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FULL SCALE FIRE TESTS WITH UNPROTECTED AND THERMAL INSULATED LPG STORAGE TANKS

B. DROSTE and W. SCHOEN
Federal Institute for Materials Research and Testing (BAM),
Unter den Eichen 87, D-1000 Berlin 45

SUMMARY

This paper presents the results of three fire tests (tank surrounding fuel oil fire) with unprotected 4.85 m³ LPG storage vessels and two fire tests (full fuel oil fire engulfment) with tanks of the same type which had been equipped with a fire protection insulation. The unprotected tanks failed after a fire duration between 7 and 12 minutes; the tank rupture caused a BLEVE. The thermal insulation which was examined is able to prevent a failure even in a full fire engulfment of up to 90 minutes. The test results in terms of temperature- and pressure-time-relations as well as the insulation design aspects are given and discussed in detail.

INTRODUCTION

Containments for the storage of LPG have to be protected against external thermal impacts because of the severe hazards caused by a release of LPG (inflammability, explosion, tank fragmenting due to physical forces). To examine the safety margins of unprotected LPG tanks BAM in cooperation with the "Technischer Oberwachungs-Verein Hannover" carried out three fire tests with a surrounding fuel oil fire. As a part of a research program, sponsered by the FRG Federal Department of Research and Development (Bundesminister für Forschung und Technologie), we performed additionally experiments to evaluate the efficiency of technical fire protection measures for the aboveground storage.

FIRE TESTS WITH UNPROTECTED LPG STORAGE TANKS

Test conditions

The design criteria of the tanks which had been used are as follows:

- gross volume : 4.85 m³
- maximum working pressure : 15.6 bar
- test pressure : 20.3 bar
- tank diameter : 1250 mm
- tank length : 4300 mm
- length of the cylindrical tank part : 3600 mm
- Korbbogen-type heads (DIN 28013, Ø 1250 x 5.7)

- tank material : StE 36 (unalloyed fine-grained steel with a minimum yield strength of 360 N/mm²)
- wall thickness (cylindrical part)
  5.9 mm (test No. 1)
  6.4 mm (test Nr. 2 and 3)
- wall thickness (heads)
  6.6 mm (test No. 1)
  6.8 mm (test No. 2 and 3)
- tank equipment : safety valve (1 ") with a "start to discharge" pressure of 15.6 bar; liquid discharge valve (3/4 "); filling valve (1 1/4 "); gas discharge valve (3/4 "); filling degree indicator.

We did not achieve a full fire engulfment but only a fire which surrounded the tank. This was made to simulate a pedestal under the tank. The tank basement was surrounded by open steel troughs in a distance of 30 cm away from the tank projection. The steel troughs had a width of 60 cm and were filled prior to the tests with fuel oil above a levelling water layer.

Each tank had been equipped with several NiCr/Ni-thermocouples and pressure measurement devices.

The tanks were filled with propane of industrial grade. The filling degree was 50 % (1.425 m³ liquid propane contents). For a variation of the propane overpressure at test begin we simulated different ambient temperatures by preheating the tanks before test no. 2 and 3.

Test results

A survey on the test conditions and results is given in Fig. 1.

test conditions and results		test no. 1 10/82	test no. 2 11/83	test no. 3 12/83
ambient temperature	(°C)	10	2	− 3
propane temperature prior to testing	(°C)	10	37	26
propane overpressure prior to testing	(bar)	5.5	13.5	9.8
time period from ignition to the start of discharge	(min, sec)	5' 40"	1' 40"	2' 30"
start of discharge of the safety valve	(bar)	16.4	17.3	16.0
time period from ignition to tank rupture	(min, sec)	12' 0"	7' 20"	9' 0"
increase of pressure from ignition to rupture	(bar)	19	25.5	20.7
liquid propane temperature when rupture occurs	(°C)	72	84 – 87	77 – 78
rupture overpressure	(bar)	24.5	39	30.5
outer wall temperature at the top of the tank when rupture occurs	(°C)	(460)*	420	–
outer wall temperature at the 45° position of the vapour space when rupture occurs	(°C)	400 – (560)*	300	–
outer wall temperature at the liquid space when rupture occurs	(°C)	125 – (420)*	90	–

