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Experimental evaluation of LPG tank explosion hazards

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Abstract

Liquefied-pressure gases (LPG) are transported and stored in the liquid phase in closed tanks under sufficiently high pressure. In the case of an accident, an abrupt tank unsealing may release enormous quantity of evaporating gas and energy that has a destructive effect on the tank and its surroundings.

In this paper, experiments with explosions of small LPG tanks are described. The data acquisition equipment applied in the tests provided a chance to learn dynamics of the process and determine hazard factors. The tests enabled a determination of temperature and pressure at which tanks containing LPG disrupt. The results enable a reconstruction of consecutive phases of the explosion and identification of hazards resulting from damage of the tanks. An explanation of the tank unsealing process with fluid parameters above critical point is given.

Keywords: BLEVE; Blast pressure; Hazard; Projectile range; Burst pressure

1. Introduction

Liquefied-pressure gases (LPG) are substances such as propane, butane and chlorine, which are transported and stored in the liquid phase in tanks under sufficiently high pressure. If, for any reason, such a tank is damaged, an abrupt pressure drop may release enormous quantities of evaporating gas and energy, which has a destructive effect on the tank and its surroundings [1]. The degree of hazard depends on many factors such as the mass of substance released, the rate of gas release, physico-chemical properties of the substance in the moment of its release, flammability and toxicity of the medium flowing out.

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Sometimes the outflow of liquefied-pressure gas is calm and does not present a menace to the environment. It happens, however, that its results can be disastrous. The most dangerous is a boiling liquid expanding vapor explosion (BLEVE). A destructive character of such explosions is usually related to an abrupt transition of the media from liquid to gas phase [2].

2. BLEVE phenomena

The BLEVE occurs when a liquid of temperature higher than its boiling point under normal pressure suddenly flows out. This leak is caused by an extensive damage of the tank, usually in several places [3]. The tank can be unsealed due to the action of an external fire source, overfilling of the tank, weakening of wall material caused by corrosion or mechanical damage as a result of a car crash, for example.

The most common type of BLEVE occurs when a pressure vessel that is partially filled with liquid is exposed to a fire [4]. Because the vessel is subjected to high heat flux from a fire, temperature of the liquid starts to increase. The pressure in the tank increases due to the increased vaporization rate. The thermally induced stresses in the tank shell, heat weakened tank and high internal pressure combine to cause a sudden, violent rupture of the tank. Most of the remaining liquid vaporizes extremely rapidly due to the pressure release and the rest atomizes to small drops due to the force of the explosion.

Because thermally induced BLEVE's result from exposure to fires, it follows that the tank contents, if flammable, once released by the tank failure, will be ignited. Therefore, this type of BLEVE generally results in a large fire or fireball.

If a pressurized tank containing a liquefied gas and its vapor is suddenly depressurised, the equilibrium between the liquid and vapor will be shifted that some of the liquid will change to vapor. If this depressurization occurs due to tank failure, the phase change from liquid to vapor may appear so rapidly that the force from expansion of the vapor will cause the liquid and vapor to be propelled violently in all directions. This behavior is often the part of the thermally induced BLEVE.

The mechanism of the BLEVE phenomenon has not been fully identified yet. In the literature, various theories have been discussed. They are based mainly on the phenomenon of liquid overheating [3,4]. They suggest that during the sudden depressurization, the liquid is momentarily in a superheated state and in some instances this may lead to homogeneous nucleation throughout the bulk of the liquid. This would cause the phase change from liquid to vapor to occur at an extremely high rate, thus creating what is called a superheated liquid/vapor explosion. Reid [5] has reported on this hypothesis and has linked the strength of the explosion immediately following a tank failure to the degree of superheat at the time the tank failed.

The liquid under a given pressure does not start boiling when reaching the boiling point. A bubble nucleation delay leads to the liquid overheating. The vapor bubbles are formed in active places, the so-called nuclei. These places are mainly in the layers close to stable elements, or they can be pollutants, crystals or ions. If the phenomenon of nucleation does not occur, the liquid temperature still grows until reaching the boundary overheating temperature. This is an unsteady state and a single active place is sufficient to cause explosive boiling. In an overheated state, the nuclei are usually fine bubbles.

