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EXPLOSIONS IN SALVUS BREATHING APPARATUS

by

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SUMMARY

This report describes the explosion of a Salvus breathing apparatus in the Derbyshire County Fire Brigade and an investigation into the possible causes of this and similar explosions.

Since all reported explosions appear to have occurred immediately upon opening the main valve of the apparatus, it is suggested that those which were not due to the failure of defective Bourdon tubes in the pressure gauges, are likely to have been due to the heat generated by the sudden compression of oxygen in the high-pressure side of the apparatus. It was found that this was sufficient to melt a heat-sensitive paint of melting point 232°C, and it was shown that the rate of compression, and hence the maximum temperature attained, could be reduced by fitting a spigot in the centre of the valve seating, provided that the diameter of the spigot did not differ from that of the hole by more than 0.001 in.; even so the temperature rise was sufficient to melt a lacquer which fused at a temperature of 176°C.

It is shown that the materials of the washers in the high-pressure side of the apparatus present an explosion hazard and it is recommended that an attempt should be made to replace these washers by ones which are incombustible in high pressure oxygen or alternatively by using metal seatings.

Introduction

During the past few years several explosions have occurred in the high-pressure side of Salvus breathing apparatus resulting in damage to the pressure gauge and often in injury to the user. Some of these explosions have undoubtedly been due to mechanical failure of the Bourdon tubes in the pressure gauges. This danger can be minimised by using a bulkhead type of gauge fitted with an efficient pressure release device - a precaution now being adopted by fire brigades.

In other explosions there is evidence of the ignition of combustible material in the high-pressure side of the apparatus. Such an accident at a Winchester fire station has been described elsewhere(1) and a further accident in the Derbyshire County Fire Brigade has been investigated.

Description of accident in the Derbyshire County Fire Brigade

From a report received from the Chief Officer of the Brigade it appears that shortly before the accident the cylinder was removed and recharged with oxygen and the set was reassembled and tested. At no time during this operation was the pressure gauge removed from the cylinder. The set was then used in a demonstration. Immediately upon opening the main valve an explosion, accompanied by a white flash, occurred in the pressure gauge assembly. The wearer's clothing was ignited and burned fiercely in the stream of escaping oxygen, but he managed to remove the set and extinguish the fire with a foam extinguisher.

The set, which had not been dismantled since the accident, was examined. It was found that the Bourden tube in the pressure gauge was intact, but that solder at the root of the tube had melted and had been blown out of the joint. The fibre washer in the pressure gauge union had disappeared leaving traces of a fine white deposit (probably ash) on the metal faces of the union. Any other ash formed could have been blown out by the escaping oxygen. The gauge had a plastic front which remained intact although it was badly blackened. A relief valve fitted at the back of the case appeared to have operated and it was probably the issue of flame from this which ignited the wearer's clothing.

Discussion of explosions in Salvus breathing apparatus

A comparison of this accident with others of which full details are available is given in Table 1. In three cases the explosion was certainly due to the ignition of combustible material and in two of these cases the fibre washer was consumed. In all cases the explosion was stated to have occurred immediately upon opening the main valve, suggesting that ignition was due to the heat generated by the sudden resultant compression of the oxygen in the restricted volume in and leading to the pressure gauge.

The temperature attained during an adiabatic compression may be calculated from the equation

$$T = T_0 \left(\frac{P}{P_0}\right)^{1-\gamma}$$

where T_0 is the initial temperature in $^{\circ}K$

T is the final temperature in $^{\circ}K$

P/P_0 is the ratio of the initial and final pressures

γ is the ratio of the specific heats of the gas at constant pressure and at constant volume.

A compression from 1 to 120 atmospheres with an initial temperature of 15°C results in a theoretical final gas temperature of 860°C. In practice, owing to the large surface area and the small volume of gas, the heat produced will be rapidly dissipated so that the maximum temperature attained will depend on the speed of compression. The design of the main valve is such that this may be rapid.

A diagram of the cross piece fitted to the oxygen bottle of a Salvus breathing set, showing the main valve assembly, is given in Fig. 1. Turning the hand wheel through quarter of a revolution lifts the valve 0.01 in. off its seating and in so doing gives an orifice sufficient to allow a rapid rise in pressure in the small space into which the oxygen flows, unless this quarter turn is performed very slowly.

There are two methods of reducing the possibility of an explosion:-

(a) The elimination of all potentially hazardous material from the high pressure side of the apparatus, and

(b) The introduction of some device to reduce the rate of rise of pressure and hence the maximum temperature attained, on opening the main valve.

