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Threats Related to Accidental Release of LPG in Rail Transport

Abstract

The transport of dangerous substances is potentially hazardous to people and the environment. Failures of installations or equipment as well as errors of people who operate them may contribute to uncontrolled release of a dangerous substance, creating a chemical threat as a result of contamination, fire or explosion. The aim of the study was to analyse the extent and scale of threats to residents and emergency services in the event of an accidental release of LPG from a tank or a railway tank in built-up areas. The inspiration was a train disaster that happened in in Italy the city of Viareggio in 2009. The Aloha program was used for needs of the research. The presented hazard zones were generated on the basis of emergency scenarios for the release of LPG. During the modelling of danger zones, parameters of emergency release of 45 tons of gas from a railway tanker in the city were reproduced. Five scenarios were devised that could occur during the uncontrolled release of LPG into the atmosphere. For each of them, the effects are listed of failures that residents of the built-up area in which the event occurred may potentially encounter. In the summary of the work, reference was made to the discussed railway disaster and its effects, as well as to modelled emergency release scenarios. An evaluation was made of the application used. It provides an example of using a mathematical model. The application is developed by The Cameo Software Suite, in cooperation with the National Oceanic and Atmospheric Administration and the Environmental Protection Agency.

Keywords: effects of uncontrolled LPG release in built-up areas, LPG release, consequences of release, forecasting scenarios, ALOHA computer program

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Zagrożenia związane z awaryjnym uwolnieniem LPG w transporcie kolejowym

Abstrakt

Przewóz substancji niebezpiecznych wiąże się z ewentualnym zagrożeniem dla ludzi i jego środowiska naturalnego. Awarie instalacji czy sprzętu, a także błędy ludzi, którzy je obsługują, mogą przyczynić się do niekontrolowanego uwolnienia substancji niebezpiecznej, stwarzając zagrożenie chemiczne w wyniku skażenia, pożaru lub wybuchu. Celem badań było przeanalizowanie zasięgu i skali zagrożeń dla mieszkańców i służb ratowniczych w przypadku awaryjnego uwolnienia LPG ze zbiornika cysterny kolejowej na terenie zabudowanym. Inspiracją była katastrofa kolejowa na terenie Włoch, która wydarzyła się w mieście Viareggio w 2009 r. Do badań wykorzystano program Aloha. Przedstawione strefy zagrożenia wygenerowano na podstawie scenariuszy awaryjnych uwolnienia LPG. Podczas modelowania stref niebezpiecznych odwzorowano parametry awaryjnego uwolnienia 45 ton gazu z cysterny kolejowej we wspomnianym mieście. Sporządzono pięć scenariuszy, które mogłyby się wydarzyć podczas uwolnienia LPG do atmosfery. Dla każdego z nich zamieszczono skutki awarii, z jakimi mogą spotkać się mieszkańcy obszaru zabudowanego, w obrębie którego nastąpiło zdarzenie. W podsumowaniu pracy odniesiono się do omawianej katastrofy kolejowej oraz jej skutków, a także do modelowanych scenariuszy. Oceniono zastosowaną aplikację. Jest ona przykładem zastosowania modelu matematycznego. Aplikacja opracowana jest przez The Cameo Software Suite, przy współpracy z National Oceanic and Atmospheric Administration i Environmental Protection Agency.

Słowa kluczowe: uwolnienie LPG, skutki uwolnienia, prognozowanie scenariuszy, program komputerowy ALOHA

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Загрози, пов›язані з аварійним викидом СНГ в залізничному транспорті

Анотація

Перевезення небезпечних речовин становить потенційну небезпеку для людей та навколишнього середовища. Неполадки установок чи обладнання, а також помилки людей, які ними керують, можуть сприяти неконтрольованому викиду небезпечної речовини, що створює хімічну загрозу внаслідок забруднення, пожежі чи вибуху. Метою дослідження було проаналізувати ступінь та масштаби загроз для мешканців та аварійних служб у разі екстреного викиду скрапленого нафтового газу з баку залізничної цистерни у забудованих районах. Мотивацією до написання була катастрофа потягу в Італії, що сталася в місті Віареджо в 2009 р. Для дослідження була використана програма Aloha. Представлені небезпечні зони створено на основі аварійних сценаріїв викиду скрапленого газу. Під час моделювання небезпечних зон відтворено параметри аварійного викиду 45 тонн газу із залізничного баку в місті. Було підготовано п›ять сценаріїв, які можуть статися під час неконтрольованого викиду скрапленого газу в атмосферу. Для кожного з них перераховано наслідки неполадок, з якими можуть зіткнутися жителі забудованої території, в якій стався інцидент. У підсумках роботи зроблено посилання на обговорювану залізничну катастрофу та її наслідки, а також на модельовані сценарії аварійного викиду. Було оцінено застосовану аплікацію, котра є прикладом використання математичної моделі. Аплікацію розроблено фірмою Cameo Software Suite у співпраці з Національним управлінням до справ океанів та атмосфери та Агентством з охорони навколишнього середовища.

