Explosion protection for vehicles intended for the transport of flammable gases and liquids—An investigation into technical and operational basics

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ABSTRACT

In Europe, the transport of flammable gases and liquids in tanks has been impacted by new developments: for example, the introduction of the vapour-balancing technique on a broad scale and the steady increase in the application of electronic components with their own power sources; furthermore, new regulatory policies like the ATEX Directives are being enforced in the European Union. With this background in mind, the present investigation aims to provide a basis for future developments of the relevant explosion protection regulations in the safety codes for the transport of dangerous goods (RID/ADR).

Specifically, the concentration of gas in the air was measured under various practical conditions while tank vehicles were being loaded with flammable gases or liquids. These spot-test data were supplemented by systematic investigations at a road tanker placed in our test field. With respect to non-electrical ignition sources, a closer investigation of the effect of hot surfaces was carried out.

With regard to improving the current regulations, the results of our investigation show that it would be reasonable to implement a stronger differentiation of the characteristics of the dangerous goods (gaseous/liquid, flashpoint) on the one hand and of the techniques applied (loading with and without vapour-balancing system) on the other hand. Conclusions for the further development of the current international regulations are proposed.

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1. Introduction

The prevention of fire and explosion hazards during the transport of flammable gases (class 2) and liquids (class 3) is a central concern of the international agreements on the transport of dangerous goods, for example, in Europe represented by the RID/ADR [1]. However, some more recent technical and regulatory developments are not yet reflected in the current regulations.

- Vapour-balancing systems are often state of the art when it comes to the handling of flammable organic liquids. However, RID/ADR currently do not yet take into account that the extension of hazardous areas is considerably reduced thereby.
- In the EU, explosion protection is regulated by the Directive 94/9/EC [2] (performance requirements) and Directive 1999/92/EC [3] (operational requirements). The Directives enforce the equivalent consideration of both electrical and non-electrical potential ignition sources, among others, whereas ADR still covers electrical ignition sources only.
- Operational measures of protection as, for example, the de-energising of equipment not qualified for use in hazardous areas needs clearer specification in ADR.

The present requirements for tank transport cover a broad range of technically quite different transport units, such as tanks for pressurised or cold-liquefied gas or tanks for flammable liquids having flash points from below −40 °C to 60 °C. As far as flammable liquids are concerned, transport units without vapour-balancing systems as well as transport units with different vapour-balancing systems (top-/bottom-loading) have to be considered. Especially for road transportation all these units (specified as FL-vehicles in the ADR) are subjected to few general requirements for explosion protection.

Our investigation was thus aimed at finding answers to the following questions:

- When, and in which areas, are explosion hazards to be taken into account at the vehicles?
- Which equipment must be regarded as a potential ignition source?
- Which operational measures can contribute to safety?

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2. Hazardous areas

2.1. Background and experimental conditions

Hazardous areas are assigned when the concentration of flammable gas or vapour in air exceeds the lower explosion limit (LEL). In our case we have to consider processes during which a vapour–air mixture with an initial concentration above LEL is released at an orifice and then diluted by mixing with the ambient air down to LEL. The range of explosive atmosphere is the largest distance between the source and the LEL-contour in the resulting vapour cloud. That range depends specifically on the hydrodynamic conditions at the source (flow rate, jet formation) and in the entraining atmosphere (wind speed, direction, and stability) as well as the characteristic properties of the flammable mixtures (initial concentration and density, LEL).

From the safety point of view, experiments have to be designed for maximum explosive ranges. According to the present knowledge (see, for example [4]) one should then – within the framework of the relevant process in practice – aim at the following limits:

- minimum wind speed, maximum stability of weather,
- maximum initial density and maximum dilution factor, and
- maximum flow rate and gas impulse.

The dilution factor is defined here as the "concentration at the source related to LEL"; it characterises the dilution range to be considered in the individual experiment.

In our project we at first tried to identify potential releases of explosive mixtures at the tank vehicles under both normal operation and failures. (A disastrous failure of the enclosure of the product was not taken into consideration at the outset because this situation commonly is not considered as subject to general regulations.)

According to the available technical information and after some interviews on-site we selected the following key situations for our experimental investigation:

- Displacement of explosive vapour–air mixtures to the open atmosphere during the filling of flammable liquids (class 3) including open systems as well as partially and completely closed vapour balancing systems.
- Atmospheric venting of tanks with flammable liquids (class 3).
- Relief of coupling components for pressure-liquefied gas (class 2).

We focused on the experimental detection of such hazardous areas by measuring the gas concentration near possible release points by means of an array of IR gas sensors.

The measurements were carried out on-site as well as in our test field.

The on-site measurements served to gain information on actual equipment and operational procedures and to identify hazardous areas typical in practice.

In Table 1, the numbers of individual test runs, the flammable products (including the respective flashpoint, if applicable), the vehicle type and the loading technique are compiled.

Due to the considerable variety of influencing parameters and due to our minor influence on them, the results of the measurements on-site have, of course, mostly the character of spot samples.

In contrast, the supporting measurements in the test field allowed for a systematic and controlled approach to the above-mentioned critical limits.

As regards the weather conditions we limited our experimental data collection to periods of low mean wind speeds (≤ 1 m/s).

Regarding the properties of the flammable substances we had to limit our experiments in the test field to propane–air mixtures and pentane–air mixtures for technical reasons. These substances allow initial vapour–air densities of up to 3 kg/m^3 and dilution factors of up to 70 when supplying 100 vol.% gaseous fuels at the source. These are approximately the maximum values which can be found in the range of organic gases. These figures are also unsurpassed in the range of relevant volatile organic flammable liquids, because here one may refer conservatively to a maximum temperature of 50 °C of the liquid [1] and to the corresponding saturation concentration at the source. Starting from C_5-compounds (e.g. pentane) the relevant densities and the dilution factors of the vapour–air mixtures decrease rapidly with increasing molar mass because the sharp decrease of the vapour pressure by far over-compensates the slight decrease of LEL.

So the mixtures used in the test field may serve as conservative substitutes for the wide range of volatile organic compounds.

Furthermore, when going to substances of lower vapour concentration (at a given temperature) this generally means an increase in the relevant flashpoints. Therefore, lower propane concentrations at the source in the test field serve to simulate the worst case situations for liquids with correspondingly higher flashpoints.

