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The Viareggio LPG railway accident: Event reconstruction and modeling

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ABSTRACT

This manuscript describes in detail the LPG accident occurred in Viareggio on June 2009 and its modeling. The accident investigation highlighted the uncertainty and complexity of assessing and modeling what happened in the congested environment close to the Viareggio railway station. Nonetheless, the analysis allowed comprehending the sequence of events, the way they influenced each other, and the different possible paths/evolutions. The paper describes suitable models for the quantitative assessment of the consequences of the most probable accidental dynamics and its outcomes. The main finding is that after about 80 s from the beginning of the release the dense-gas cloud reached the surrounding houses that were destroyed successively by internal explosions. This fact has two main implications. First, it shows that the adopted modeling framework can give a correct picture of what happened in Viareggio. Second, it confirms the need to develop effective mitigation measures because, in case of this kind of accidents, there is no time to apply any protective emergency plans/actions.

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1. The accident

The paper investigates quantitatively the LPG release due to a train derailment in Viareggio (Italy), from the overturning of the tank cars to the explosion and the burn down of some houses, cars, and people. In a number of assessment points, different accidental scenarios have been investigated because the exact sequence and time-line of the events was unknown. This analysis, together with the assessment of the injuries, damages, and the reports from eyewitnesses, are the basis for a reliable and detailed accident investigation.

On Monday, June 29, 2009 at 11.48 PM, a freight train loaded with LPG derailed while it was crossing the station of Viareggio, a coastal city northwest of Pisa (Tuscany). The train had left Trecate (in the province of Novara, near Milan in northern Italy) in the late afternoon, after loading LPG from the Sarpom (Exxon) refinery and was southbound to Gricignano, a little town in the province of Caserta (near Naples). The train transported 630 t of LPG distributed in 14 tank cars. Due to safety reasons, the train was not supposed to stop in Viareggio, and it traveled at 90 km/h, *i.e.* below the speed limit of 100 km/h. When the train was off the Viareggio station, the front axle of the first tank car broke and the wagon derailed. The investigation identified a crack in the connection between the axle and the wheel that caused the axle section to reduce progressively up to the point of catastrophic yielding. The tank car detached from the locomotive, overturned, and dragged nine more cars off the rails. Eventually, the first tank car crashed into an I-shaped stake that was embedded in the ground for signaling purposes and produced a longitudinal cut in the metal vessel about 50 cm long and a few centimeters wide, along with a partial crack. The effective dimensions of the hole are difficult to assess because the examining judge seized the derailed wagon. However, according to people who could examine it, an approximate dimension of the trapezoidal hole was about 90–220 cm^2 and the hole pointed toward the ground.

Although anomalies are difficult to detect due to the automated engines of modern locomotives, the drivers felt a strong jerk on the traction. Thus, they went to the window and saw that the first tank car had gone off the rails. The drivers immediately applied the emergency brakes and began to smell the gas that was released by the crack, and started spreading and boiling/evaporating on the ballast. They collected the carriage sheets, jumped off the train and run away, leaping over pools of LPG on the ballast. Eventually, the drivers took shelter behind a party wall of the station [1]. The locomotive run ended about 35 m from the first derailed wagon. A similar distance separated also the first derailed wagon and the second overturned tank car.

A white and short dense-gas cloud moved towards Terminetto neighborhood, which surrounds the railway station on both sides of the ballast, with a distance between the railroad and the nearest house as short as 11 m (*i.e.* there was no safe distance between the railway and the adjacent houses). The gas cloud entered the ground floors and basements, and accumulated until an ignition source caused an explosion and/or fire. It is not clear whether the initial ignition source was on the ballast or in the surrounding houses. Some people reported that the ignition occurred on the station

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Nomenclature

A	Lateral area of the tank car licked by the flames [m^2]
A_h	Crack (hole) area [m^2]
c_D	Discharge coefficient
cp_L, cp_V	Liquid and vapor specific heats [J/(kg K)]
g	Gravity constant [m/s^2]
h_L	Height of liquid in the tank car [m]
I	Radiative heat flux [kW/m^2]
L	Length of the tank car [m]
$\dot{m}_{disch}$	Liquid flow rate from the hole in the tank car [kg/s]
$\dot{m}_{evap}$	Mass flux evaporating from the liquid inside the tank car to maintain the equilibrium internal pressure [kg/s]
m_L, m_V	Liquid and vapor masses inside the tank car [kg]
P	Pressure inside the tank car [Pa]
P_a	Ambient (atmospheric) pressure [Pa]
Q_{irr}	Heat flux radiated by the pool-fire [kW/m^2]
R	Radius of the tank car [m]
t	Time [s]
T	Temperature of the liquid inside the tank car [K]
T_{eb}	Boiling point [K]
TL	Thermal load [s(W/m^2)$^{4/3}$/10^4]
V	Volume of the tank car [m^3]
V_L, V_V	Liquid and vapor volumes inside the tank car [m^3]
x_V	Vapor fraction

