Fire Research Note
No 1018

THE TRANSMISSION OF EXPLOSION OF FLAMMABLE GAS/AIR MIXTURES THROUGH A FLAME GAP ON A VENTED VESSEL

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July 1974

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FR Note No. 1018
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SUMMARY

Measurements of the rates of pressure rise and a photographic study of the flames emerging from the maximum experimental safe gap apparatus have shown that although relief venting may reduce the maximum explosion pressure it may increase the rate of pressure rise within the time interval when the reaction zone and following hot combustion products are flowing through the flange gap.

In some explosions the presence of the relief caused acoustic standing waves, and the resultant movement of gas interfered with the combustion wave.

Schlieren and direct photographs of the transmitted explosions have shown that, in vented explosions, transmission through a flange gap need not necessarily occur nearest to the igniting source, and in some cases ignition took place in two locations simultaneously. With ethylene/air and propane/air mixtures the transmissions occurred during the initial stages of the explosion. With hydrogen/air mixtures the transmission of the explosion occurred when the explosion pressure reached 25 per cent of the peak value.

As the location of the explosion transmission through a flange gap is largely unpredictable, the timing of the newly formed flame front outside the vessel with ionisation detectors opposite the igniting source may be inaccurate.

Department of the Environment and Fire Offices' Committee
Joint Fire Research Organization

THE TRANSMISSION OF EXPLOSION OF FLAMMABLE GAS/AIR MIXTURES THROUGH A FLANGE GAP ON A VENTED VESSEL

1. INTRODUCTION

Work carried out on the evaluation of the maximum experimental safe gap (MESG)[1,2], in an 8 litre volume vessel with and without explosion relief protected with a flame arrester has shown that the reduction of the maximum explosion pressure afforded by the arrester could permit an increase of the MESG. This work[1] has also demonstrated that, in vented explosions, the smallest MESG was obtained with the igniting source near the flange and near the vent.

This finding appeared at variance with earlier experimental results and theoretical analyses[3,4,5,6], suggesting that a reduction in the maximum explosion pressure results in a degrease of the MESG, (although an ignition near the flange required the smallest MESG). This paper describes experiments to produce evidence resolving this apparent contradiction.

2. APPARATUS AND MATERIALS

2.1. Explosion vessel

The experiments were carried out using an 8 litre stainless steel cylinder of height and internal diameter 216 mm (8.5 in) and wall thickness 25 mm (1 in). The top and bottom of the vessel consisted of separate end plates, 25 mm (1 in) thick, which could be kept apart from the cylindrical wall by silver foil shims. The cylinder was sandwiched between two end cups (Fig.1). All contact surfaces between the end cups, end plates, and the cylinder were finished to an accuracy of ± 0.006 mm (0.00025 in).

The assembly was held together in a press (Fig.2) in which an hydraulic ram exerted 7¼ tons axial compression on the whole cylinder assembly. When the assembly was subjected to the maximum stresses produced by an unvented explosion, the yield of the frame holding the cylinder did not exceed 0.006 mm(0.00025in).The test cylinder was provided with a gas inlet, via a non-return valve, a pressure transducer and spark electrodes (Fig.1).

The whole cylinder assembly was enclosed in a 0.13 mm thick polyethylene bag which also contained the flammable mixture during the experiments. This bag burst if the ignition of the flammable mixture surrounding the test vessel took place; it remained intact if there was no transmission of explosion.

2.2. Flange gaps

The experimental flange gaps were produced by six stacks of 25 x 13 mm silver shims equally spaced between the cylinder and the upper end plate. The shims were measured using a micrometer before being put in, and the gap finally verified with feeler gauges after the apparatus was compressed by the hydraulic ram.

2.3. Method of ignition

The flammable mixture was ignited inside the vessel by means of an inductive spark generated between a pair of spark electrodes 2 mmapart, located 10 mm away from the flange gap, using a 12 volt automotive induction coil (Fig. 1).

2.4. Flame speed measurements

The progress of flame was monitored by ionisation probes. These were spaced copper wire electrodes with 10 volt DC potential difference; when the flame arrived at the electrodes it caused an electric current to flow and this was recorded. There was one probe which stretched across the whole diameter of the arrester, 10 mm above the top surface of the arrester, and this would indicate flame front traversing the upper surface of the arrester after emergence. The other detector was situated nearest to the igniting source 5 mm away from the outside edge of the flange gap and this intercepted a flame front generated outside the vessel in the vicinity of the igniting source. In all cases this probe signalled this flame front first. A third detector was fitted inside the explosion vessel in the centre of the bottom flange and this signalled the arrival of the most advanced portion of the flame front within the vessel moving away from the igniting source towards the bottom flange of the explosion vessel.

The event of ignition of the flammable mixture outside the cylinder and the progress of the subsequent flame front were recorded by 16 mm cine pictures at speeds between 1,000–2,500 pictures per second. Both direct and Schlieren pictures were taken. The conventional Schlieren system was used through acrylic windows inserted in the polyethylene bag. This consisted of a horizontal knife edge, mercury lamp illumination and two mirrors (Figs 3 and 4 show the respective arrangements).

2.5. Flammable gases

6.5 per cent ethylene/air and 28 per cent hydrogen/air mixtures were used. These were prepared by metering and subsequent mixing, after which the mixtures entered the explosion vessel and the surrounding bag which were both charged by displacement of the initial atmosphere of air.

2.6. Arresters

In some tests the explosion vessel had a top flange with a central 110 mm diameter vent protected by an arrester. In tests with the ethylene/air mixture the vent was covered with a crimped ribbon arrester of 0.05 mm thick stainless steel crimp height 0.63 mm (0.024 in) having a length of aperture of 25 mm (1 in).

In tests with the hydrogen/air mixtures, the vent was covered with an arrester made from 12.5 mm (0.5 in) thick metal foam, (a commercial product designated 80 grade Retimet). Both arresters were housed in a mild steel frame, clamped tightly to the face of the end plate.

2.7. Pressure measurements

6 The explosion pressures were measured with a commercial quartz transducer, and the time/pressure curve displayed on an oscilloscope screen was recorded photographically simultaneously with the ionisation gap records.

2.8. Procedure

The apparatus was charged with the flammable gas by displacement, allowing not less than ten changes of the atmosphere, after which the gas inside the explosion vessel was ignited, and records were taken.

3. RESULTS

3.1. Explosion vessel vented: ethylene/air mixture

Initially five tests were carried out using 6.5 per cent ethylene in the flammable mixture. In these tests the explosion vessel had a vent of 110 mm diameter covered with the crimped ribbon arrester, the vessel had a gap 0.75 mm (0.030 in) wide, this being 0.025 mm (0.001) larger than MESG for this vessel. The maximum explosion pressures in these tests ranged from 4.5 to 5 kN/m^2 (0.65 to 0.70 lb/in^2). In all tests the explosion was transmitted through the gap. The time from ignition to the arrival of the flame front at the ionisation probe located opposite the ignition was 40 ms in each of four of the tests. These experiments were repeated after renewed but identical assembly of the apparatus. The maximum explosion pressures in this series ranged from 4 to 6 kN/m^2 (0.6 to 0.9 lbf/in^2) and the time from ignition to arrival of the flame at the ionisation gap measured in four of the tests ranged from 28-35 ms.

Several cine films were taken of the explosion transmission, using either Schlieren or direct photography. Figure 5 shows selected direct photographs taken during the first series of experiments. The event of ignition was not indicated on this film and was 14 ms before the development of the flame kernel outside the flange gap; the light produced by the combustion could be seen through the flange gap. At first a short luminous line appeared in line with the spark gap: this moved to the right of the picture. As combustion proceeded, the path travelled remained illuminated. In the following pictures a larger section of the gap was illuminated, and the position of the shims was indicated by the absence of the illumination. After 14 ms the gas outside was ignited. At this stage however, a fully-developed flame emerged from the other side of the vessel (on the left of the picture) and its size indicated that it had developed at very much the same time as the recorded flame. Once the flame kernel appeared it grew very quickly.