Concerning the release conditions, our test facility was able to achieve and even exceed the maximum expected flow rates for those processes with continuous release (filling, atmospheric venting). The mixtures were then mostly piped to a road tank trailer positioned in our test field and released to the atmosphere from different selected positions at the trailer.

2.2. Concentration measurement and evaluation

The concentration measurements were carried out by means of six infrared gas concentration sensors (lower sensitivity limit: 0.02% gas in air by volume; upper limit of range: approximately LEL).

The IR gas sensors were calibrated for the specific substance in use, and they allowed data acquisition with a metering time period of $T_{90} \approx 10$ s and a resolved length scale of about 5 cm (characteristic length of sensor volume).

For each measurement series, the sensors were placed at appropriate distances from the relief opening, and the time lapse of the vapour concentration was recorded for the time period of a specific operational process, for example, "filling of a tank compartment".

Table 1
List of on-site measurements

Number of tests	Substance	Flashpoint (°C)	Vehicle	Loading technique; maximum filling rate
15	Gasoline	<−35	Road tanker	Bottom loading, vapour balancing, closed; max. 4×150 m^3/h
10	MTBE	−28	Rail tank wagon	Top loading, vapour balancing, sealed riser; 300 m^3/h
2	Methyl-acetate	−13	Road tanker	Top loading, vapour balancing, stopper; 50 m^3/h
1	Vinyl-acetate	−8	Rail tank wagon	Top loading, vapour balancing, closed; 50 m^3/h
6	Ethanol	12	Road tanker	Top loading, open venting; 50 m^3/h
1	n-Butyl-acetate	27	Road tanker	Top loading, vapour balancing, sealed riser; 50 m^3/h
10	Propane	–	Road tanker	Closed system; 25 m^3/h

2.2.1. Continuous releases

Situations with nearly constant outflow rates occur as a result of product filling or atmospheric out-breathing, when a nearly stationary, leeward-directed vapour plume develops in the atmospheric wind field. On the basis of simultaneously recorded data of wind velocity and wind strength, and by taking into account the density of the vapours, the centre of this plume could be determined by an appropriate (re-)positioning of the sensors. Due to the stationary conditions at the source, the probability density distribution of measured concentration data is expected to be time invariant (for constant weather conditions).

For a situation with stationary outflow, Fig. 1 shows for two IR sensors at different distances to the source typical courses of the concentration as a function of time.

It is apparent that at sensor IR 3 the concentration exceeds the upper limit of the measurement range (here: 1.7 vol.%) during a part of the measurement time. Such situations are difficult to avoid without a priori knowledge of the concentration fluctuations. In order to get some quantitative figure on the likelihood of the atmosphere being hazardous for these cases, we evaluated and denoted P_{LEL}, the fraction of measurement time in percentage during which LEL was exceeded. According to its formation, P_{LEL}-data follow binomial distributions; the corresponding uncertainty is calculated from the coefficient of variation and is displayed in the graphic presentation of the data.

The other typical case is represented by the signal from sensor IR 5 in Fig. 1 where the measurement range is not exceeded. In such cases we evaluated and denoted the maximum value of the concentration found in the relevant measurement time interval as $c_{max,s}$. A thorough mathematical treatment of the statistical scatter of the $c_{max,s}$-data is problematic even with much larger data sets [5] and is not achievable here due to the limited amount of data.

However, from all available data we may conclude that any explosion hazard is negligible when the noted maximum concentrations $c_{max,s}$ fall below 0.5*LEL. In this sense, the reported $c_{max,s}$ data may be used to support a meaningful safety assessment.

2.2.2. Transient releases

Situations with highly non-stationary outflow rates occur during the opening of dome holes (class 3) or during the disconnection of product lines (class 2). The gas flow rapidly rises to the maximum value and then declines to zero with a time constant depending on the volume of the reservoir a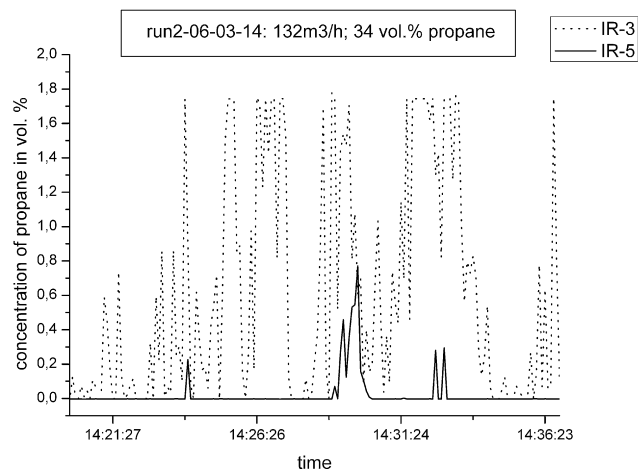nd the flow resistance of the orifice. For such cases the sensors were positioned in the presumed direction of the generated jet and at distances where a dilution approximately to LEL is registered. The underlying characteristic time constant of the relief process may be roughly estimated from the duration of significant concentration signals.

These measurements have been performed on-site only. As a result, we noted the maximum concentration $c_{max,t}$. measured under transient flow conditions.

2.3. Experimental results and discussion

2.3.1. Loading without vapour balancing

Top-loading without vapour collection as operational procedure comprises the filling of flammable liquid and the simultaneous release of the displaced gas atmosphere via the open dome hole (stationary flow at source). This procedure may imply considerable air pollution and so it is undesirable or even banned by law in Europe [6] for gasoline.

For an experimental investigation we simulated this procedure in our test field by releasing propane–air mixtures of various concentrations via the open dome hole of a tank trailer. Fig. 2 shows the dimensions of the trailer and an example of the positions of the gas sensors for a set of experiments. The diameter of the dome hole is 630 mm.

Typical results are shown in Fig. 3a and b. The positions of the IR sensors and the wind direction are as given in Fig. 2, the mean wind speed was 0.5 m/s. The shortest path on the tank wall between the centre of the dome hole and the respective sensor is given as distance to the source. The volume flow rates were adjusted to about 130 m^3/h, which is representative of the maximum filling rates via one loading arm in practice.

The three different propane concentrations at the source serve to simulate the effects of different vapour pressures (LEL = 1.7 vol.% for propane). For safety considerations run 3 with nearly pure propane is the most conservative case; in terms of the initial vapour density, the consecutive dilution and dispersion process may be regarded as substitute for the dilution of petrol vapour–air mixtures at a temperature of about 26 °C. In this case the explosive range extends up to distances of 5 m (see Fig. 3a and b).