Ключові слова: наслідки неконтрольованого викиду СНГ на забудованих територіях, викид СНГ, наслідки викиду, прогнозування сценарію, комп›ютерна програма ALOHA

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Introduction

The chemical industry is one of the most dynamically developing industries in the world. The most common and also the cheapest type of transport, especially for hauling large loads over long distances, is rail transport. Apart from relatively low transport costs per unit mass of goods and the possibility of bulk transport, it offers an extensive network of railway routes as well as a relatively high movement speed. Every transport of dangerous goods by rail poses a threat to people and to the environment. All kinds of failures or human errors can contribute to an uncontrolled release of a hazardous substance, posing a chemical threat, and consequently a risk of contamination, fire or explosion. As main communication routes and a large number of industrial plants are located in urban areas, transport of dangerous goods has to proceed through these areas [3, 7]. For this reason, the transport of hazardous materials has been subjected to detailed procedures and international legal regulations to reduce the risk of adverse events in the process of transporting dangerous goods or to limit the extent of possible damage [16]. The occurrence of such an emergency in residential areas directly affects the safety of the people, the surrounding infrastructure and the environment [1, 14]. Performing computer simulations related to the uncontrolled release of substances has proven to be helpful for emergency services to assess the scale of the threat, thanks to the possibility of modelling various emergency scenarios [2, 11]. Rail transport is also used to transport LPG, a liquefied fuel that is a mixture of saturated hydrocarbons, mainly propane and butane. The phenomenon that may occur when releasing gas from the tank is flash fire when the ignition is initiated in a given volume of the mixture of combustible substance with air – fig. 1.

Fig. 1. Fire of a cloud LPG with the air – flash fire
Source: [5]

Another phenomenon is the jet fire. It is a fire that may persist for a long time, which is why it poses a significant threat due to the effects of heat radiation. Such radiation affects adversely construction elements and equipment, reducing their strength and exposing them to destruction [4, 12]. This is especially dangerous when the damaged tank spontaneously heats up or when the fire is directed at an adjacent tank fig. 2.

Fig. 2. Jet Fire
Source: [5]

The next phenomenon is BLEVE (Boiling Liquid Expanding Vapour Explosion), a physical explosion. In this case, during a long heating process of the tank jacket, the temperature of the medium increases, the pressure increases rapidly, which in turn leads to bursting of the tankers [6]. If there is a flammable substance in the tank, the gas cloud formed after the explosion may become ignited to form a spherical fire fig. 3.

Another phenomenon is the VCE (Vapour Cloud Explosion); if there is no immediate ignition of the leaking medium, it promotes the spread of a combustible substance that mixes with air. Delayed ignition causes flash fire or VCE type chemical explosion, i.e. gas or liquid vapour cloud explosion [13, 15]. A specific case of such a phenomenon is an explosion in unlimited UVCE (Unconfined Vapour Cloud Explosion). The explosion of such a mixture creates a strong wave of overpressure, which further accelerates the spread of the combustion reaction [10, 17].

As mentioned above, the inspiration for the study was the train crash that took place in Viareggio, Tuscany. A train derailment occurred and in an uncontrolled way 45 tonnes of LPG were released from one railway tank. There was an explosion of dispersed gas and the resulting fire spread onto neighbouring infrastructure. As a result 32 people died, 27 were injured.