In another film where the event of ignition was timed, it was found that 13 ms elapsed from ignition to the development of the external flame kernel. Although on projecting these pictures, what appeared to be some faint chemi-luminescence could be seen before the flame front developed but this was too faint to be printed. Therefore, several Schlieren pictures of this transmission were taken during the second series of experiments. Figure 6 shows a selected sequence. In this film the time of the igniting spark was indicated on the film; the emergence of the hot jet is evident on the right of the second picture - this jet appeared 10 ms after ignition. After a further 5 ms flame combustion, shown by lateral spread larger scale turbulence with asymmetry could be distinguished at the side of the jet. These films did not show the pre-flame reactions (illumination) indicated by the direct photographs. The first appearance of light emerging from the flange gap shown in direct photographs frame Fig.5, coincides with the event of ignition indicated in the Schlieren films frame 5, Fig.6. Figure 7 shows the typical pressure and flame movement record taken at the same time as the cine pictures, Figs 5 and 6. The initial deflection on the top trace indicates arrival of the flame zone at the ionisation gap outside the vessel situated nearest the igniting source. The deflection on the second trace indicates the arrival of the flame front at the centre of the bottom flange of the explosion vessel. The bottom trace is the pressure record. The ionisation gap nearest the igniting source indicated the arrival of the flame 28 ms after the igniting spark was generated - thus the time interval between ignition and the interception of the flame by the ionisation detector was 14 ms longer than indicated by the appearance of the flame kernel in Figure 5.

The pressure record shows pronounced oscillations, the frequency of these increasing with time. These were followed by high frequency oscillations, apparently not resolved by this time base. This event coincided with the fracture of the polyethylene bag and possibly to triboelectric effects caused by the cable movement, created these signals 40 ms after the igniting spark was generated. Direct cine pictures were taken showing the ignition of the surrounding flammable mixture.

3.2. Explosion vessel not vented - ethylene/air mixture

Eleven tests were carried out using the unvented vessel, with a 6.5 per cent ethylene/air mixture . In all tests the flange gap was adjusted to 0.75 mm (0.030 in), as in the previous tests this gap being 0.025 mm (0.001 in) larger than MESG for such conditions. The maximum explosion pressure was 336 kN/m^2 (48 lbf/in^2) in each test, although the explosion was transmitted through the gap in 7 tests. Figure 8 shows selected cine pictures taken at 1300 frames per second illustrating the development of the flame. The first visual sign of the combustion taking place within the vessel was a bright point shown on the first frame. This point widened gradually to illuminate a wider section of the flange gap. The left-hand edge of this region was much brighter than the remaining section and extended along the gap, and after 10 ms flame combustion occurred outside the gap. The next frames show an elongated luminous region - the last picture showing this luminosity greatly intensified. Several Schlieren pictures were taken of the same experiment. Figure 9 shows a selected series of pictures of the ignition of the flammable mixture. On this film the generation of the spark was indicated and this showed the jet of hot gas emerging 5 ms afterwards and after a further 3-3.5 ms it was possible to distinguish the flame combustion by observing the changed pattern of turbulence. Thus the Schlieren photographs detected the flame much earlier than direct photographs. Figure 10 shows the flame travel and the pressure traces. The deflection on the top trace shows the arrival of the flame front at the ionisation probe nearest the igniting source; 20 ms elapsed after generation of the spark before the flame front arrived at the gap; the second trace indicates the arrival of the flame front at the bottom of the explosion vessel 20 ms later. The third trace is the time/pressure curve.

3.3. Explosion vessel vented: hydrogen/air mixture

One test was carried out, using a 28 per cent hydrogen/air mixture, with the explosion vessel provided with the arrester relief, and a flange gap 0.33 mm (0.013 in). Direct cine film could not be used because of the low luminosity of premixed hydrogen/air flames. Figure 11 shows a selected sequence of Schlieren pictures taken at 1600 frames per second. After the spark was generated 8 ms elapsed before hot gases emerged from the flange gap, followed after a further 2.5 ms by flame combustion. The sixth photograph shows that in a place remote from the igniting source another transmission occurred - this however could not be detected until it reached the focal plane of the Schlieren system; finally both flame fronts merged.

Figure 12 shows the oscilloscope flame and pressure record. The deflection on the top trace is a signal from the ionisation detector situated nearest the igniting source, and shows the arrival of the flame front 11.5 ms after the event of ignition, this being quite close to the value indicated by the film in Fig.11. The deflection on the second trace shows the arrival of the flame front at the bottom of the explosion vessel 7.5 ms later. The third trace shows the explosion pressure. The traces indicate that the outside flammable mixture was ignited when the explosion pressure within the vessel attained one-fourth of the maximum value of 32 kN/m^2 (4.5 lbf/in^2) and transmission occurred after the second acoustic vibration, shown on the trace.

3.4. Comparison of initial rates of pressure rise in vented and unvented explosions

The direct comparison of the rate of pressure rise during an explosion in a vented and an unvented explosion vessel was carried out using 6.5 per cent ethylene/air flammable gas in an unvented vessel and in a vessel provided with 110 mm (4.3 in) diameter vent covered with a metal foam arrester. In both tests the flange gap was 0.76 mm (0.030 in). The records are shown in Fig.13a and 13b. In both records the deflection on the uppermost trace indicates the presence of flame above the upper surface of the arrester, the deflection on the second trace indicates the presence of flame outside the explosion vessel nearest the igniting source. The third trace indicates the arrival of the flame front at the centre of the bottom flange; the fourth trace is the pressure record.

When the initial section of these traces is compared, it becomes apparent that the explosion within the closed vessel proceeds with no sudden changes in rates of pressure rise (Fig.13a); on the other hand the vessel with the vent shows rapid fluctuations in the pressure (Fig.13b). In fact the peak pressure value of the first vibration is higher than the corresponding value shown by the pressure record of the unvented explosion. Thus, during the initial stages of the explosion, the rates of pressure rise produced by the vibrations exceed corresponding pressure rises shown by the unvented explosion.

4. DISCUSSION

A great deal of work has been carried out on explosion transmission through a single orifice[3,4,5], and the mechanism of transmission was elucidated with orifices[5,6]. It is generally agreed that the hot gases emerging from the orifice, after mixing with the surrounding flammable gas may ignite it. For this to occur the mixing must be of such a nature that the temperature and the flammable gas concentration attain specific values appropriate to the prevailing conditions. All photographic evidence supporting these conclusions was obtained with the single orifices and this evidence was extended to flange gaps and subsequently a mathematical model of the ignition was derived by Phillips[6].

Photographic evidence presented in this paper confirms that the gases outside the flange gap were ignited by the flowing hot combustion products, but the actual process of ignition was more complex than indicated by the experiments with single orifice. In all cases hot gases emerged as a flat sheet and the flame reaction commenced in the mixing zone of the combustion products and the surrounding gas. Photographs also indicated that before external ignition occurred, the flame within the explosion vessel was of considerable size and the hot combustion products at this stage were emerging over a substantial section of the flange gap.

Frequently the mixture was ignited simultaneously at two locations which were up to 15 cm (6 in) apart. Once the external flame was established it spread preferentially along the gap, following the boundary of hot and cold gas. There were no pronounced differences between the mechanism of the transmission with vented and unvented explosion vessels. The shape of the flames was much the same and the flame in all cases developed in a similar manner. The presence of an arrester however had a considerable influence on the mode of combustion within the explosion vessel and this was manifested by the shape of the time/pressure curve. All pressure records of unvented explosions were smooth with no oscillations indicating the combustion proceeded in a regular manner with no rapid changes in rate.

The presence of a vent resulted in a disturbed combustion with the rate of reaction changing rapidly, thus producing pronounced oscillations on the pressure record. These oscillations were caused by fluctuating combustion creating standing pressure waves. Such waves would impart substantial motion to the flame front, driving it towards the flange gap when the wave was creating positive pressure near the flange. Such movement would be of consequence when the flame front reached the flange, because the passage of the combustion products are seen to coincide with the vibrational peaks on the pressure records.

5. CONCLUSIONS

1. The insertion of vents to the test vessel does not decrease the MESG.
2. The presence of a vent may increase the rate of pressure rise during the initial stages of an explosion.
3. The rate of pressure rise in a vented explosion is not uniform; a number of rapid changes in the rate of pressure rise are evident, and such rates may have negative values.
4. The explosion may be transmitted through the gap in more than one place.

6. REFERENCES

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7. ACKNOWLEDGEMENT

Thanks are due to M Senior and C P Finch who took the cine pictures, and operated the Schlieren apparatus.