As can also be seen from Fig. 3a and b the comparatively lean mixture with 14 vol.% propane in air is dispersed below LEL within a distance of about 0.5 m (dilution factor about 10). The density of this mixture is comparable with, for example, saturated ethanol vapour–air mixtures at temperatures above 50 °C.

In Germany we found vapour displacement via the dome hole in practice only at ethanol filling stations. In a corresponding on-site measurement, the displaced vapours from ethanol at 20 °C (source concentration 5.9 vol.%) did not exceed $c_{max,s}$ = 1 vol.% (33% of LEL) at distances ≥0.5 m from the source. This roughly confirms the above-mentioned substitution.

In our test field we also investigated the vapour displacement via the vapour balance connection, which was positioned in a cabinet at about half the length of the trailer and 0.65 m above ground level. The diameter of the release opening is 100 mm. In our test the horizontally escaping stream was immediately deflected 45° towards the ground by a plate. In the test runs, the IR sensors were positioned downwind from the source on a line at ground level. The distance of the individual IR sensor from the source was measured along that line.

In the first set of experimental runs we selected release conditions (flow rate and initial concentration) close to the parameter of the above discussed dome release. The wind direction was nearly vertical to the tank axis and the mean wind speed was 0.25 m/s. The concentration data as measured at different distances from the source are shown in Fig. 4a and b.

Fig. 1. Typical concentration signals from two IR sensors at different distances from the source. The outflow at the source is stationary; fluctuations are generated by atmospheric turbulence.
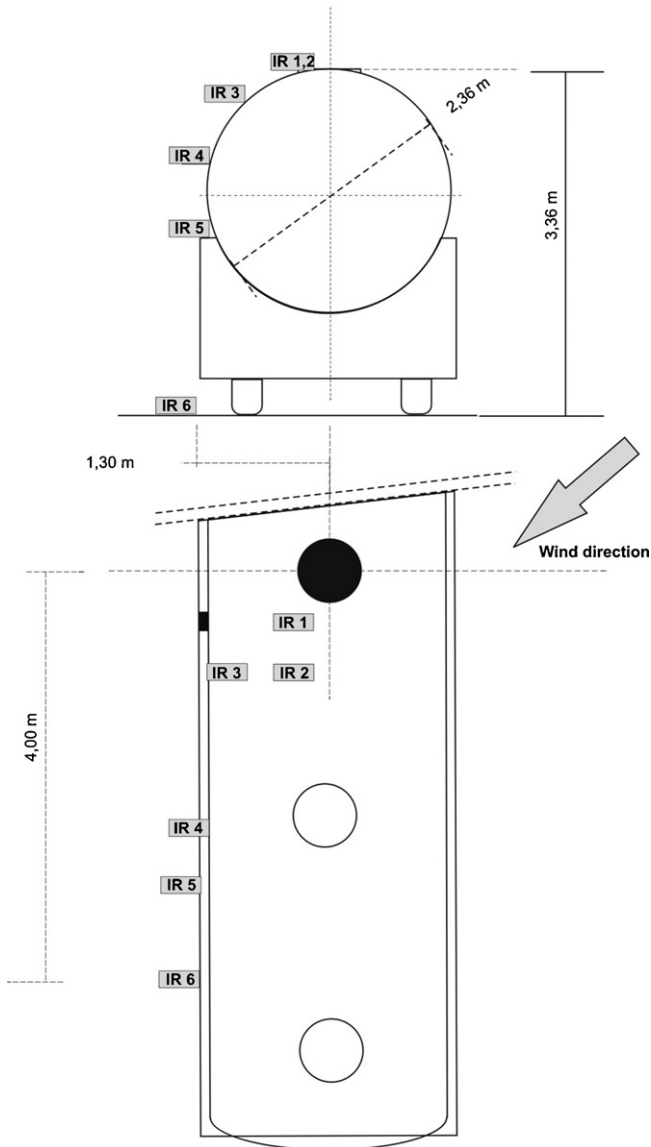
Fig. 2. Dimensions of the road tank trailer and positions of the dome hole (black circle) and of the six IR sensors for a typical experimental set-up.
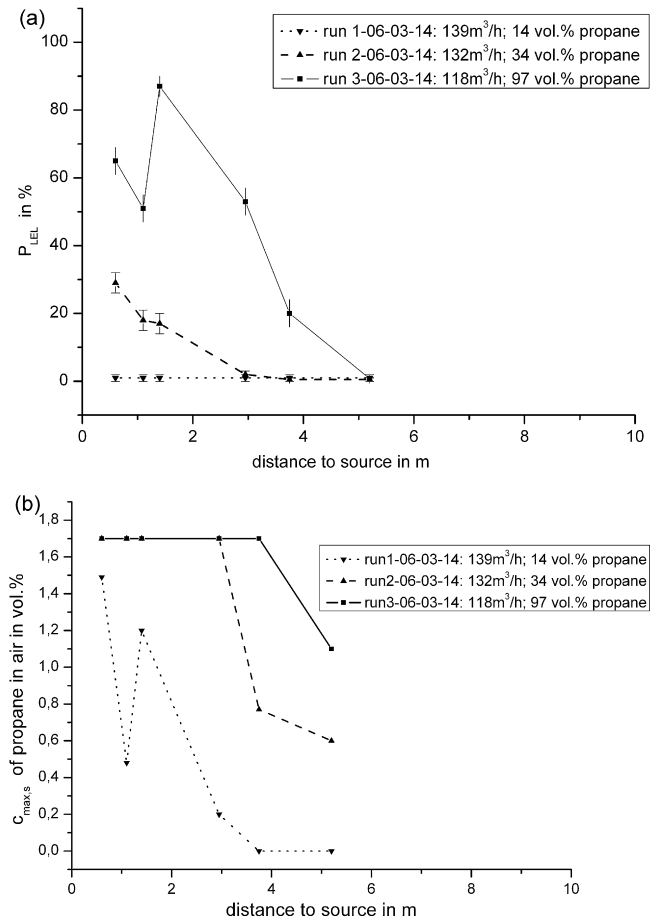

Fig. 3. Typical results from dome hole releases of propane–air mixtures (LEL = 1.7 vol.%). The set-up of the IR sensors is according to Fig. 2. The stationary flow rate is approximately as generated by one filling arm. (a) Fraction P_{LEL} of measurement time during which LEL was exceeded in percent as a function of the distance from source. (b) Maximum concentration $c_{max,s}$ as a function of the distance from the source.