Fig. 3. BLEVE physical explosion of a tank wagon creating a fireball spherical fire
Source: [5]

The train comprised an electric locomotive and fourteen tank wagons with a marking, carrying a total of almost 632 tonnes of liquid LPG. At 23:48 the train set passed through the Viarregio station at a speed of about 90 km/h. Security cameras installed at the railway station recorded sparks intensely escaping from the front part of the first tanker truck, caused by damage to one of the truck's axles. A few meters away, the connection between the axle and the wheel cracked, which led to the derailment of tank cars. The catastrophic rupture caused overturning of the first tank wagon and its detaching from the locomotive. The speeding tank car stopped a few hundred meters away, and was braked by rubbing the derailed outer surface of the tankers against the tracks and ballast. The first ten wagons derailed, of which five more fell over, and only one of them released gas. The last four tank cars remained on the tracks. During deceleration, the first overturned wagon hit a metal element of the railway infrastructure causing the tank plating to be cut. Through the resulting tear, gas release started over the next few tens of seconds. There was a leak resulting in the formation of vast backwaters and dispersion of the cloud of evaporated gas. Figure 4 shows derailed wagons. On the right, the first tank-car wagon in the set disconnected from the locomotive, from which leakage and gas dispersion took place towards the buildings at Ponchielli Street [8, 9].

Fig. 4. Spreading fire along the railway line and pool fire
Source: [5]

ALOHA

The application has limitations that affect the reliability of the resulting threat zone model. When modelling the emergency scenario, it is necessary to enter detailed data with parameters of the substance and the reservoir from which the emission is to occur, as well as atmospheric conditions. In order to present the scale of threats to residents of built-up areas and employees of emergency services in the event of an accidental release of a hazardous substance, use was made of the example of the railway disaster of 29 June 2009 in Viareggio, Italy. In the modelling of danger zones, the following disaster parameters were mapped for individual scenarios: place of incident, meteorological conditions, mechanically damaged tank of a railway tanker and gas leakage. Emergency release of hauled gas from the first railway tank was assumed. Based on an analysis of the incident in Viareggio, a summary was developed of data necessary to carry out the emergency release simulation. Due to limitations of the ALOHA program, which does not contain mixtures of substances in its database, pure propane gas was used to model the danger zones. LPG is a liquid hydrocarbon mixture, and its application is mainly based on homogeneous substances. The parameters used to model the danger zones were as follows: the place of incident – Viareggio, Italy, 2 m above sea level, latitude: 43°52’13.46 “N, longitude: 10°15’16.47” E, urban agglomeration, dense terraced buildings, two-storey houses, air temperature – 23°C, relative humidity – 94%, stability class F, wind speed of 0.7 m/s from the sea in the E-SE direction, measurement from a height of 10 m, cylindrical tank, horizontal – railway tank with total capacity 110 m 3, 15.95 m long and 3.04 m in diameter, content – 100% propane, threshold values for AEGL (Acute Exposure Guideline Levels) 1 (60 min): 5500 ppm, AEGL 2 (60 min): 17,000 ppm, AEGL 3 (60) min): 33,000 ppm, heavy gas model, liquefied gas under pressure, total mass of substance in the tank 45 650 kg, size of the leak from which the leak occurred 50 cm × 2.44 cm, time since the collision of the tank with metal object and cut out to ignite a dispersed gas cloud.

Failure scenarios

Using the data contained in the analysis of the event, five scenarios were devised that could occur during an uncontrolled release of LPG gas into the atmosphere. Next for each of them, hazards and consequences were presented of accidents that residents of built-up areas and working emergency services could face. In the summary of the work, reference was made to the discussed railway disaster and its effects, as well as to modelled emergency release scenarios.

Scenario 1 assumes derailment and unsealing of the rail tanker as a result of mechanical damage, followed by leakage of the liquid gas fraction creating a spill and complete evaporation into the atmosphere. This assumption does not comprise the ignition of the cloud of evaporated LPG gas formed. This scenario is one of the least likely due to the extreme flammability of the gas-air mixture. The risk of an inflammatory stimulus in the area of gas cloud release in an urban agglomeration is very high. Figure 5 shows the propane gas dispersion, directed by the wind and the area of release in the AEGL concentration range.

The presented zones comprise residential buildings, mainly two-storey houses. The gas would disperse close to the ground, where it can be found in depressions, sewage wells and basements of residential houses. Propane-butane hydrocarbon is not classified for acute toxicity, regardless of the route of its administration. However, the danger remains in high concentration of gas vapours, which may cause nausea, headaches and dizziness. In extreme cases it can lead to unconsciousness and death by displacing oxygen from the environment. The released gas creates a very high risk of ignition and explosion in concentrations between the explosion limits. The release area contained in the red zone is additionally within the gas explosion range. The problem for emergency services would be the necessity of elimination of possible factors initiating ignition in the red zone, as well as the evacuation of residents to a safe zone.