Greek letters

α	Metal absorptivity
γ	Adiabatic constant
ΔH_{ev}	Latent heat of evaporation [J/kg]
ρ_L, ρ_V	Liquid and vapor densities [kg/m^3]

ballast and then a flash-fire propagated to the surrounding houses. Other witnesses claimed that the ignition of the dense-gas cloud occurred in the basements and ground floors of the houses, and that a flash-fire back propagated to the derailed tank car. However, when the ignition occurred, an explosion was triggered, and the fire propagated through the gas cloud. The literature reports flame velocities for LPG and C_3–C_4 fractions of about 1–3 m/s in the laminar regime [2–5]. The flame velocity increases significantly and may reach as high as 10–20 times the initial velocity. Therefore, the flash-fire took only a few seconds to propagate from the ballast to the surrounding houses or *vice versa*. It is difficult to report the time elapsed between the release of LPG and the first explosion. Some witnesses reported 2 min, while others reported that 5 min had elapsed. Five houses collapsed due to inner explosions, and the following fires engulfed several buildings. Almost all of the remaining houses in Ponchielli Street burned due to the resultant fires that engulfed the area surrounding the station. On the other side of the station on Burlamacchi Street, the dense-gas cloud diffused into the premises of the Green Cross (analogous to the Red Cross) and ignited, destroying almost everything. The fire, produced by the spreading of LPG released by the punctured wagon, could be seen from far away. Actually, the flames reached the electric grid.

A man who was walking on the pedestrian crossing above the station (at about 8 m above the ground) was practically vaporized. Fourteen people died immediately: some under the collapse of buildings, some due to the toxic substances released by the fires, some were literally run over by the flame radiation. Eventually, thirty-two people died and more than thirty citizens were seriously injured. About 1100 people had to evacuate their homes for safety reasons, due to either unsafe buildings or the possibility of

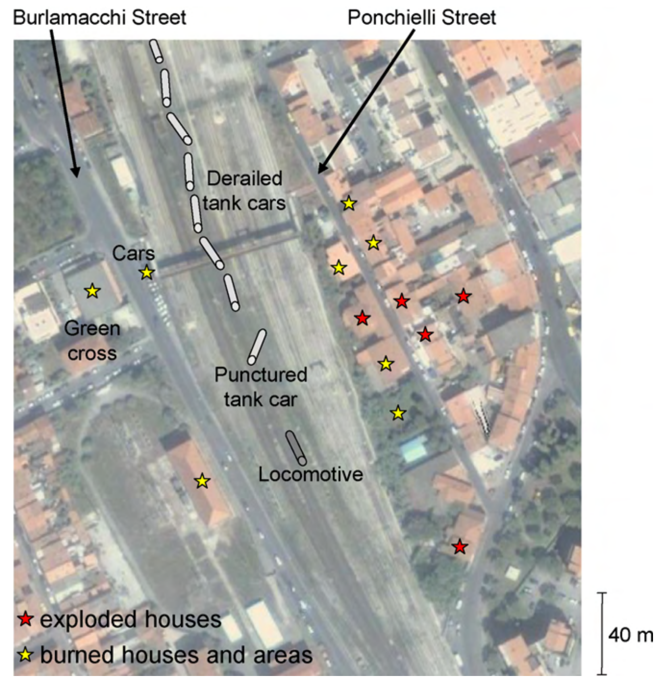

Fig. 1. Identification of the exploded and damaged houses.

exposure to further risks. In fact, the firefighters had to remove the LPG from the derailed wagons that withstood the accident. The major infrastructural damages were valued at 32 M€. Fig. 1 shows the aerial view of Terminetto neighborhood and the positions of the exploded and damaged houses.

