Consequences of the failure of mobile gas vessels

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Small, mobile propane gas vessels are widely spread and comprise additional hazards in case of a surrounding, intensive fire. The aim of the presented work is to holistically investigate the potential consequences of failure of these off-the-shelf propane gas vessels in case of an absence or malfunction of safety devices. In order to generate a statistically valid dataset, a total of 15 identical propane gas bottles without pressure relief device, each containing m = 11 kg of liquid propane, were underfired in horizontal position. For each selected fire type (wood fire, petrol pool fire, propane gas fire), five vessels were tested under identical conditions. Next to extensive camera equipment including a high-speed camera, systems to record the internal pressure of the gas cylinder, the resulting shock wave overpressure (three positions) and the flame and vessel temperature (three + three positions) during the underfiring were used. Also the unsteady, highly dynamical thermal radiation caused by the explosion of the expanding gas cloud was logged. The fragments were georeferenced and weighed after each test. The experiments prove the failure of all the gas cylinders at a burst pressure of p_b = [71 … 98 bar] with a fragmentation into up to seven parts (average: four objects) and a subsequent explosion of the expanding vapour after mixing with the surrounding air. The overpressure measured in the close-up range (distance to the cylinder d = 5 m) resulting from the shockwave caused by the cylinder burst was up to p_{max} = 0.27 bar, which can potentially lead to significant injuries to humans and damage to building structures and infrastructure, especially in connection with the explosion and the resultant thermal radiation. The distance covered by the fragments after the failure was up to r = 260 m; 47% of the fragments hit the ground more than r = 50 m away from the position of failure.

Keywords: Failure of gas vessels, propane cylinder, gas explosion, consequences, fragmentation

Introduction

Mobile, off-the-shelf gas cylinders containing liquid gases (mainly propane) are widely spread and can be found on construction sites, in workshops, in recreational vehicles, in private households and restaurants, for example. Thus, in case of a fire, it is not uncommon that gas cylinders are involved. Often the rescue forces are not able to perceive or to confirm the presence of these containers comprising additional hazards. Due to the heat transfer into the liquid propane inside the vessel, more of the liquid propane gets vaporised, leading to a considerable pressure increase. Safety devices like (thermal) pressure relief devices (PRD) assure the venting of the high-pressure gas, before the burst pressure of the cylinder has been reached. Furthermore, the heat impact on the container material might cause a decrease in the burst pressure of the cylinder.

In spite of installed safety devices, failure of a propane cylinder is possible in general, leading to severe hazards like fragmentation, thermal radiation and high temperatures due to a vapour cloud explosion, blast waves etc. Depending on the condition of the vessel itself and the safety devices, the position of the affected container, the sequence and intensity of the heat and/or fire exposure, a failure of the vessel is a realistic possibility. The failure leads to a sudden release of the liquid propane, a concluding vaporisation and turbulent mixing with the ambient air. This propane air mixture might ignite abruptly, depending on the mixing ratio and the presence of a sufficient source of ignition, which is usually present in case of a fire.

The described scenario is not unrealistic, as several accidents involving failing propane vessels that have been exposed to a fire or an intensive heat source are documented in the media and in mission reports of fire services, often with serious injuries, near-misses and/or even fatalities occurring. For example, a fragment of a propane cylinder that was heated by a burning asphalt cooker on a roof killed a passer-by in Duesseldorf (Germany), (Leineweber 2008). Another example happened in Marseille (France) in 2015 during a house fire, (Marins du feu 2015). Two firefighters were seriously injured, when a propane vessel exploded.

The European standard EN 1442 (DIN EN 2008) regulates the requirements concerning design and construction of the small, refillable welded steel LPG cylinders with capacities of V = [0.5 … 150 dm^3]. This standard also describes the calculation of the minimum burst pressure and the hydraulic test to prove the compliance with this requirement. The requirements on the valves are standardized and defined in ISO 15995 (ISO 2006). According to this international standard, safety devices like pressure relief valves (PRV) can be installed to avoid the potential bursting of the gas vessel. The European standard EN 13953 (DIN EN 2015) regulates design, dimensioning etc. of these safety valves that are mandatory in Germany due to the regulations of (ADR 2015).

A number of previous scientific projects and publications deal with the behaviour of gas vessels in fire or with intensive heat flux into a gas cylinder. In a small test series (Birk et al. 2003), six propane cylinders equipped with PRVs were underfired with three different burner configurations. In the tests with the three steel containers, the PRV released the content as prescribed, no vessel failure occurred. But the three cylinders made of aluminium failed within a time period of t < 10 min. The focus of this research was set on the operation of the PRV, not on the consequences of vessel failure. Another publication (Hora et al. 2015) deals with the effects of failure of gas vessels for different substances (oxygen, acetylene, hydrogen, propane) on building structures. A test series with several LPG cylinders (filling mass m = 5 kg and m = 11 kg), that were underfired with a gas burner, is described in (Stawczyk 2002). The reported distances of the fragments are up to r = 300 m. The results of a test series with three small camping gas cartridges (m = 0.44 kg mixture of propane and butane) that failed after having been underfired by a barbecue grill are described in (Davison et al. 2008). All the previous work described here and most other publications dealing for example with gas tanks for vehicles like (Weyandt 2007) comprise only single experiments (e.g. change of the burner configuration, different fill levels of the containers, different types of vessels), or test series including only a very small quantity of identical test objects. Thus, valid conclusions about possible consequences of a potential failure of a gas vessel are hardly possible using existing data.

The presented experimental test series is part of an interdisciplinary project within the German federal institute for materials research and testing (BAM). The focus of the project “CoFi-ABV” (Complex Fires – Consequences of accidental failure of gas tanks) is to investigate holistically the consequences of failure of gas vessels by considering complex fire and explosion scenarios. Vessels for alternative fuels used in vehicles constitute the core of the project.

Experimental set-up

The following section comprises a comprehensive description of the gas vessels and the measures taken to prepare them for the experiments, the measurement equipment used and the bonfire test set-up. It enables the check of other, past and future test series for comparability.

Preparation of gas vessels

For the described test series, 15 identical, commercial off-the-shelf gas cylinders were used. These cylinders are made of two large pieces with one circular weld seam at half height of the cylinder and have a tare weight of m = 11.5 kg. They comply with EN 1442 (DIN EN 2008) and are marked according to EN 14894 (DIN EN 2013). The volume of the containers is $V = 27.2\ dm^3$. Their test pressure is defined to $p_h = 30$ bar. For this type of gas vessel, EN 1442 demands a burst pressure of at least $p_b = 50.1$ bar.