In further experimental runs we increased the flow rate to about 600 m^3/h, which corresponds to the total rate of simultaneous filling by four loading arms, see Fig. 5a and 5b.

When comparing – for similar initial concentrations and release rates – the P_{LEL} and $c_{max,s}$ data from dome release (Fig. 3, run 3) and vapour connection release (Fig. 4, run 3), the release from the vapour balance connection shows a significantly larger hazardous range in the wind direction (about 10 m). The difference can be attributed

- to a jet formation in direction of the wind in contrast to the diffuse emanation as in the case of the dome-release test and
- to the comparatively minor vertical dispersion due to the lower elevation of the source above ground.

Another important feature is to note when comparing releases from the vapour balance connection with similar mass flow rate but of different initial concentrations of flammable substance: run 3 in Fig. 4 and run 2 in Fig. 5 have a similar release rate of flammable volume (118 m^3/h and 115 m^3/h of pure propane vapour respectively),

but the extension of explosive atmosphere – using, for example, the criterion $P_{LEL} \leq 1\%$ – is 4 m for the lower initial concentration (20 vol.%) and 10 m for the higher one (88 vol.%).

We attribute this to the fact that the dilution within the measured distances is predominantly governed by the dispersion of the continuous turbulent jet flow in the nearly stagnant surrounding air (flow velocities of the mixture in the source orifice about 5 m/s and 20 m/s. Supposing self-similarity of the flow and concentration fields, one might expect then a predominant scaling of the concentration field with the initial source concentration rather than with the absolute rate of release of flammable substance [7].

2.3.2. Loading with vapour balancing

Depending on the product, two different loading techniques may be discerned:

- The top-loading technique uses some form of plug for the dome hole to fit the product line and the vapour line. When attaching and removing the plug the tank is temporarily open (transient outflow at the dome hole).
- Closed systems are required for toxic products or for gasoline (for example, by the European VOC-Directive [6]). This is commonly fulfilled by bottom-loading systems, equipped with self-sealing product couplings for each compartment and for the vapour balance coupling (one for all compartments). It is common practice
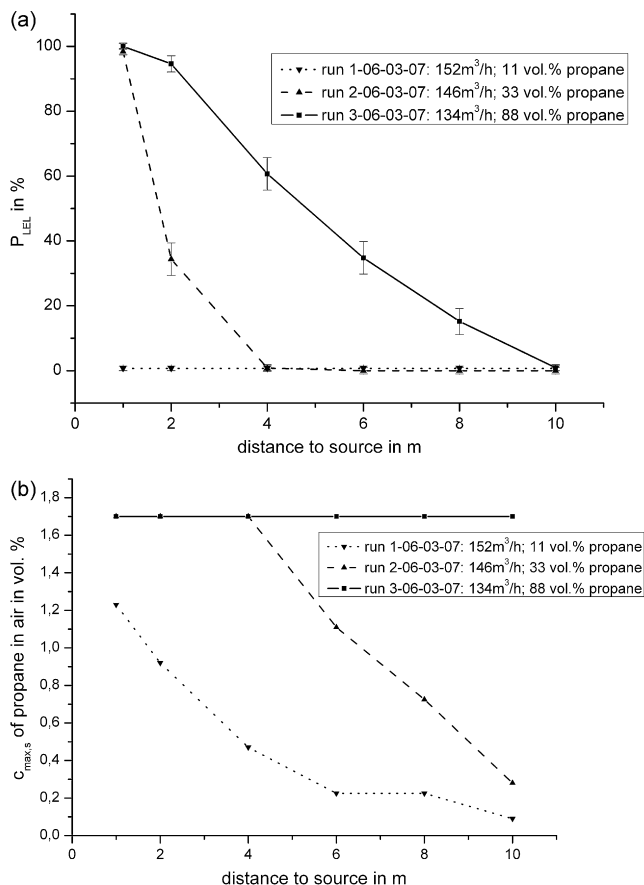
Fig. 4. Typical results from vapour balance coupling releases of propane–air mixtures (LEL = 1.7 vol.%). The arrangement of IR sensors is linear on the ground (see text). The stationary flow rate is approximately as generated by one filling arm. (a) Fraction P_{LEL} of measurement time during which LEL was exceeded in percent as a function of the distance from source. (b) Maximum concentration $c_{max,s}$ as a function of the distance from the source.

Fig. 5. Typical results from vapour balance coupling releases of propane–air mixtures (LEL = 1.7 vol.%). The arrangement of IR sensors is linear on the ground (see text). The stationary flow rate is approximately as generated by four filling arms. (a) Fraction P_{LEL} of measurement time during which LEL was exceeded in percent as a function of the distance from source. (b) Maximum concentration $c_{max,s}$ as a function of the distance from the source.

that each tank compartment (up to six) can be loaded alternately with gasoline or diesel fuel (switch-loading).

Experimental investigations of the loading processes with vapour balancing were only performed on-site.

Top-loading processes were investigated for the filling of road tankers with *n*-butyl acetate and methyl acetate and for the filling of rail tank wagons with methyl tertiary butyl ether (MTBE). The vapour pressure of MTBE matches that of some gasoline types and is by far the highest of the three investigated substances (at a given temperature, for example, 270 mbar at 20 °C). Furthermore, the rail tanks have a volume of 80 m³ in contrast to a road tanker compartment of about 10 m³. Aiming for conservative conditions we therefore concentrated on the loading of rail tank wagons with MTBE and investigated about 10 such processes. The temperature of the ambient air and at the bottom of the tank was about 22 °C whereas the wall temperatures on top of the tank amounted up to 42 °C.

Fig. 6 shows by way of example the geometry and dimensions of the dome hole and cover lid and the positioning of the IR-sensors on top of the tank (cat walk) to scale. Fig. 7 gives the time lapse of the concentration together with time marks for the relevant operating states. The corresponding measured maximum concentration $c_{max,t}$ of MTBE in vol.% is noted in Fig. 6 at the sensor symbols.