Possible reasons for the final rapid failure of the vessel may be either structural instability of the vessel, rapid over-pressurization due to a dynamic 'head space' impact of the two-phase swell initiated upon a depressurization (initiated by the formation of a thermal crack or tear which arrests), and/or the rapid quenching of its crack tip, due to the two-phase discharge, that results in large local thermal stresses which cause the uncontrolled vessel failure [6].

The following phenomena may be observed as a result of release of the tank content to the environment:

- splashing of a burning liquid;
- generation of a blast wave;
- formation of primary and secondary projectiles;
- fireball formation.

3. Hazard factors

Direct hazards following from BLEVE are projectiles and a blast wave. If the medium is toxic the ground may be contaminated chemically. On the other hand, if the medium is flammable and gets ignited immediately, a fireball may be formed and heat radiation, which is directly connected with it as well as secondary fires and explosions, may occur. If the flammable medium is not ignited immediately, the delayed ignition can result in extensive fires and in some cases even in secondary explosions.

The fireball created by the mixture of vapor and the liquid explosively dispersed by the sudden rupture of the tank is limited by the energy in the tank. It can catch fire from an external source of fire. The process of cloud burning can be divided into three stages:

- ignition of the cloud edges;
- dilution of the cloud by air;
- expansion of the flame through the cloud.

The range of vapor flammability for liquids generating the phenomenon of a fireball is from the lower flammability limit to the upper flammability limit, typically 1.5–9.0% [8].

There are many publications which give empirical equations and models to calculate approximate geometrical dimensions, duration and heat flux of a fireball. Some simply assume the diameter, location, and surface emissive power of the fireball are constant over the full duration of the event [9–11]. The model described in [12] provides a more realistic representation of the true behavior of fireballs by employing equations that account for fireball growth, lift-off, and changing radiative characteristics. Thermodynamic changes that occur during the release of superheated liquids are incorporated into the model, making it suitable for predicting the radiant heat effects of fireballs formed as a result of cold catastrophic failures of pressure vessels, as well as fireballs created by BLEVE incidents.

4. Experimental

The aim of the tests was to analyze the processes which take place inside a tank containing LPG, and to identify hazards resulting from damage of the tanks. The experiments were

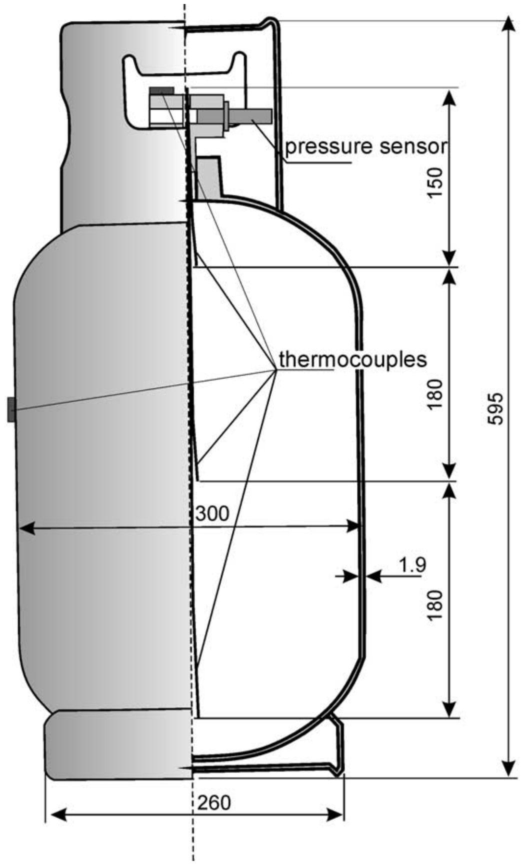

Fig. 1. Scheme of the tank with sensors.

carried out in standard cylindrical tanks of capacity 5 and 11 kg filled with propane or propane–butane mixtures.

For the needs of the experiment, the tank was modified. Instead of a shutting valve, a specially designed head was mounted. It allowed sensors to be inserted into the tank. The tank walls remained intact. Measuring sensors were installed directly on the external surface and inside the tank to monitor the basic parameters during the experiment. The scheme of the tank is shown in Fig. 1.

Standard gas burners such as the ones used in households were applied in the experiment as a fire source. In all experiments, the bottoms of the tested tanks were heated. This burner allowed us to simulate the real fire influence on the LPG tank.

