$ | Air content % by volume at NTP | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | Before test | After test |
| 152.4 | 19800 (65000) | 5.72 | 0 | 9.3 | 7.24 | 0.45 | 18.5 | 6.56 |
| 152.4 | 19800 (65000) | 5.72 | 0 | 9.3 | 9.61 | 0.477 | - | 7.38 |
| 152.4 | 19800 (65000) | 5.72 | 40 | 9.3 | 8.96 | 0.432 | - | 4.87 |
| 152.4 | 19800 (65000) | 5.72 | 40 | 9.3 | 8.89 | 0.432 | - | 5.84 |
| 152.4 | 19800 (65000) | 5.72 | 40 | 9.3 | 8.08 | 0.434 | 19.8 | 7.1 |
| 177.8 | 19800 (65000) | 5.72 | 0 | 15 | 7.79 | 0.50 | 19.4 | - |
| 177.8 | 19800 (65000) | 5.72 | 40 | 15 | 7.93 | 0.455 | 19.4 | - |
| 177.8 | 19800 (65000) | 5.72 | 40 | 15 | 8.83 | 0.455 | 15.6 | 5.5 |
| 177.8 | 19800 (65000) | 5.72 | 40 | 15 | 7.79 | 0.409 | 15.9 | - |

## Table 5

## DE-SUPERSATURATION BY NITROGEN BUBBLING

4.6 m$^3$ (1000 gal) tank full, vent size 63.5 mm

| Altitude (ft) m | Altitude pressure kN/m$^2$ | Aeration time min | Fuel temp °C | Tank max. differential pressure kN/m$^2$ | Fuel overflow m$^3$ | Nitrogen bubbling flow rate at NTP m$^3$/s × 10$^{-4}$ |
|---|---|---|---|---|---|---|
| 19800 (65000) | 5.72 | 0 | 15 | 0 | 0.20 | 7.08 |
| | | 0 | 12 | 0 | 0.182 | 7.08 |
| | | 40 | 13.5 | 0 | 0.182 | 4.25 |
| | | 40 | 13.5 | 1.24 | 0.20 | 1.415 |
| | | 40 | 13.5 | 1.6 | 0.182 | 1.415 |
| | | 40 | 12 | 3.03 | 0.227 | 0.667 |
| | | 40 | 14.5 | 4.56 | 0.218 | 0.333 |
| 16750 (50000) | 9.1 | 40 | 14.5 | 0.43 | 0.196 | 6.67 |
| | | 0 | 18 | 0.42 | 0.191 | 4.72 |
| | | 0 | 22 | 1.02 | 0.196 | 4.72 |
| | | 40 | 22 | 2.0 | 0.173 | 4.72 |
| | | 40 | 22 | 4.0 | 0.187 | 2.36 |
| | | 40 | 22 | 2.5 | 0.178 | 2.36 |
| | | 40 | 22 | 3.81 | 0.178 | 2.36 |
| | | 40 | 14.5 | 5.9 | 0.200 | 0.333 |
| | | 40 | 14.5 | 5.02 | 0.218 | 0.333 |
| 13700 (45000) | 14.76 | 40 | 12.0 | 2.04 | 0.186 | 7.08 |
| | | 40 | 13.5 | 3.16 | 0.186 | 4.25 |
| | | 40 | 12.0 | 4.24 | 0.196 | 3.54 |
| | | 40 | 12.0 | 4.84 | 0.196 | 1.415 |
| | | 40 | 13.5 | 5.04 | 0.191 | 0.667 |
| | | 40 | 14.5 | 5.74 | 0.186 | 0.333 |

Note. Nitrogen flow supplied throughout climb and during pump start.

# SYMBOLS

| | |
|---|---|
| $d$ | vent diameter |
| $c$ | tank volume |
| $k$ | constant of proportionality |
| $k_1$ | constant |
| $L$ | liquid volume |
| $m_a$ | mass of air in ullage at $P_a$ |
| $m_e$ | mass of air in ullage at $P_e$ |
| $m_R$ | mass of air in fuel released on agitation |
| $n$ | a constant dependent on $P_a$ |
| $P$ | partial pressure of gas above liquid |
| $P_a$ | pressure altitude above fuel |
| $P_e$ | equilibrium pressure after agitation in a closed tank |
| $P_G$ | ground level pressure |
| $\Delta P_O$ | maximum differential pressure in open vented full tank |
| $\Delta P_U$ | maximum differential pressure in open vented tank with ullage |
| $Q$ | amount of fuel overflow |
| $Q_O$ | amount of fuel overflow from open vented full tank |
| $Q_u$ | amount of fuel overflow from open vented tank with ullage |
| $R$ | gas constant |
| $S$ | percentage volume of gas dissolved in liquid |
| $T$ | temperature |
| $U$ | proportion ullage in tank |
| $V$ | ullage volume |
| $X$ | $(1 - u)k/u + (1 - u)k$ |

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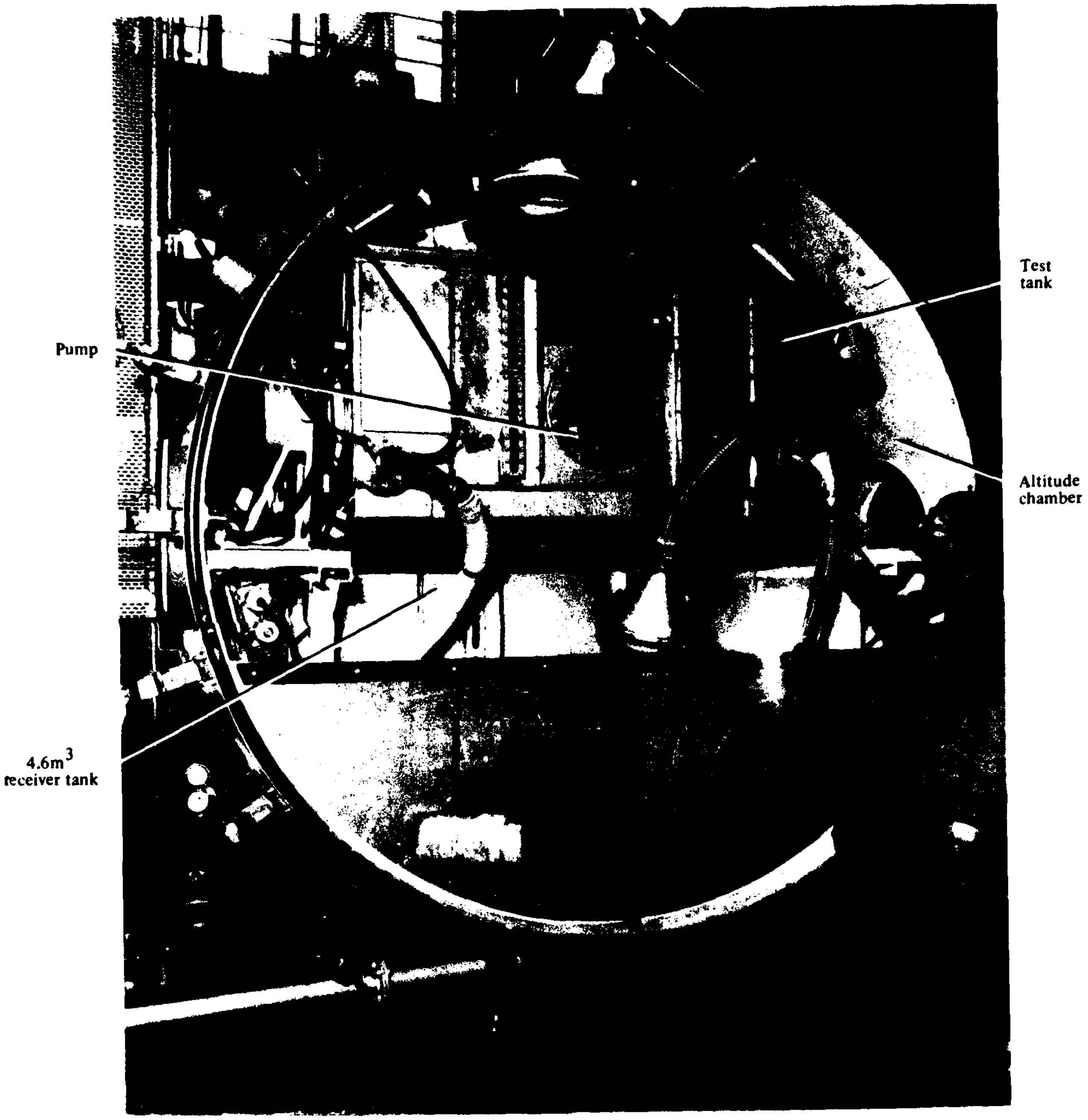