* burning propane due to a leakage at the top nearby the valve area

Fig. 1 Test conditions and results of three fire tests with unprotected 4.85 m³ LPG storage tanks (filling degree: 50 %)

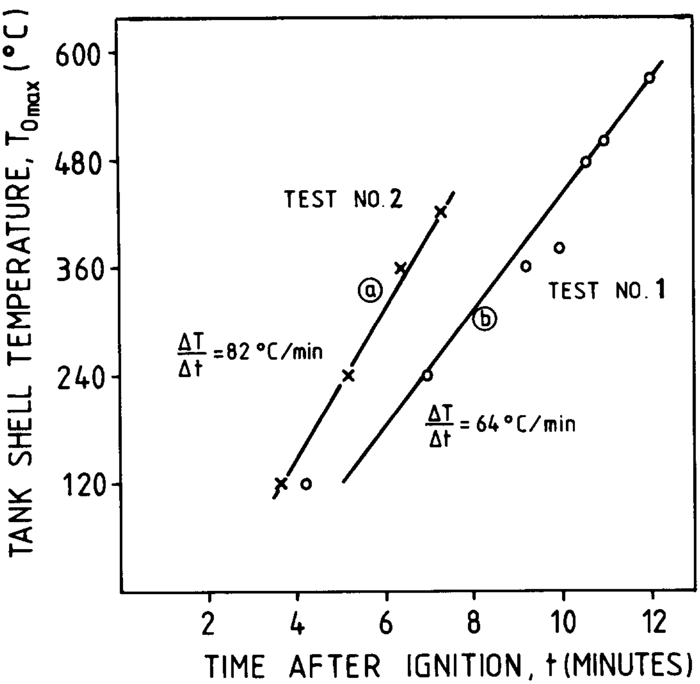

Fig. 3 Maximum tank shell temperatures measured during two fire tests with unprotected LPG storage tanks

As a consequence of the unprevented overpressure increase and the parallel running drop of the tank shell's resistance against inner overpressure,the tanks ruptured after fire test durations of 7 minutes and 20 seconds, 9 minutes or 12 minutes. The tank rupture was followed by a huge fire ball of ignited propane and tank fragments' rocketing. More details on these BLEVE phenomena and on tank fragments size and flight distances are given in (refs. 1, 2).

Discussion of the tank failure mechanism

One significant result with respect to tank bursting is the nearly reciprocal dependence between the time until a tank rupture occurs (t_R in min) and the Propane temperature at test begin (T_B in °C). Valid only for test conditions we used,we found the relation:

$$t_R = 13 - 0.154\ T_B$$

Although the liquid Propane temperature rise (after a delay of a full fire development of approximately 1 to 2 minutes) was nearly 6.7 - 7.4 °C/min (Fig. 2a) the corresponding overpressure rise increase with higher starting overpressure values (Fig. 2b).

The corresponding overpressure rises are:

1.8 bar/min (test no. 1)
2.6 bar/min (test no. 3)
4.1 bar/min (test no. 2)

The reason for this effect is the decrease of the latent heat of vaporization with increasing temperatures.

There are two reasons for a tank rupture in a fire accident:

1. Increase of inner overpressure caused by the LPG temperature increase and no sufficient pressure relief of the safety valve;
2. Decrease of the vessel's overpressure resistance caused by an increasing tank shell temperature and a corresponding drop of the yield and tensile strength.

The second element of the failure mechanism is demonstrated in Fig. 4.

