COMPARISON OF THE EFFECTS OF DIFFERENT FIRE TEST REGIMES ON PASSIVE FIRE PROTECTION MATERIALS

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In the past, HSE's Health and Safety Laboratory (HSL) has studied the performance of a variety of passive fire protection (PFP) materials in protecting a part-filled LPG tank subjected to hydrocarbon pool fire engulfment. However, this is only one potential fire incident scenario that can threaten a process vessel; another is a jet fire, perhaps resulting from an ignited release from a leaking flange or failed pipework. Flashing liquid propane jet-fire tests on PFP protected propane tanks are described together with sonic propane vapour jet-fire tests on PFP protected steel boxes. Comparisons between the two types of jet fire and with the hydrocarbon pool fire engulfment test are made.

Passive Fire Protection, Jet-Fire, Pool Fire, Process Plant Protection

INTRODUCTION

There have been a number of incidents involving the pressurised release and subsequent ignition of LPG and other hydrocarbons. The potential consequences of which have unfortunately been dramatically illustrated by the disasters at the PEMEX LPG Installation, Mexico City in 1984 and the Piper Alpha North Sea Installation in 1988. Both these disasters resulted in major loss of life, 500 and 167 lives respectively, and catastrophic damage to the plant. These and other incidents demonstrate the need to provide adequate fire protection of plant to guard against its failure and therefore escalation of the incident. The protection of process plant against hydrocarbon fires is recognised as an important component of this.

Passive fire protection (PFP) materials have been used for many years. Tests of their effectiveness initially simulated cellulosic fires and more recently hydrocarbon pool fires, for example the furnace based temperature-time tests described in BS 476. In the past, in considering the fire protection of process plant, HSE's Health and Safety Laboratory (HSL) has studied the performance of a variety of PFP materials in protecting a part-filled propane tank subjected to hydrocarbon pool fire engulfment [1]. However, this only represents one potential fire incident scenario that can threaten a process vessel; another is a jet fire, perhaps resulting from an ignited release from a leaking flange or failed pipework. Such jet fires may be potentially much more challenging to PFP materials because of the high, localised heat flux and mechanical erosive effects.

Large scale fire testing [2] is very expensive and there is currently no generally accepted and validated reduced scale test although an Interim Jet Fire Test (IJFT) [3, 4] has been developed and is in the process of being evaluated. Small scale testing has the potential to allow fire protection systems to be evaluated and compared, although it is recognised [5] that the weaknesses in some complex assemblies may only be revealed by large scale testing.

This paper describes work done by HSL, which was sponsored by HSE's Technology and Health Sciences Division (THSD), using two different jet fire facilities. One facility is fuelled by flashing liquid propane (up to 5 kg/s at 14 barg) and was used to study the performance of two types of PFP materials, one cementitious (a lightweight cement based material) and one intumescent (an organic coating which intumesces in a fire to form an insulating char) on a part-filled two tonne LPG tank. The other is a smaller sized jet-fire facility using a sonic propane vapour jet (up to 0.55 kg/s at 6 barg) which has been used to test the same two PFP materials on a steel box substrate. The results from the two jet-fire facilities are compared. The differences between the performance of PFP materials subjected to hydrocarbon pool fire engulfment and jet-fire impingement are also considered.