Fig.1a. $4.6m^3$ (1000 gallon) fuel test facility

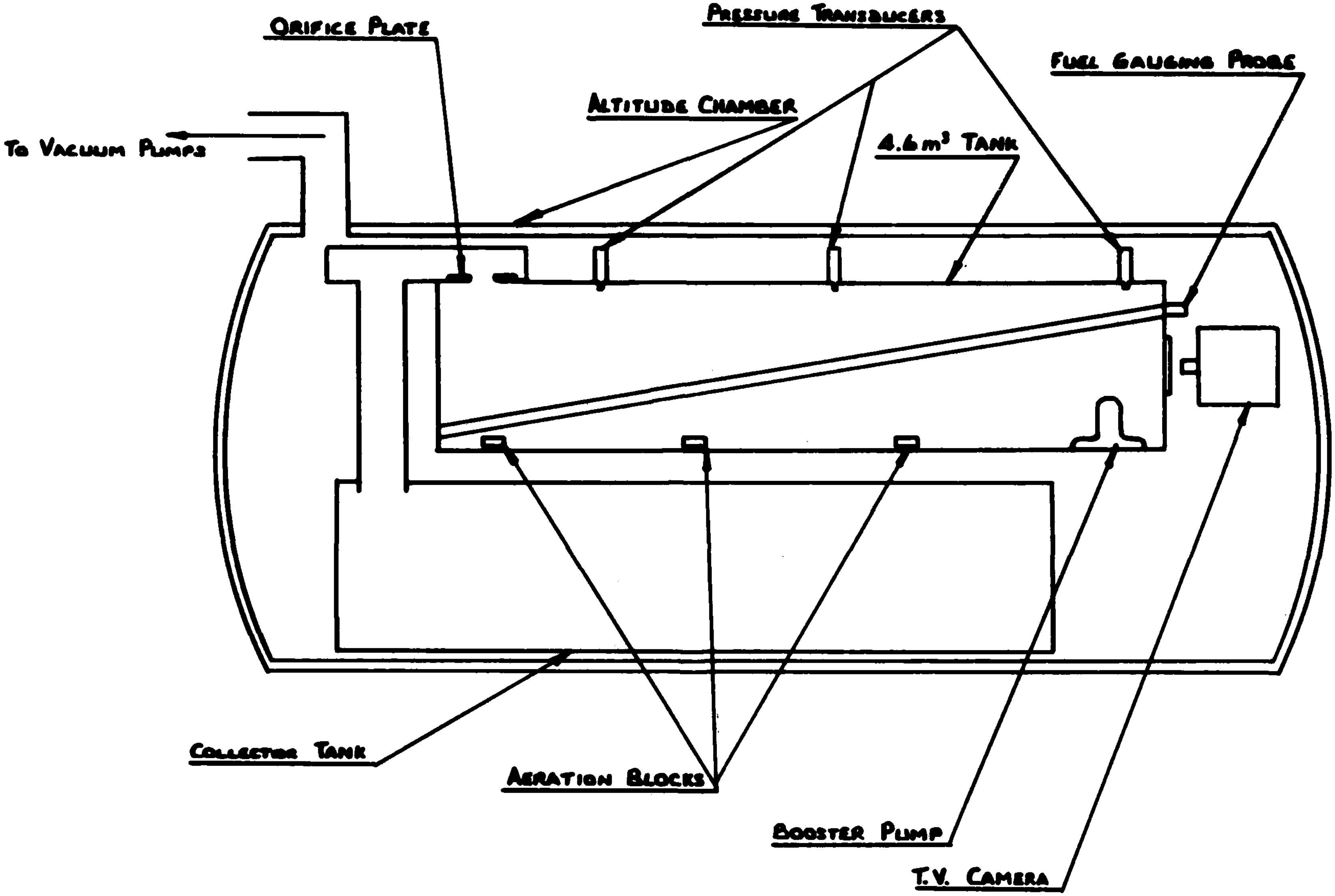


Fig.1b Diagrammatic arrangement of 4.6 $m^3$ tank and altitude chamber

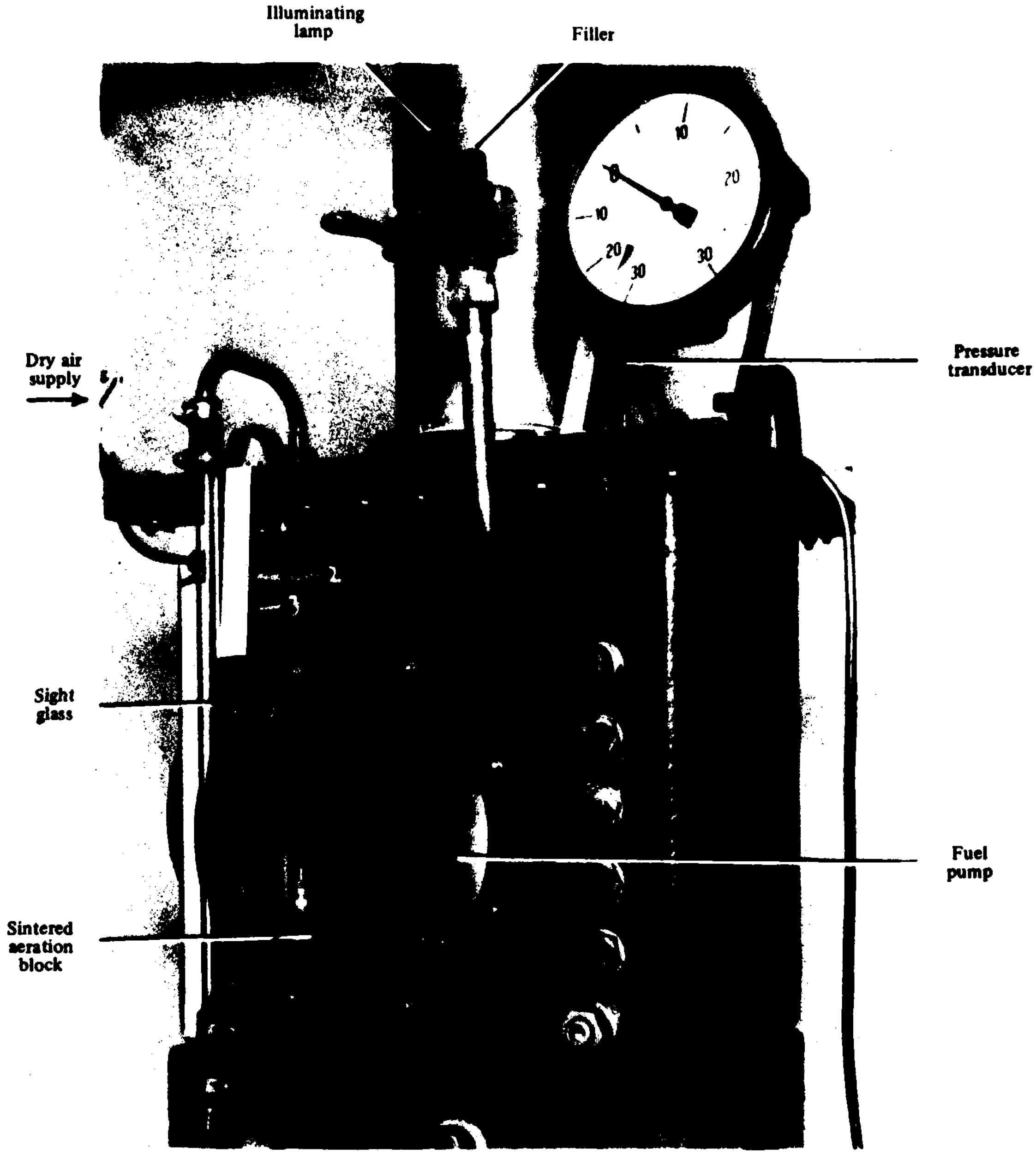


Fig.2a. 55ℓ (12 gallon) test rig

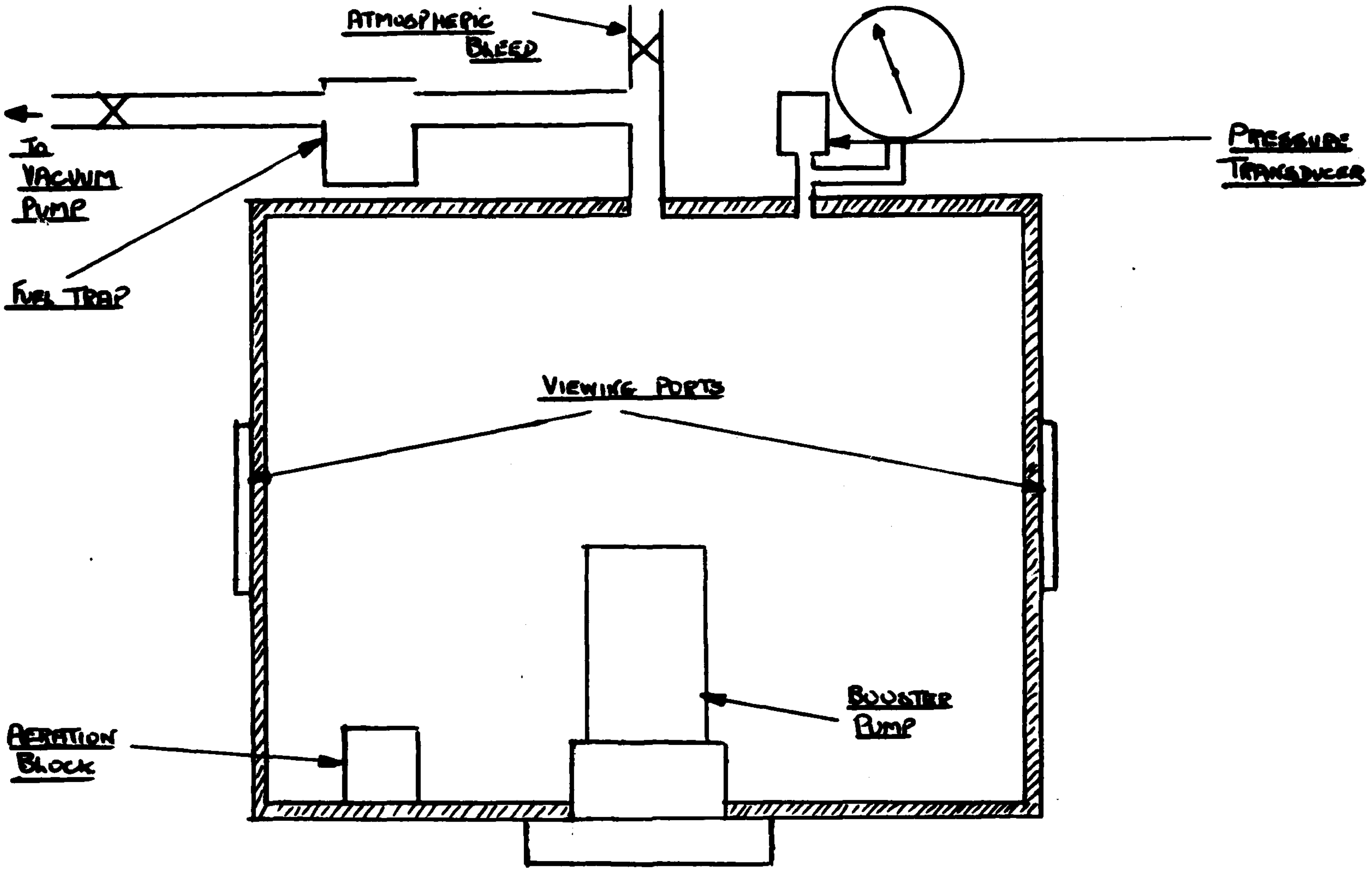