Measurement of the temperature attained on opening the main valve

An attempt was made to measure the temperature attained in the high-pressure side of the apparatus on opening the main valve, using heat-sensitive paints which melt at known temperatures. It was found that these paints dry to a powder having a grain size of the order of 0.001 in. A glass rod was drawn out to a diameter of approximately 0.01 in. and this was set in solder in a brass nipple. The end was then drawn out to a filament having a diameter of approximately 0.001 in. and protruding 0.1 in. from the end of the nipple. A few grains of paint were picked up on the filament and the nipple was inserted in an adaptor fitted to the cross-piece of an oxygen bottle taken from a Salvus breathing apparatus as shown in Fig. 2. The paint was subjected to one or more rises of pressure by rapidly opening the valve after which it was examined under the microscope for signs of fusion. It was found that a paint having a melting point of 232°C fused completely after one compression but that one having a melting point of 288°C showed no signs of fusion after ten compressions.

The explosion hazard of seating materials used in Salvus breathing apparatus

Several washers of the types used in the pressure gauge unions were obtained from the Derbyshire County Fire Brigade. There were two types, one of red and the other of white fibre. An examination of the ash in the pressure gauge union of the apparatus involved in the accident showed that the washer must have been one of the white type.

Both types of washer were found to continue to burn in air if placed on a wire gauze and ignited.

A white washer was placed in a horizontal, open-ended glass tube with a slow stream of oxygen passing through it. The tube was heated until the washer burst into flame, when the source of heat was removed. The washer burned brightly until it was almost consumed; it then exploded and shot out of the end of the tube.

No explosion resulted when the experiment was repeated using a red washer, although this also burned brightly.

Unsuccessful attempts were made to ignite both types of washer by passing a high-pressure stream of oxygen through both fast and slow leaks at a washer-metal interface.

Attempts to ignite small roughened fragments of the washer materials by sudden compression of oxygen also proved unsuccessful.

Mabbs(2) using more elaborate apparatus to ensure a more nearly adiabatic compression has ignited fibre in block form by sudden compression of oxygen to 2145 lb/sq. in., and in powdered form by sudden compression of oxygen to 2070 lb/sq. in.

Guter(3) has measured the ignition temperature in high pressure oxygen of many seating materials. A few of his results are given in Table 2.

TABLE 2

IGNITION TEMPERATURES OF SEATING MATERIALS

MATERIAL	MEAN IGNITION TEMPERATURE IN OXYGEN AT 100 atmospheres
	°C
Grey horn fibre seats	236
Red vulcanised fibre (block)	220
Red vulcanised fibre (shavings)	212
Nylon	243 (but one sample ignited at 160°C)
Teflon	No ignition at 350°C and 250 atmospheres
Polyvinyl alcohol phosphorylated with $POCl_3$	No ignition at 350°C and 250 atmospheres

It will be noticed that the ignition temperatures of the first four substances are of the same order as the melting point of the heat sensitive paint which fused on opening the valve in the experiment described earlier. Although ignition of the washers would not be expected to occur on every occasion, dependent upon how carefully the valve is opened, the chance of ignition always exists especially if small separated or protruding fibres of the material are present.

Reduction of the rate of rise of pressure on opening the main valve

In order to reduce the rate of rise of pressure on opening the main valve Messrs. Siebe-Gorman suggested fitting a spigot in the centre of the valve seating as shown in Fig. 3. This would have the effect of throttling the initial flow of oxygen, but would not impede the flow when the valve was fully open.

Experiments were carried out, in conjunction with the Safety in Mines Research Establishment at Buxton, to determine the extent to which careful opening of the valve would reduce the rate of rise of pressure, and to examine the throttling effect of two sizes of spigot, one differing in diameter from that of the hole by 0.0005 in. and the other by 0.0025 in. The pressure rise was measured by a piezo-electric quartz crystal gauge which was fitted directly to the cross-piece of an oxygen bottle on the arm opposite the valve. The gauge was connected through an impedance-convertor to a cathode-ray oscillograph fitted with a drum camera. The oscillograph record, which shows the minimum rate of rise of pressure obtained by opening the unmodified valve with extreme care, is reproduced in Fig. 4A. The record of the maximum rate of rise of pressure, obtained by opening the unmodified valve as rapidly as possible, is given in Fig. 4B. These figures show that if the valve is operated very carefully the time taken for the pressure to rise to its maximum value, normally about 120 atmospheres, may be as long as 150 milliseconds but that this time can be reduced to 50 milliseconds by a quicker opening of the valve.