FIRE TESTS

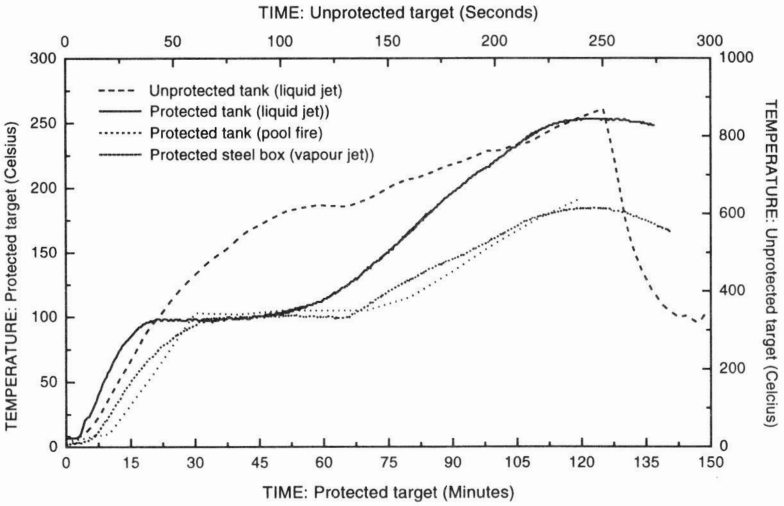
Pool fire testing

Pool fire testing of 500 litre propane vessels coated in various PFP materials was carried out in the 1980's at HSL [1]. The wall thickness of the vessels was 4.7 mm on the parallel section and 5.2 mm on the end caps. One experiment was carried out on a vessel coated with a cementitious material applied to a thickness of 46 mm. The vessel was positioned above a test bund 4.0 m long x 2.5 m wide lined with refractory bricks and surrounded by a wind break (figure 1(a)). The vessel was 40% filled with propane. The bund was filled with enough kerosene to sustain a 2 hour fire (see figure 1(b)).

Thermocouples were attached to the surface of the vessel (beneath the PFP material) and also to the surface of the material. The PFP surface temperatures rose fairly rapidly to around 500 °C then more slowly to a maximum of about 1000 °C on the downwind side of the vessel. The vessel wall temperatures above the liquid level rose to about 110 °C during the first 10 minutes of the test, remained at this level for about an hour, then began to rise again reaching about 200 °C by the end of the 2 hour test (see figure 4). The vessel wall temperatures below the liquid level rose to about 60 °C during the first 10 minutes of the test, remained at this level for about an hour, then rose to about 100 °C by the end of the test. The temperatures were all very similar, particularly during the 'plateau' phase.

The initial pressure of the vessel contents was 4.7 barg and this rose steadily until the pressure relief valve (PRV) first lifted at a pressure of 16 barg 35 minutes into the test. Once the pressure had reached 17.7 barg, the PRV cycled continuously until the end of the test, when there was still some liquid remaining. At the end of the test, small cracks could be observed in the PFP material, but it remained intact.

Figure 4. Maximum temperatures for cementitious materials



Flashing liquid propane jet fire tests

This facility (figure 2(a)) was constructed as part of a joint CEC (contract STEP - CT90 - 098) / THSD sponsored project 'Hazard consequences of jet-fire interactions with vessels containing pressurised liquids'. The project as a whole was to investigate, experimentally and theoretically, jet flames and the thermal response of vessels and flange connections.

Jet nozzle diameters up to 38 mm could be used with a 10.4 tonne capacity supply system mounted on load cells to allow measurement of mass. Flow rates up to 5 kg/s were achievable by pressurising the storage tanks with nitrogen up to a pressure of 14 barg. The whole facility was remotely controlled to allow for possible failure of the target vessel. For the tests, an 80° V-shaped nozzle with a hole equivalent to a 12.5 mm diameter circular orifice was used, giving a mass flow rate around 1.5 kg/s depending on the nitrogen pressure used.

Two trials were performed on 1700 kg capacity propane vessels with a wall thickness of 7.2 mm on the parallel sections and 7.4 mm on the endcaps. These were protected by passive fire protection material; one cementitious product and one intumescent product were tested. The thickness of the coating was left to the discretion of the manufacturer, but they were asked to provide protection against a 1.5 kg/s liquid propane jet fire for 90 minutes.

The tanks were 20% filled with propane and were instrumented with type K thermocouples which were metal sprayed onto the vessel before application of the PFP coating. In each trial, a jet was impinged upon the target until the wall temperature exceeded 250°C or the pressure inside the tank exceeded the design pressure. The jet conditions for each trial are summarised in table 1.

Table 1. Jet conditions

PFP type	Jet flow rate			Trial duration
	First 30 min.	**Second 30 min.**	**Final period**	
Cementitious	1.9 kg/s	1.2 kg/s	1.3 kg/s	105 min 20 s
Intumescent	1.5 kg/s	1.1 kg/s	1.1 kg/s	90 min 20 s

In both trials, the jet flames essentially enveloped the tank (see figure 2(b)). However, in the trial on the tank with an intumescent coating, due to a combination of an opposing wind and loss of nitrogen pressure as a result of failure of a seal, the flames only appeared to engulf the front of the tank although no substantial differences were observed between the temperatures recorded at the front and back of the tank.