During the experiment the following parameters were measured and recorded:

- temperature of the tank walls;
- temperature of the liquid and gas phase of propane in the tank;

- pressure in the tank;
- overpressure around the tank.

To monitor the process parameters prior to and during the explosion, a Data Acquisition and Control System was designed and constructed.

5. Results and discussion

During subsequent tests the following parameters were changed:

- initial filling of the tank;
- the way the tank was placed (horizontal and vertical);
- the place of explosion (either open or close space).

During the first stage of tank heating process, the pressure within the tank followed the vapor pressure curve for propane (saturation line) shown in Fig. 2. Near the point A (85 °C, 35 bar) the measure points deviated from vapor pressure line. Point A is related to the change from two- to one-phase medium (see Fig. 3). The most probable reason was the exceeding of the critical tank load. For propane, the critical load value is about 43% volume fill. Tank failure took place with temperature and pressure value above critical point.

The failure time was assumed to be the moment, at which pressure in the tank dropped rapidly due to the beginning of the tank unsealing (see Fig. 4). We could observe rapid pressure decrease but it is difficult to explain exactly the mechanism of tank failure. We assume that adiabatic expanding of supercritical fluid took place. Part of the supercritical fluid mixes with the ambient air as a vapor and rest of it expands as two-phase subcritical medium. Confirmation of the two-phase media state in tank is seen from the pressure change

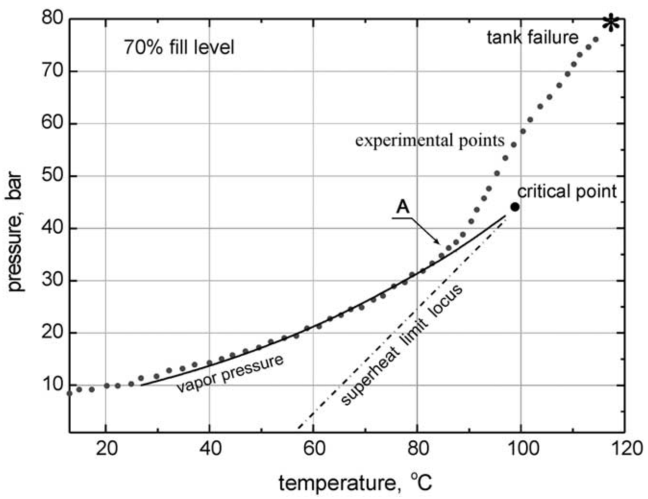

Fig. 2. Vapor pressure vs. temperature for propane: experimental data.

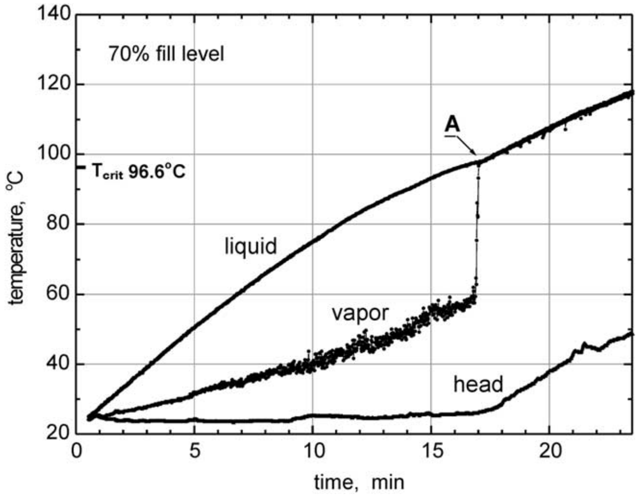

Fig. 3. Temperature inside the 70% filled tank.

curve after initial time of failure (see Fig. 4) and pictures of propane cloud in the moment of explosion (see Fig. 5) which consists of liquid propane droplets. The pressure drop sends the liquid into a superheated state and initiates a boiling response from the liquid. The next violent pressure increase could result from the fact that explosive boiling generated vapor faster than it could be freed through hole in the tank.