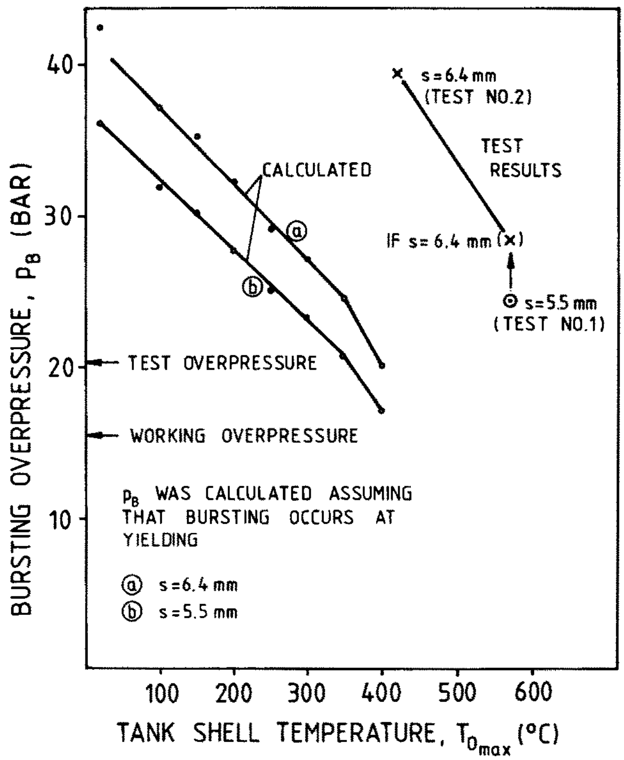

Fig. 4 Comparison of calculated tank bursting pressures and test results

In Fig. 4 we show the calculated relation between bursting overpressure and maximum tank shell temperature. This calculation is based on the well-known formula for cylindric pressure vessels under the assumption that rupture will occur when the materials yield strength is exceeded(what will probably be too conservative). For the calculation we used the yield strength's temperature dependence as given in the material standard for the fine-grained steel StE 42 (ref. 5).

The comparison of the calculated values with test results in Fig. 4 shows that the vessels have a reasonable margin of safety according to the distance between test results and calculation. But nevertheless, the remarkable tank resistance against inner overpressure is not able to prevent or to delay a tank failure significantly in a full fire engulfment because of the quick overpressure increase which is the dominant part of the failure mechanism. Although in test no. 2 the bursting overpressure was the highest one (39 bar) the time until the tank bursting occured was the lowest one (7 minutes, 20 seconds). The reason is the highest Propane temperature at test begin and the subsequent fastest overpressure rise because of the smaller latent heat of vaporization at higher temperatures. Thus the failure mechanism in terms of relations between

- the tank's bursting pressure and maximum tank shell temperature (or fire duration resp.)
- the LPG overpressure and LPG temperature (or fire duration resp.)

can be summarized schematically as shown in Fig. 5.

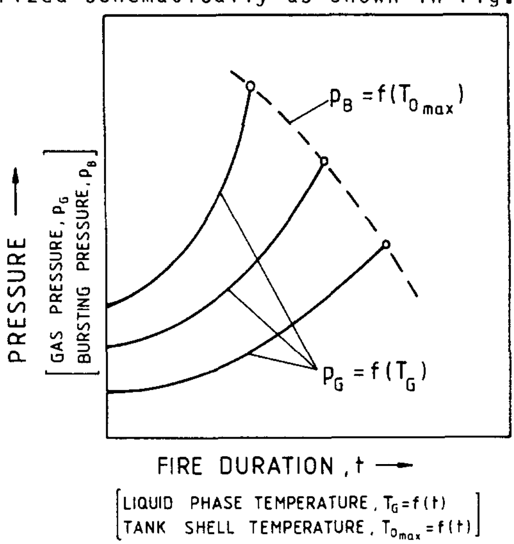

Fig. 5 Relations leading to a tank failure in a fire engulfment (schematically)

The overpressure increase was not stopped or significantly delayed by the start of discharge of the safety valve. The discharge capacity of the safety valve is specified with 64 m³/min (air at normal conditions); this capacity is sufficient only in case of a slight temperature increase or to prevent a tank bursting by overfilling. The resulting temperature and overpressure rise of the liquid phase is shown in Fig. 2.