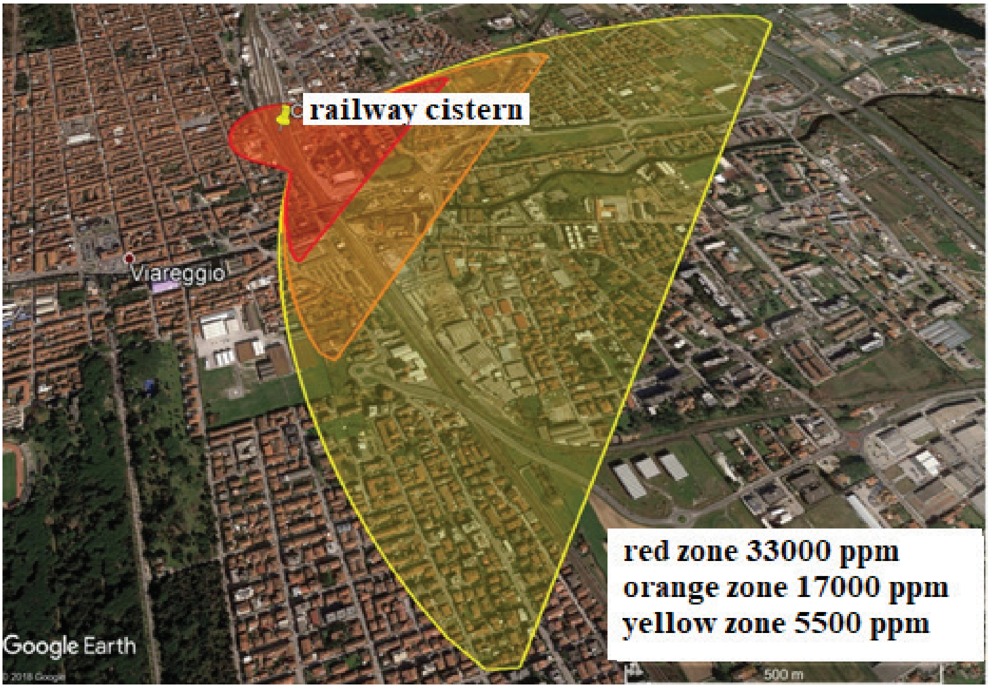

Fig. 5. Range of danger zones for scenario 1

Source: [5]

Scenario 2 assumes derailment and unsealing of the rail tanker due to mechanical damage, followed by leakage of the liquid gas fraction creating a spill and causing complete evaporation into the atmosphere. The released gas is extremely flammable and, in appropriate concentrations, forms flammable and explosive mixtures with air. Figure 6 shows the range of zones that, with the assumed parameters and in the absence of immediate ignition, would reach the released gas formed in the cloud.

Scenario 2 presents the range of a dangerous flammable zone (red zone) in which the concentration may reach a value above LEL (lower explosion limit). It poses a direct threat to residents and emergency services. During the spill, the gas cloud would spread close to the ground. Initially concentration values would be higher than UEL (upper explosion limit), but with increasing distance from the place of the event, the concentration of gas vapours would change to values within the explosive range. This situation poses a risk of explosion of residual gas in hollows, sewers and inside houses when in contact with an ignition source. After reaching the appropriate concentrations, the scattering cloud of gas can also undergo the dangerous phenomenon of flash fire with the recurrence of the flame to the source, as well as the phenomenon of UVCE causing the threat of overpressure wave. A flash fire can cause severe burns to people in the area of release.