The regular cylinder valves with the PRD have been removed and replaced by a ¼” tube adapter and a needle valve. Due to these modifications, no safety device can prevent the pressure increase in the cylinder caused by the heat flux during a test. Afterwards, the containers were filled with m = 11 kg of liquid propane (purity ≥ 95%), so that the volume of each cylinder was filled to 81.3% ($\rho = 0.501\ kg/dm^3$ for liquid propane at $T_{ambient} = 20°C$ (Yaws 1999)). The gross weight of each cylinder was m = 22.5 kg.

Measurement equipment and instrumentation

Comprehensive measurement equipment was used during the test series. Next to pressure and temperature measurement systems, several video cameras (including one high-speed camera and a camera installed on an unmanned aerial vehicle, UAV) were used. Bolometers recording the thermal radiation were installed in the surrounding. Figure 1 depicts schematically the measurement set-up. For data acquisition, two AD converter systems were used. One system was equipped with an additional thermocouple input signal conditioner and was set to a data acquisition frequency of f = 100 Hz. The other AD system was used for the pressure recordings and was set to f = 1000 Hz.

The surface temperature of the vessels in the fire impact until vessel failure was measured using type K thermocouples (diameter d = 1.5 mm) at three positions (top, bottom and mid position) around the vessel at half the cylinder length (12, 3 and 6 o’clock position, TIR 101 to 103, cf. Fig. 1). In a radial distance of approximately d = 25 mm to these positions, the corresponding flame temperature was recorded with three more type K thermocouples (diameter d = 3 mm, TIR 104 to 106, cf. Fig. 1). These thermocouples were covered by a little metal sheet that was welded on the vessel surface. Another thermocouple (type K, diameter d = 1.5 mm) was integrated into each cylinder through the tube adapter and positioned in the liquid phase (TIR 107, cf. Fig. 1). The last thermocouple TIR 108 (cf. Fig. 1) was used to assure a permanent compliance with the specified operational conditions of the pressure sensor PIR 201 (piezo-resistive sensor, $p_{max} = 100$ bar, accuracy a = 0.5% of full scale (FS) typical), which monitored the pressure inside the gas vessel during the fire impact until failure of the container. The pressure sensor was integrated into the end of a 6 m tube (diameter d = ¼”), which was mounted to the tube adapter at the gas vessel outlet.

The three pressure sensors in the near field (PIR 202 to 204, cf. Fig. 1, distance to gas vessel d = [5 m; 7 m; 9 m], piezo-resistive sensor, $p_{max} = 2$ bar, accuracy a = 0.25% FS typical) were used to detect and measure overpressure waves resulting from vessel failure itself or subsequent reactions. They were mounted to a stand at a height of h = 1 m above the ground with their membrane aligned parallel to the direction of movement of the blast wave.

Two robust HD cameras with a frame rate of f = 50 1/s covered the near field around the gas vessel with distances of d = 7 m and d = 9 m from two different perspectives. Another HD camera with f = 50 1/s was stationed in a distance of approximately d = 200 m for an overview video recording of several experiments. At the same position, a high-speed camera with a frame rate of f = 2000 1/s and an 800 mm objective monitored in detail the sequence of the vessel failure. A 4K camera attached to an UAV (f = 25 1/s) complemented the video recordings by another perspective.

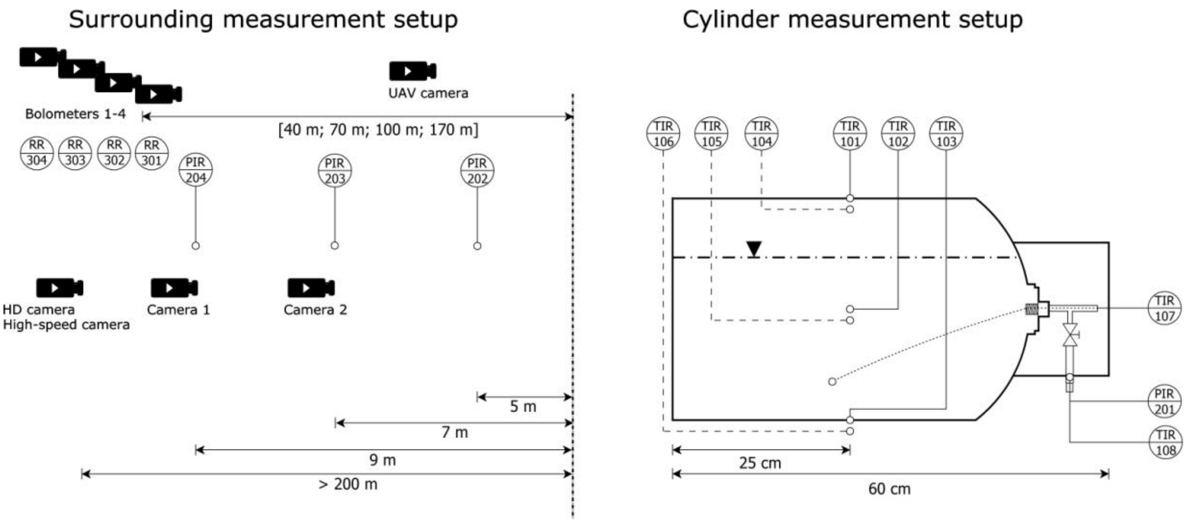


Fig. 1: Schematic diagram of the measurement set-up and instrumentation for the bonfire tests

For measurement of the thermal radiation, four bolometers (Medterm and LP111) were used. They were positioned in distances of d = [40 m; 70 m; 100 m; 170 m] away from the gas vessel. The first two bolometers (RR 301 and 302, cf. Fig. 1) have an integration time of 150 ms and 250 ms respectively for the recording of the radiation, while the two remote bolometers (RR 303 and 304, cf. Fig. 1) have a shorter integration time of 45 ms, which is characteristic for the specific construction and design of the sensor. The combination of pitch and aperture angle was adjusted to assure the visibility of the complete fireball.

The localization of the fragments of the failed containers in reference to their original position was conducted using a GPS supported system and a laser distance measurement system.