Fig.2b Sectional diagram of 55 litre test tank

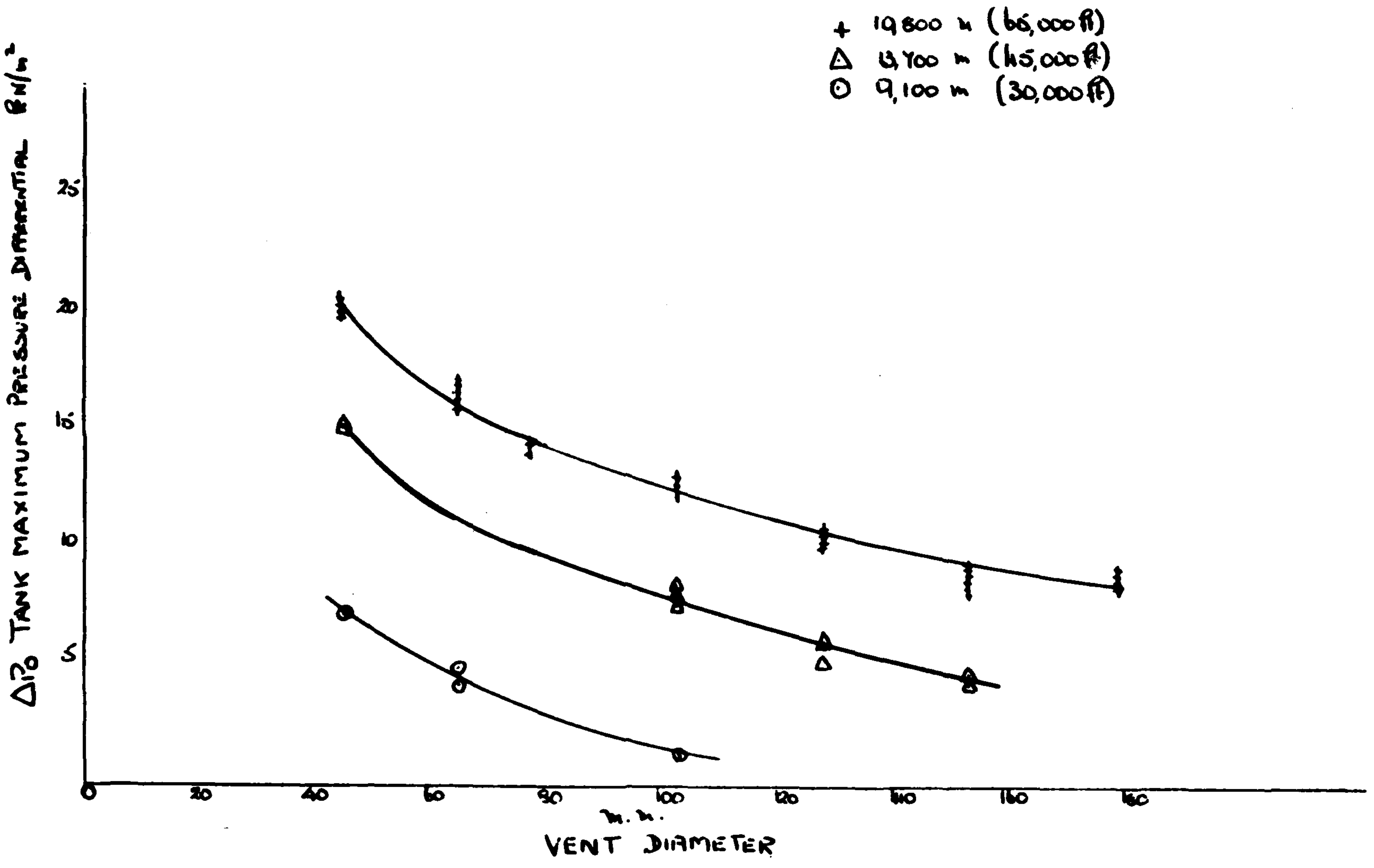


Fig.3 Variation of tank differential pressure with vent diameter - large tank - zero ullage

Fig.4

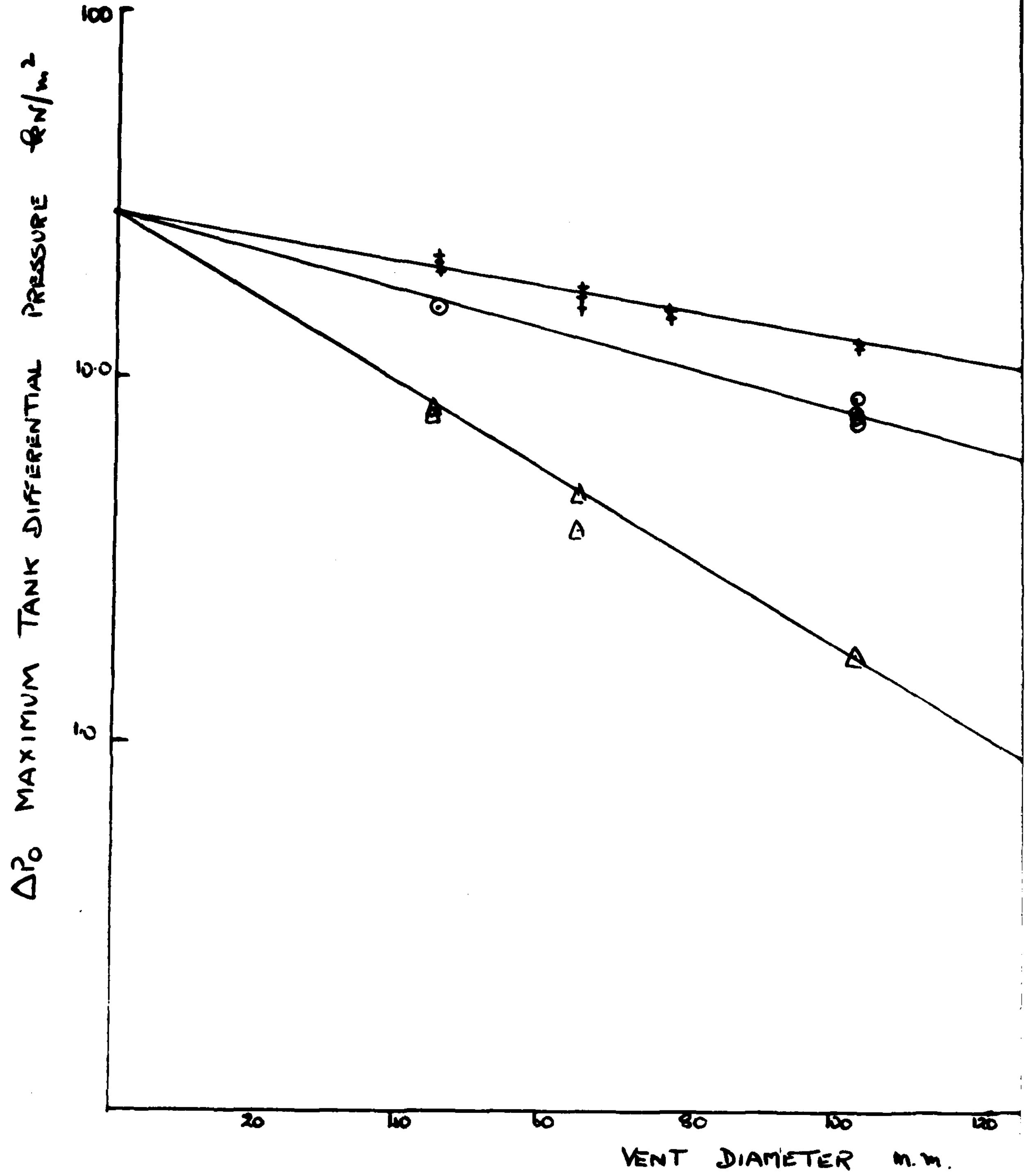
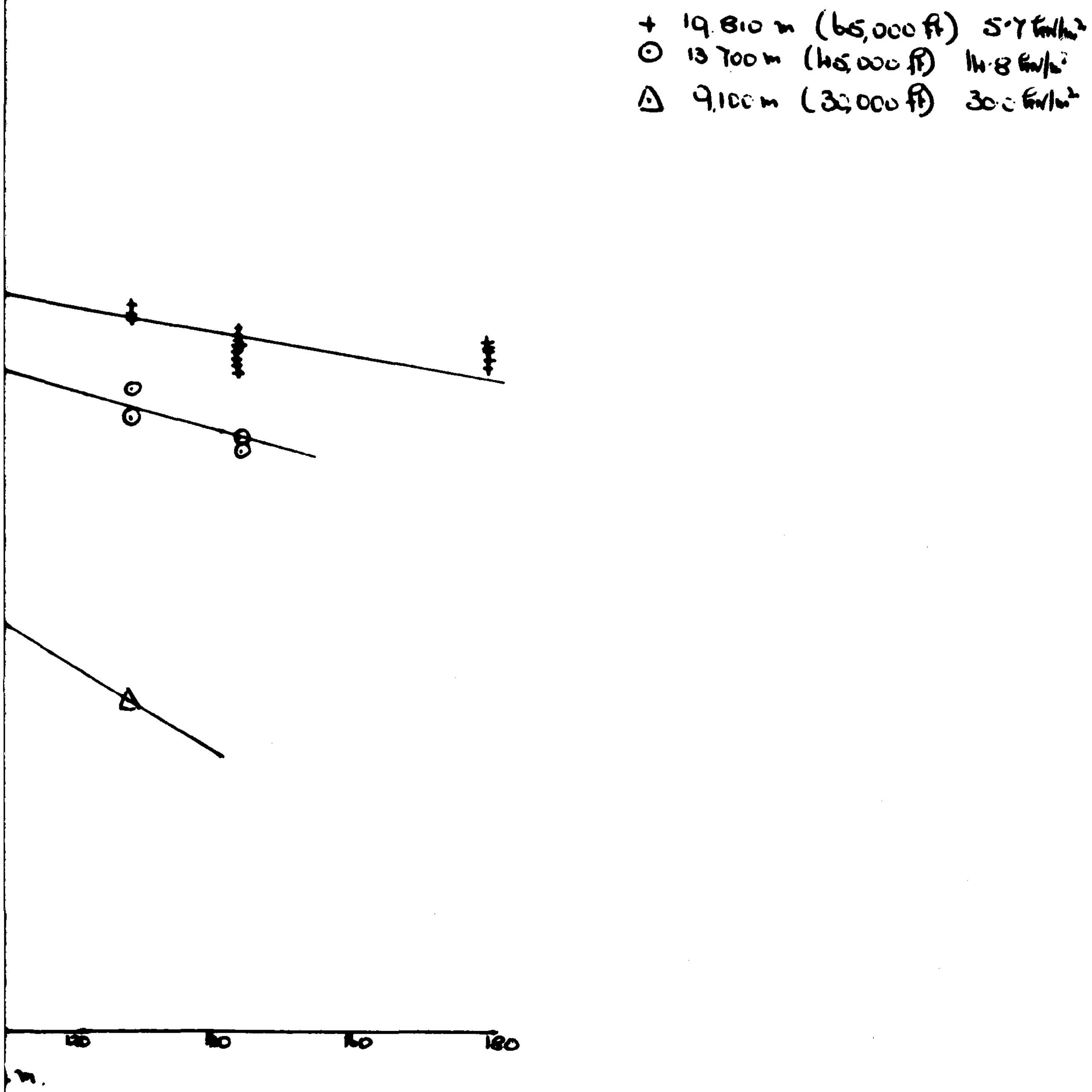