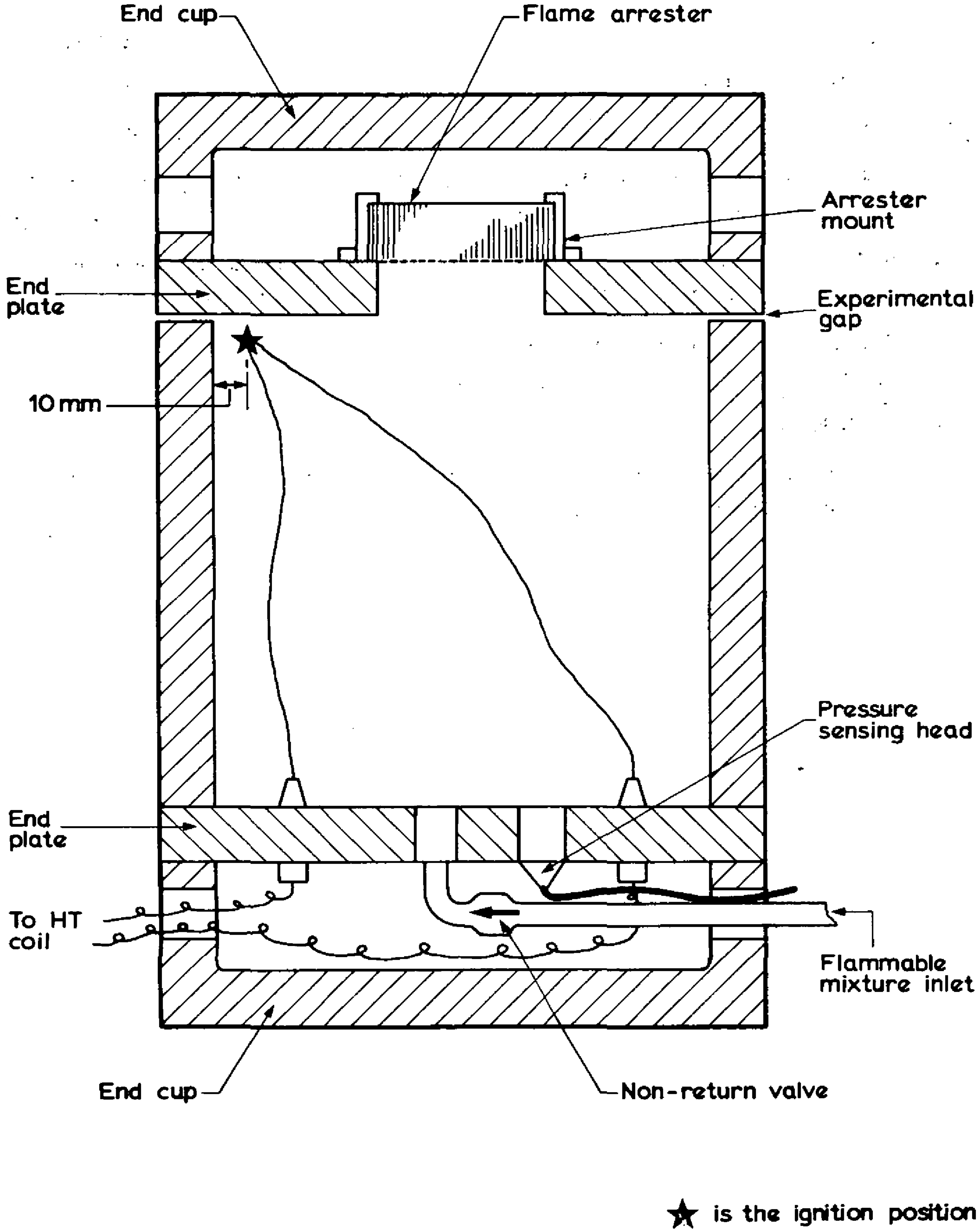


Figure 1 Cross-sectional view of the explosion vessel

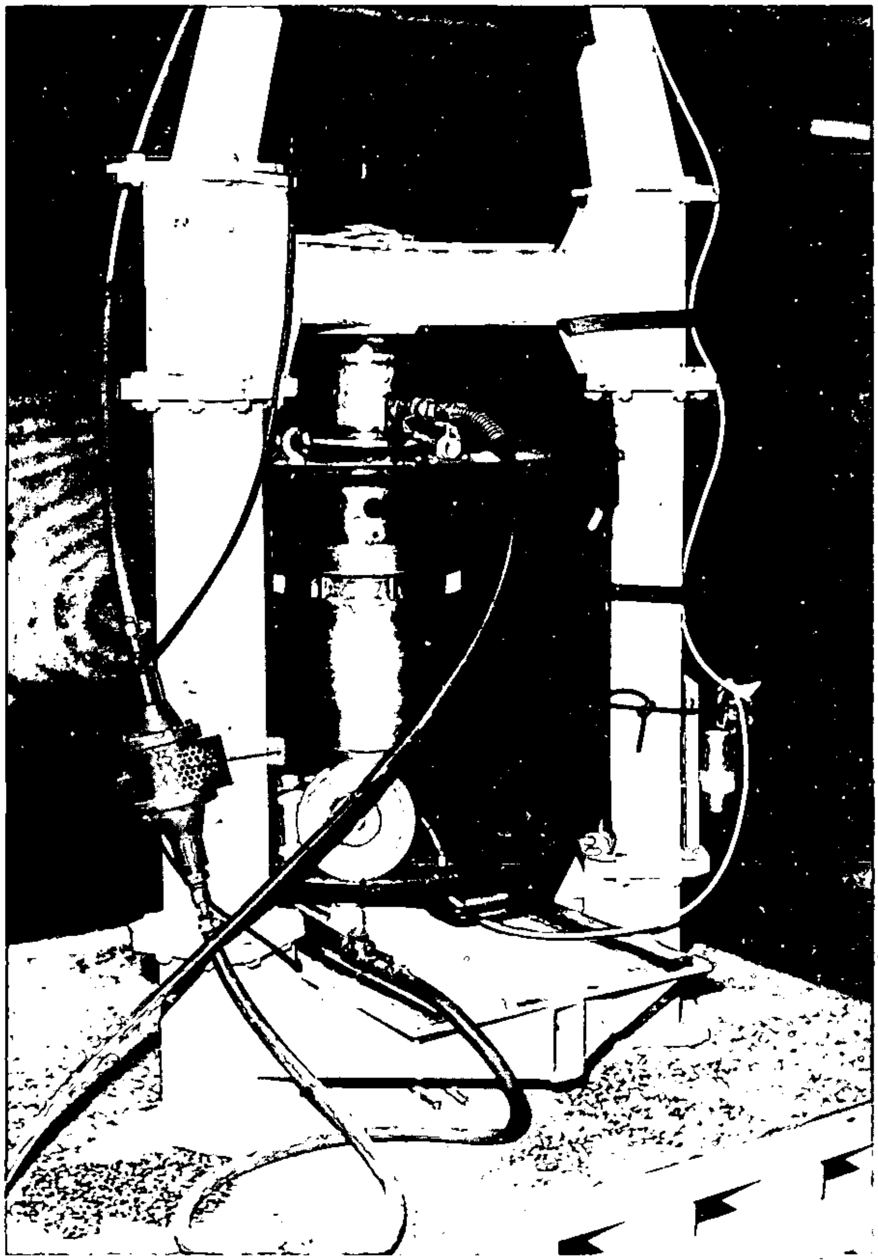


FIG.2. TEST VESSEL ASSEMBLED IN PRESS