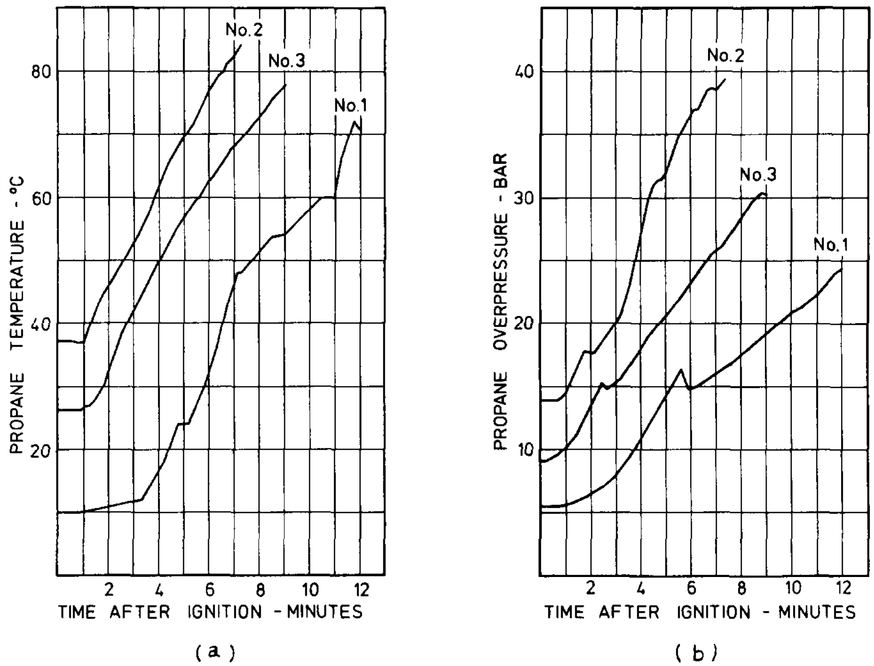

Fig. 2 Temperature (a)- and overpressure (b)-time-curves of the liquid propane in fire tests with unprotected LPG storage tanks

The temperature values of the tank shell at the liquid space of the tank content are similar to those of the liquid phase temperatures. The tank shell temperatures at the vapour spaces are much higher; the maximum tank shell temperature is always measured at the top of the horizontal cylindric vessel. The time-dependence of maximum tank material temperatures are plotted in Fig. 3.

FIRE TESTS WITH THERMAL INSULATED LPG STORAGE TANKS

Requirements

Considering the results mentioned above which demonstrated the very low margin of fire safety of unprotected aboveground LPG storage tanks, the need of effective technical fire protection measures is evident. The FRG regulations (ref. 3) for LPG storage vessels bigger than 6 m^3 require

- underground or earth-covered (at least 0.5 m) storage,
- a thermal insulation of aboveground storage vessels that is able to prevent a failure over a fire duration of 90 minutes,
- or water spraying (100 l/m^2h) of aboveground storage vessels in combination with certain safety distances to other buildings. (Our investigations of this item will be presented in another paper on this meeting.)

The reason for our experiments on the effectiveness of a thermal insulation was that no existent construction has been proved to fulfill the requirement of a protection over a 90 minutes fire engulfment.

Thermal Insulation Design

Based on conventional insulation techniques (e. g. for the fire protection of building structures or for the heat insulation of steam generators and pipes) we constructed a tank insulation as it is shown schematically in Fig. 6.