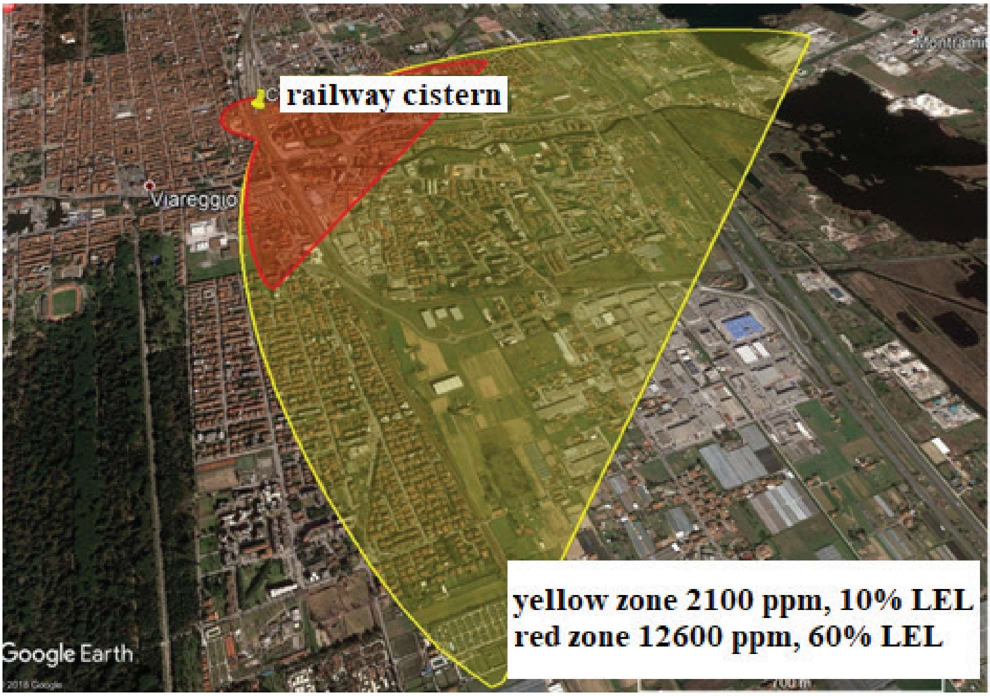

Fig. 6. Range of zones for scenario 2

Source: [5]

Scenario 3 assumes derailment and unsealing of the railway tanker due to mechanical damage, followed by leakage of the liquid gas fraction with formation of a spill and gas evaporation. The forming gas cloud disperses towards nearby buildings, after which, following the passage of some time from the failure, it ignites inside the release area.

There can be many causes of ignition due to the agglomeration nature in the affected area. The scenario of such an event most often assumes a chain reaction including the occurrence of several fire phenomena accompanying the release of LPG. These can be: flash fire with VCE explosions, return of the flame to the source of the leak and ignition of backwaters, or stream fire depending on the circumstances of the event. Figure 7 shows the ranges of hazardous areas for explosions of gas and air mixtures with specific values of overpressure generated.

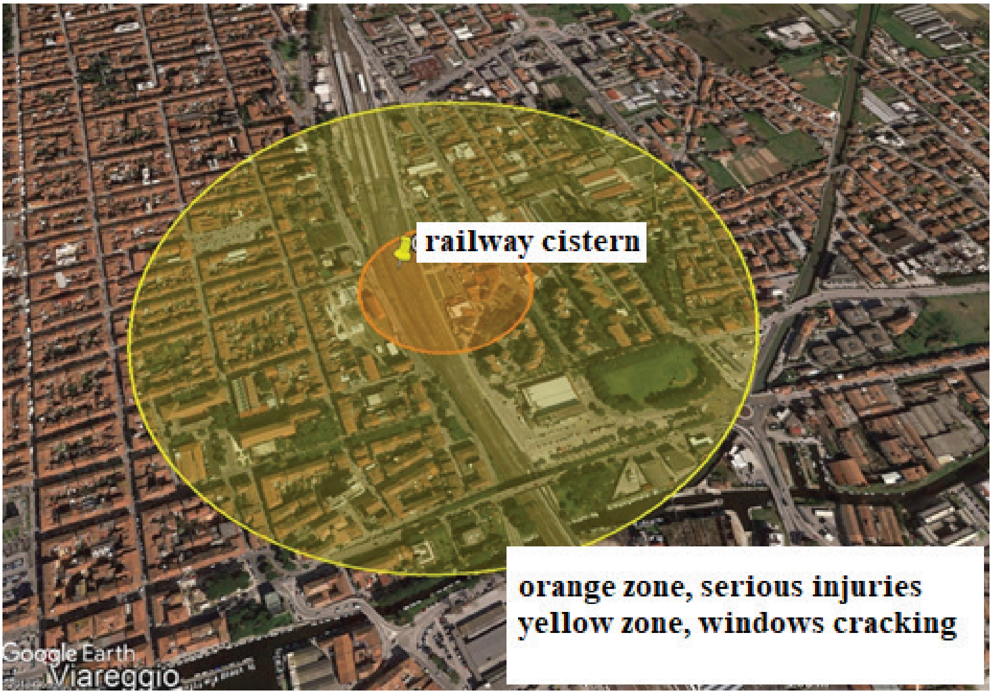

Fig. 7. Range of zones for scenario 3

Source: [5]