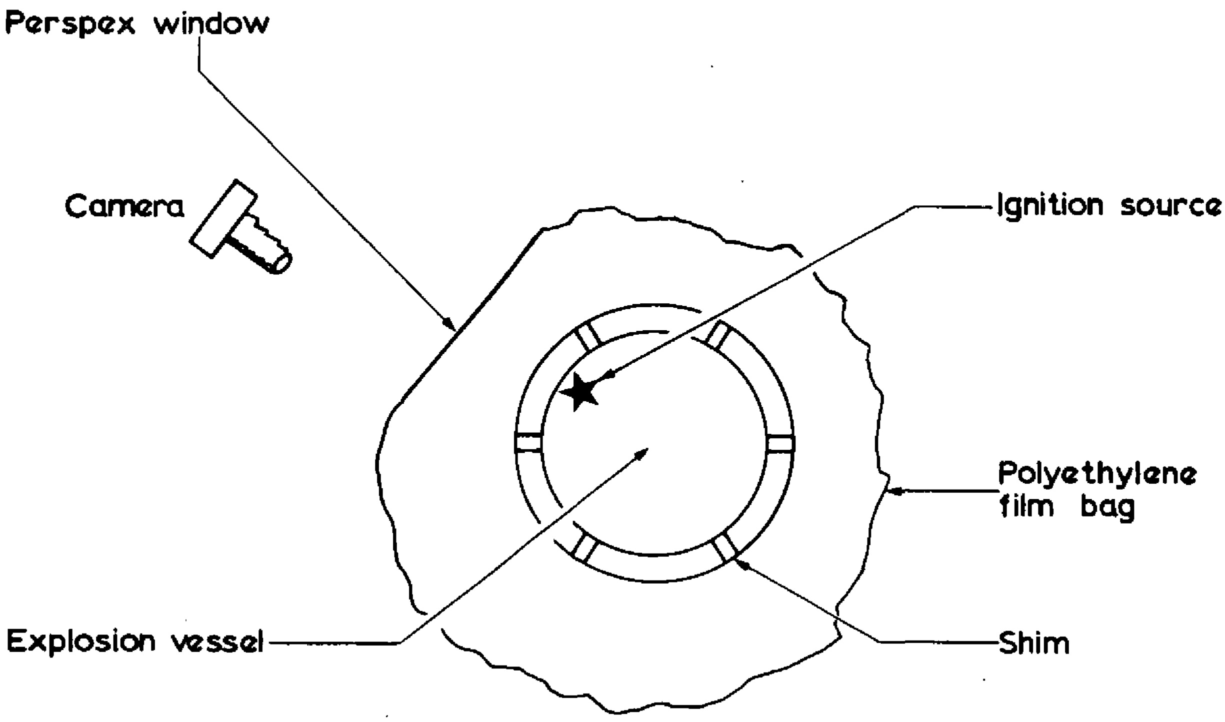


Figure 3 Arrangement for direct photographs

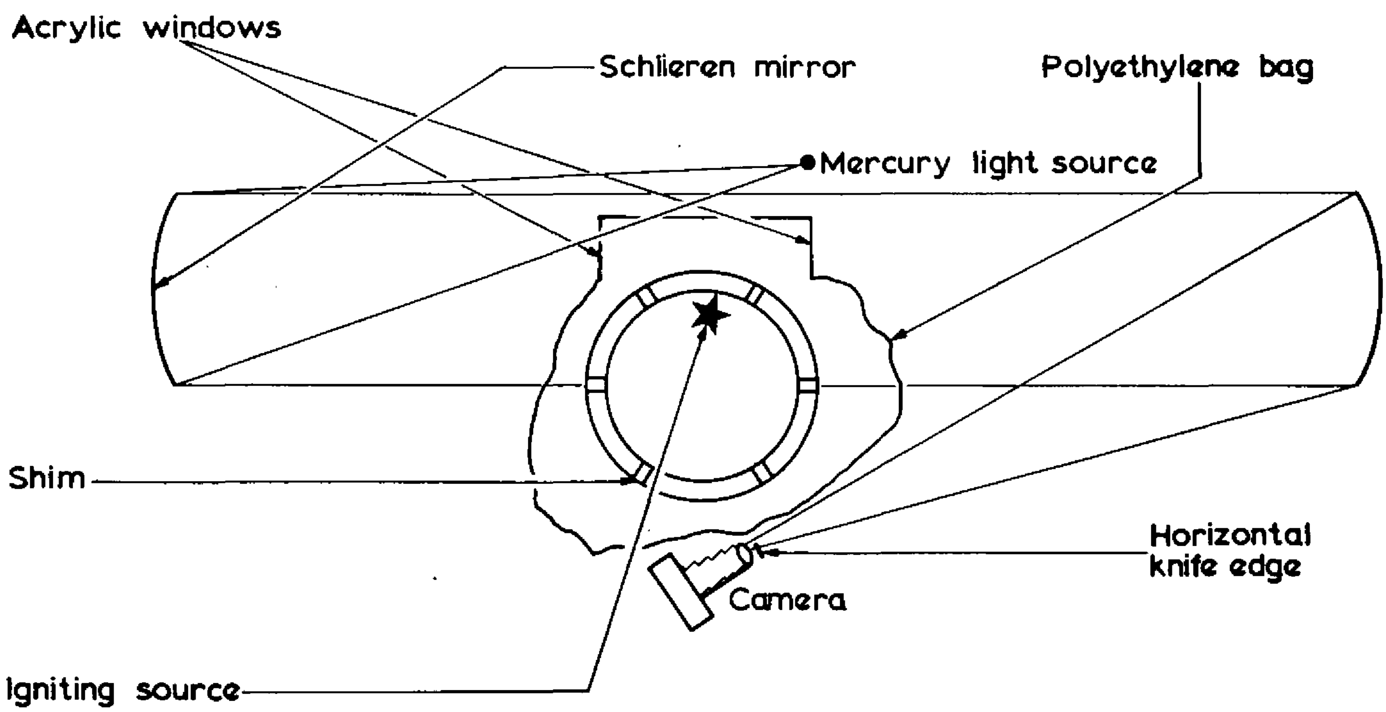
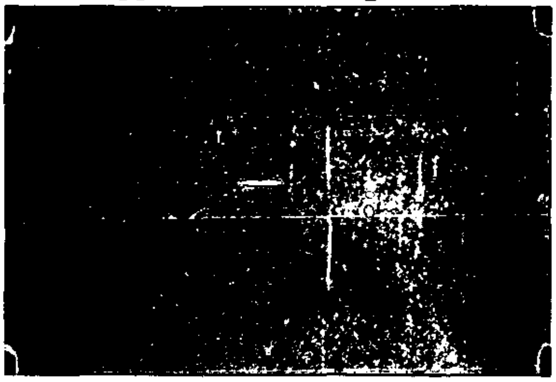