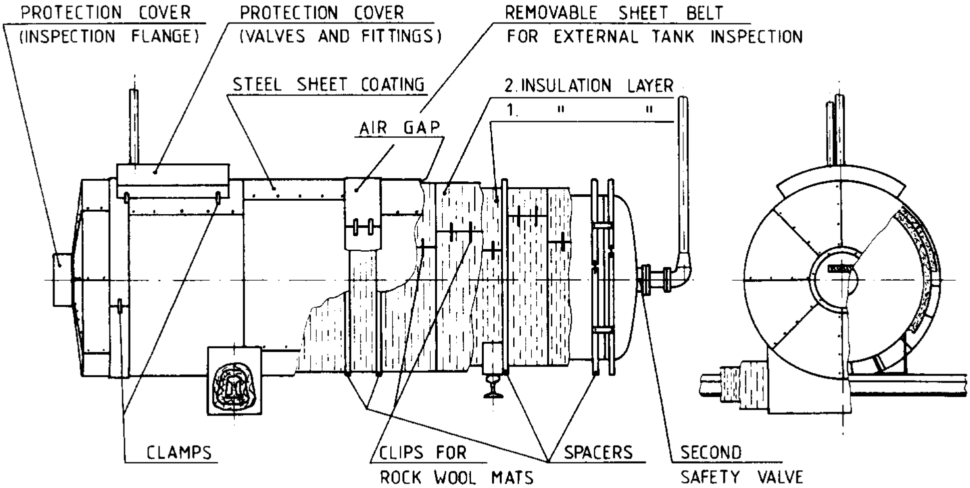

Fig. 6 Design of the thermal insulation

For thermal insulation we used fibrous mineral wool material stitched with steel wire (commercial name ISOVER MD 2). The tank surface was covered with two layers of this insulation material (1. test: 80 mm, 2. test: 100 mm thick) and incapsulated with a watertight steel sheet coating of 1 mm thickness; distance pieces of flat steel profiles which were connected to the tank carry the insulation construction and provide an air gap of 30 mm between the inner fibrous mineral material layer and the outer steel coating.

The temperature dependence of the thermal conductivity of the mineral wool according to the producer specification is as follows:

λ(W/mK)	0.033	0.041	0.047	0.056	0.068	0.082	0.098	0.12
T(°C)	0	50	100	150	200	250	300	350

Test conditions

We performed two fire tests with 4.85 m³ tanks of the same design as described in the first chapter. As an additional safety measure we equipped the tanks with a second safety valve (start to discharge pressure 19 bar) which was connected to the tank behind an inspection flange of one of the tank heads. Inside the tank this second safety valve was connected to a pipe reaching into the vapour space; a pipe outside the tank was installed for the gas release.

The tests had been carried out on the BAM test site at Lehre (near Braunschweig, Niedersachsen) using an open fuel oil pool fire with a surface area of 3 m x 6 m. The full fire engulfment produced by this facility can be interrupted immediately by clapping down a trap that lets the burning fuel oil flow into an underground tank where it is extinguished. The test objects had been instrumented by thermocouples (fire, tank shell surface, vapour and liquid space) and pressure gauges. A finally prepared tank (second test) sited at the fire test facility is shown in Fig. 7.

The Propane filling degree was 50 % in the first and 20 % in the second test. The tests were controlled and monitored using video cameras by the test personal which was located in a bunker 200 m away from the fire test facility.