Fig.4 Maximum pressure rise against vent



nst vent diameter 4.6 $m^3$ tank - zero ullage

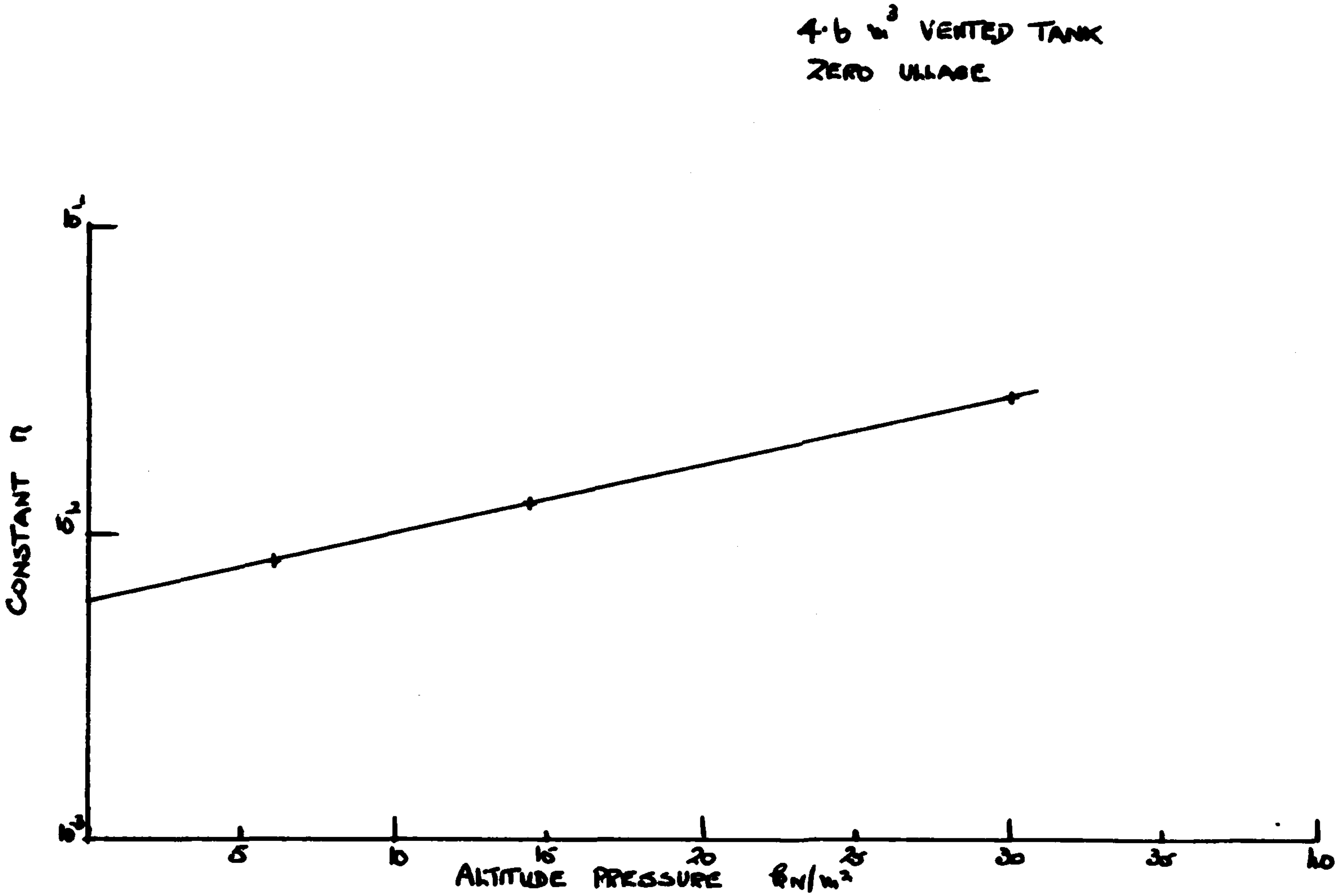


Fig.5 Variation of n with altitude pressure

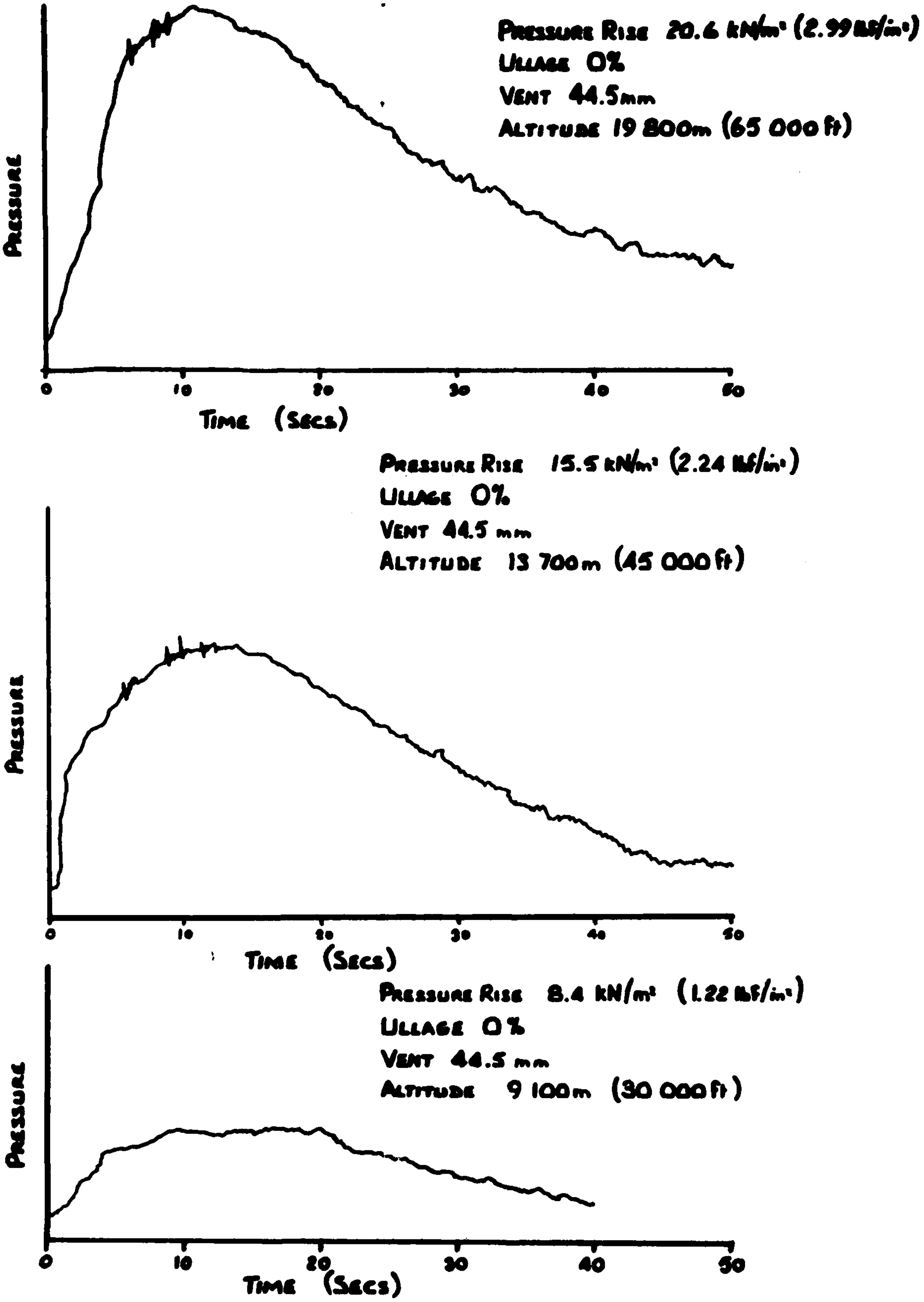


Fig.6 Typical pressure-time traces - 44.5 mm vent

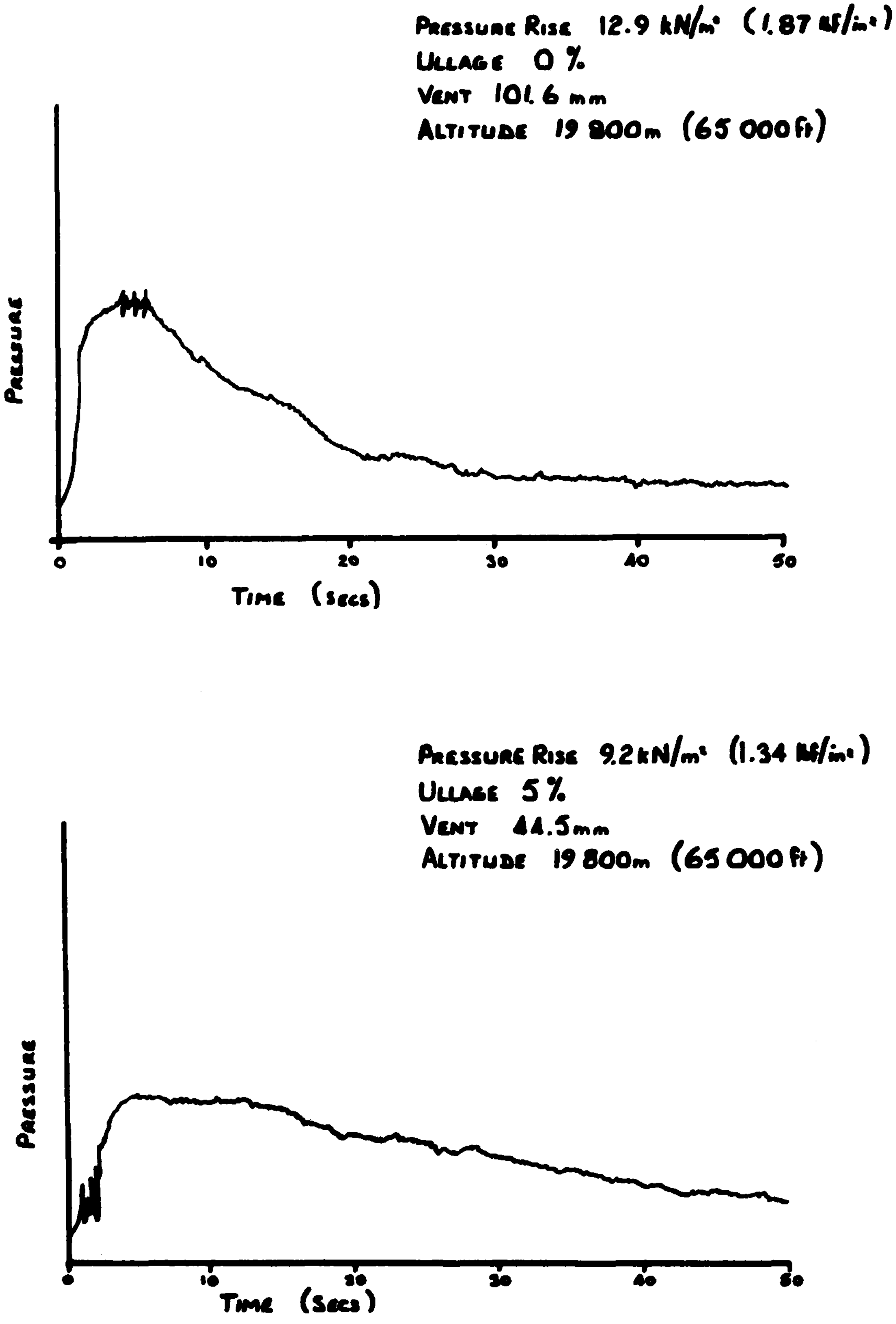