Bonfire test set-up

Three different types of bonfire were used. Five propane gas cylinders were underfired with each of the three bonfire types under comparable conditions. All the propane cylinders were underfired in horizontal position. An assessment of the impact of the specific weather on the test results is presented in Fig. 6 and section 3.2.

The experiments using wood and petrol as fuel took place on the large blasting area of the BAM Test Site Technical Safety (TTS) in Baruth/Mark in Brandenburg. The wood fire (cf. Fig. 2a) was realized using about 180 roof battens (with dimensions of 200 cm x 4 cm x 6 cm) resulting in a total of V = 0.85 m^3 of wood. The set-up was prepared in accordance with the UN 6(c) test (United Nations 2009). Ignition from the distance was accomplished using a petrol diesel mixture that was distributed on a layer of paper on half height of the stack of wood, and a pyrotechnical initiator. For the petrol pool fire, V = 0.1 m^3 of petrol in a trough with dimensions of 1.5 m x 1.5 m were used (Fig. 2b). For ignition, the pyrotechnical initiators were used as well. The last fire method using propane took place on a different test site on the TTS, the gas fire test bench. A total of 20 propane burners (5 x 4) with a mass flux of dm/dt = 0.18 kg/min of liquid propane for each nozzle assured an intensive bonfire (cf. Fig. 2c). A spark igniter and a pre-evaporator were also part of the experimental set-up for the third fire method.

a) Stack of wood

Corresponding tests: pc01 – pc05

b) Petrol pool

Corresponding tests: pc06 – pc10

c) Propane burner test bench

Corresponding tests: pc11 – pc15

Figure 2: Set-up for the three types of bonfire, identifiers of corresponding tests

Results

The major results of the destructive test series and a comprehensive analysis are presented in this section.

General description

Without safety devices like a PRD, the experimental set-up and procedure successfully ensured the failure of all 15 cylinders in the test series in a similar manner within a time period of t = [70 … 152 s]. After ignition, the temperature measured in the flame area immediately starts to rise. With a short delay, also the casing temperatures (TIR 101 to 103, cf. Fig. 1) follow this trend. During the intensive fire impact on the container, the resulting net heat flux into the cylinder causes a significant increase of the temperature of the liquid phase (TIR 107, cf. Fig. 1). Due to the increased temperature of the liquid propane, the vaporization of the liquid gas increases significantly and the pressure inside the container (PIR 201, cf. Fig. 1) starts to rise. Caused by the drastically increased temperature of the pressure vessel, a downgrading of the tenacity of the steel and the bursting pressure is possible. These two effects, the increase of the inner load on the container casing and the decrease in stability of the material, finally cause failure of the cylinder. An opening of the high-pressurized container, a subsequent sudden expansion of the gas and a resulting pressure wave occur. The complete amount of vaporized and liquid propane is released, the liquid phase vaporizes abruptly afterwards. Due to the high turbulence and energy, the vaporized gas is mixed with ambient air and is ignited subsequently. The result is a large, ascending fireball, depending on the type of fuel of the bonfire, high temperatures in the near surrounding and an intense thermal radiation.

Figure 3 exemplarily depicts the result of the failure of a propane cylinder, the ascending fireball (diameter approximately d = 13 m) after ignition of the propane/air mixture. Because of the bonfire type (propane fire), only propane released from the gas vessel is involved in the reaction and the fireball. Thus, the diameter of the fireball is comparatively small.

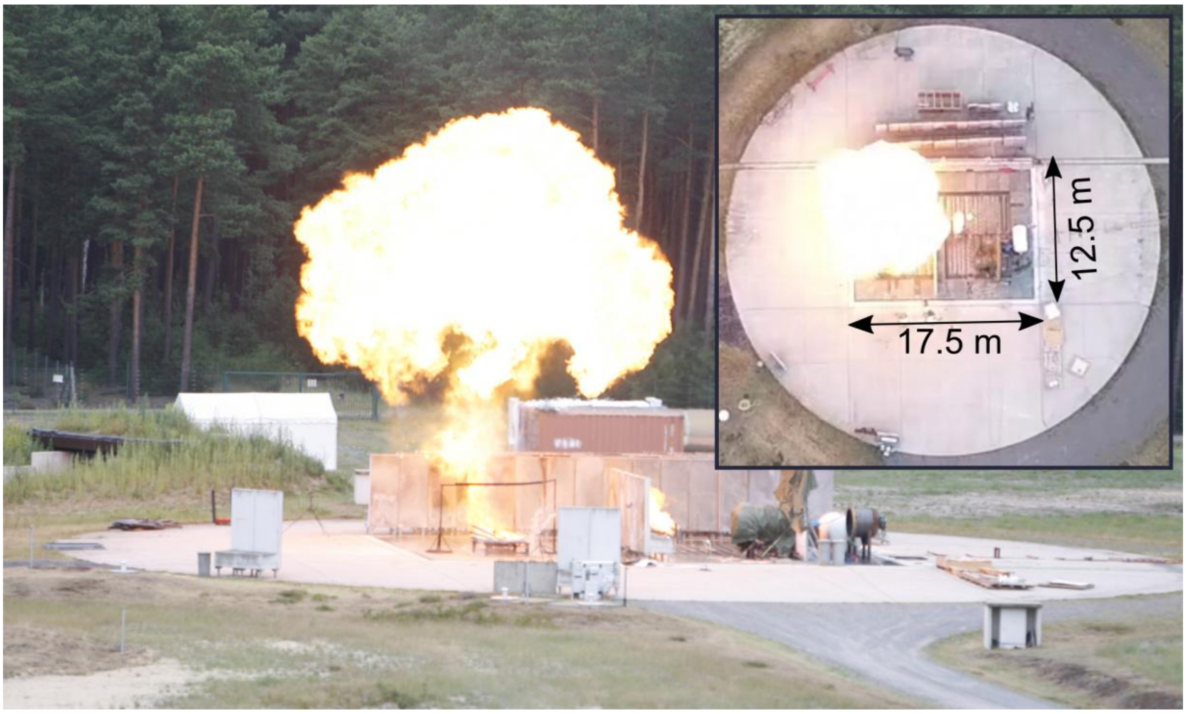


Fig. 3: Exemplary view on the fireball after failure of the gas vessel on the propane burner test bench (test pc12), side view and aerial view

The sequence presented in Fig. 4 gives a detailed insight into the process taking place when the vessel fails. In the first picture, short before failure, the enclosing propane bonfire under and around the cylinder and the intensive fire impact on the container can be seen. The shoulder of the cylinder is oriented to the right in this sequence and the following photographs. It can be seen, that the cylinder is still intact, but the increased diameter of the cylinder due to the high inner pressure and the strain of the metal can be observed. In the second picture, the container releases the complete propane and the liquid phase begins to vaporize, which continues in the third picture. The gas cloud ascends due to the impulse of the opening process and buoyancy. In the fourth picture, the gas cloud (mixture of propane and ambient air) is ignited by a source of ignition near the propane burner test bench. The reaction starts at the lower part of the gas cloud and spreads spherically to the sides and upwards (cf. fifth and last picture). The severe, destructive impact of vessel failure on the test bench and one major fragment rocketing from the reaction zone to the left can be observed clearly in the last four photographs.