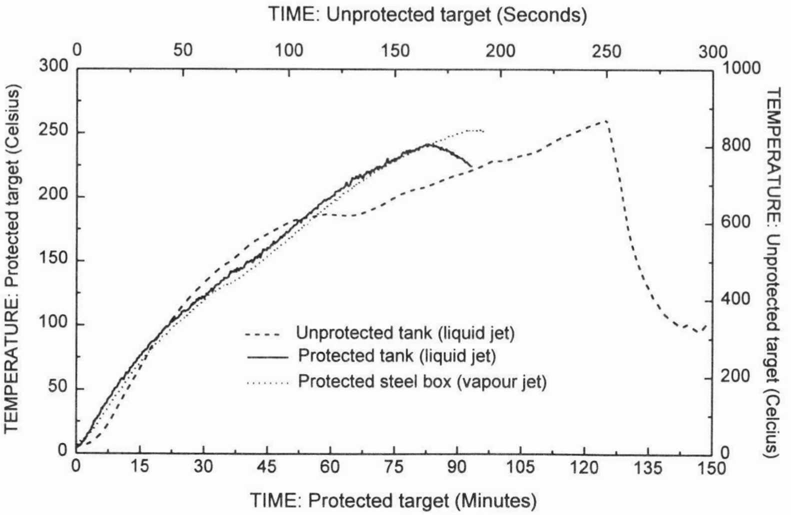
In the trial with a tank coated with 40 mm of cementitious material (reinforced with galvanised, hexagonal wire mesh of size 76 mm diagonal), the vapour pressure remained steady for five minutes and then rose steadily at about 0.2 bar/minute until the PRV opened at 16.0 barg after 48 m 2 s. The PRV opened and shut three times before remaining slightly open (sections of the rubber valve seating had broken off).

When the tank with an epoxy intumescent coating (nominal 13 mm thickness reinforced with carbon fibre/glass fibre mesh of size 12 mm x 8 mm) was tested, the vapour pressure rose steadily until the PRV opened at 17.5 bar after 53 minutes. The pressure dropped and then rose to and remained at 15.5 barg. with a slight, continuous leak from the PRV.

The wall temperatures of the tank coated with cementitious material reached 100 °C after 16 minutes and remained at this temperature for 24 minutes as water of crystallisation was driven off. Wall temperatures at the top of the tank then began to rise reaching a maximum of 233 °C at the time the jet fire was turned off (see figure 4). The temperatures rose a further 20 °C after the jet was turned off before falling. For the tank coated with intumescent material, the temperature rose steadily reaching a maximum of 251 °C at the time the jet was turned off and then began falling almost immediately afterwards (see figure 5).

Apart from fine cracks and a slight colour change from pale grey to pale yellow, the cementitious coating remained intact. The intumescent material was charred over the complete surface apart from a small area at the end to the left of the jet. The char contained some deep cracks but there was unexpired material under the char over most of the surface except for a small area at the top of the left hand end (as viewed in figure 2) of the tank.

Figure 5. Maximum temperatures for intumescent material



Propane vapour jet fire tests

This facility was constructed to carry out the interim jet fire test (IJFT) for determining the effectiveness of passive fire protection materials [3]. This test is currently [4] being assessed for reproducibility by British Gas, and the Offshore Safety Division (OSD) of HSE has placed an extramural research project to investigate the possibility of broadening the test's applicability to tubular sections. The IJFT involves impinging a 0.3 kg/s propane vapour sonic velocity jet flame on a coated 1.5 x 1.5 x 0.5 m steel box (made from 10 mm thick mild steel) which may be fitted with a vertically positioned , 0.25 m deep central web. Although the dimensions of the test specimen are small compared to typical structural or plant items and the mass flow rate of gas is substantially less than might expected in a real situation, the characteristics of this jet fire have been investigated and compared with a larger scale gaseous-phase jet fire [6] and found to be similar. The scale of this test allows it to be performed indoors or outdoors and is less expensive than larger scale tests.