Figure 4 Arrangement for Schlieren photographs

First appearance of light

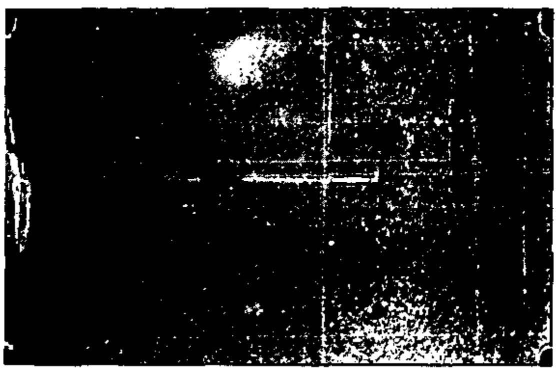


0ms

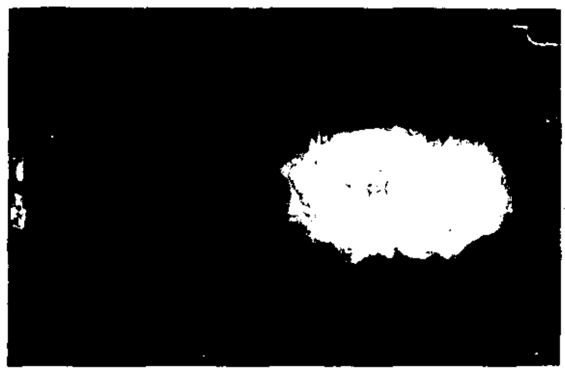
14.5ms

10ms

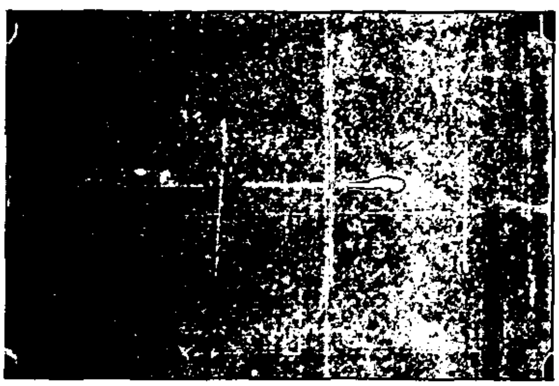
15.4 ms



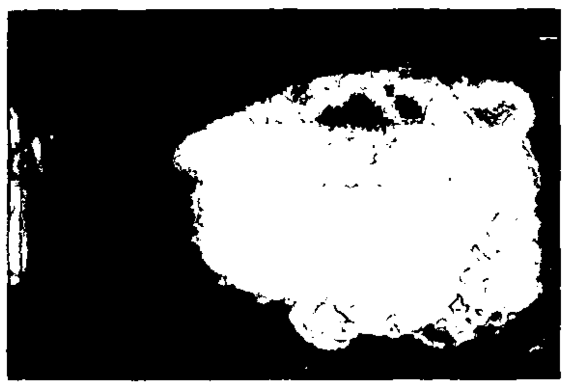
11.8ms



16.3ms



13.6ms



19.9ms