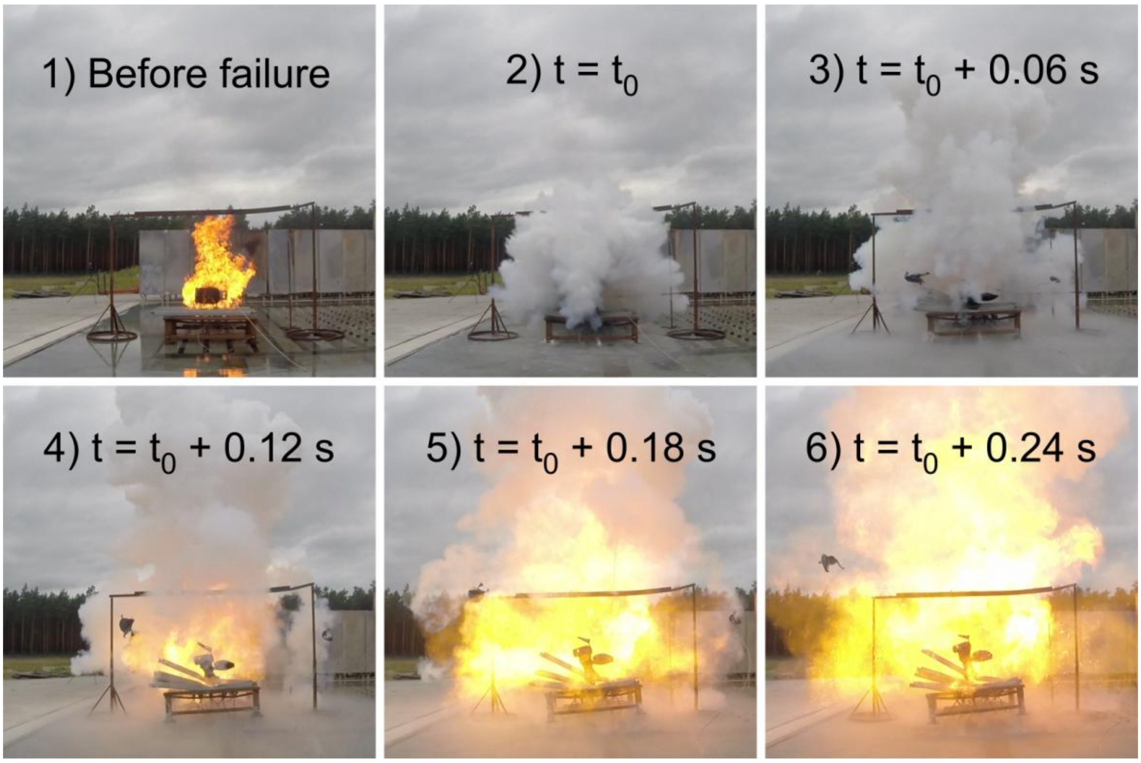


Fig. 4: Exemplary sequence of the process during failure of the propane cylinder on the propane burner test bench (test pc12), camera 2, frame rate f = 50 1/s

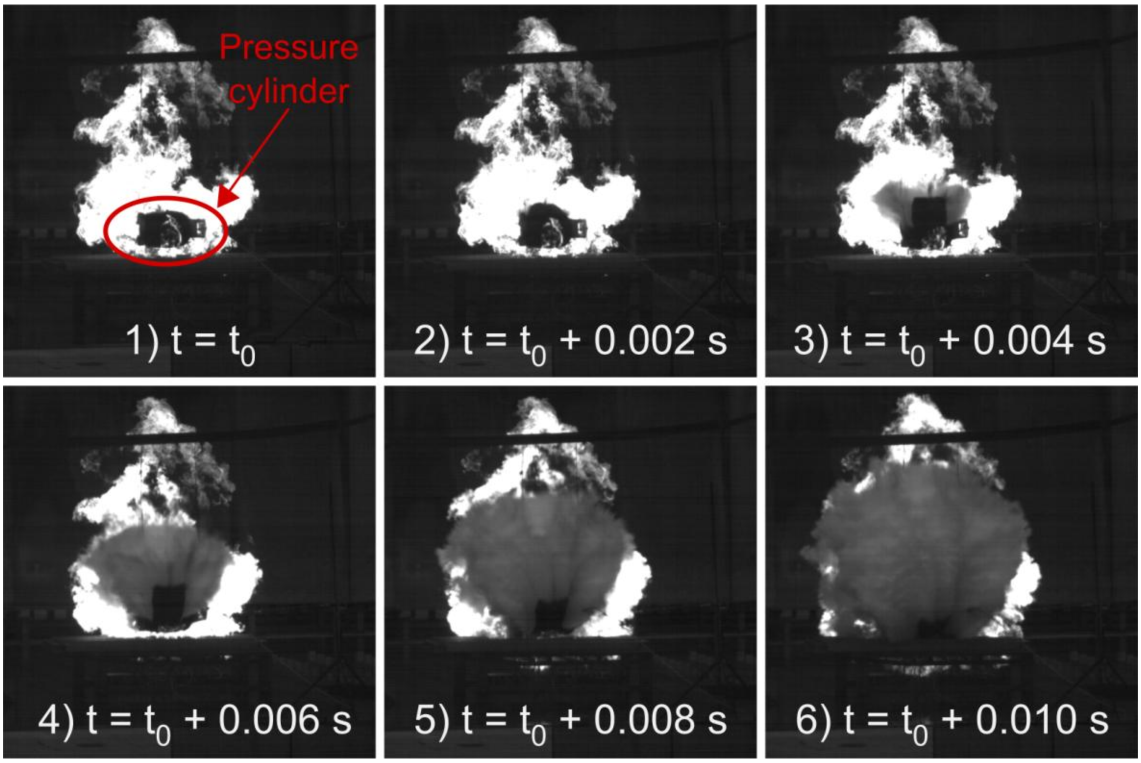
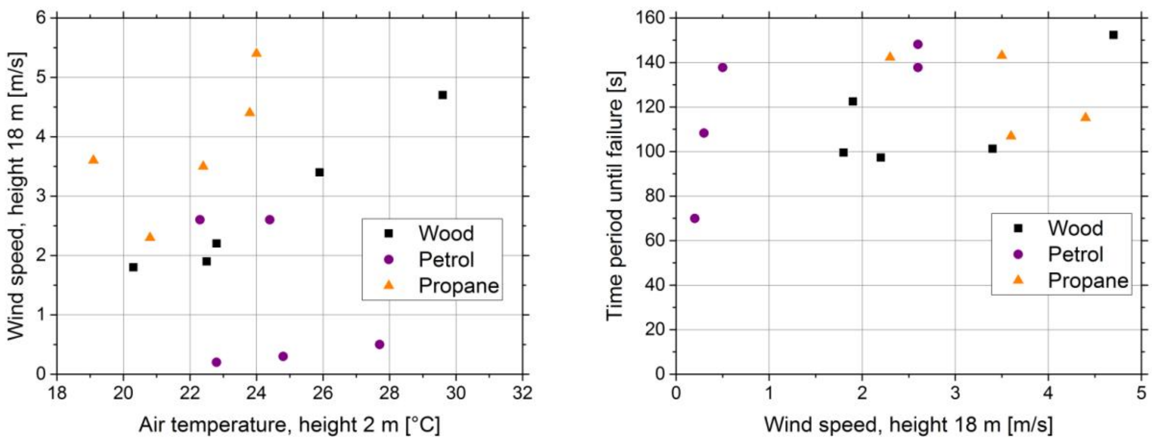