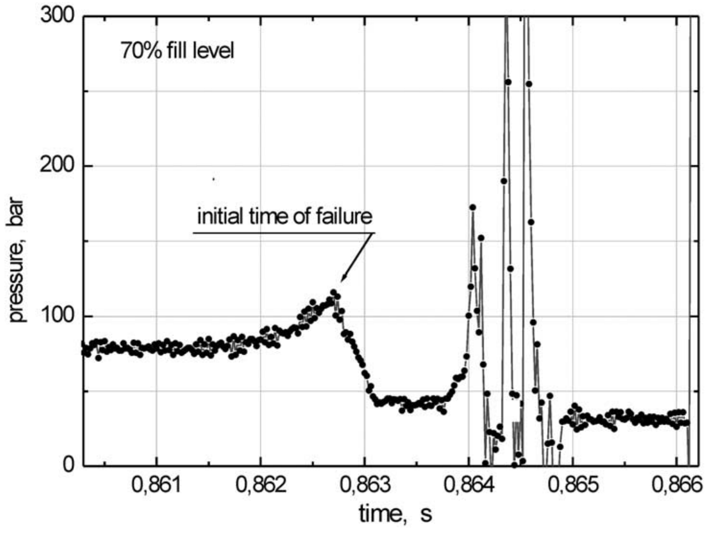

Fig. 4. Running pressure at the moment of explosion.

Fig. 5. Propane cloud after tank failure.

The temperature of the propane, at which the tank was disrupted, depended on the level of tank fill. The tanks with fill level of 80% or greater were disrupted when propane temperature was about 120 °C and the runs were characterized by a uniform temperature growth for liquid and vapor phases.

Tanks failed when temperature exceeded 115 °C in the case of 80% fill level and 150 °C in the case of 40% fill level and the internal pressure before tank failure was in the range 75–120 bar. Tanks failed with no outside intervention. The fill level determined the maximum value of internal pressure reached in the tanks at the time of failure.

The maximum temperature of the cylinder walls was about 120 °C. Thermal weakening of steel, from which the tested cylinders were made, occurs above 1000 °C. The observed wall temperatures had no significant effect on a decrease of material strength. It can be assumed that unsealing of the cylinder was mainly a result of a sudden pressure growth inside the tank. The internal tank pressure does play an important role in formation of the initial local creep rupture. In a thermally weakened tank, a failure will form when the local pressure-induced hoop stress exceeds local strength of the material.

The heater was placed under the bottom of the tank to avoid heating the vapor space. In the initial period of the tank heating, the temperature in the liquid phase was higher than in vapor phase. Significant differences between the temperature of these phases were observed for tank fill level less than 80% (see Fig. 3). After several minutes, the vapor phase temperature rapidly increased to the liquid phase temperature. Probably in this moment, the tank content changed from the di- to mono-phase medium. The lower fill level causes the higher tank failure temperature.

Unsealing of the tank was accompanied by a blast wave that appeared in all tests. The amplitude of waves depended directly on the pressure inside the tank during the explosion

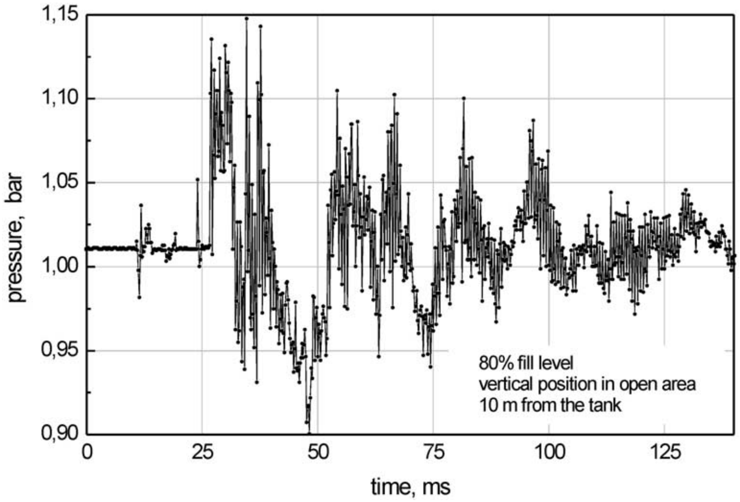

Fig. 6. Blast wave pressure at the distance 10 m from the tank in open area.

and on the distance from the sensor. Peaks visible on the graphs (Figs. 4 and 6) correspond to the processes of tank unsealing and an intense liquid evaporation.