It was found that, when the valve was modified by fitting a spigot in the centre of the seat, the rate of rise of pressure was less dependent on the manner of opening the valve. Oscillograph records of the rates of rise of pressure on opening valves fitted with the two sizes of spigot are shown in Figs. 4C and 4D. The time taken for the pressure to build up was 375 milliseconds using the valve fitted with the larger spigot, but with the smaller spigot the time was 175 milliseconds, little better than could be achieved by opening the unmodified valve carefully.

The experiment using heat sensitive paints was repeated using both the smaller and the larger spigots. It was found that with the smaller spigot the paint melting at 232°C still fused completely on one compression but with the larger spigot this paint could not be fused and a paint melting at 176°C only showed evidence of fusion after several compressions.

Conclusions and recommendations

In the report on the accident at the Winchester Fire Station[1] certain recommendations were made which, it is considered, should be re-emphasised. Briefly they are:-

(1) All possible sources of contamination with oil or grease, including the use of metal polish and immersion tests in possibly greasy water, should be avoided.

(2) The use of lubricants in gland packings is undesirable.

(3) Bulkhead-type pressure gauges should be fitted. These should have a plastic front and a back which will blow off easily.

(4) Personnel should not look at a pressure gauge while turning on the oxygen.

From the investigation described in this report it is now possible to add the further recommendations given below.

It appears that the fitting of a spigot in the centre of the existing valve seating may reduce the risk of an explosion by throttling the initial flow of oxygen, but to be effective the spigot must not differ in diameter from the hole by more than 0.001 in. This may prove to be a very small clearance to maintain in practice.

It is considered most undesirable that the high-pressure side of the apparatus should be fitted with washers which are capable either of initiating or increasing the severity of an explosion. The work of Guter[3] has shown that the fitting of nylon washers would be no improvement. The possibility of fitting washers of Teflon or polyvinyl alcohol phosphorylated with $POCl_3$ might be investigated. However attention is drawn to the conclusion reached by Mabbs in 1923[2] which Guter repeated in his report[3].

> "The investigation has shown that all practicable seat materials for "oxygen pressure regulators are combustible under conditions which may "occur occasionally in service. The two inter-dependent causes for "ignition of the seat are:-
>
> "1 Heat generated by the sudden compression of oxygen or air "in the high pressure inlet tube of a regulator, and
>
> "2 small separated or protruding fibres of the material on the "surface of the seat exposed to high pressure gas."

"The ideal solution for the elimination of this fire and explosion hazard would be a metal seat."

It is considered that an attempt should be made to produce a breathing apparatus having all-metal seats in the valves, connectors, and unions on the high pressure side, and a tapered needle and seating to the main valve which would restrain the initial surge of oxygen on opening the valve.

Acknowledgements

The measurements of rate of pressure rise were carried out at the Safety in Mines Research Establishment using equipment designed there and the authors are indebted to Mr. H. Robinson and members of his Section, in particular Mr. S. Margesson for their co-operation.

References

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(2) MABB, J.K. Report to the Oxygen Regulator Research Committee of the Compressed Gas Manufacturers' Association on the Investigation of Oxygen Regulator Seat Materials. November, 1923.

(3) GUTER, M. Ignition in High Pressure Oxygen. The British Oxygen Co., Ltd., Research and Development Report No. 1312 issued by TPA 3 Technical Information Bureau for Chief Scientist, Ministry of Supply. S. and T. Memo No. 13/50. July, 1950.

TABLE 1

A Comparison between accidents involving Salvus Breathing Apparatus of which details are available