Fig. 5: Exemplary sequence of the process during failure of the propane cylinder on the propane burner test bench (test pc12), high-speed camera, frame rate f = 2000 1/s

Using the high-speed camera with a frame rate of f = 2000 1/s, a detailed insight into the failure process itself and the subsequent events was obtained. Figure 5 presents the sequence of the vessel failure with very short time increments of $\Delta t = 0.002$ s starting with rupture of the container at time $t = t_0$. In the first picture, the pressure cylinder with the extended diameter is depicted, it is the moment of the occurrence of the first observable fracture at the upper part of the casing. Within the next two time steps, the fracture becomes larger, the casing is peeled off normal to the cylinder axis. The last three photographs depict the advancing release of the entire, pressurized content of the container, the vaporization of the liquid propane and the turbulent mixing with ambient air. The seam weld itself remained intact.

The potential influence of the surrounding conditions (especially wind) on the bonfire tests is presented in Fig. 6. The test series took place in summer 2016 at air temperatures between $T_{ambient} = 19°C$ and $T_{ambient} = 30°C$ with a moderate, not constant average wind speed of up to $v_{wind} = 5.5$ m/s (measured in a height of h = 18, cf. Fig. 6a). Figure 6b depicts the relationship between the time period Δt_b until failure of the gas vessel and the average wind speed v_{wind} during the respective test. There is no distinct tendency to a prolonged time period until failure with stronger winds; the corresponding correlation coefficient results to $\sigma_{t,v} = 0.47$. An analysis of the video data reveals, that the wind tends to deflect the flames of the bonfire and thus to slightly weaken the fire impact. But it can be stated that all recorded time periods until failure are in the same magnitude (t = [70 … 152 s]) with only one outlier.



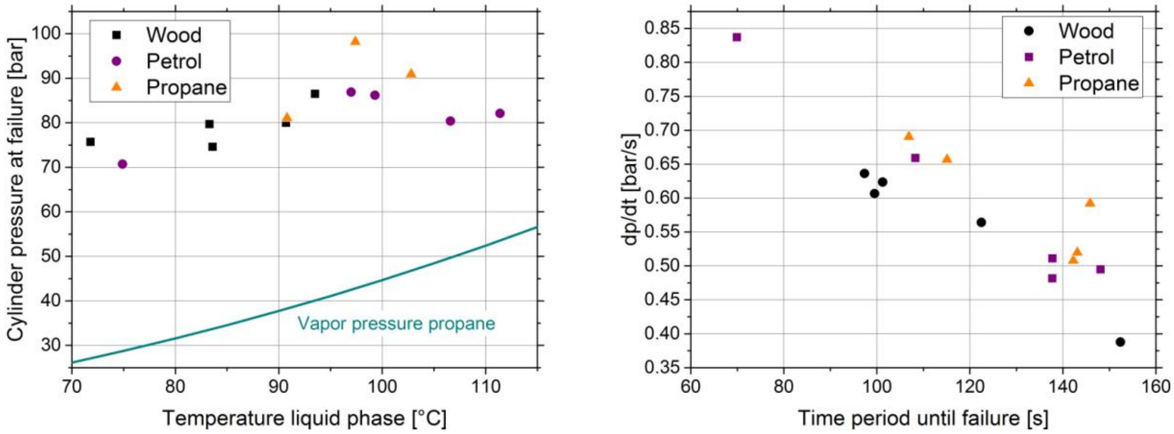
a) Wind speed and air temperature on the test site TTS

b) Influence of the wind speed on the test site TTS on the time period until failure of the propane cylinder

Fig. 6: Weather conditions during the bonfire tests

Status of the vessel at time of failure

Figure 7a presents the state variables inner pressure p_{201} and temperature of the liquid phase T_{107} at the time of failure of the gas container. Furthermore, the corresponding vapour pressure for propane is included. At the time of failure, the tested gas cylinders had inner pressures in the range of $p_{201} = [70.7 \dots 98.2$ bar] and temperatures of the liquid phase of $T_{107} = [71.8 \dots 111.4$ °C]. In all tests within the test series, the cylinder pressure considerably exceeded the vapour pressure associated with the established temperature of the liquid propane. The correlation between the two state variables is not very distinctive, the correlation coefficient is $\sigma_{p,T} = 0.43$. Figure 7b depicts the relationship between the average gradient of the pressure inside the cylinder and the time period until failure of the gas vessel. The time period until failure starts, when the flame temperature below the cylinder (TIR 106, cf. Fig. 1) reaches an increase of $\Delta T = 5$ K compared to the “cold” condition, and ends with the fracturing of the casing. These two parameters have a very distinct (negative) correlation, the correlation coefficient is $\sigma_{p',t} = -0.89$. In case of very high pressure gradients (caused by a very intensive, effective fire impact), very short time periods until failure are possible.