When modelling the danger zones in scenario 3, use was made of information as to the time of delayed ignition of the released gas cloud. On its basis, the program simulated the depicted zones of hypertension after the initiation of the explosion. The red zone was not reached, but 5 buildings were completely destroyed as a result of a collapse, which was caused by internal VCE explosions of a dispersed gas cloud. The farthest collapsed house was about 100 m from the derailed cistern. The broken windows of a residential building were recorded not more than ca. 200 m from the scene of the incident. The orange zone represents the area which sustained the biggest damage by the explosion and ignition of LPG. Scenario 3 shows the ranges of hazardous areas in which residents and rescuers are exposed to the effects of an excess pressure wave. Ignition of a gas cloud that has been accumulated inside residential buildings causes complete destruction as an effect of collapse. This poses a real threat to residents and working emergency services, preventing evacuation. VCE and UVCE explosions generate high-speed shards falling off the objects encountered on the path of hypertension, which can lead to serious injury. After the commencement of flash fire, instantaneous fire returns to the source of the leak and backfire fire. Extremely high heat radiation makes evacuation difficult for residents, causing severe burns.

Scenario 4 assumes derailment and unsealing of the rail tanker due to mechanical damage, followed by gas leakage with immediate ignition and jet fire. A jet fire will cause the entire mass of gas released to burn out and not dissipate as a combustible cloud. In such a case the threat consists of a flame of a dozen or so meters, which can direct itself to nearby combustible materials, causing the spread of fire. The length of the stream will depend on the size of the hole from which the gas leaks and the pressure inside the tank. If the gas leak occurs in two phases, apart from the jet fire, a gas spill will be created, which will affect the damaged tank. Long-term heating of the tank will lead to structural weakening of the steel and increase of pressure inside the tank. These conditions can cause the tank to explode and rupture.

Scenario 4 assumes an immediate jet fire that accompanies an accidental leak. The maximum flame length can be even 72 m. The nearest buildings are only a few meters away from the crash site. In this scenario, the dangerous explosion cloud does not spread. Being in the red and orange zones of residents and rescuers poses a direct threat to health and life. This is caused by the influence of thermal radiation from jet fire. An additional threat created by this fire is the heating of all combustible materials in the zone, causing them to burn. In the case of built-up areas, the buildings are of a residential nature and motor vehicles are parked on the street. This makes it difficult to carry out firefighting operations and the possibility of reaching victims and their safe evacuation is impeded. The most dangerous situation would be the one in which heat radiation would self-heat the tank or another rail tank truck, causing it to explode.