Variants of the IJFT were carried out inside a U-shaped enclosure (see figure 3(a)) which consisted of 4.0 m high walls on three sides enclosing an area approximately 3.0 m x 8.0 m with a concrete floor. The walls were constructed from clay common bricks with a refractory brick lining. The propane vapour for the jet fire test was supplied from an indirectly fired vaporiser (heated by hot water boilers). The vaporiser was supplied with liquid propane from the same propane supply vessels as used for the liquid propane jet fire facility. The flow was controlled using a pressure regulator with an averaging pitot linked to a control valve.

A steel box with a web was chosen for the trials. Although the test specimen with the vertical web is intended to simulate edge features such as those on structural steelwork, it is considered that the temperature response of the rear, flat face could simulate flat steelwork or large vessels. The web was included to add to the pool of test data available. The test specimen was instrumented with type K thermocouples fixed to the rear side of the target, i.e. the side not impinged by flames, and inside the vertical web. It was supported on a scaffolding frame and on a lightweight block wall at its front edge so that its base was approximately 1 m above the floor of the enclosure. The block wall was 3.8 m from the front of the open side of the test cell. The lightweight blocks were also built up around the sides and across the top of the test specimen preventing flames from impinging upon the sides or rear of the specimen. The gap between the block walls and the specimen was filled with a ceramic fibre blanket. The tip of the 17.8 mm diameter jet nozzle was positioned 1.0 m from the flat face of the test specimen (not the vertical web), horizontally central and 0.375 m vertically above the lower edge of the specimen.

A number of tests have been carried out including two intended to be comparable with the two liquid propane jet fire trials described above. These had the same PFP materials applied to the same thicknesses although the epoxy intumescent material had additional metal reinforcing mesh on the vertical web. Only the rear flat face data is used for comparison with vessels.

In the test on a 40 mm thick coating of cementitious PFP material, the maximum temperature recorded on any of the thermocouples on the flat, rear face after 105 minutes was 184 °C (see figure 4), recorded from a thermocouple positioned above and to the right of the centre of the specimen.

For the 13 mm thick coating of epoxy intumescent PFP material, the maximum temperature recorded on any of the thermocouples on the flat, rear face after 90 minutes was 253 °C (see figure 5), recorded from a thermocouple positioned in the top, right corner of the specimen. However, it should be noted that bare metal was exposed on the web leading to much higher temperatures.

Apart from fine cracks and the characteristic loss of water of crystallisation, the cementitious coating remained intact. The intumescent material was charred over the complete surface area. Fibre mesh was visible over most of the lower half of the left hand side (looking from the direction of the jet) and some of the char had lifted off the char beneath it in this area. Char thickness measurements were made and some char was cut away; no unexpired material remained beneath the char.

COMPARISON AND DISCUSSION

Temperature

A comparison of the test regimes can be made by comparing temperatures achieved at various times during the test (figures 4 and 5). In each case, the maximum temperature occurred above the liquid level within the vessel, i.e. on an unwetted surface. Although there are differences between the rates of initial heat transfer to the thermocouples, due to different thicknesses of material and different (front face / back face) thermocouple positions, the rates of temperature rise are similar. Although the vessels were of different sizes and had different fill levels, the comparison is still valid as it is the heating of the unwetted wall which causes failure in unprotected vessels, as demonstrated by liquid propane jet fire tests carried out on unprotected propane vessels, also as part of the JIVE project [7].

Table 2 shows the maximum temperatures attained after 20, 40, 60, 80 and 100 minutes (plus 120 minutes for pool fire only) for the three fire test regimes, namely hydrocarbon pool fire (pool), flashing liquid propane jet fire (liquid) and propane vapour jet fire (vapour) on the cementitious PFP material. It should be noted that for the pool fire test, the nominal material thickness was 46 mm whereas for the other two tests it was 40 mm.

Table 2 - Maximum temperatures attained (cementitious material)

Time (min)	**Pool**	**Liquid**	**Vapour**
20	90 °C	102 °C	69 °C
40	110 °C	121 °C	99 °C
60	105 °C	139 °C	99 °C
80	115 °C	173 °C	130 °C
100	160 °C	221 °C	162 °C
120	190 °C	-	-

Table 3 - Maximum temperatures attained (intumescent product)

Time (min)	**Liquid**	**Vapour**
20	112 °C	91 °C
40	175 °C	141 °C
60	223 °C	196 °C
80	249 °C	237 °C
90	231 °C	253 °C

Table 3 shows the maximum temperatures attained after 20, 40, 60, 80 and 90 minutes for two of the fire test regimes, namely flashing liquid propane jet fire (liquid) and propane vapour jet fire (vapour) on the epoxy intumescent PFP material. The nominal material thickness was 13 mm for both tests. It should be noted that the liquid propane jet fire test was terminated shortly after 80 minutes, when the temperature reached 250 ^{0}C, for safety reasons.