FIG.5. DIRECT PHOTOGRAPH OF IGNITION, ETHYLENE-AIR MIXTURE, 0.75 mm FLANGE GAP

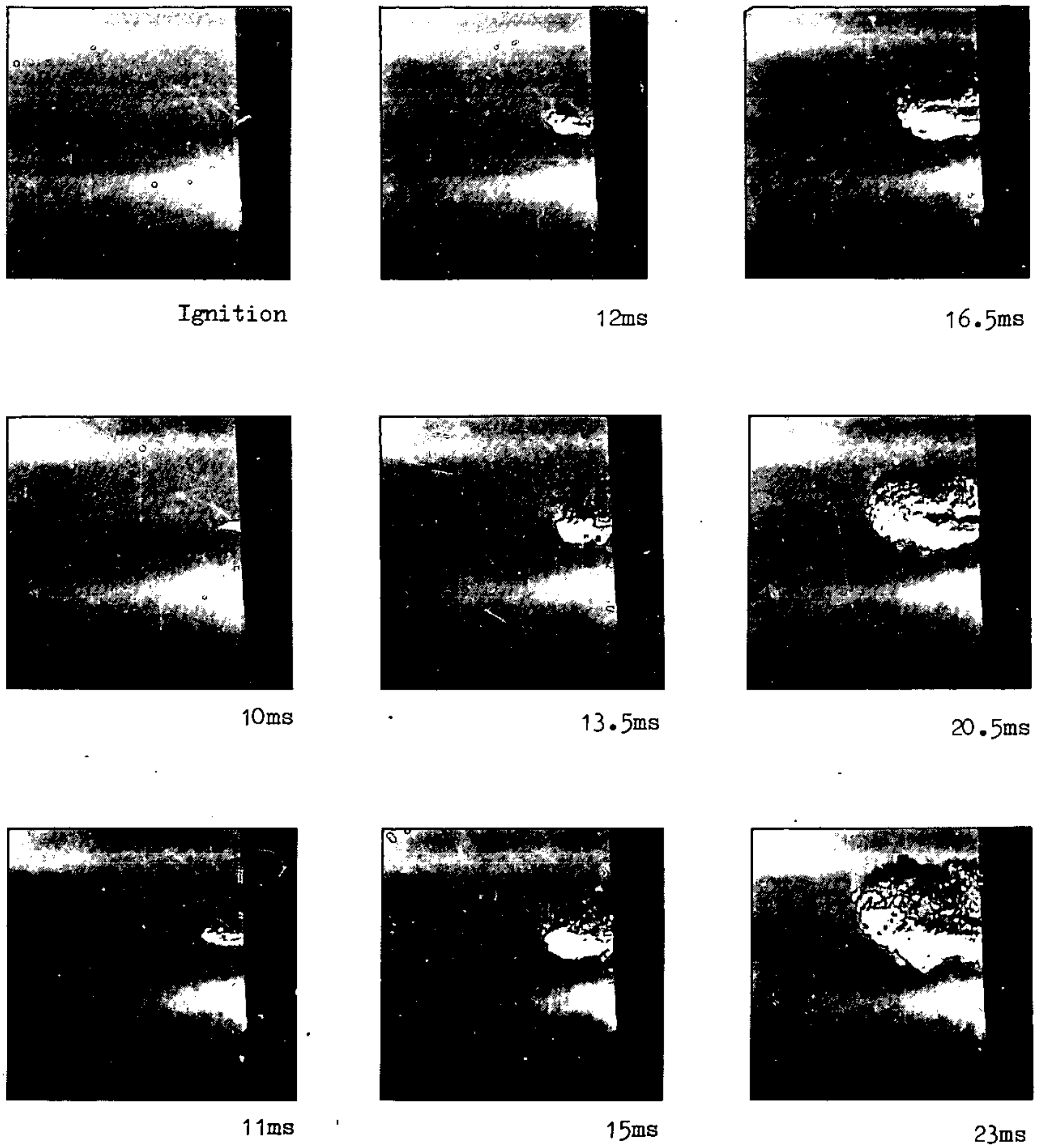


FIG.6. SCHLIEREN PHOTOGRAPHS OF IGNITION, ETHYLENE-AIR MIXTURE, 0.75 mm FLANGE GAP

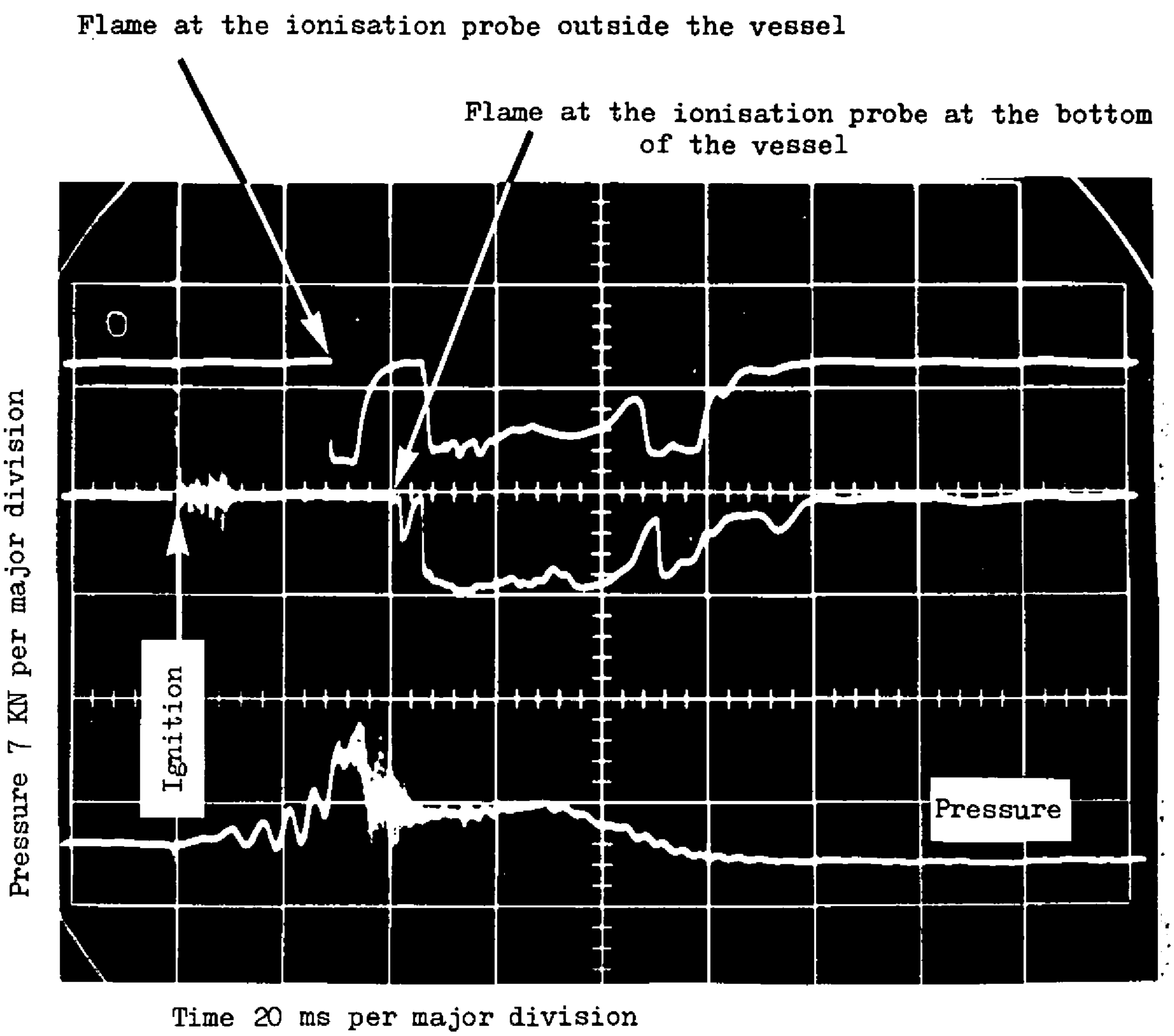


FIG.7. PRESSURE AND FLAME MOVEMENT RECORD, ETHYLENE-AIR MIXTURE, 0.75 mm FLANGE GAP