Date and Location of accident	Treatment of apparatus before accident	Condition of pressure gauge after explosion	Condition of pressure gauge union after explosion	Remarks
July 1945	New fibre washer fitted in pressure gauge union.	Bourdon tube fractured. Interior of tube covered with black material which on combustion in Oxygen yielded 25% of Carbon.	Not reported	Not certain to be due to explosion of Carbonaceous matter.
January 1947 Fire Force 20	Cylinder replaced by a newly filled one which had returned from the compressing firm with leather washers beneath the blank caps.	Bourdon tube intact but solder had blown out of joint at root of tube. Evidence of great heat.	The union nut for cylinder, fibre washer and slow leak grub screw were quite bright and clean.	
Hampshire Fire Service (1)	Serviced and tested. Pressure gauge was found to be out of alignment. Union nut was loosened, gauge aligned and nut tightened.	Bourdon tube had burst Blackening on back of gauge dial.	Fibre washer had disappeared. Some blackening on inside of limb of cross-piece which connects to gauge.	The throttling device fitted to pressure gauge inlet, consisting of a 5/16 in. long screw with a 0.052 in. diameter hole through it, was considered to be ineffective.
Kent Fire Brigade June 1950.	Gauge replaced by a new one.	Bourdon tube fractured. Signs of a black deposit around fracture.	Not reported	
Derby Fire Brigade	Cylinder removed and re-charged but gauge was not removed from cylinder.	Solder at root of Bourdon tube had melted and blown out of the joint.	Fibre washer had disappeared leaving a white deposit.	

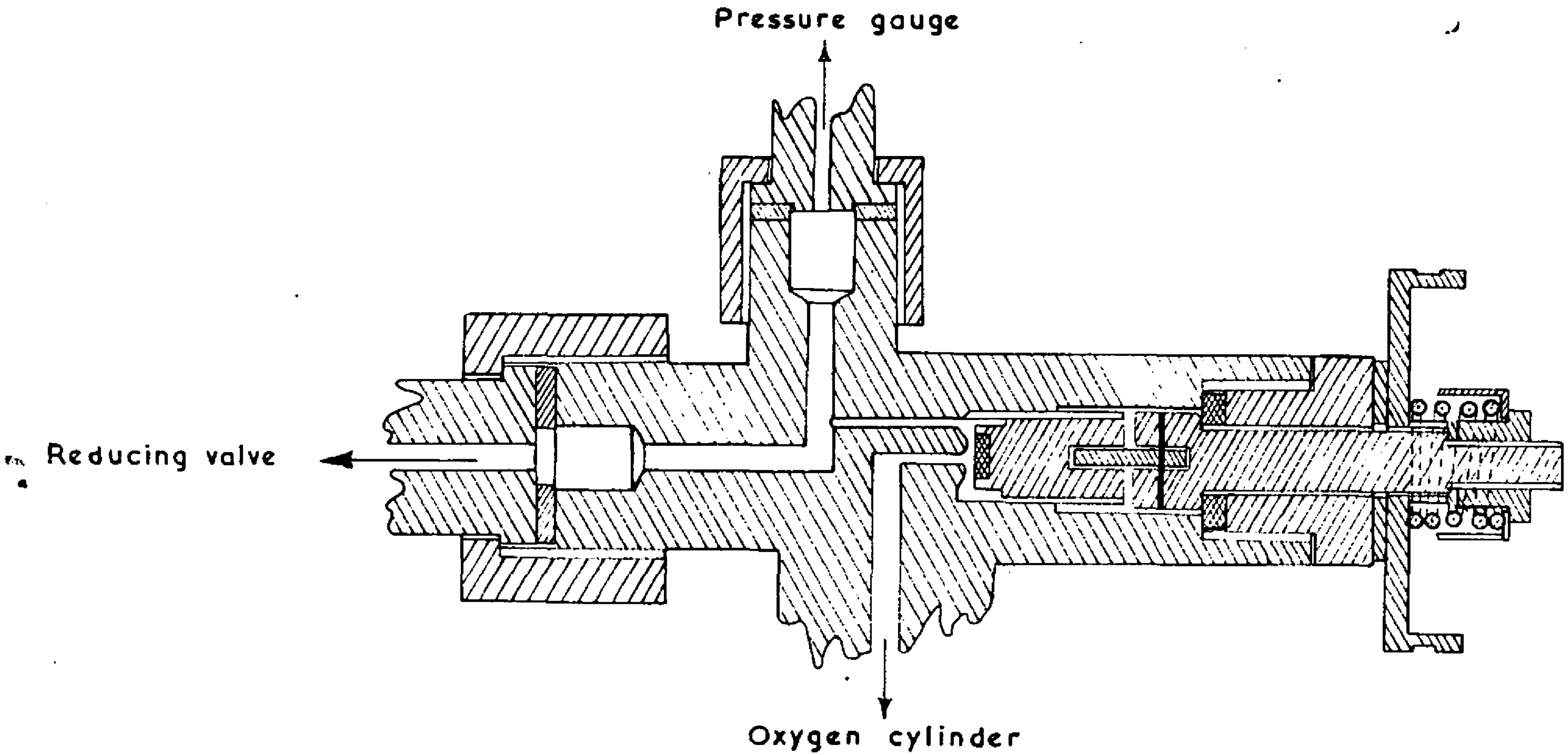

FIG. 1. DIAGRAM OF CROSS PIECE FITTED TO OXYGEN CYLINDER.
SHOWING MAIN VALVE ASSEMBLY
(1½ TIMES FULL SIZE)