Summing up all findings and data with a view to safety aspects the following can be stated:
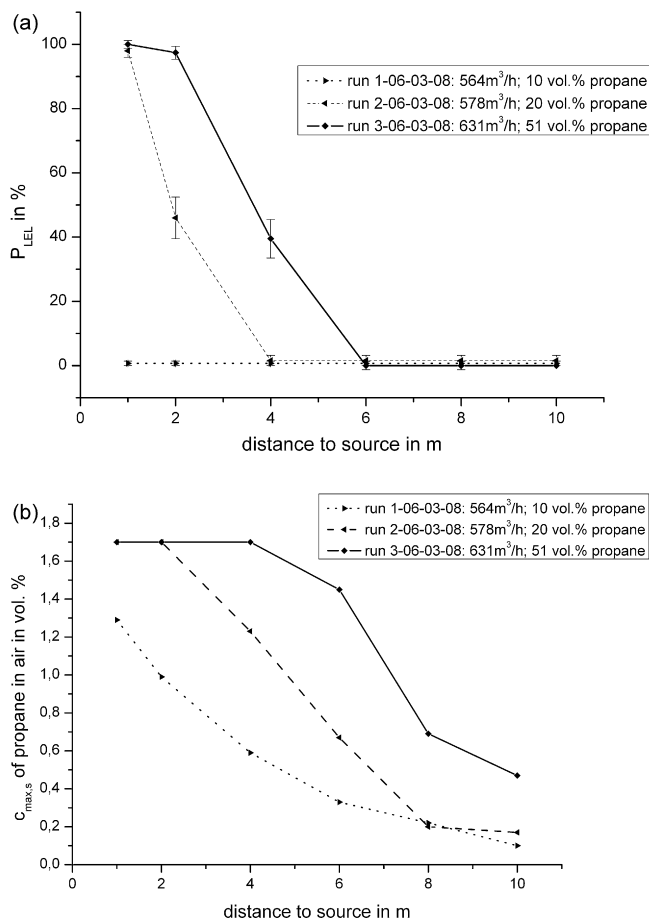
- Any significant vapour release is limited to the short periods (about 2 min) needed for the coupling operation at the beginning and the end of the filling process (Fig. 7).
- All the tankers in the train had the same history with regard to atmospheric influences and load. Nevertheless about half of the tested tanks did not show the first gas burst. In these cases apparently the tanks arrived at the filling station with the dome not being closed gas tight.
- The present experimental data relate to releases of MTBE-vapour–air mixtures from rail tankers and indicate an extension of the transient explosive atmosphere (LEL = 1.6 vol.% [8]) up to a distance of 0.8 m from the source, see Fig. 6.

Clearly the critical process is here the opening (and pressure relief) of an empty tank for flammable liquids. On the one hand this is one of the most common processes when handling flammable liquids. On the other hand the resulting specific hazardous areas are hard to estimate generally due to a multitude of influencing parameters.

The vapour pressure (concentration at source) inside the tank depends on

- the concentration of the gas balanced into the tank during the previous discharge of liquid,
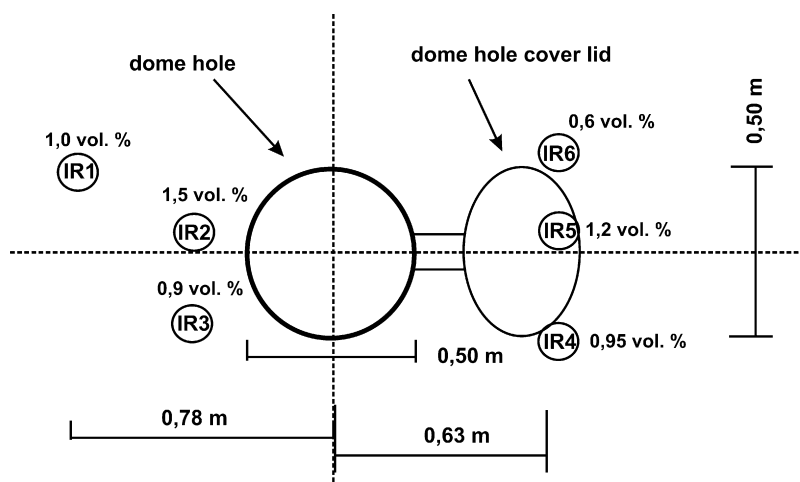- the temperature and amount of any residual liquid,

Fig. 6. Positions of IR sensors on top of the tank (cat walk) and corresponding maximum concentrations $c_{max,t}$ of MTBE (LEL = 1.6 vol.%) during a typical filling via the dome hole with vapour balancing (plug).

- the span of time after the discharge (homogenisation by convection or diffusion).

The overpressure in the tank before opening depends on:

- the temperature changes (gas, liquid, and tank wall) in the time span between the previous discharge and the moment of opening,
- the amount of residual liquid (possible evaporation and build-up of vapour pressure),
- the leak rate and duration of any leakage,
- the set pressure of any pressure relieving device.

The shape and duration of the resulting vapour cloud depends further on

- the geometry and flow resistance of the venting orifice,
- the volume of the vented tank.

In the present experiments we were able to select conservative conditions regarding the properties of the liquid and the tank volume but other important parameters like "temperature at discharge", "amount of residual liquid" and "solid angle covered by the gas jet" were not accessible under the conditions of a busy filling station.
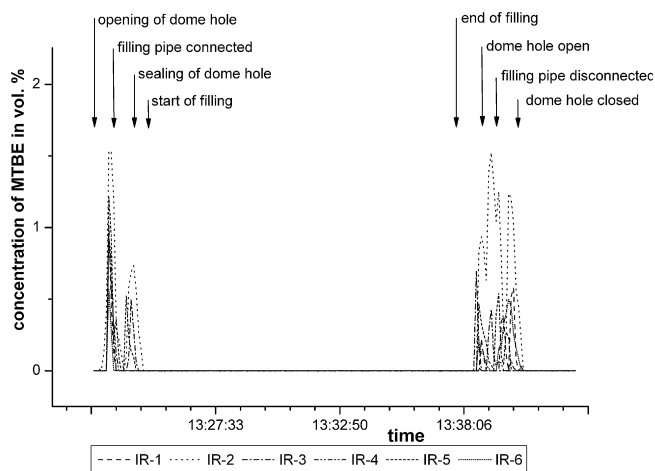

Fig. 7. Concentration of MTBE (LEL = 1.6 vol.%) as function of time during a typical filling via the dome hole with vapour balancing (plug).