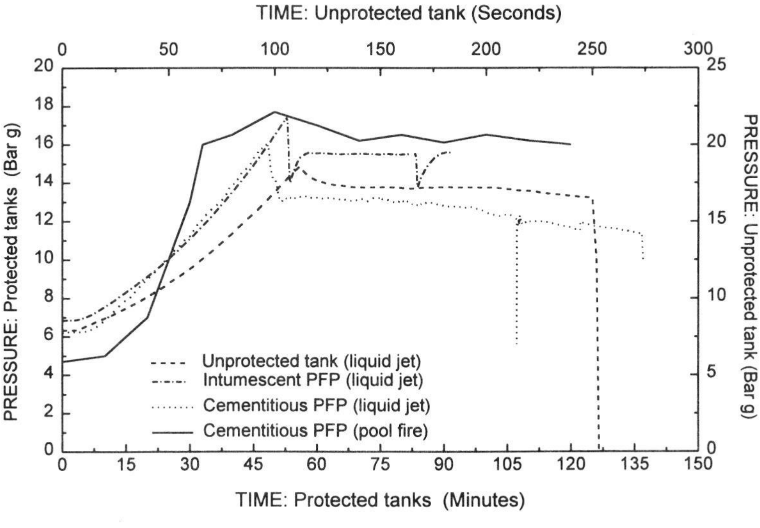
There is no such critical temperature in the IJFT (using the propane vapour jet) and the test can continue for the prescribed time or until the metal substrate of the target specimen is exposed.

It is instructive to compare the performance and temperatures measured for the PFP protected vessels with those observed during liquid propane jet fire tests carried out on unprotected propane vessels mentioned above. These vessels were tested to failure and had different propane fill levels (20, 41, 60 and 85%). Using the same liquid propane jet fire facility (mass flow rate of 1.5 kg/s), the 20% full vessel failed 4 minutes 10 seconds after the start of the test. At failure, the maximum shell temperature recorded was 870 °C.

Pressure

The pressure rise can be compared between vessels exposed to a liquid propane jet fire and a hydrocarbon pool fire. This is shown in figure 6. The difference in starting pressures is due to the differences in ambient temperature at the time of each test. The initial pressure rise is steeper in the pool fire than in the jet fire tests. This is probably due to the different fill levels, tank size and material thickness.

Figure 6. Pressure in vessels



The highest pressure reached is largely a function of PRV performance, rate of heat input and fill level. There is usually some variation although all the PRVs used were rated at the same value (17.6 barg). It is possible for the seal and the spring in a PRV to be affected by fire even if they were protected from direct flame impingement (as they were in these tests). In the case of the jet fire test on the cementitious PFP material, it can be seen that, after the initial opening of the PRV, the pressure continues to fall steadily, probably due to the PRV leaking. The sudden drop in pressure to around 5 barg shown on this graph was due to the PRV opening after the jet fire had been shut off.

The plot for the pool fire test is an approximate curve. The PRV opened and re-seated 30 times during this test, each time with a pressure drop of about 1.5 bar.

These results can be compared with those measured during the 20% full unprotected vessel jet fire test mentioned above. The pressure rise occurred much more quickly in this test, the time taken for the PRV to open being 112 seconds at a pressure of 18.6 barg. The PRV remained open until the tank failed after 4 minutes 10 s at a pressure of 16.5 barg.

Observations and discussion

It is to be stressed that the purpose of the research was to compare different fire test regimes, not to establish the performance of specific PFP materials. The PFP specimens were solely chosen to achieve this goal. Where there are differences in performance of the two materials tested, this should not be construed as indicating that one material is better than the other.