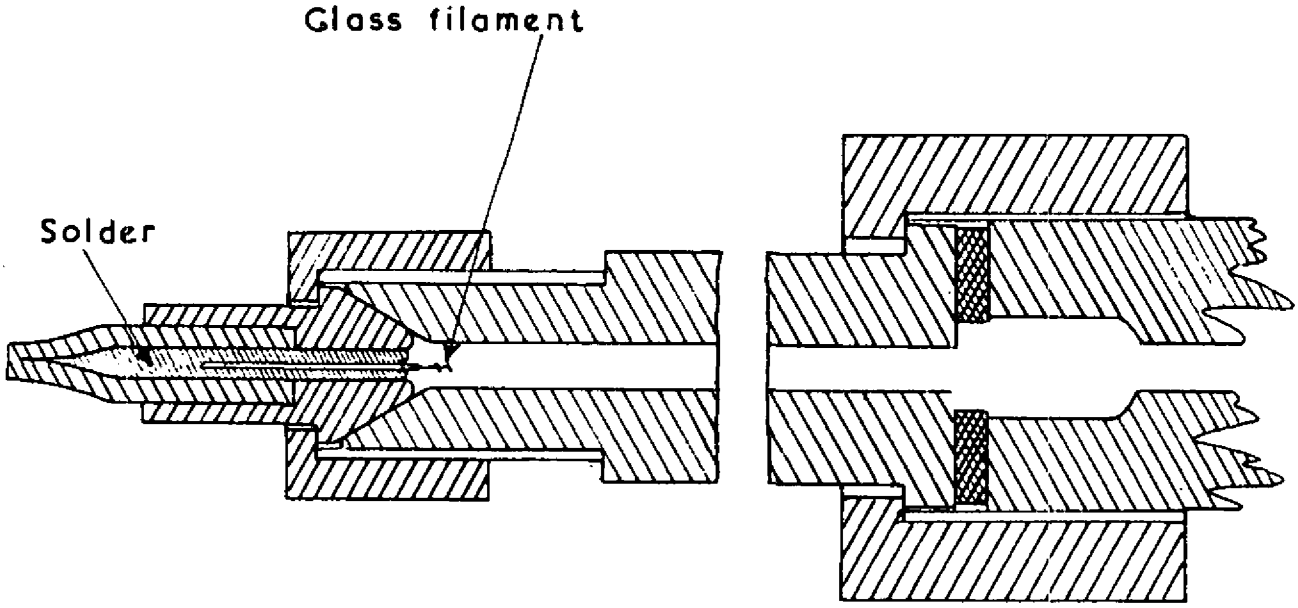

FIG. 2. DIAGRAM SHOWING GLASS FILAMENT CARRYING GRAINS OF HEAT SENSITIVE PAINT INSERTED IN ADAPTOR FITTED TO CROSS PIECE OF OXYGEN BOTTLE