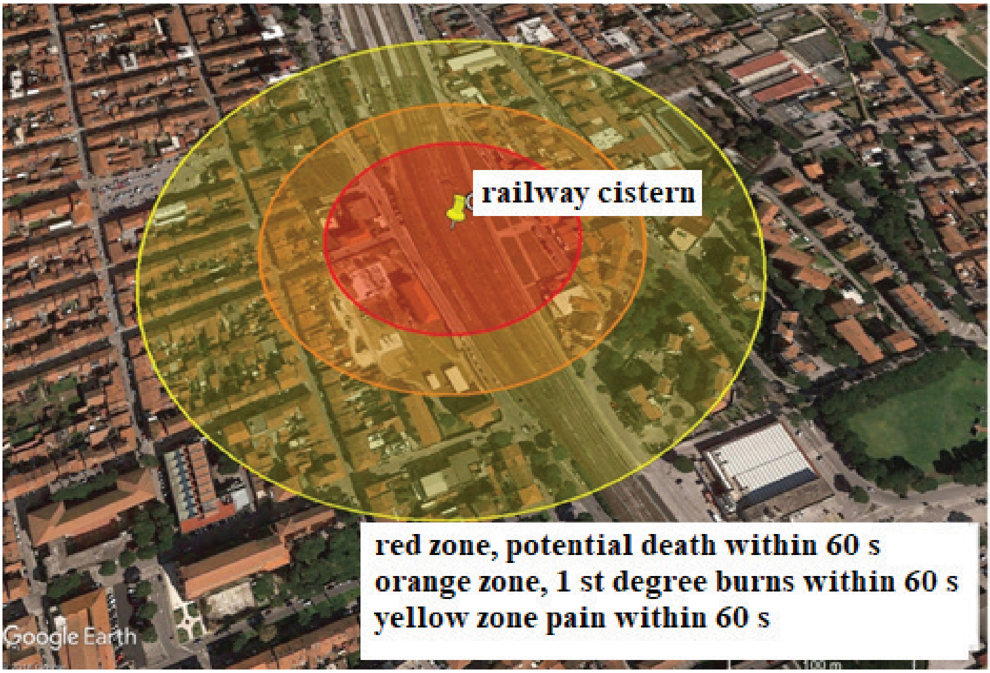

Fig. 8. Range of zones for scenario 4
Source: [5]

Scenario 5 is the result of a direct impact of a jet fire or pool fire flame from a gas backfill on another rail tanker. Excessive overheating of the tank jacket causes an increase in internal pressure and structural weakness. In the absence of effective cooling of the heated tank, the tanker ruptures and ignites boiling liquid vapours. This phenomenon is called the BLEVE physical explosion. In liquefied flammable gases, a fireball spherical fire is generated. In this scenario, the ranges of hazardous zones were modelled for only one tanker, where 100% of gas is involved in the explosion. The explosion of a railway tank filled with 45 t LPG is one of the main emergency scenarios that should be assumed during such an event. Figure 11 shows the ranges of danger zones in relation to different values of heat radiation intensity generated by the same BLEVE explosion.

In the event of an emergency event related to a BLEVE physical explosion and a fireball spherical fire, threats to the built-up area will be catastrophic. Residents and rescue services will be exposed to the generated pressure surge with the fragmentation of fragments of the tank of a railway tanker and thermal radiation emitted by a burning fireball. Shredding of torn tanks is never the same. The number and size of fragments of an exploding pressure vessel is different for each event. The heat flux generated by the burning fireball can ignite flammable materials at the point of release and spread the fire. The red zone, the range of which determines the value of heat radiation at the level of 35 kW/m^2 (Figure 9), is similar to the diameter of the produced fireball. Presence in this zone during an explosion results in death. The BLEVE explosion generates the largest real danger zones. For comparison, the red zone of 10 kW/m^2 is about five times larger than in the case of a jet fire.

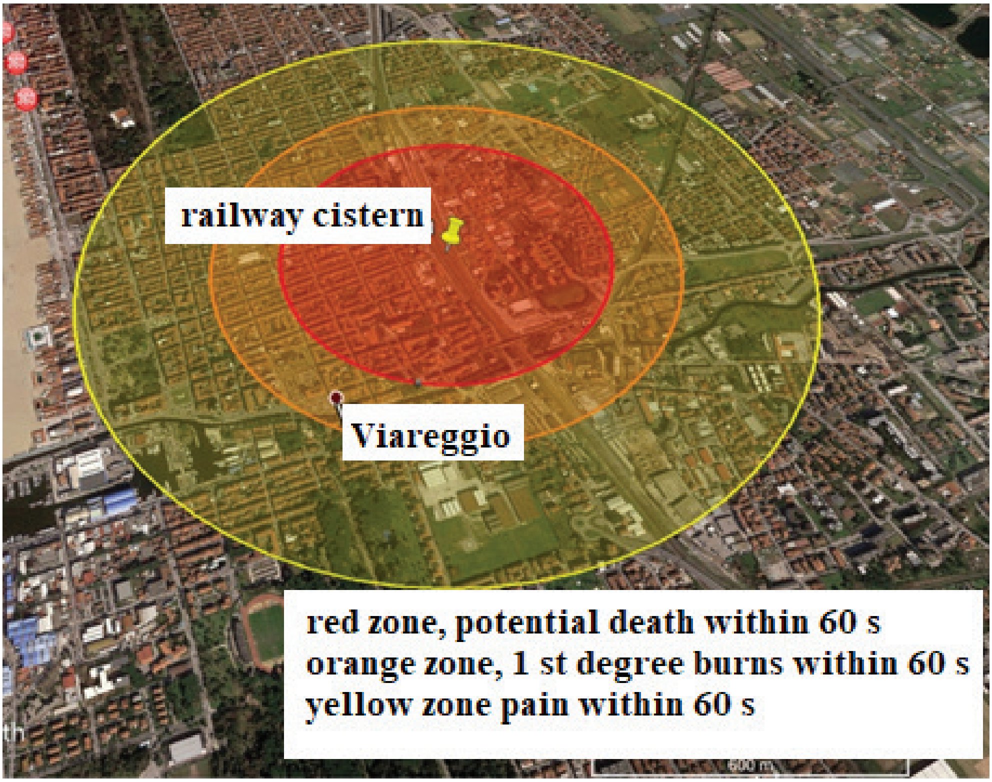

Fig. 9. Range of zones for scenario 5

Source: [5]