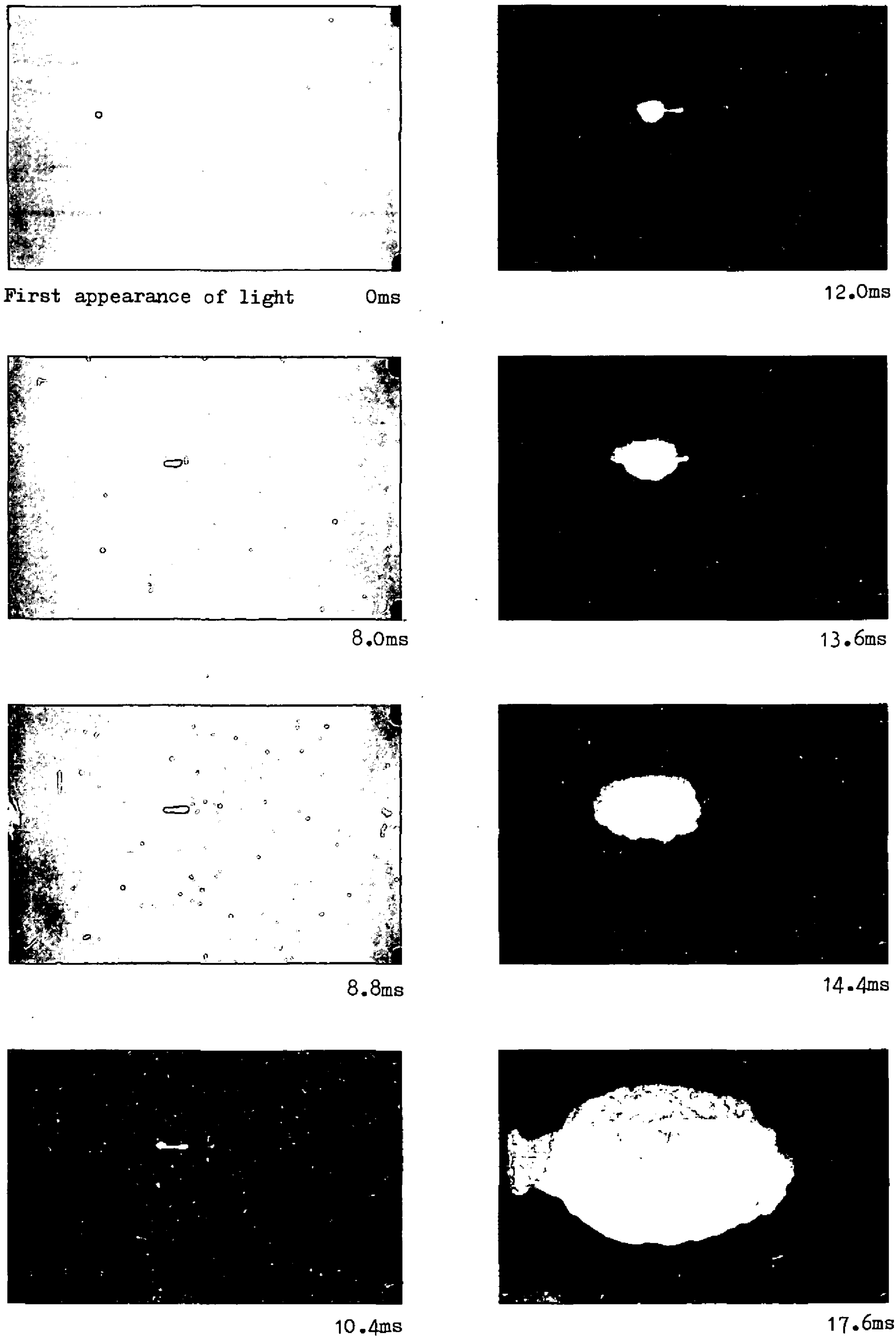


FIG.8. DIRECT PHOTOGRAPH OF IGNITION, ETHYLENE-AIR MIXTURE, 0.75 mm FLANGE GAP

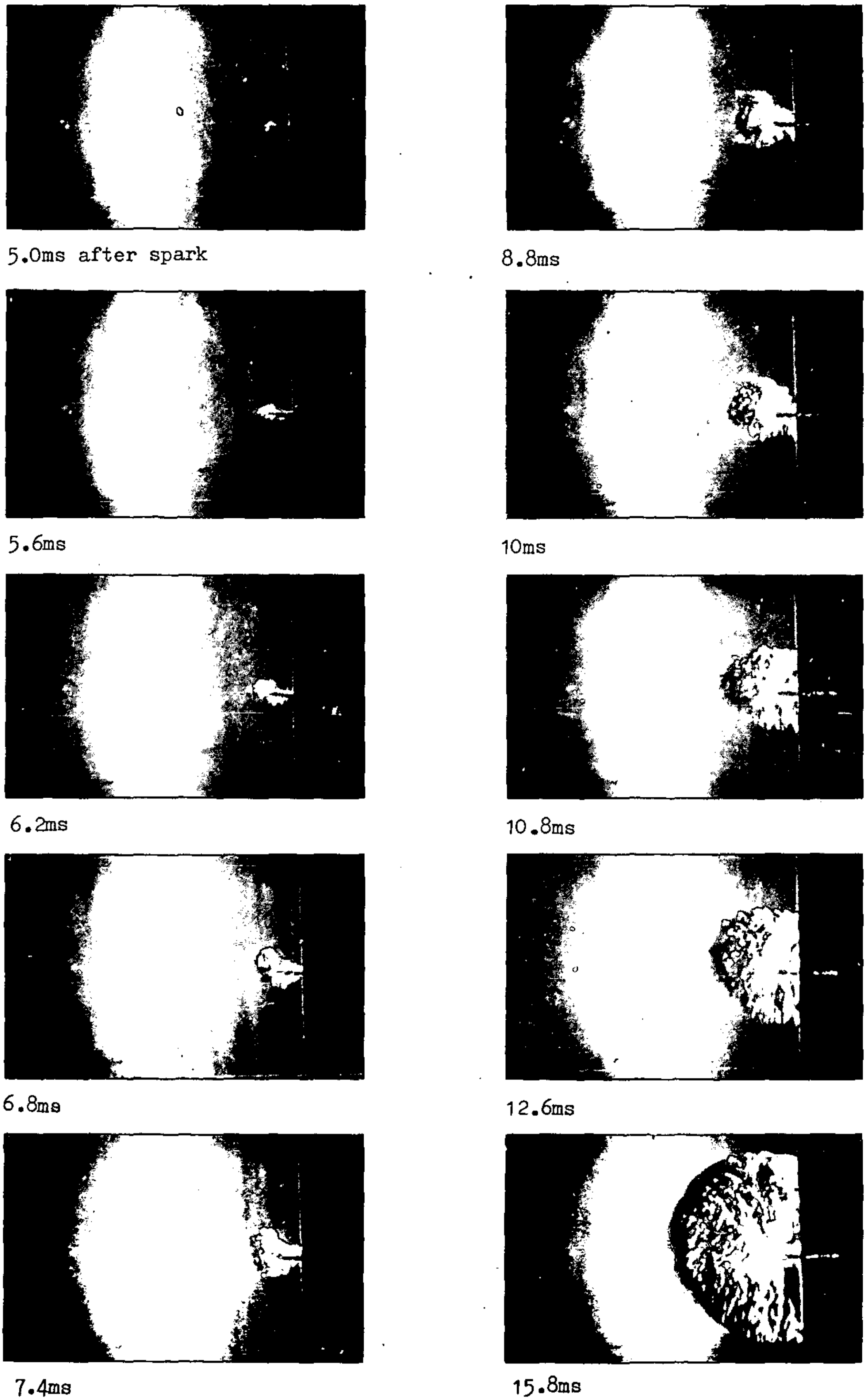


FIG.9. SCHLIEREN PHOTOGRAPHS OF IGNITION, ETHYLENE-AIR MIXTURE, 0.75 mm FLANGE GAP

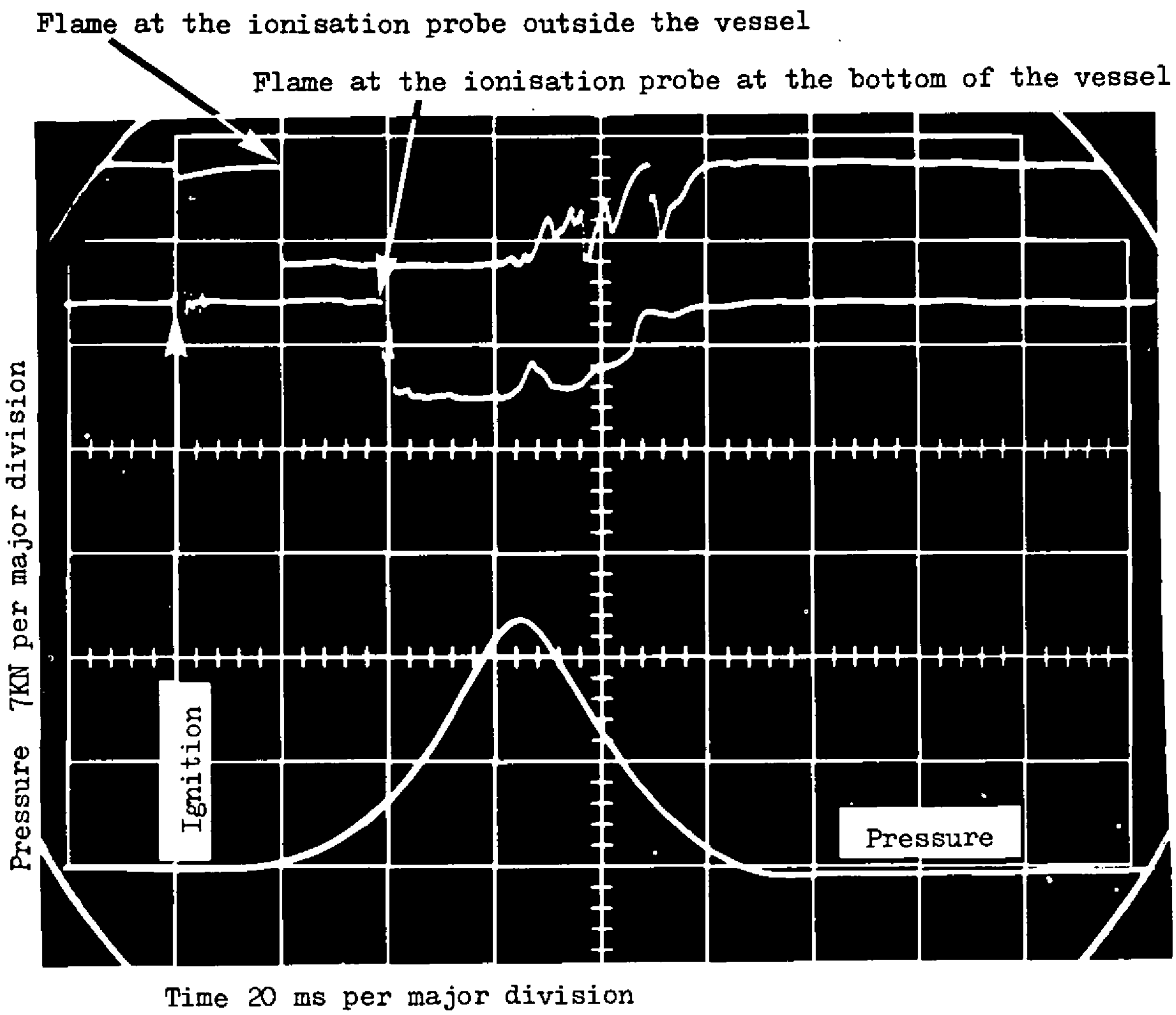
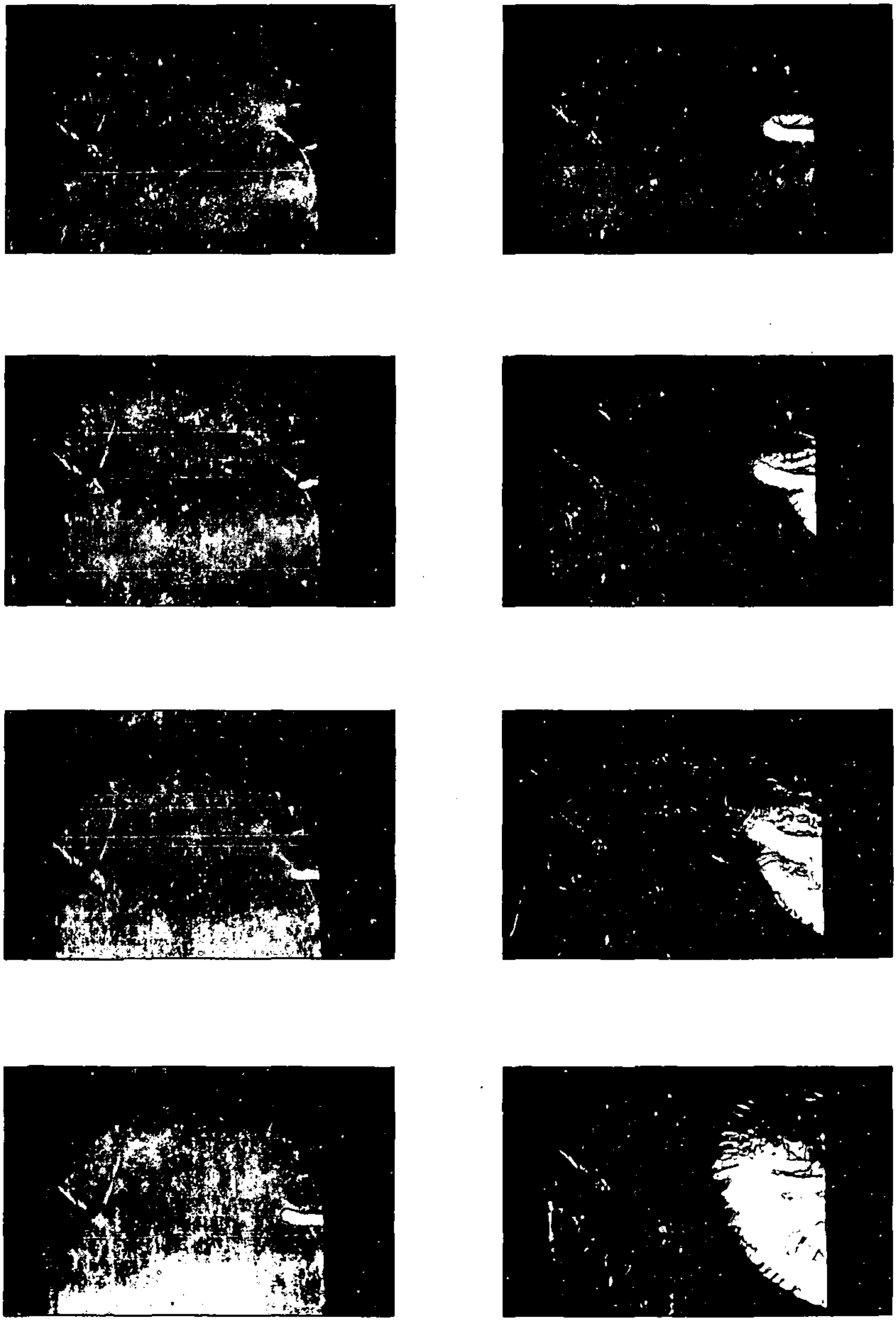