Therefore, to get a rough calculative estimate for worst case situations, we refer to MTBE (vapour pressure, LEL) and anticipate a maximum temperature rise from 20 °C at the time of discharge of liquid to 50 °C at the time of opening the vapour space; the latter temperature value is taken over as maximum from RID/ADR. From the amount of released fuel, the radius R_{calc} of a resulting hemispheric vapour cloud with homogeneous LEL-concentration may be calculated and may serve as indication of the maximum explosive range. For a 10 m^3 tank R_{calc} is then significantly different for a completely liquid-free tank (R_{calc} = 2 m) and a tank with continuously evaporating liquid rest (R_{calc} = 4.8 m). For a rail wagon with 80 m^3 tank these radii respectively scale by a factor 2 (cube root of tank volume).

In principle the formation of a gas jet covering a solid angle smaller than 2π would be even more critical than the assumed hemispherical cloud. On the other hand the simplifying assumption of a homogeneous concentration has been proved to be extremely conservative from comparisons with more realistic CFD-models [9].

For bottom-loading processes with closed vapour balance systems we performed about 15 on-site tests on road tankers. The usual procedure was the simultaneous loading of gasoline and diesel fuel, where the displaced vapour–air mixtures were conveyed via the one vapour balance coupling to the filling station premises.

The IR-sensors were positioned on the ground, 0.65 m vertically below the self-sealing product line connections and the vapour balancing connection. The results of the experimental runs (normal operating conditions, ambient air temperature up to 23 °C, tank wall temperature up to 40 °C) are summarised as follows: gasoline vapour concentrations above the sensitivity limit (0.02 vol.%) were detected only directly after the disconnection of the vapour line and only for some 10 s. In nearly all cases the peak concentration then ranged below 30% LEL and only in one case was LEL reached. It became apparent that vapour–air mixtures emanate from both open-ended vapour line sections after disconnection due to the influence of gravity. The respective mixture volumes depend on the diameter (typical 100 mm) and on the length of the vapour lines between coupling and the respective sealing valves (2 m up to 8 m).

2.3.3. Atmospheric venting

Atmospheric venting of tanks transporting flammable liquids may occur during strong solar irradiation and a corresponding heat-up phase of the tank atmosphere. The venting takes place via a venting device (e.g. p/v-valve) on top of the tank or via the vapour
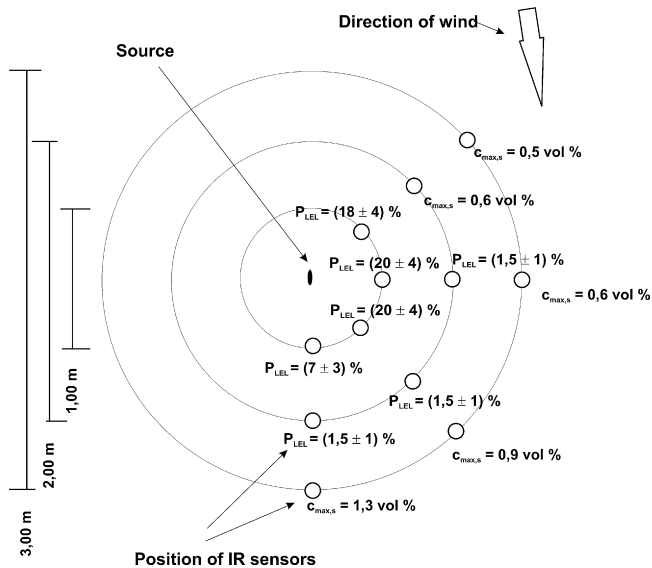
Fig. 8. Positions of IR sensors on ground level for simulating atmospheric venting. Release rate 4 m^3/h; source concentration 30 vol.% n-pentane in air (LEL = 1.4 vol.%). Depending on the signal level P_{LEL} or $c_{max,s}$ are given at the sensor positions.

balancing connection, which is switched to "open" during transport.

For this experimental investigation we decided to simulate worst case conditions in our test field in the following way.

Firstly, the maximum out-breathing flow rate of a 80 m^3 tank (rail tank wagon) during atmospheric heat-up under conservative conditions was calculated according to a corresponding guideline [10]. The resulting flow rate of 4 m^3/h was then used in the experimental field tests described below.

The vapour–air mixture of a highly volatile liquid was simulated in the experiments by a mixture of 30 vol.% n-pentane in air. This mixture could be handled safely in our facility and corresponds – with regard to density and mean molecular mass – to a saturated gasoline vapour–air mixture at about 40 °C.

The vent opening was simulated by the mouthpiece of a hose with a diameter of 50 mm positioned on ground level of a flat concrete area. The ground level position is untypical for venting devices in practice but it was chosen as most conservative after some preliminary tests with the source at elevated positions.

The IR-sensors were positioned concentric to the source successively at radii of 0.5 m, 1 m and 1.5 m. Fig. 8 shows for a set of measurements the positions of the IR-sensor, the wind direction and the resulting maximum concentrations $c_{max,s}$ as well as the probability P_{LEL} to exceed LEL (for n-pentane: LEL = 1.4 vol.%). The data indicate for explosive concentrations a maximum range of approximately 1.5 m.

Simultaneously, we determined the range of explosive atmosphere directly by approaching a propane torch flame (length approximately 50 mm) from the leeward direction. In 10 repeated tests the individual distances for ignition were found in the range of 1.0 m to 1.5 m. This corresponds very satisfactorily with the measured concentration data. It proves explicitly that the resolution in time and space of the applied method for measuring concentrations is well suited for assessing hazardous areas.

2.3.4. Relief of pipe coupling equipment (pressure-liquefied gas)

During the normal operation of tankers for pressure-liquefied gas, a release of flammable gas occurs only when the product line is disconnected after loading or unloading. Usually the coupling is locked by an upstream and downstream valve thus isolating a volume of approximately 0.6 l (mass of 300 g) of pressure-liquefied propane. Before disconnecting, this volume has to be relieved via a separate relief line.

The experimental investigation of this relief process was carried out at a typical filling station (technical grade propane).

Fig. 9 illustrates that filling station to scale with the essential dimensions of the investigated site and the positions of the IR-sensors in a plane vertical to the ground and to the tank axis and containing the relief line. The relief is started manually. Due to the formation of propane droplets and/or condensing water droplets the shape and duration of the propane gas jet can easily be observed. At the investigated site the jet is axis-symmetric and – directed vertically downward – impacts after a free path of 0.4 m on a nearly horizontal plate covering the manifold.