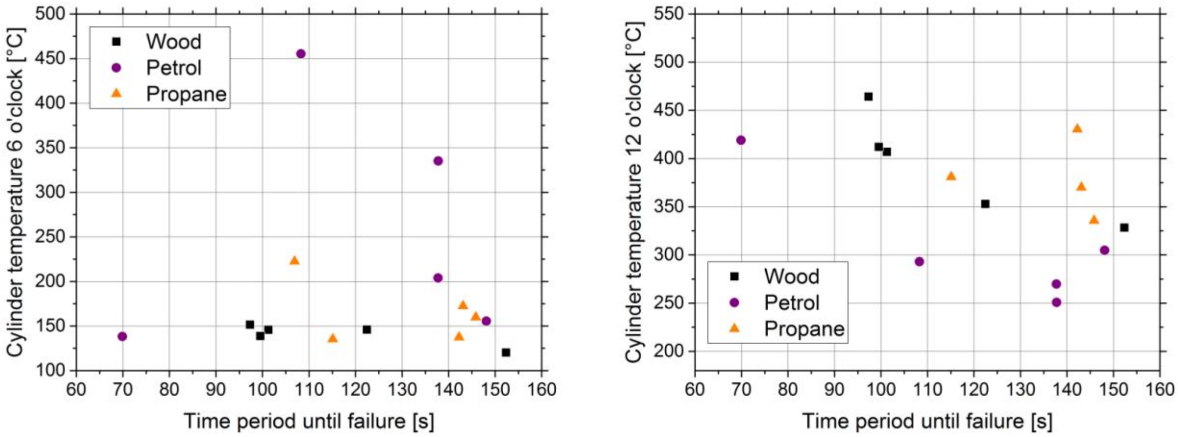


a) Comparison of the cylinder pressure (PIR 201, cf. Fig. 1) and the temperature of the liquid phase (TIR 107, cf. Fig. 1) at the time of failure

b) Comparison of the pressure gradient (PIR 201, cf. Fig. 1) during the period of fire impact and the time period until failure of each tested gas cylinder

Fig. 7: Main parameters describing the status of the vessel at the time of failure

The temperatures of the cylinder casings at the time of failure are depicted exemplarily for two measuring positions in Fig. 8. At the first position, at the bottom of the gas vessel (6 o'clock position), mainly quite low temperatures in the range of T_{103} = [120 … 225°C] with two higher outliers for the petrol fire occur, cf. Fig. 8a. The reason for that is the efficient cooling of the metal casing by the liquid phase. At the second position, at the top of the gas vessel (12 o'clock position), much higher temperatures T_{101} occur generally, although the fire impact is decreased compared to the much more fire exposed bottom of the cylinder, cf. Fig. 8b. But the cooling efficiency of the gas phase is much smaller. This data reveals, that the top of the casing of a gas container is the most vulnerable area in a bonfire, the highest probability for fractures occurs here. This data confirms the analysis of the high-speed videos, cf. Fig. 5. At the bottom, no correlation between the casing temperature and the time period until failure becomes evident; the correlation coefficient is $\sigma_{T,t}$ = -0.02. At the top, this (negative) correlation is more distinctive, the corresponding coefficient is determined to $\sigma_{T,t}$ = -0.55.



a) Temperature at the bottom of the cylinder (TIR 103, cf. Fig. 1)

b) Temperature at the top of the cylinder (TIR 101, cf. Fig. 1)

Fig. 8: Temperature of the cylinder casing at the time of failure

Impact on the surroundings

Fragmentation

Bursting of a gas cylinder with pressurized gas inside leads to a fragmentation of the casing. The 15 gas vessels of the test series fragmented into a total of 62 major fragments. In one case, the cylinder remained one piece after the fracturing without any further fragmentation and remained directly at the test bench. In most other cases, the cylinder fragmented into several parts, in average four pieces. In one case, seven fragments were found. Overall, 90% of the tare weight of the 15 cylinders (m = 11.5 kg) was found after the tests. Thus, a significant portion of the fragments is missing, consisting of mainly smaller objects. In Fig. 9, all registered major fragments are depicted with their mass and the corresponding range (distance from the original position of the intact vessel to the final location). The maximum range detected was r = 260 m.

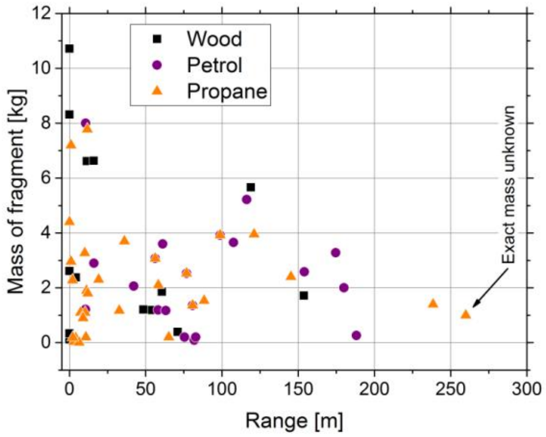
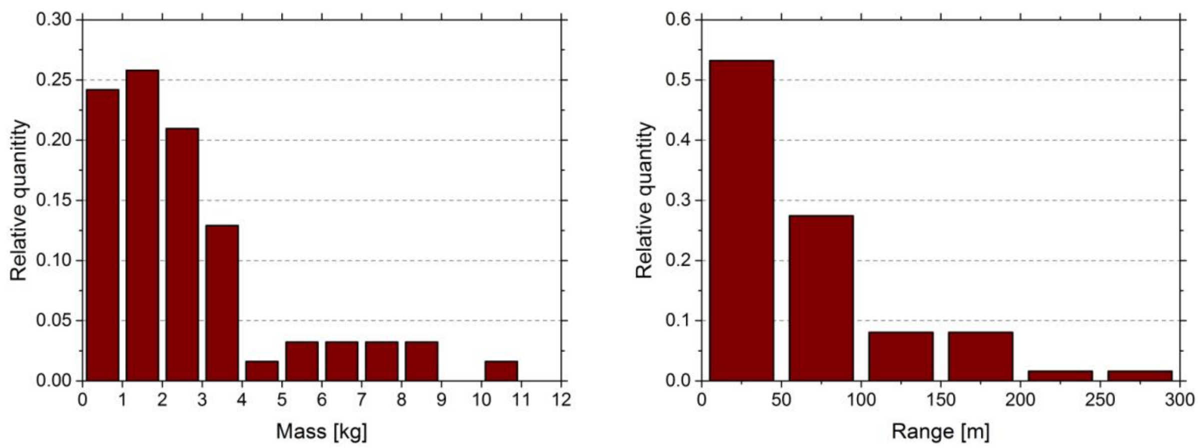