FIG.10. FLAME MOVEMENT AND PRESSURE TRACE RECORD



0.6ms interval between pictures

FIG.11. SCHLIEREN PHOTOGRAPHS OF IGNITION, HYDROGEN-AIR

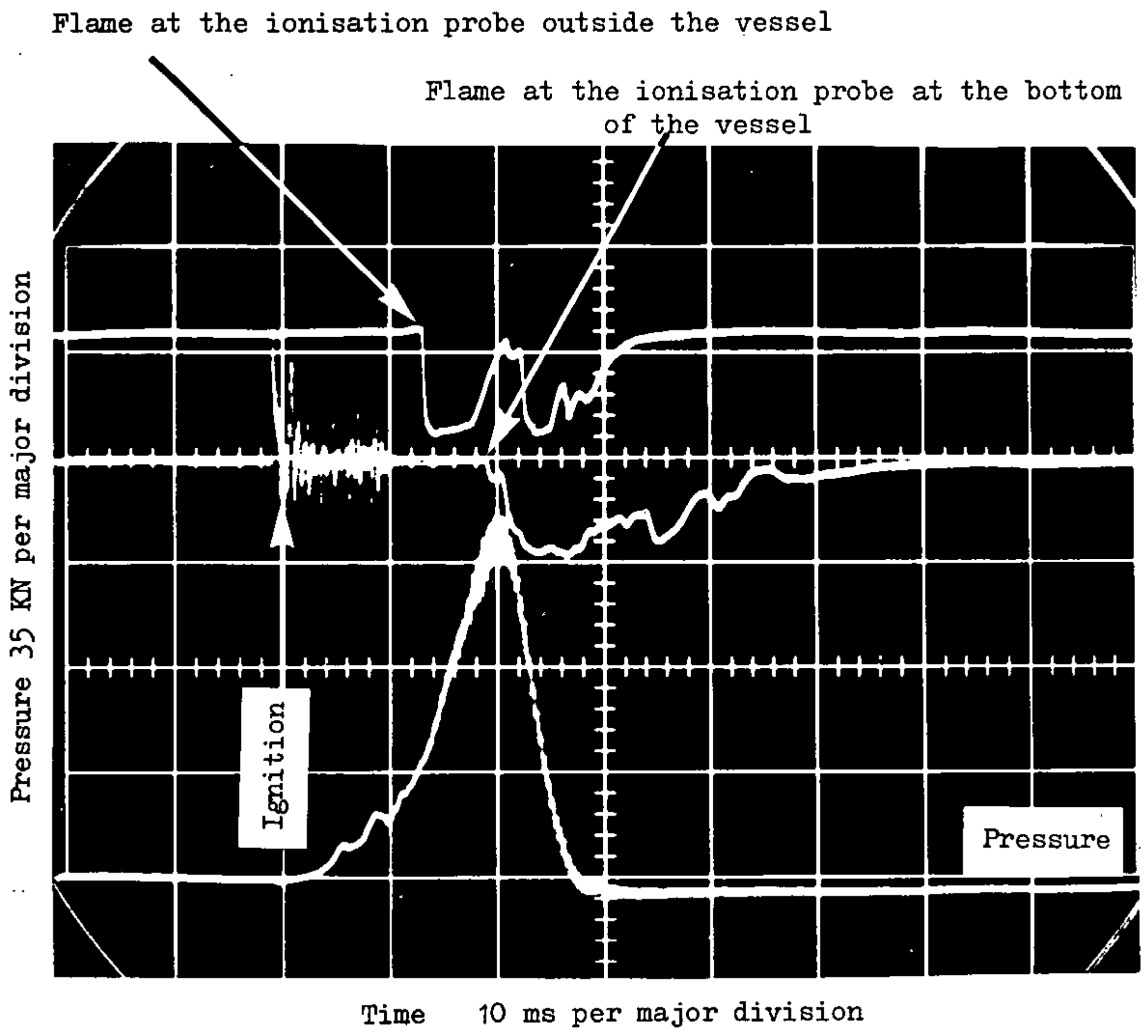
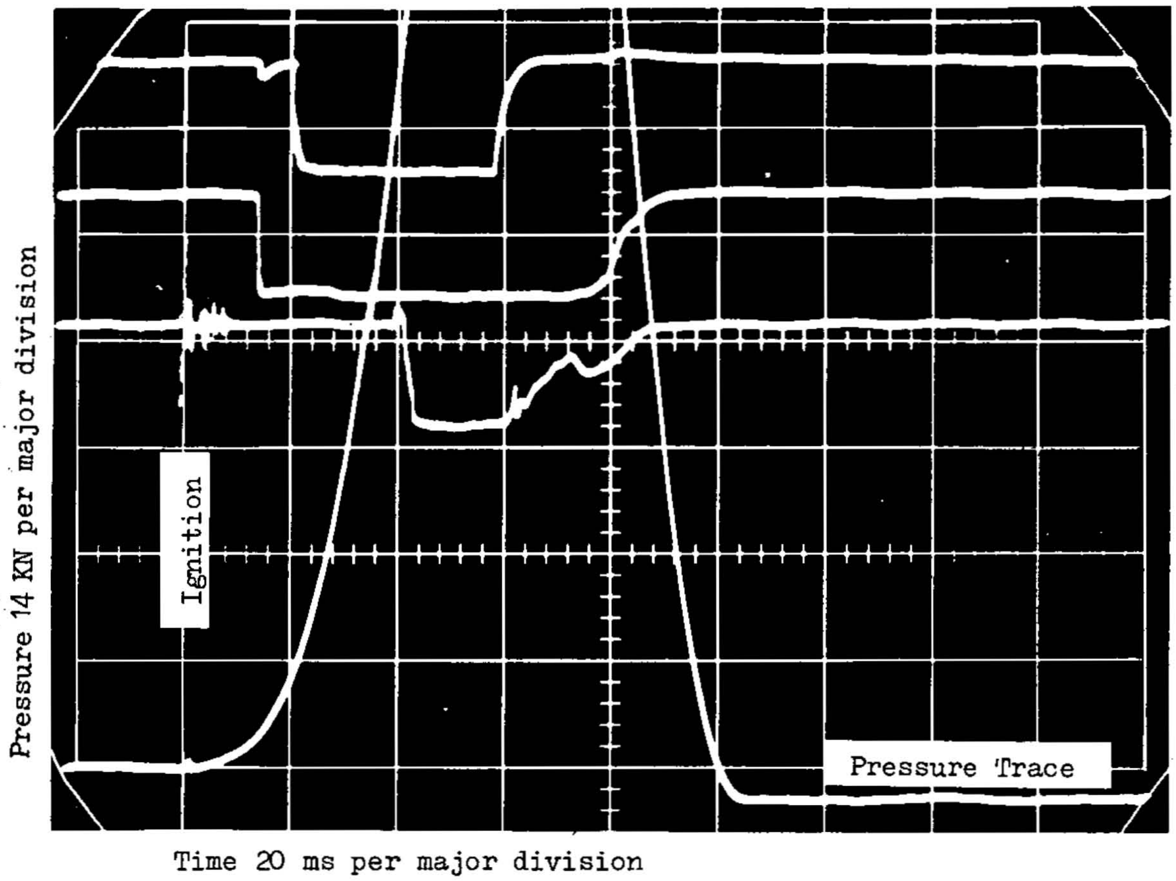


FIG.12. PRESSURE AND FLAME MOVEMENT RECORD



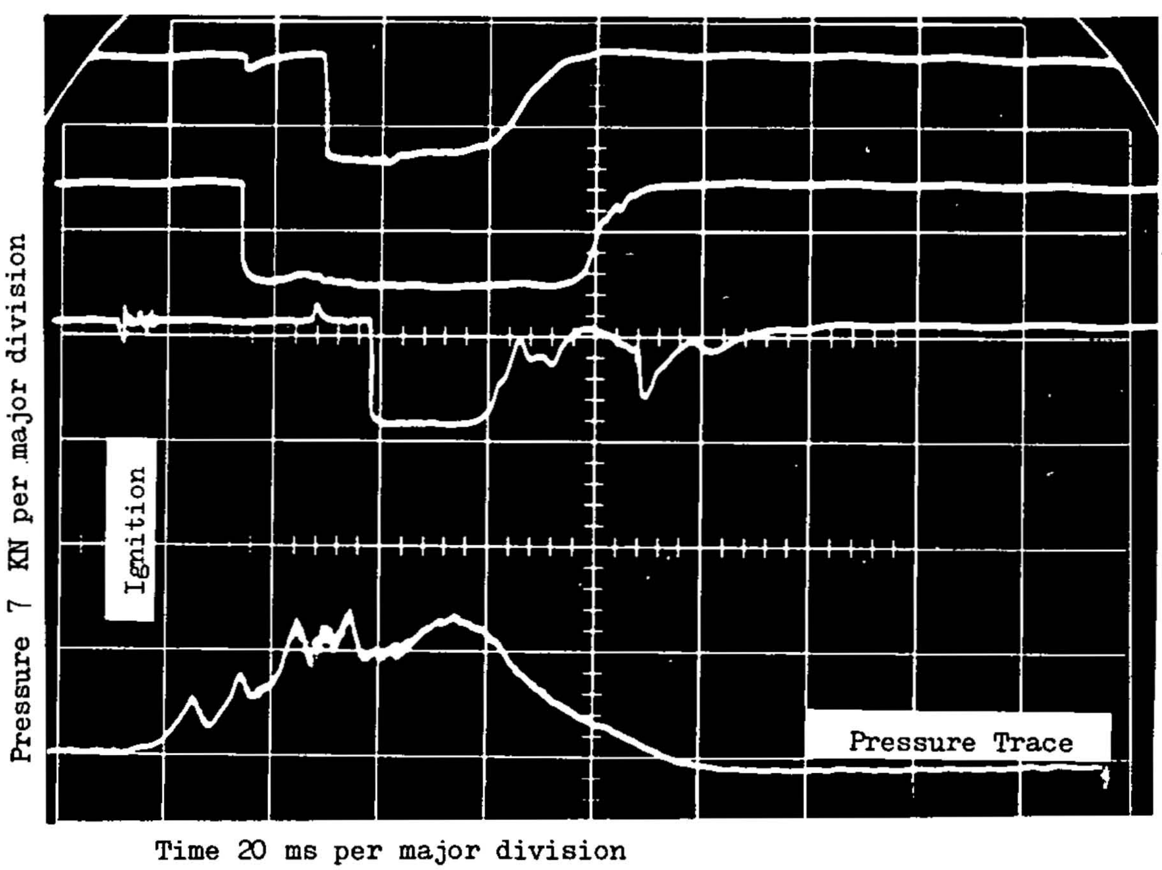


FIG.13. PRESSURE AND FLAME MOVEMENT RECORDS

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