A maximum value of blast pressure amplitude measured at a distance of 10 m from the tank was about 1.15 bar (see Fig. 6). A theoretical maximum value of overpressure caused by trinitrotoluene (TNT) explosion can be estimated from the formula [7]:

$$\frac{\Delta p}{p} = 1.06\lambda^{-1} + 4.3\lambda^{-2} + 14\lambda^{-3}$$

where $\lambda = r/q^{1/3}$; r, the distance from the load (m); q, the TNT load mass (kg).

To match values of overpressure obtained during the experiments, the explosion of a propane–butane mixture in the 11 kg tank is equivalent to the explosion of about 0.7 kg of TNT.

During the explosion, usually three–five main projectiles and several single, smaller fragments were formed. All tanks were split in a similar way and the fragments included elliptical ends of the tank (see Fig. 7). In each test, the thread on the head was cracked and all sensors were pulled out (see Fig. 8). The upper part of the cylinder was usually detached along with a large fragment of the sidewall. The sidewalls formed two or three projectiles.

For safety reasons, the tests were carried out on an embanked artillery range, therefore, part of the projectiles was smothered on the embankment, and so their range was much smaller than on flat ground. The range of projectiles depends on their shape and weight. The biggest elements of the cylinder were found at a distance of about 70 m from the experimental rig. At the maximum range, 200–300 m, flat fragments of the cylinder or compact elements of small mass (e.g. the head) were found.

The tested tanks are very often stored in closed rooms. The experiments allowed us to estimate damages in a partially closed building. Projectiles of the cylinder and the formed

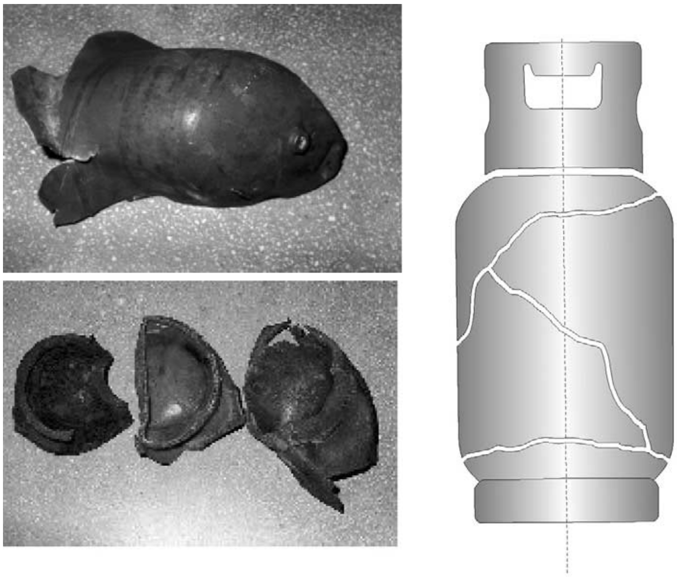

Fig. 7. Tank fragments after explosion and scheme of tank disrupture.

overpressure wave disturbed the structure of the building walls, shifting the partition brick walls by few centimeters (see Fig. 9). The explosion caused also that plaster fell from the walls. In several places, there were holes in the wall caused probably by the impact of the detached valve.

The overpressure wave constitutes a serious hazard particularly in closed rooms. The overpressure decreases with the distance from the tank. During the test, at the distance of 2 m from the tank, overpressure of amplitude at the upper limit of the pressure sensor indications of at least 0.5 bars was observed (see Fig. 10). According to the literature [13], this overpressure may damage human ear, disturb building structure, overturn people and break window panes.

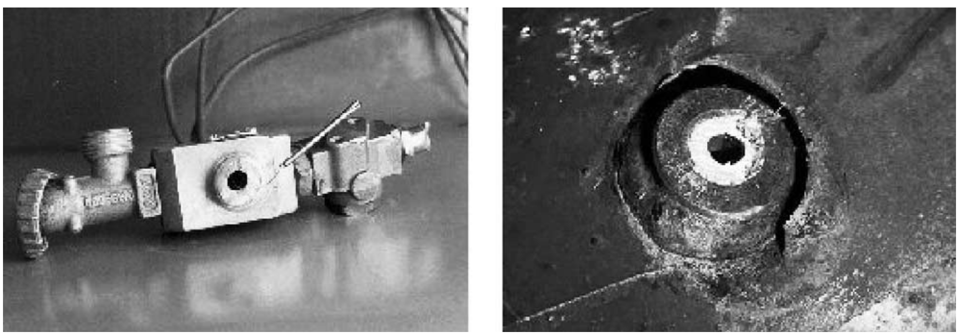

Fig. 8. Head after explosion and the place of tank splitting.