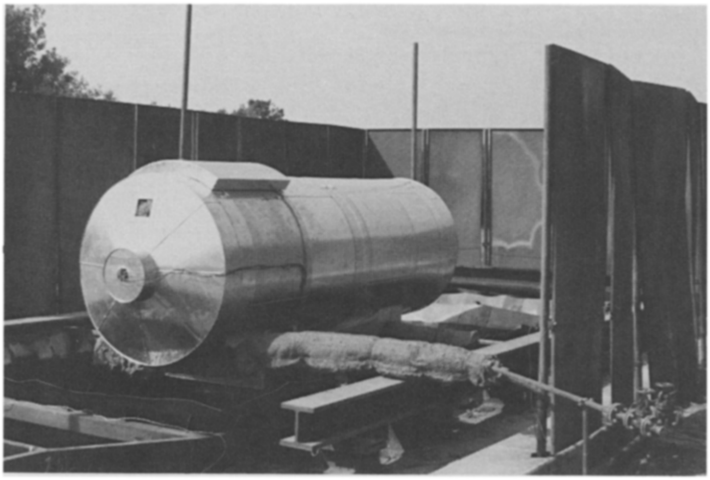

Fig. 7 Thermal insulated and instrumented 4.85 m³ LPG tank in the open fuel oil pool fire test facility (second test)

Test results

The first test with an insulation material layer thickness of 80 mm had to be interrupted after a fire test duration of 70 minutes. The reason for this test stop was not an undue increase of the inner overpressure ($<$ 17 bar) and also the average tank shell surfaces temperatures remained below 250 °C, but a rough leakage of the tank valves (located at the top of the tank cylinder) caused a torch fire which heated up the tank material. The reason of that leakage was an unsufficient construction of the insulation covering the valves' area and the heat resistance of the valve gasket materials was too low. As a consequence of this we optimized the tank design for a second test:

- the insulating cover of the valves area at the top of the tank was fully steel sheet incapsulated and overlapped the tank cylinder insulation wider than before,
- the gasket materials of the valves were changed into plastic materials with a better heat resistance (Viton instead of Perbunan, Teflon instead of Polyamide),
- the insulation layer thickness was increased from 80 mm to 100 mm.

With this up-graded tank we run a fire test successfully over a full fire engulfment time of 90 minutes without getting any dangerous situation. For this test we chose only a very low filling degree of 20 % what is a very conservative test parameter because of the low heat capacity of the tank contents. The propane overpressure at test begin was 9.0 bar. 53 minutes after fire ignition the first safety valve started slowly to discharge at an overpressure of 14.8 bar and the overpressure remained below 15 bar during the fire test. Our experience with the second safety valve was not the best one because this valve was leaking and caused a slight gas release. In Fig. 8 the tank in the fire test with a stronger torch flame above the release pipe of the first safety valve (right) and a slighter flame above the second safety valve (left) can be seen. But the very low overpressure increase during the fire test led us to the conclusion that only one safety valve (like the first one we used) is sufficient for pressure relief if a tank is thermal insulated like that one of the second test.

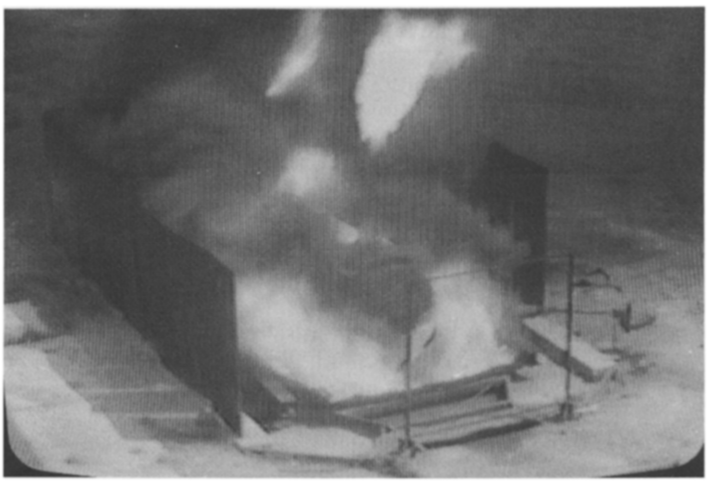

Fig. 8 Insulated LPG storage tank with operating safety valve in the fire test

The tank and its insulation after the 90 minutes fire test is shown in Fig. 9.