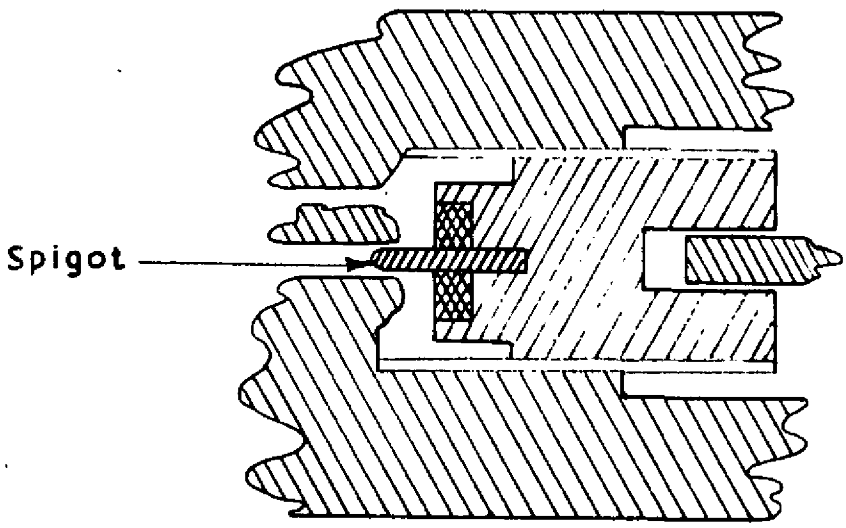

FIG. 3. DIAGRAM OF MODIFIED VALVE SHOWING SPIGOT FITTED IN CENTRE OF SEATING

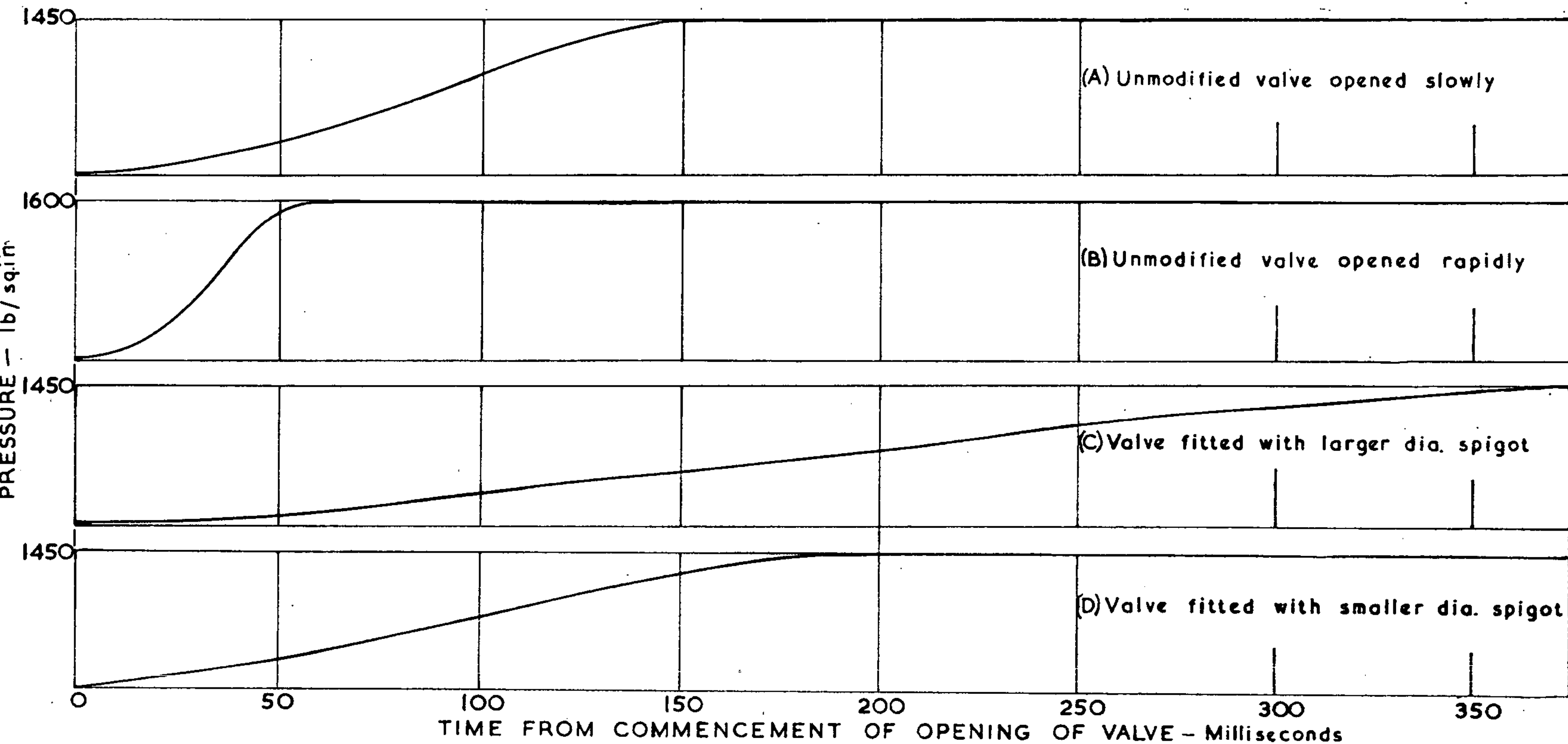

FIG. 4. OSCILLOGRAPH RECORDS OF PRESSURE RISE