From the results, the following observations can be made:

- the pool fire regime appears similar to the propane vapour jet fire regime when comparing rear flat face temperatures from the IJFT on cementitious material. However, this may be misleading as the heat losses from the non-exposed surface are different;

- heat appears to be transmitted faster to the tanks than to the IJFT specimen. This may be due to reduced heat losses from the non-exposed surface in the tanks;

- the results from the two jet fire tests appear to be broadly comparable; and

- the propane vapour jet fire was the only test regime which stripped PFP material away to reveal bare metal (on the web) and is therefore probably more mechanically erosive at close range than the other fires.

CONCLUSIONS

The following conclusions may be drawn:

- the hydrocarbon pool fire test may be less severe than the jet fire tests and therefore may not correctly predict the fire performance of PFP materials against the more challenging effects of a jet fire. It is therefore important that the type of fire which might be anticipated in a particular situation, as well as its duration, is considered in selecting the PFP and its method of application.

- the two jet fire test regimes studied gave broadly similar temperature results. The results discussed in this paper do indicate that the LPG vapour jet fire facility (using rear flat face results) provides a similar measure of the fire performance of PFP materials compared to the LPG liquid jet fire facility. It is therefore concluded there is a case for developing a standard jet fire test, along the lines of the vapour jet test facility used in this work, which would enable the economical assessment of fire performance of PFP materials against jet fire impingement.; and

- PFP materials can offer a substantial degree of protection from jet fire when compared to an unprotected vessel.

ACKNOWLEDGEMENTS

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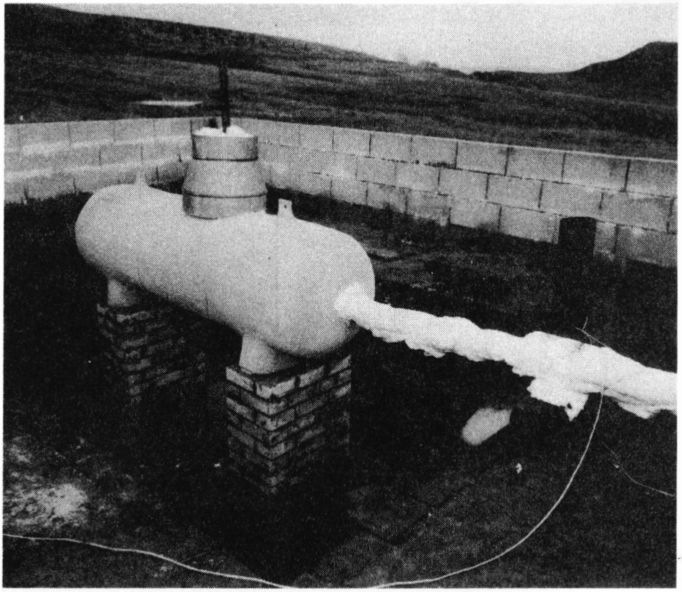