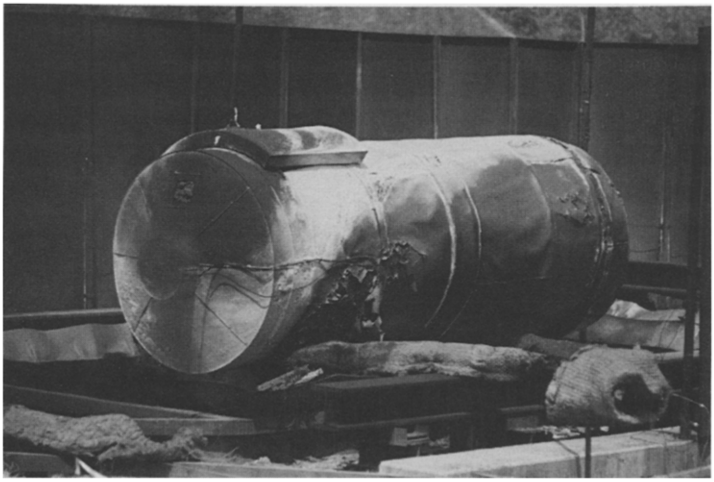

Fig. 9 Thermal insulated LPG storage tank after a 90 minutes fire test

The valves remained leaktight and in function, with exception of one minor leakage of the filling valve (Fig. 10).

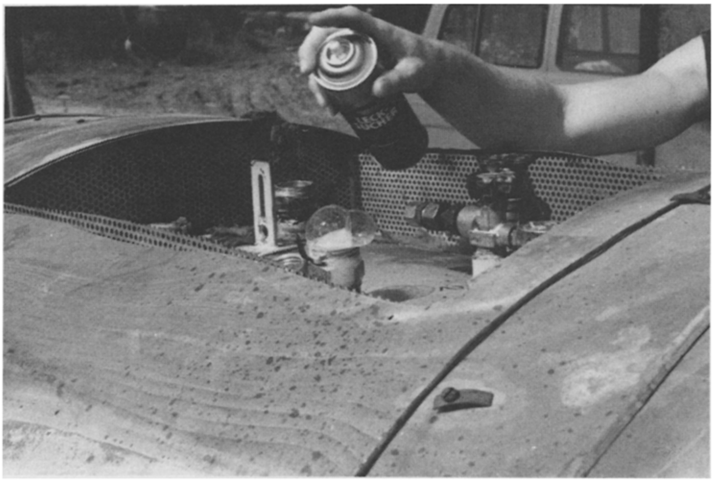

Fig. 10 Valves after the 90 minutes fire test (insulation cover removed)

A selection of the second test measurements is shown in Fig. 11 and 12.