Fig. 10 shows for three repeated relief processes the propane concentration as a function of time. The relief processes were completed within 30 s. The maximum concentrations in the jet (as measured by sensors IR 4 and IR 5, see Figs. 9 and 10) were successfully reproduced in the repeated test runs. This is to be expected because the flashing liquid produces a gas jet of high impulse and so the relevant dilution process is governed by this reproducible jet itself and not by the turbulence in the atmospheric flow (as in most other cases).

Taking into account all six test runs for this specific condition and geometry we state $c_{max,t}$ = LEL at a linear distance of about 0.9 m from the nozzle. However it must be noted, that other conditions such as an unobstructed jet might lead to larger explosive ranges.
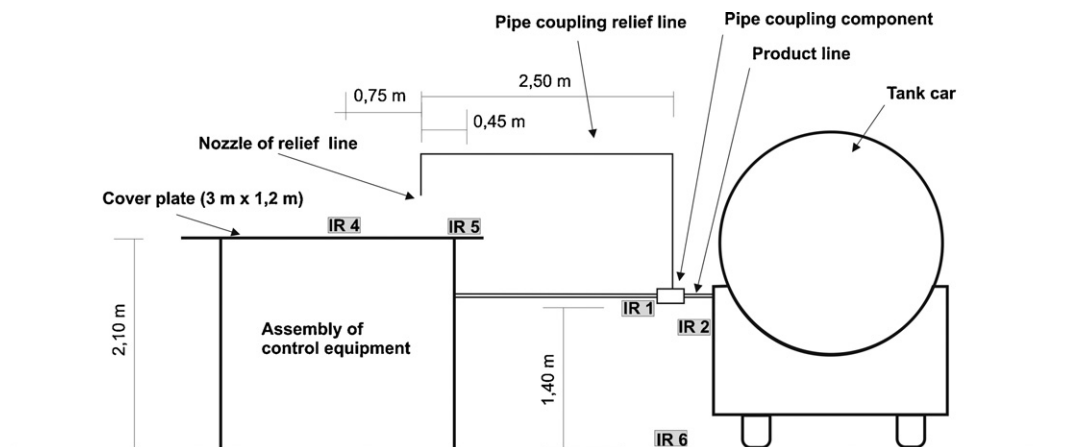

Fig. 9. Scheme of a typical filling station for liquefied gas (road tanker) including the arrangement of the IR sensors for a series of measurements.
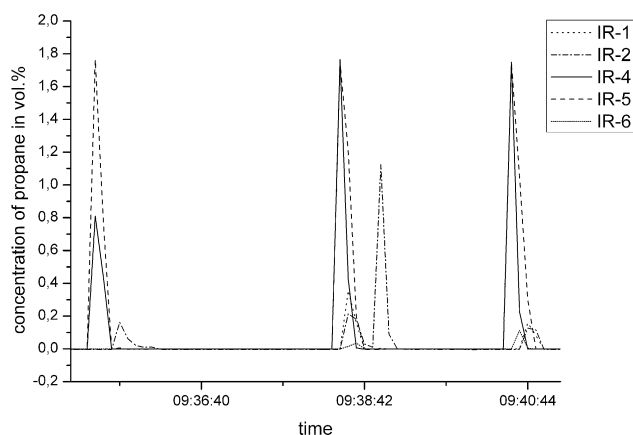
Fig. 10. Concentration of propane (LEL = 1.7 vol.%) as a function of time for three consecutive relief processes of the coupling for liquefied propane. The positions of the IR sensors are as given in Fig. 9. The released mass of propane is 300 g in each process.

In contrast, gas pockets which "fall" from the open coupling or from the roof of the cabinet to the ground are influenced by atmospheric turbulence, as indicated by the considerable scatter of the corresponding concentration data, which may be characterised by $c_{max,t} = 0.45$ vol.% (approximately 25% of LEL) 1.4 m below the coupling on ground level. This will also be greatly influenced by the detailed geometry of the site.

Therefore we checked and supplemented the experimental results by estimating the worst case situation. For that it is supposed that the maximum extension of the hazardous area is reached when the total amount of fuel locked in the coupling volume forms a hemispherical vapour air cloud with a homogeneous concentration of LEL = 1.7 vol.%. The radius of that hemisphere turns out to be 1.7 m, confirming the above mentioned conservative character of such estimates [9].

3. Ignition sources

3.1. Background

The present regulations take only electrical equipment into account as a potential source of ignition and the relevant assessment and rating complies with international electrical standards and allows appropriate protection measures in practice.

In contrast to this, non-electrical equipment remains largely neglected in the regulations. But of course, mechanical ignition sources such as sparks from grinding and impacting and hot surfaces must not be neglected a priori.

Mechanical sparking is possible in case of failures; it is, however, not considered here further due to the comparably low probability of occurrence. By contrast, hot surfaces exist during normal operation at the motor, the turbo charger, the exhaust and the brakes.

Customarily it is required that the surface temperature of such equipment does not exceed the standard ignition temperature $T_{z,standard}$ of the relevant flammable substance.

However, it is well known from the literature [11] that the actual temperature $T_{z,real}$ necessary for ignition is often considerable higher than the tabulated standard ignition temperature $T_{z,standard}$. Details depend on

- the geometry: $T_{z,real}$ decreases with increasing size and convexity of the hot surface,
- the prevailing flow conditions: $T_{z,real}$ decreases with decreasing flow velocity of the flammable mixture.
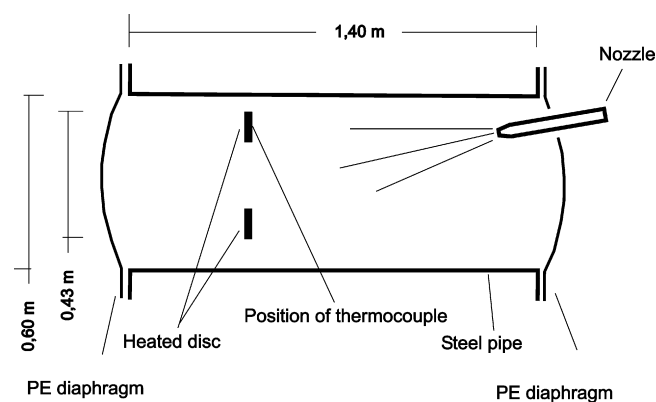

Fig. 11. Scheme of the set-up used for testing the actual ignition temperature $T_{z,real}$ by example of a model brake disc.