Fig.7 Typical pressure-time traces - 44.5 mm and 101.6 mm vents

Fig.8

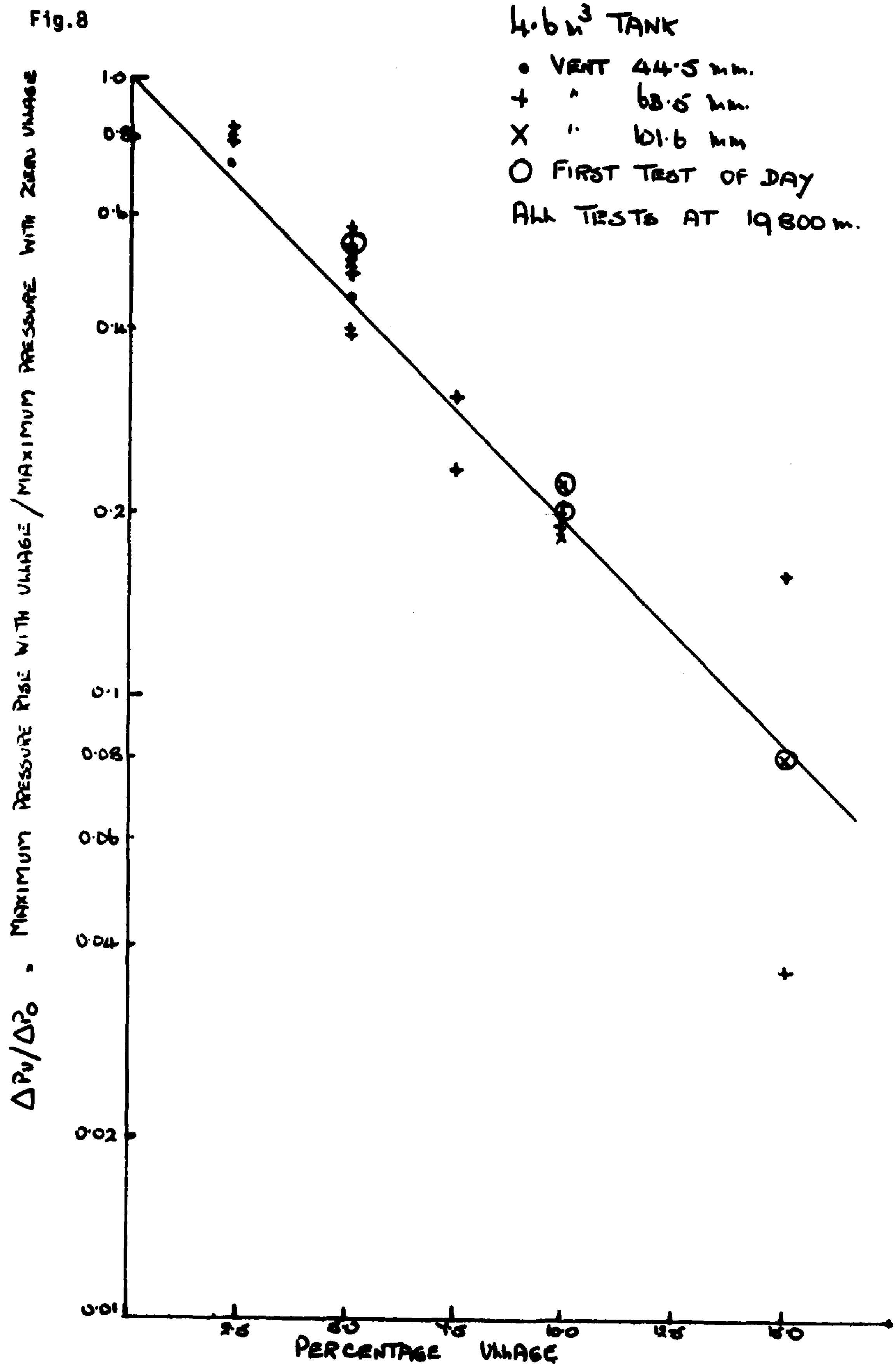


Fig.8 Variation of $\Delta P_U/\Delta P_0$ with ullage

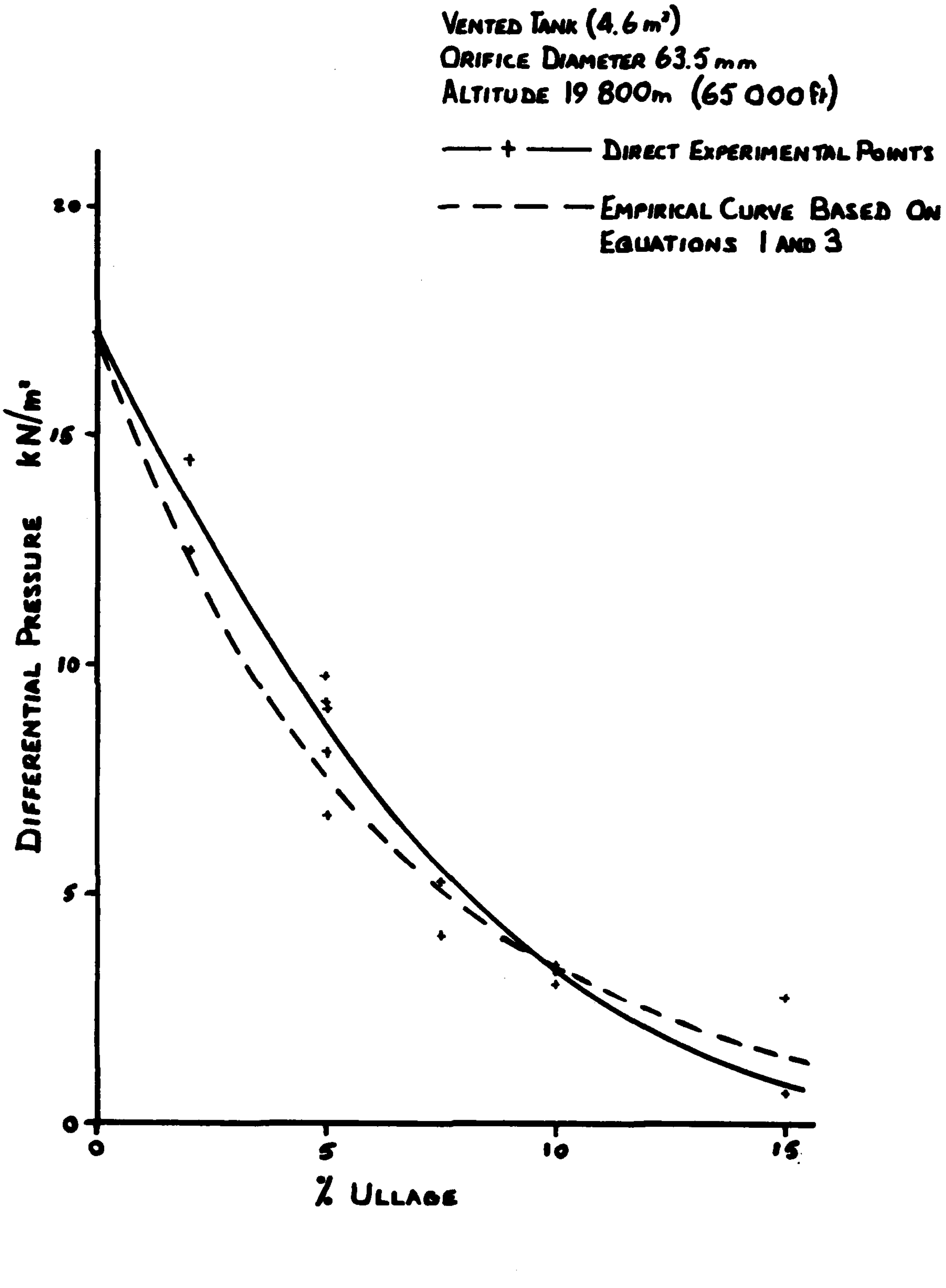


Fig. 9 Variation Of Pressure Rise With Ullage

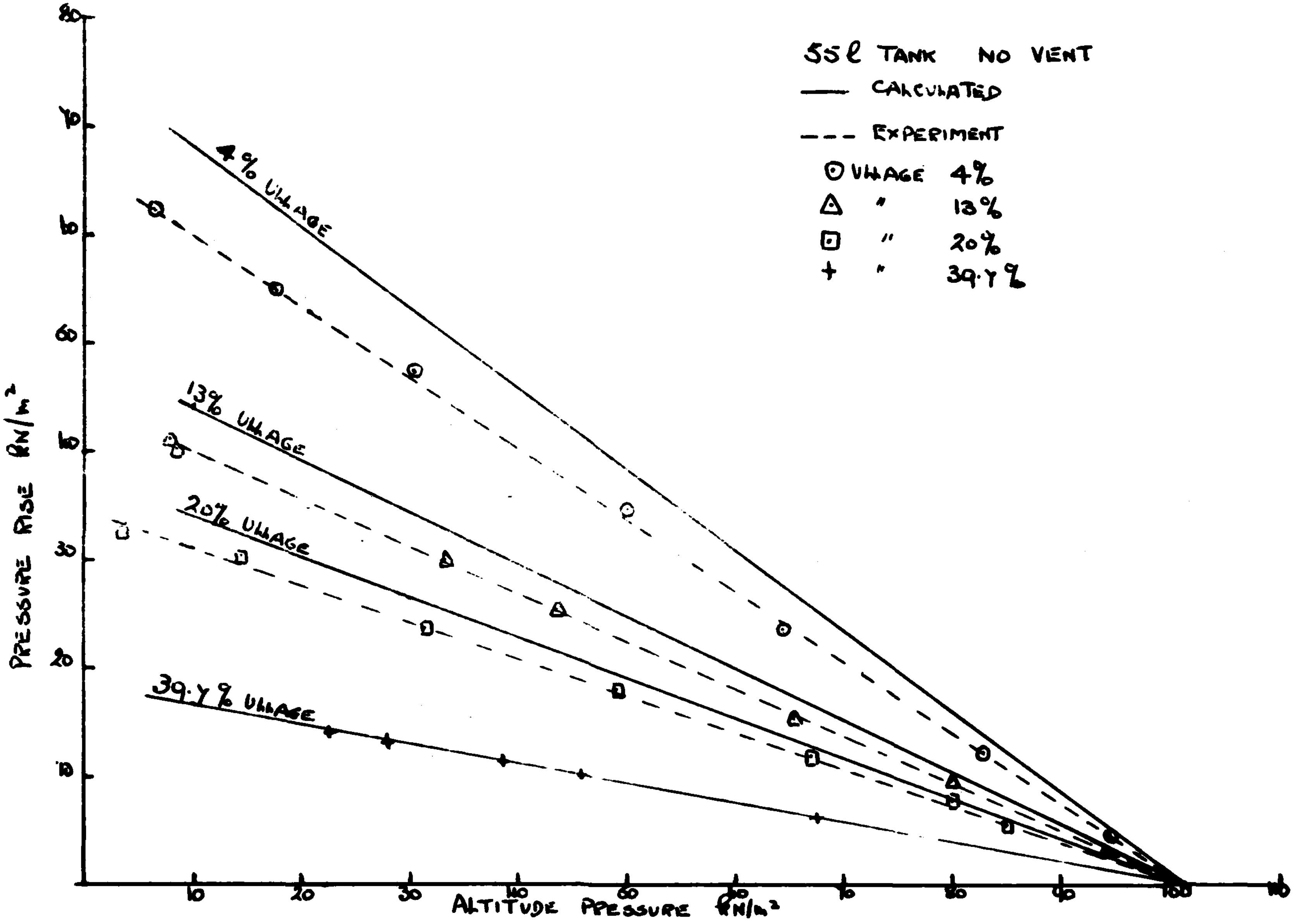