Fig. 9: Depiction of the mass of the 62 major fragments resulting from the failure of 15 propane cylinders and their corresponding range (tare weight of one cylinder: m = 11.5 kg)

A further analysis of the fragments and their characteristics is enabled by Fig. 10. Figure 10a depicts the relative distribution of the fragments regarding their mass. The average mass of the fragments is m = 2.5 kg, 83.9% of the fragments have a mass of m = 4 kg or less. Details about the distance covered by the fragments after vessel failure is presented in Fig. 10b. 81% of the detected fragments fly up to r = 100 m, approximately one half of all fragments fly up to r = 50 m (53%). The average distance covered by the fragments is 56.7 m, the median of the range is 39.1 m.



a) Relative quantity of the fragments regarding their mass b) Relative quantity of the fragments regarding their range

Fig. 10: Relative distribution of the fragments

Blast wave

At three positions in the close-up range, the resulting overpressure caused by the abrupt expansion of the pressurized gas in the fracturing gas vessel was recorded. In Fig. 11, the peak pressures measured in all 15 tests are depicted. The maximum pressure, that was detected in a distance of 5 m, is $p_{202,max}$ = 0.27 bar (pc10). With increasing distance to the origin of the overpressure, the values decrease significantly. The pressure peaks detected can be traced back to the abrupt expansion of the gas after the fracturing of the casing. The subsequent uncontained explosion of the propane air mixture does not cause discrete pressure peaks of this magnitude.

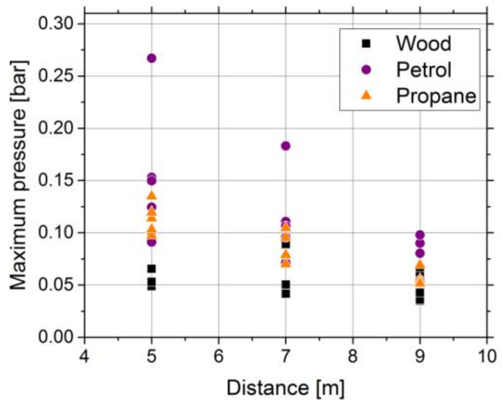


Fig. 11: Maximum measured overpressure of the blast wave resulting from failure of the gas cylinders (PIR 202 to 204, cf. Fig. 1)

Fireball and thermal radiation

Regarding thermal radiation, Fig. 12 depicts an exemplary measurement and calculated approximation of the maximum intensity I_{max} of the thermal radiation for a vessel failure caused by a wood fire (pc01). The four markers represent the maximum of the measurements with the bolometers (RR 301 to 304, cf. Fig. 1), while the dashed line is the heat flux calculated from an analysis of the video sequences using the Stefan-Boltzmann law, cf. Eq. 1. For the fireball parameters, an assumption based on other experiments was made, resulting in an estimated flame temperature of $T_f = 1200°C$, the emission factor was set to $\varepsilon_f = 0.8$. The view factor ρ, describing the approximated solution of the surface integral for transmitting radiation between two geometric surfaces (radiator and absorber) without considering temperature and other factors, was calculated using (VDI 1991). The transmission factor τ represents the damping of the radiation for carbon dioxide and water in air. The maximum dimension of the fireball was approximated using a coextensive trapezoid. Figure 12 reveals that the first two bolometers (RR 301 and 302, cf. Fig. 1) with the longer integration time of the sensor underestimate the maximum intensity of the thermal radiation, as the long integration process acts as a low-pass filter, so that the measured maxima become smaller. In contrast, the faster, remote bolometers (RR 303 and 304, cf. Fig. 1) in distances of d = 100 m and d = 170 m are in good accordance with the calculated data using the Stefan-Boltzmann law. In a distance of d = 10 m, a calculated peak intensity of $I_{max} = 29.3\ kW/m^2$ results from the fireball. Ten meters farther away, at d = 20 m, a calculated peak intensity of $I_{max} = 9.9\ kW/m^2$ remains.

$$I = \rho\sigma\varepsilon_f\tau_{air}\left(T_f^4 - T_{ambient}^4\right) \qquad \text{(Eq. 1)}$$

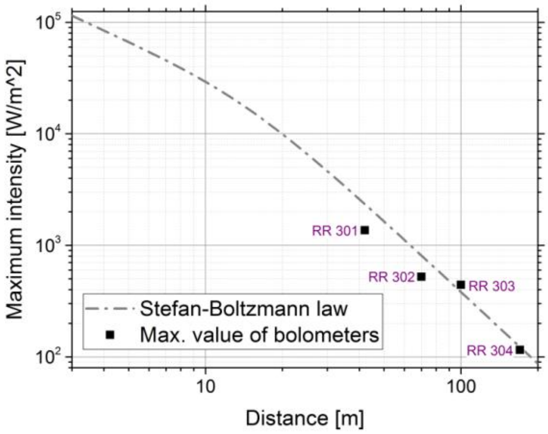


Fig. 12: Maximum intensity of the thermal radiation, comparison between the maximum heat flux calculated using the Stefan-Boltzmann law and the video sequence of the fireball and the measurements using the four bolometers (RR 301 to 304, cf. Fig. 1, test pc01, wood fire)

Discussion

All 15 identical containers involved in this test series failed within less than t = 3 min of intensive fire impact and heat flux. An operational safety device like a PRD will prevent or at least delay this hazardous event. Although the high casing temperatures might cause a downgrading of the tenacity of the steel, the required burst pressure p_b was significantly exceeded in the tests with all 15 containers.