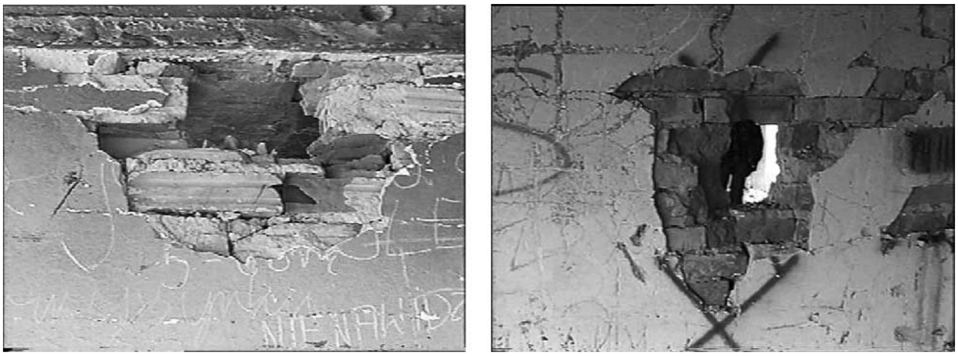

Fig. 9. The wall destruction after explosion in closed area.

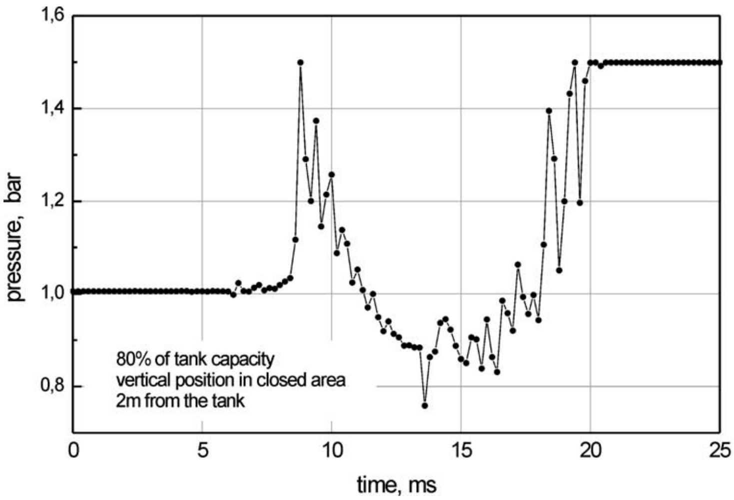

Fig. 10. Blast wave pressure at the distance 2 m from the tank in closed area.

One of consequences, which may accompany a physical explosion, is a fireball. This phenomenon was not observed in any of the tests because each time the blast wave extinguished the burner—the only source of fire, which could ignite the expanding vapor cloud.

6. Conclusions

Analysis of the results leads to a conclusion that in all tests BLEVE took place. As a result of the explosion, the characteristic effects, including blast wave and projectiles, occurred.

The blast wave in an open space does not present an immediate threat to life. It may cause material damage.

The most serious threat are flying projectiles. Most of them were dispersed in the radius of 100 m from the tank. The maximum range was up to 300 m. According to literature, the maximum range for 11 kg tanks is below 200 m. We found on the basis of the tests that the probable danger zone is substantially larger. The most probable reasons for our results differing from previous reports are differences in tank construction (shape, size and material).

Explosion of a tank in a closed room is a serious danger to the health and life of people staying in the building. The greatest danger to life is caused by projectiles, which can bounce against the room walls. Blast wave may cause serious damage of hearing and also disturb the building structure.

Analysis of all earlier mentioned hazards accompanying BLEVE allows us to conclude that an exclusion zone with a radius of 300 m can ensure protection for people against all hazardous consequences of explosions of the 5 and 11 kg tanks filled with the propane–butane mixture. For the needs of rescue services, an exclusion zone of 50 m in radius should protect against blast wave.

Results of this study have been approved by the Main School of Fire Service in Warsaw, and have been taken into account when developing the methods of rescue procedures in the case of BLEVE type explosions.

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