Fig.10 Comparison of theoretical and actual pressure rise - closed tank

Fig.11

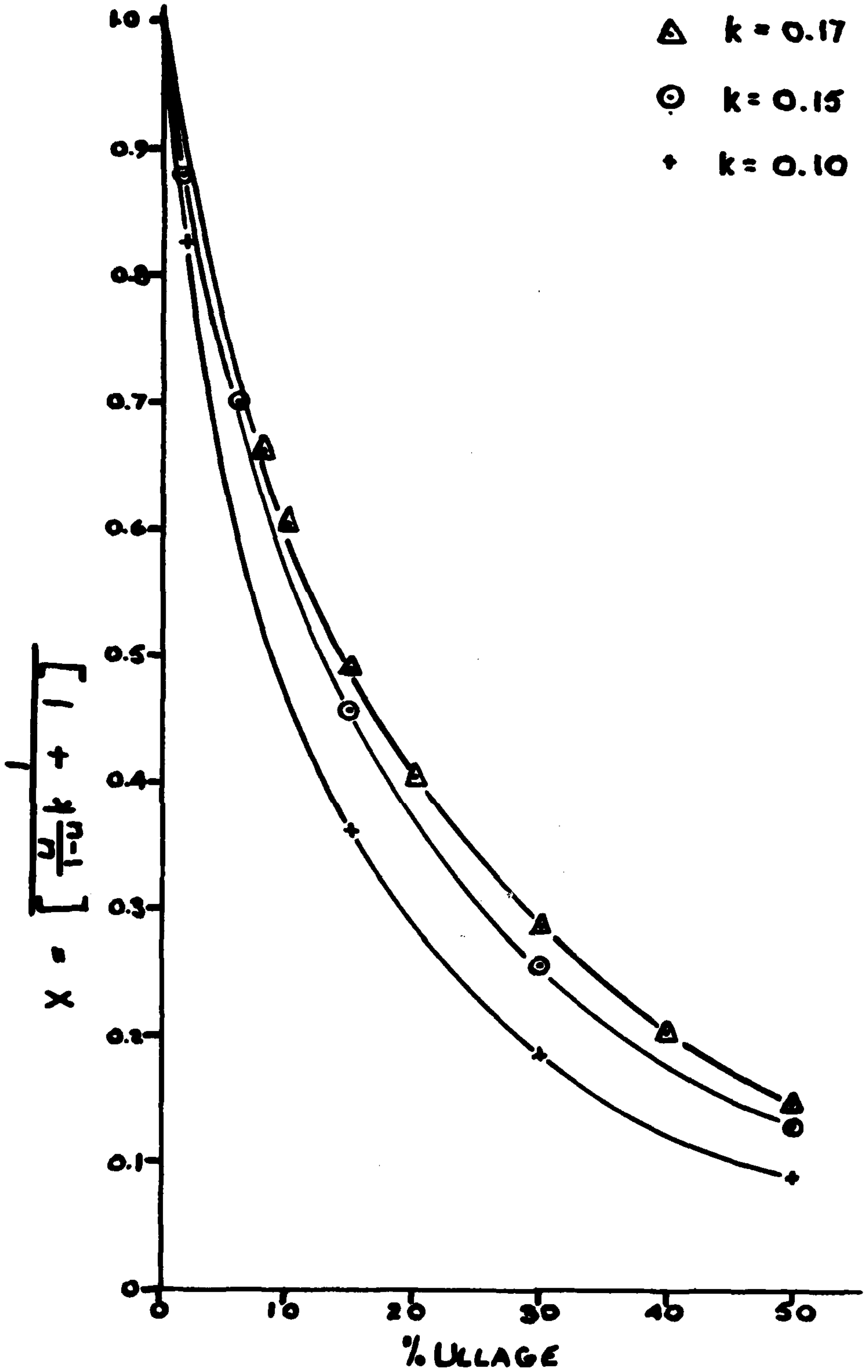


FIG. 11 VARIATION OF $\frac{1}{\left[\frac{U}{1-U}k + 1\right]}$ WITH ULLAGE

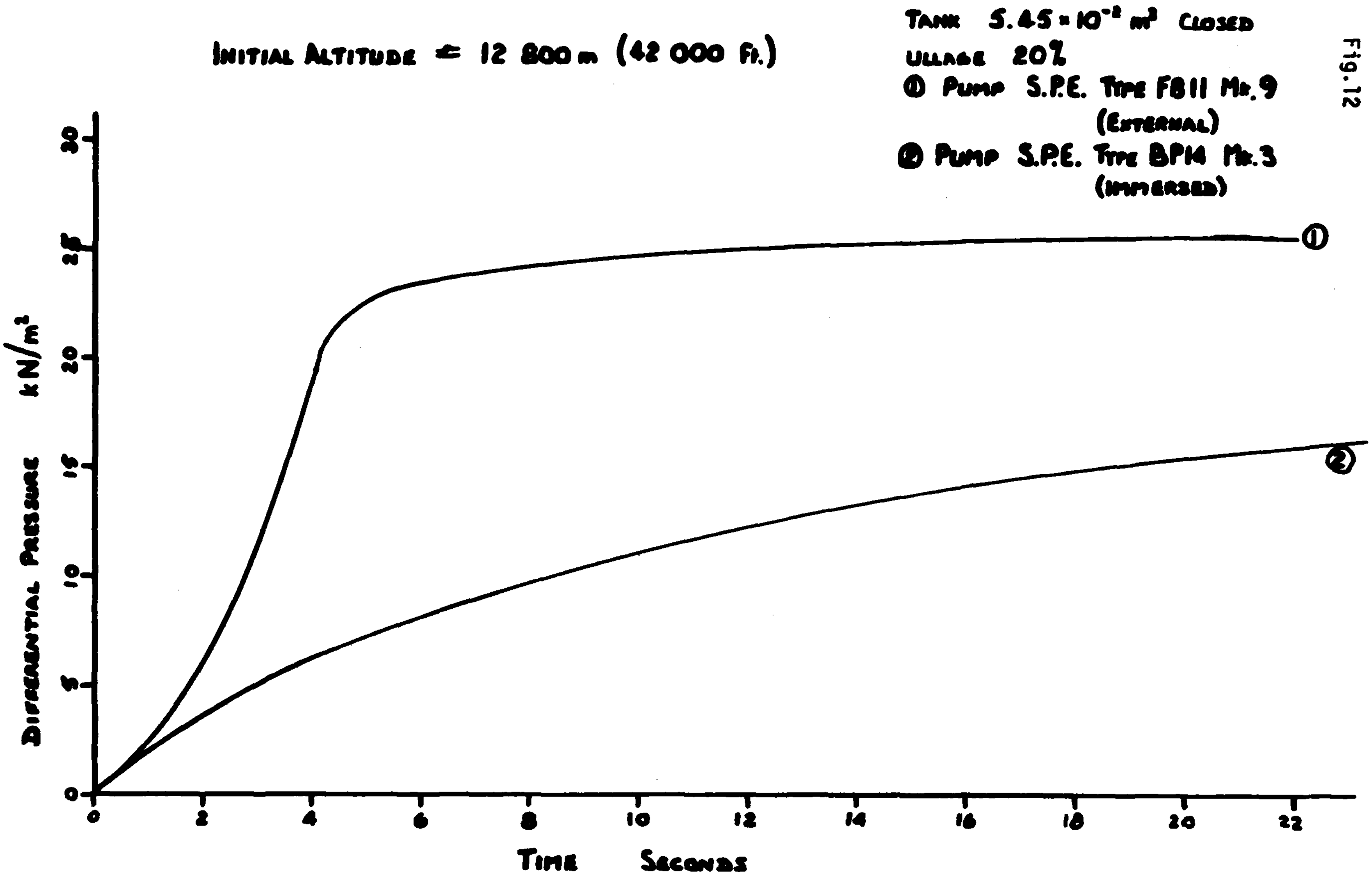


FIG. 12 COMPARISON OF EXTERNALLY MOUNTED AND IMMERSED PUMPS (CLOSED VENT)