Summary and conclusions

The transport of hazardous materials such as LPG has very serious consequences in the event of their emergency release in built-up areas. The railway disaster of 29.06.2009 that took place in the Italian city of Viareggio, shows clearly the scale of damage in the infrastructure surrounding the place of failure. This disaster illustrates the dangers that residents of built-up areas and employees of emergency services may face in the event of an emergency release of a hazardous substance into the environment. LPG gas is classified as a hazardous substance due to its flammability and the ability to form explosive mixtures with air in the range of appropriate concentrations. Based on the information pertaining to the railway disaster, computer simulations were performed using the ALOHA program to present ranges of modelled danger zones for selected emergency scenarios. After performing the simulation, it may be concluded that ALOHA application allows modelling the reach of hazardous areas during an accidental release of various hazardous substances. The result of the assumed event scenario is the length of the zone range calculated according to the appropriate gas dispersion model. Obtaining more accurate zones will be possible after entering detailed parameters related to a given failure into the program.

1. The ALOHA application is based on homogeneous substances, and LPG is a hydrocarbon mixture. This makes it difficult to model the zones, releasing hazardous mixtures into the atmosphere. Therefore, all the simulations presented were developed for pure propane gas, which is one of the components of LPG, next to butane. The ranges of hazardous areas developed for pure propane are slightly higher than for pure butane. Results of the modelled range of hazardous zones for propane and butane gases during the BLEVE explosion were compared for comparison and attached to the work.
2. The ALOHA program is an implementation of the atmospheric dispersion model aimed at estimating the extent of impact of dangerous chemical pollution gas released to the atmosphere. ALOHA enables the user to assess the degree of dispersion of chemical cloud under the influence meteorological conditions based on the analysis of parameters physicochemical, reactivity, toxicological data and the urbanization characteristics of the incident site.
3. The developed scenarios make it possible to estimate the scale of the hazard for a built-up area where LPG was released. The BLEVE physical explosion scenario is the greatest threat in this case. An explosion of a tank filled with liquefied gas

can cause huge damage to the surrounding urban infrastructure. The released energy in the form of an overpressure wave scatters torn fragments of the tank over considerable distances that can cause serious physical injury to people. Thermal radiation from the burning ball of fire causes burns that threaten the health and life of exposed people. A fireball spherical fire will generate a very high heat flux for 13 seconds.

4. When modelling danger zones, the program does not take into account any encountered terrain or construction obstacles. Due to its having a higher density than air propane-butane gas will spread near the ground, where in dense building development and the presence of many solid obstacles it will have a smaller dispersion range. Heavy gas will penetrate through openings into sewage wells, basements of houses and will lie in hollows, creating a risk of explosions. The width of the release area will depend on the stability of meteorological conditions, mainly wind direction and strength. The program does not take into consideration the variability of constants introduced during modelling.
5. The ALOHA application does not allow for chain reactions that may accompany LPG gas releases. The incident in Viareggio took place as a chain reaction, where the ignition ignited caused flash fire, VCE explosions that led to the total collapse of five buildings, as well as ignition of pool fire. The leaking gas fed a fire that spread to buildings adjacent to the railway lines. When modelling, we can only choose one event scenario.
6. The ALOHA program can be used by on-site rescue and firefighting services to estimate the extent of hazardous areas. It is a helpful tool in determining the area from which residents should be evacuated in order to reduce the number of victims. The software allows modelling the range of danger zones, depending on the selected emergency scenario. Knowledge of the type of hazardous substance is necessary.
7. The main goal was to present the possibility of using computer simulations in managing threats to the environment and the health or life of living organisms. The management strategy is understood as all emergency procedures, training of rescuers or a time schedule for conducting rescue operations. It was assumed that the use of efficient simulation techniques may result in increased effectiveness in understanding the interrelationships between many factors depending on the source of risk and, as a result, improvement of decision making processes to protect man and the environment.

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