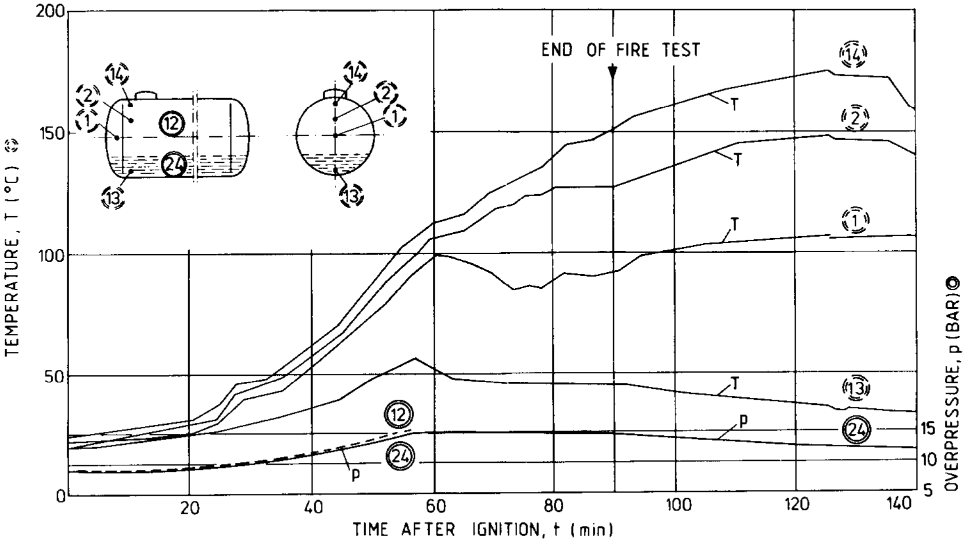

Fig. 11 Vapour and liquid space temperatures (T) and over-pressure (p)

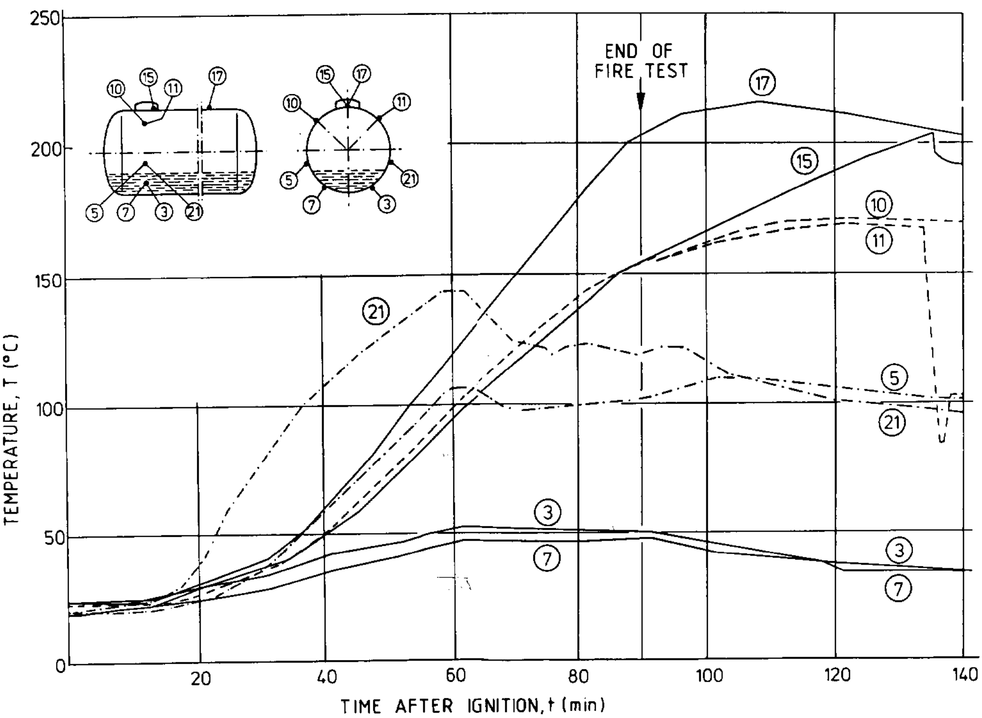

Fig. 12 Tank shell temperatures

The tank shell temperatures at the liquid space (3, 7 in Fig. 12) are comparable to those of the liquid propane (13 in Fig. 11). The tank shell temperatures at the vapour space increase in the direction to the top of the tank cylinder and are comparable with the vapour space temperatures measured at the comparable height inside the tank. The maximum tank shell temperature of 215 °C was measured at the top (17 in Fig. 12) 20 minutes after the end of the fire test. For more details see (ref. 4).

Conclusions

The thermal insulation design evaluated in the second fire test in combination with fire-proof or heat-resisting (up to 250 °C) gasket materials for valves and fittings is able to prevent a failure of a LPG storage tank even in a 90 minutes full fire engulfment. Based on the investigated design, recommendations for a fire protection insulation of aboveground storage tanks on LPG filling stations had been incorporated into the corresponding requirement (ref. 6).

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