Therefore $T_{z,standard}$ is often a very conservative limit in practice.

On this background we decided to carry out ignition tests with a typical break disc, which is of maximum size and of flat shape – that is to say most "convex" – compared to the other relevant pieces of equipment in question.

3.2. Experimental

For the ignition tests we selected hexane ($T_{z,standard} = 230\,°C$) and diethyl ether ($T_{z,standard} = 175\,°C$) as customary substances with low $T_{z,standard}$.

Hexane can be seen as a substitute for gasoline which – among dangerous goods with low standard ignition temperature – makes up the predominant amount of tank transports.

Diethyl ether has one of the lowest standard ignition temperatures lying very close to the lower limit $T_{z,standard} > 135\,°C$ of the temperature class T4, which covers practically all substances apart from carbon disulphide.

Experimental ignition tests under real practical conditions clearly do not come into question. In order to simulate relevant situations we manufactured a full-scale electrically heated model brake disc from steel (diameter 430 mm, maximum-attainable surface temperature 570 °C). This disc was suspended vertically in a horizontal steel pipe (diameter: 0.60 m, length: 1.40 m). The end flanges of the pipe were loosely closed by PE-diaphragms to allow the accumulation of gas–air mixtures in the pipe. Fig. 11 gives a schematic sketch of the set-up.

Hexane–air mixtures of 2.1 vol.%, 5 vol.% and 10 vol.% were flushed at a rate of 300 l/min (mean flow velocity about 0.02 m/s) through the pipe. Simultaneously the disc was heated-up from ambient to 570 °C. In no case an ignition of the vapour–air mixtures could be registered.

As premixed diethyl ether–air mixtures could not be produced in a definite way in our facility we decided to spray that liquid directly into our test set-up. To provide a steady slight venting only the lower half of the pipe flanges was covered by a diaphragm. While steadily increasing the temperature of the disc we sprayed 20 ml of the liquid within 2 s on the disc and repeated this every 120 s. In this way we could confirm that an ignition of the vapour–air mixture took place only when the surface temperature of the disc exceeded 370 °C.

4. Conclusions for explosion protection

With regard to the occurrence and duration of hazardous areas in the course of time our investigations highlight that the most extended hazardous areas are sharply limited to the well known

and defined time period of loading. This simple statement implies two important consequences:

- The attribution of zones to such areas makes no sense because zoning bases on probabilities of occurrence and a loading process causing the simultaneous occurrence of a hazardous area is not a matter of probability.
- Any gas explosion is caused by a coincidence of ignition source and explosive atmosphere in space and time; so in such cases of well known critical time periods during loading explosion prevention may readily be achieved by switching off/avoiding ignition sources.

Among the investigated processes only the atmospheric out-breathing gives rise to a probabilistic approach with regard to the occurrence of explosive atmosphere. Here the usual rating as "occasionally" leads to the attribution of a zone 1 in accordance with present regulations [1].

All the other investigated processes are related to the loading of product. The appropriate measures of protection are here

- installation of protected equipment in that area or
- de-energising of non-protected equipment for the loading period in that area.

For the first option the degree of protection needs to be specified, taking into account that the related time span with explosive atmosphere is maximum about 15 min for these cases. In our view these rather short periods suggest that protection by "restricted breathing" [12] or possibly even "ingress protection" [13] provides the necessary level of safety. Since restricted breathing is a protection typical for equipment suited for zone 2, we eventually propose "suitability for zone 2" for equipment in the relevant area (instead "suitability for zone 1" as in the present regulations).

For the second option to become an effective means of protection we see the need for a binding ruling that unprotected equipment with potential ignition sources in the relevant area shall be de-energised from the start of the loading process until its end. Such mandatory operational requirement clearly has to cover both electrical and non-electrical equipment.

With regard to the spatial extension of hazardous areas our experiments confirm that the loading situation is the most critical one and that the release mode (volume flow rate) and the flashpoint in case of liquids are the main influencing factors.

According to the used technique, the release modes differ considerably for gases (class 2) and liquids (class 3) and in the latter case releases are significantly influenced by the potential use of a vapour balancing system.

As regards liquids the lower flash points largely bring about higher vapour pressures, which means higher fuel loads in the displaced tank atmosphere and so a trend to larger explosive ranges. The present relevant regulations incorporate only an upper limit for the flashpoint (60 °C). For worst case scenarios we therefore must refer to data gained from low flashpoint liquids like gasoline and MTBE or from substitute propane–air mixtures with extreme propane content (above 80 vol.%).

With a view to rule-setting for the handling of flammable liquids we assess relevant processes as follows.

For the filling via the open dome without vapour balancing system we may refer to our conservatively designed field experiments. Accordingly a maximum range of 10 m for the explosive atmosphere during loading of a road tanker should be taken into account.

For vapour balancing systems which require a short opening of the vapour space for coupling we refer to our on-site investigations at a rail tanker ($80 \, m^3$) and to a rough calculative estimate. On the basis of this information we estimate that the range of explosive atmosphere after opening a liquid free road tanker compartment ($10 \, m^3$) will hardly exceed 2 m.

The investigation of loading processes with vapour balancing systems and self-sealing couplings revealed hazardous areas for some 10 s after decoupling and extending about 0.6 m below the coupling component. The vapour balance coupling often serves as vent opening during transport and the related hazardous area (see the following paragraph) exceeds that with regard to duration and extension.

For the atmospheric venting of tank compartments with a volume of up to $80 \, m^3$ we performed experiments under conservative conditions and – as result – we recommend to take account a maximum range of 1.5 m from the source as zone 1.

For pressure-liquefied gases we refer to the customary technique of releasing about 300 g gas during the disconnection of coupling components. On the basis of on-site tests supplemented by a rough worst case estimate, a transient 1.5 m range of explosive atmosphere at the relief orifice during de-coupling should be taken into account.

As regards ignition sources during the normal operation of road tankers potential non-electrical ignition sources may arise from hot surfaces of components such as motor, turbo charger, exhaust and brakes. From systematic ignition tests under conservative conditions we conclude, that substances down to the temperature class T4 (ignition temperature >135 °C) will not be ignited in practice as long as the surface temperature of the relevant equipment remains below 350 °C.

Conclusions for a further development of the ADR have been summarized in an informative text proposal [14], which is accessible on the home page of the UNECE group.

Acknowledgements

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