The hazards and potential consequences of failure of commercial, off-the-shelf propane cylinders are severe. Next to primary blast injuries caused by the pressure wave and the thermal impact, the fragments rocketing from the reaction zone with high energy are the key factor to the lethal potential of explosions and additionally have a long-range impact (Neitzel et al. 2012). A significant portion of the fragments have flying distances after failure that exceed common, required safety distances for firefighters dealing with a fire near or around a gas cylinder. Special hazards arise, as the additional hazardous potential caused by gas vessels is not always known to the rescue forces, so that adequate safety distances are not permanently assured.

An overview of the current recommendations for German firefighters regarding operations with gas containers and a fire impact is given in Tab. 1. The focus of the recommendation given by the German fire service regulation 500 (AFKzV 01/2012) lies on large tank wagons, tank trucks and industrial tanks, not on small, off-the-shelf propane cylinders that were the object of the described experimental series. The recommended safety distances from the German fire protection association (vfdb 11/2013) are distinguished very clearly according to the size of the specific tank. The presented figures are for gas cylinders with a filling mass of less than m = 33 kg, so the vessels used for this research project are directly covered by this recommendation.

Recommendation, guideline, regulation	Type of gas vessel	Radius of danger zone	Radius of shut-off zone
FwDV 500 (AFKzV 01/2012) (German fire service regulation 500, CBRN hazards)	Large tank wagon, tank truck, industrial tank	300 m	1000 m
vfdb recommendation (vfdb 11/2013) (German fire protection association)	Gas cylinder with a filling mass m < 33 kg	50 m	100 m

Tab. 1: Safety distances for German firefighters for operations involving liquid gas vessels

A significant portion of the measured distances covered by gas vessel fragments after failure exceeds the recommended safety distances of the vfdb recommendation. Nearly half of the fragments resulting from failure of small gas vessels potentially hits the ground within the shut-off zone (r = 100 m) and thus constitute a severe hazard for firefighters and other rescue forces even working outside the direct danger zone. Approximately 19% of the fragments potentially even overshoot the shut-off zone. The safety distances presented in the German fire service regulation 500 were not exceeded during the test series.

Next to the fragments, also the overpressure and the thermal radiation can cause severe injuries to humans in the near field of the failing gas vessel. According to (Kaiser et al. 2000), the measured overpressure occurring in the close-up range around the failing gas container can lead to injuries to humans (tilting over of persons, fissure of the eardrum) and structural damages (burst of window glasses, destruction of brickwork). Contrary to the damage that might be caused by flying fragments, the hazard caused by overpressure and thermal radiation in the presented scenario is predominantly limited to the recommended danger zone of r = 50 m. In general, it has to be taken into account, that a contained or partly contained scenario would have drastically aggravated consequences, for injuries to humans cf. (Almogy et al. 2004) for example.

Conclusion

In a destructive test series, 15 identical commercial, transportable and off-the-shelf propane gas vessels filled with m = 11 kg of liquid propane were underfired using three different fuels (wood, petrol, propane gas) in horizontal position. Due to the intensive heat flux and the configuration without any pressure relief device (PRD), all 15 containers failed within a time period of t = [70 … 152 s] after an increase of the inner pressure up to p_{201} = [70.7 … 98.2 bar]. The cylinders fractured at the top, where the highest casing temperatures occurred. Afterwards, a sudden expansion of the gas occurred and the entire filling was released, which led to an abrupt vaporization of the liquid phase. The gas cloud was mixed with ambient air and was ignited subsequently.

Extensive camera equipment including one high-speed camera (f = 2000 1/s) was used to gain a detailed insight into the events taking place during failure of the cylinder. Measurements of the casing temperature (at three positions), the flame temperature (at three positions) and the temperature of the liquid phase during the heat impact until failure of the vessel were performed to enable a detailed analysis of the heating process and the status of the vessel at the time of failure. Pressure measurements in the close-up range around the cylinder (distance of d = [5 m; 7 m; 9 m]) resulted in overpressures caused by the shockwave of up to $p_{202,max}$ = 0.27 bar. The unsteady, highly dynamical thermal radiation caused by the explosion of the expanding gas cloud was recorded using four bolometers and afterwards compared with an analysis of the fireball using an approach based on the Stefan-Boltzmann law. In a distance of d = 10 m, a typical peak intensity of the thermal radiation of I_{max} = 29.3 kW/m^2 affects the surrounding.

The 15 cylinders fragmented into a total of 62 major fragments that could be detected. They were weighed and georeferenced afterwards. The maximum distance covered by a flying fragment was r = 260 m. In average, the cylinders fragmented into four objects with an average mass of m = 2.5 kg. A flying distance of r = 50 m away from the origin was exceeded by 47% of the fragments. The lethal potential of the fragments of the vessel itself and secondary, accelerated objects is predominant in explosion scenarios comparable to the one presented in this article.

People in the surrounding of a gas cylinder in a fire may suffer severe primary and secondary blast injuries due to the presented effects of vessel failure, also significant damages to buildings and infrastructure are a potential consequence. The distances covered by a substantial portion of the fragments exceed the recommendations for safety distances for German firefighters responding to a fire involving small propane gas vessels. Based on the presented data and results of the test series, valid deductions on the consequences of failure of small liquid gas vessels and necessary safety measures are possible, in case of an absence or malfunction of safety devices like pressure relief valves.

Nomenclature

Variable	Unit	Description
a	%	Accuracy
d	m	Linear measure, diameter
f	1/s	Sampling rate, frame rate
h	m	Height
I	W/m^2	Intensity
m	kg	Mass
p	bar	Pressure
r	m	Range (of fragments)
t	s	Time, time period
T	°C; K	Temperature
v	m/s	Speed
V	m^3	Volume

Variable	Unit	Description
Δ	-	Difference
ε	1	Emission factor
ρ	kg/m^3	Density
ρ	1	View factor
σ	1	Correlation coefficient
σ	$W/(m^2K^4)$	Stefan-Boltzman constant
τ	1	Transmission factor
Subscript	**Description**	
b	Burst	
h	Test	
f	Flame	
max	Maximum	
nnn	Measure regarding nnn (cf. Fig. 1)	

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