Figure 1 (a). Pool fire test setup

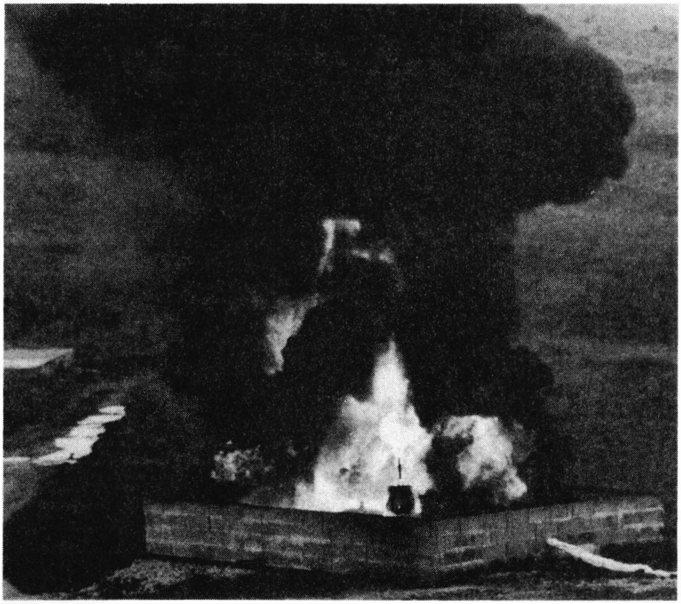

Figure 1(b). Pool fire engulfment

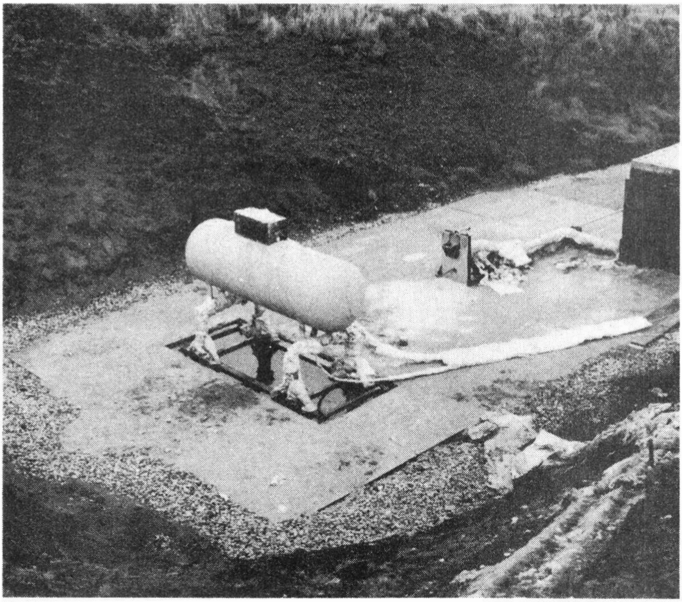

Figure 2 (a). Liquid propane jet fire setup

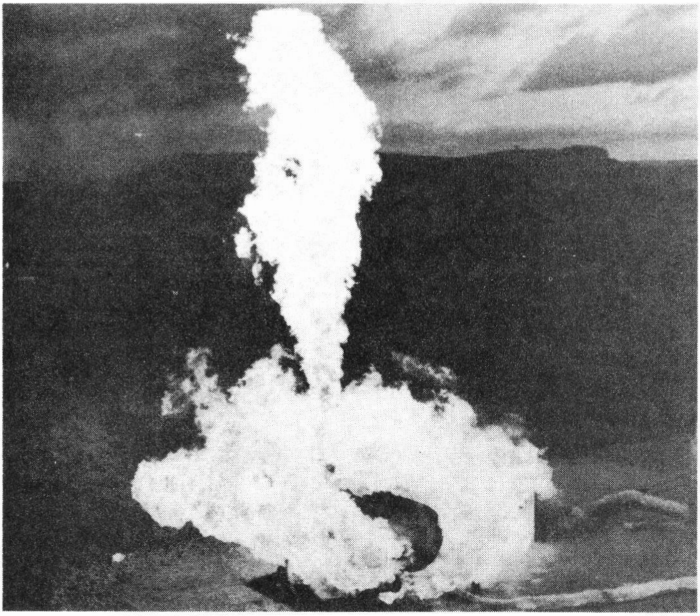

Figure 2 (b). Liquid propane jet fire engulfment

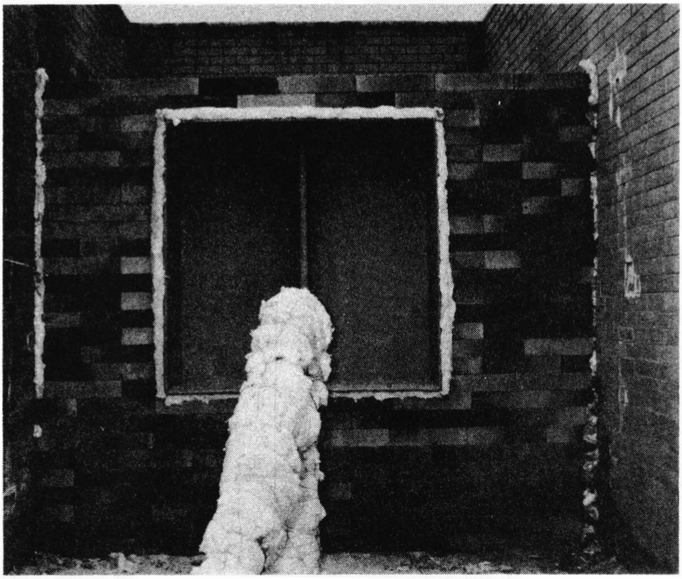

Figure 3 (a). Propane vapour jet fire setup

Figure 3 (b). Propane vapour jet fire engulfment