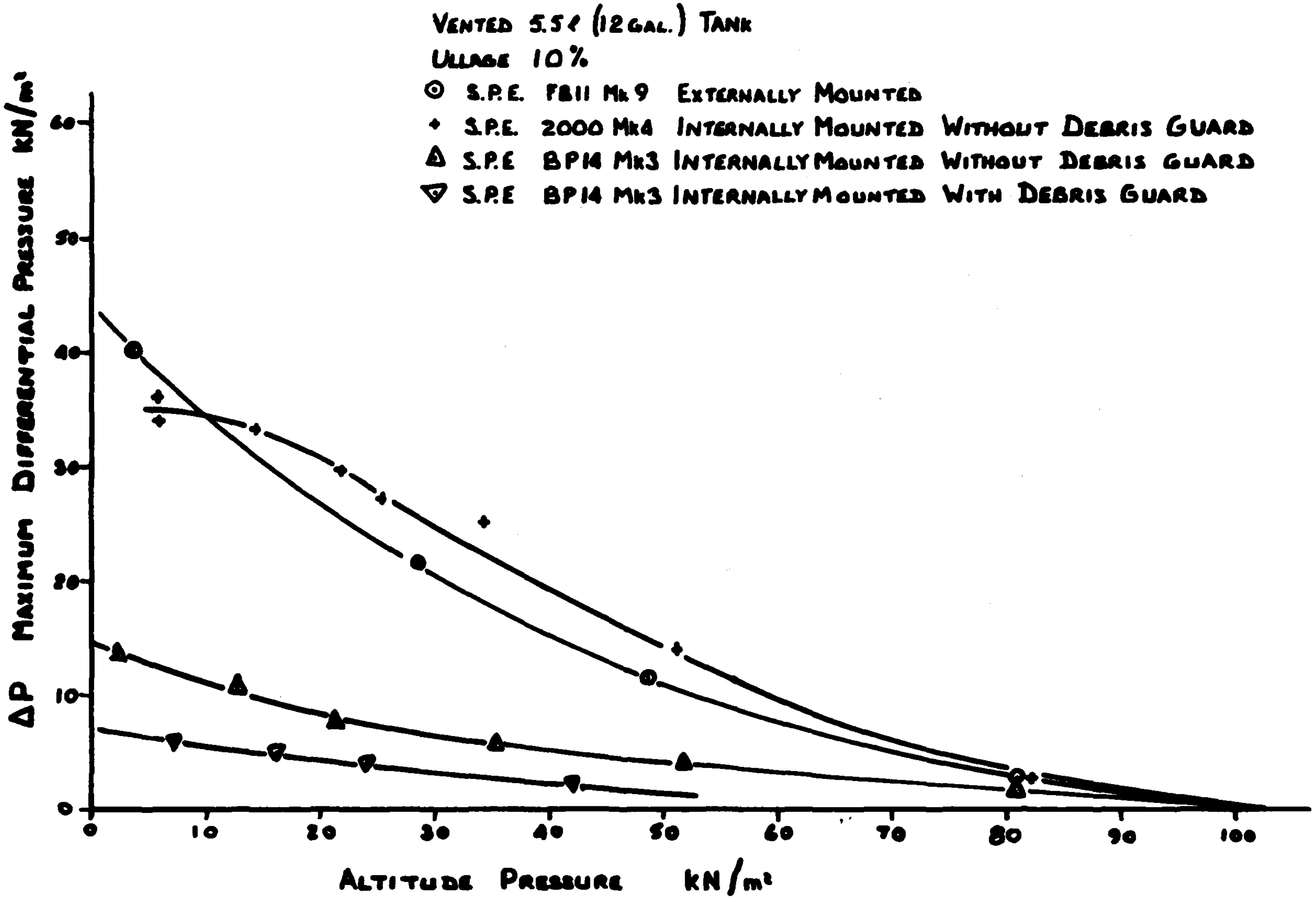


Fig. 13 Vented Small Tank With Various Agitation Levels

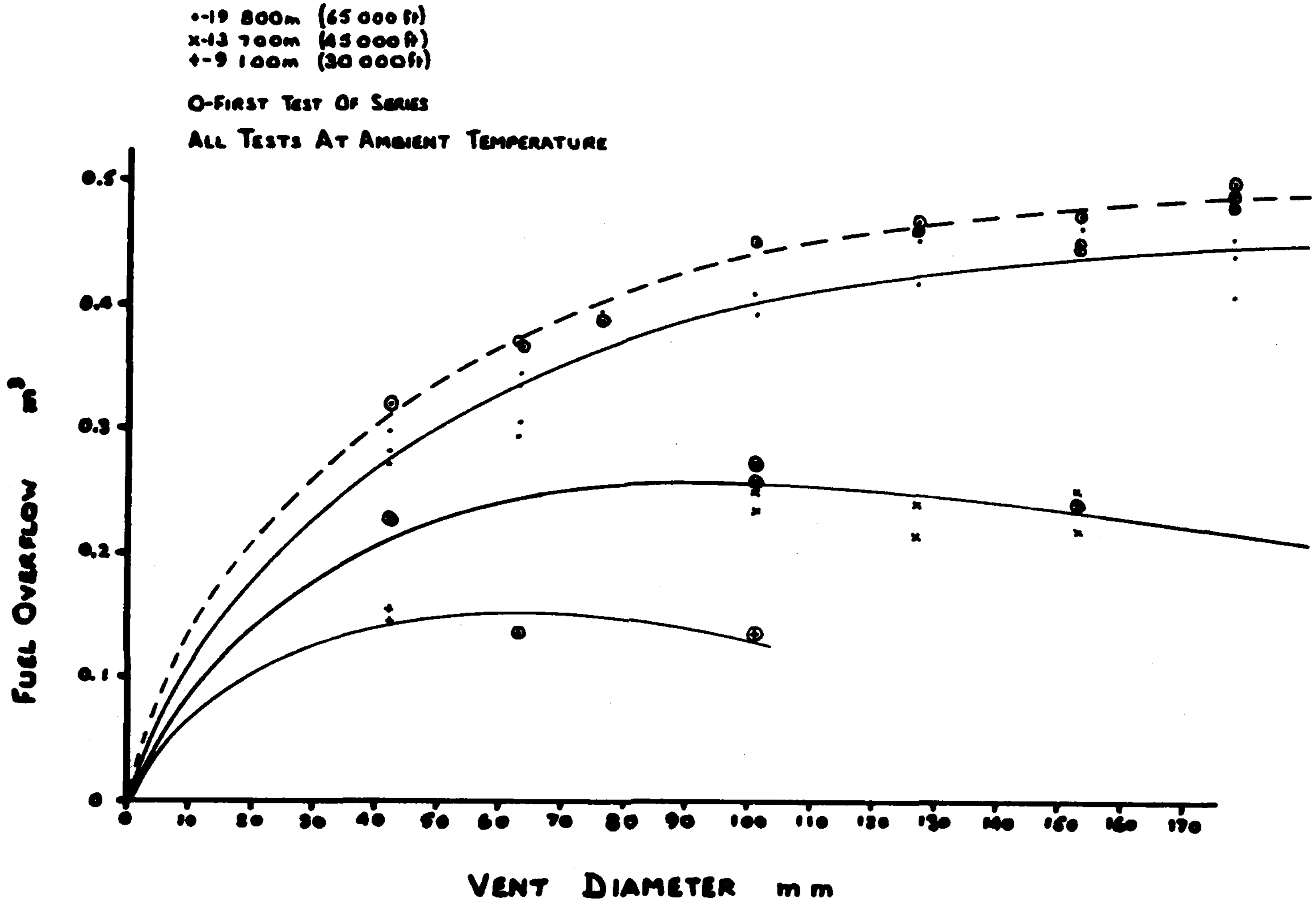


FIG 14 FUEL OVERFLOW 4.6 m³ TANK WITH ZERO ULLAGE

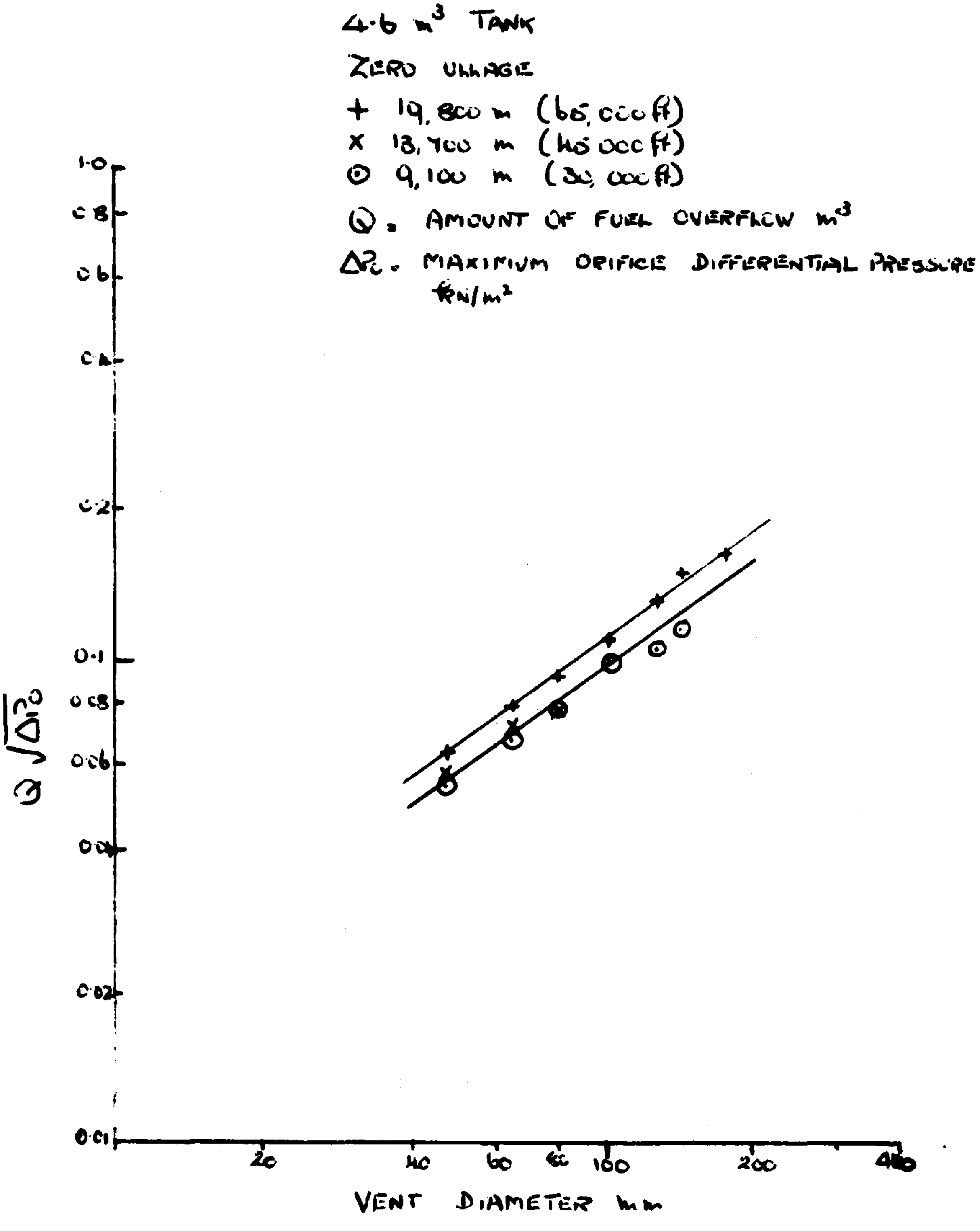


Fig.15 Variation of $Q\sqrt{\Delta P_0}$ against vent diameter

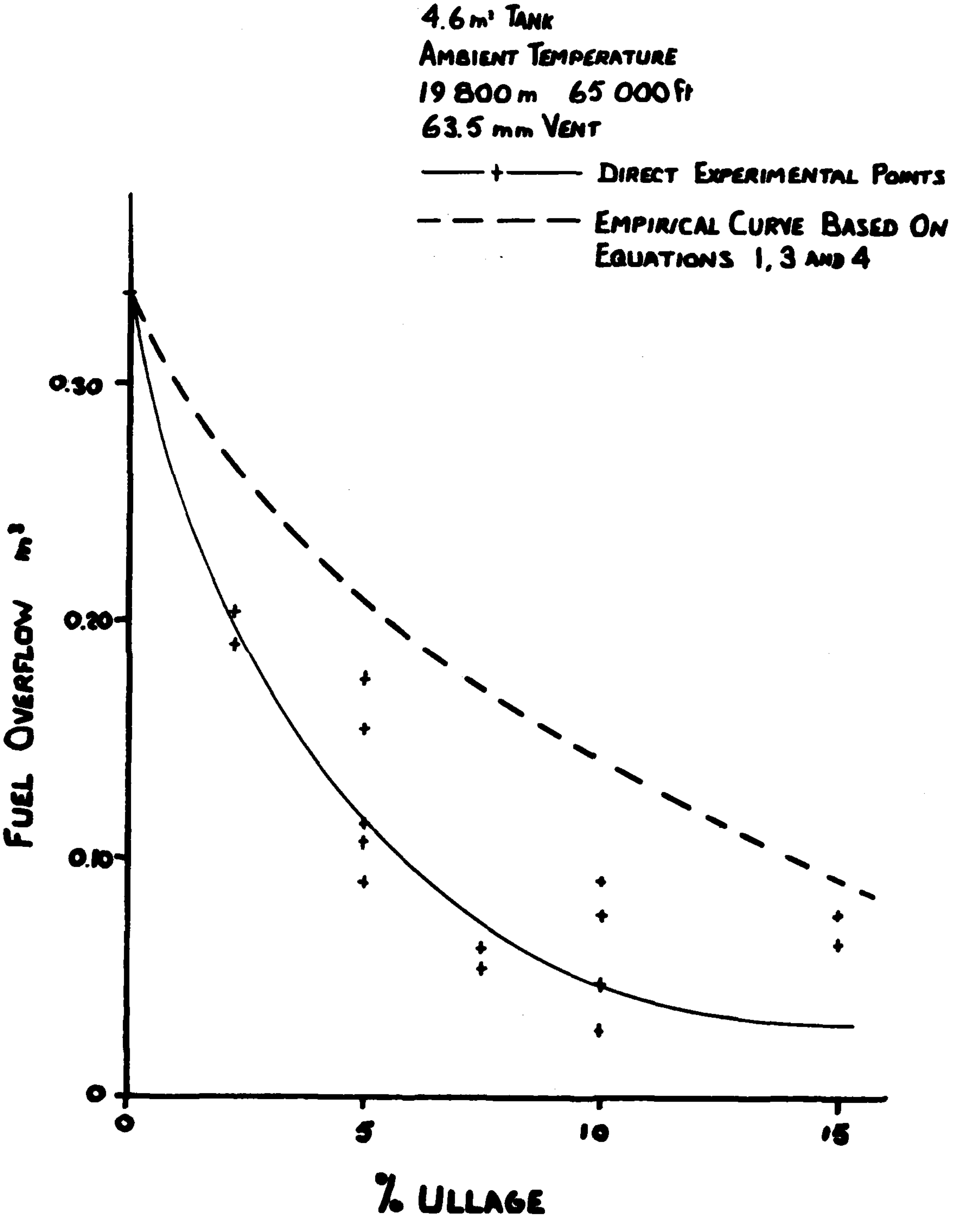


FIG.16 VARIATION OF FUEL OVERFLOW WITH ULLAGE

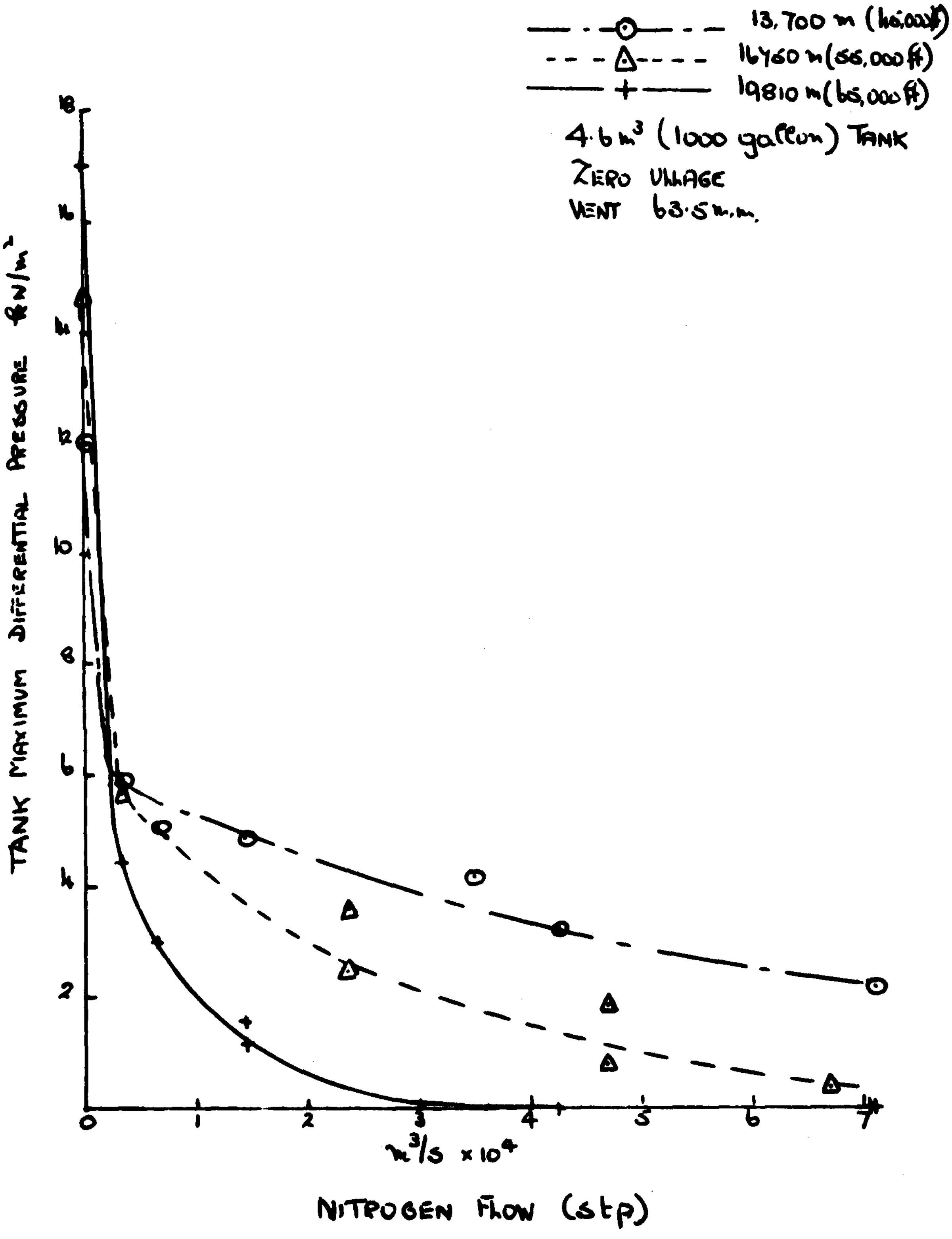


Fig.17 Effects of nitrogen bubbling on pressure rise

# DETACHABLE ABSTRACT CARD

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Although some empirical equations for the tank differential pressure and overflow have been derived, it was not possible to obtain general equations for design use. This was due to the large number of parameters involved, especially the rate of air release, which is dependent on the agitation produced by the booster pump.

It is concluded that if operation of any aircraft fuel system is likely to produce rapid de-aeration, for example, by the starting of a fuel booster or transfer pump at altitude, simulated tests are necessary to prove the system.

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