For a quantitative assessment of the accident consequences, it is necessary to consider a number of interlinked and/or consequential phenomena, where the events to model are:

- the release of liquid LPG from the crack in the tank car;
- the flash of the liquid jet stream in the atmosphere;
- the spreading and boiling/evaporation of the LPG pool on the ballast;
- the dispersion of vapors emitted from the tank car and of those evaporated from the pool;
- the dilution of the dense-gas cloud due to the atmospheric and self-induced turbulence, and the presence of obstacles such as the permeable fence at the railroad borders and the houses on its path;
- the formation of gas pockets inside the houses, their ignition, and the magnitude of the following explosion;
- the ignition of the liquid pool, and the subsequent pool-fire.

The following sections discuss the aforementioned phenomena and the assumptions made in the use of different models.

2. The release phase

The derailed and punctured tank car was a horizontal cylinder 15.95 m long and 3.04 m large (see Fig. 2 and Table 1).

The exact amount of LPG loaded in the first tank car is unknown. Since the train transported 630 t distributed in 14 tank cars, a straightforward computation gives 45 t of LPG in each tank car. This value is in line with the maximum allowed freight load of the GATX 462R rail tank car (*i.e.* the derailed and punctured wagon) that is 46.5 t (Table 1). The LPG composition is another unknown variable, because LPG is a variable mixture of C_3 and C_4 isomers, with trace amounts of lighter and heavier hydrocarbon compounds. All the

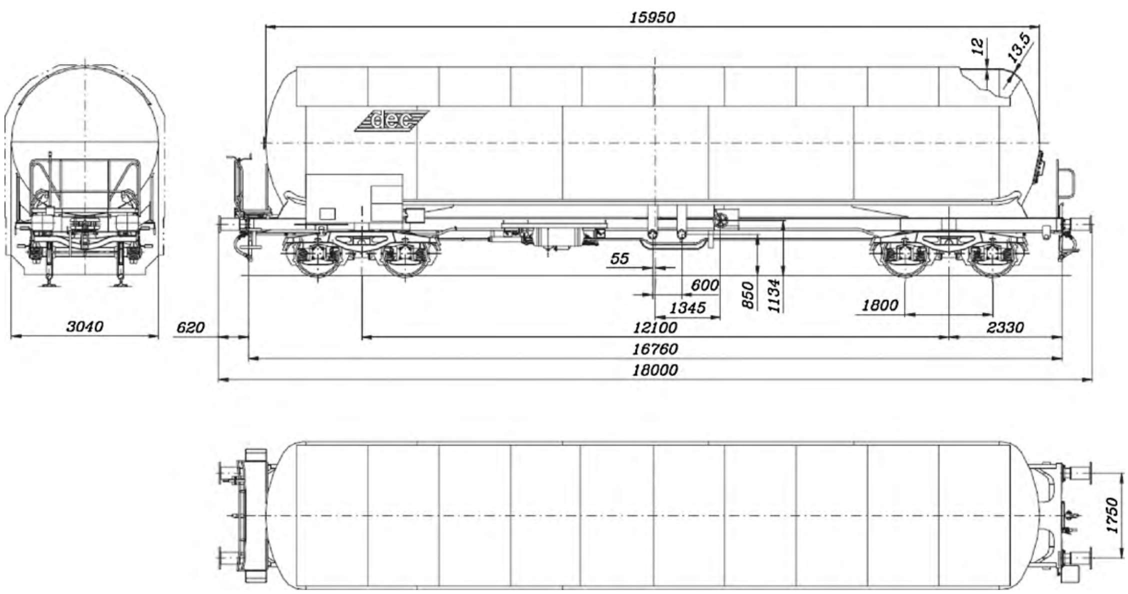

Fig. 2. Geometrical dimensions [mm] of the 462R rail tank car (www.gatx.eu/en/leaflets).

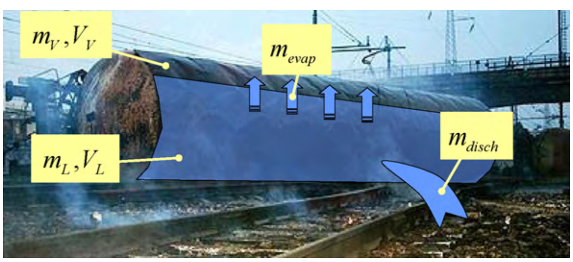

Fig. 3. Illustration of the terms and the symbols used to model the tank car dynamics.

simulations reported in the following assume that the LPG was pure n-propane.

Since the crack was in the bottom part of the derailed tank car, the release was liquid. During the discharge, no air could enter the vessel because of the crack position, and because the tank car was pressurized. Consequently, a fraction of the liquid evaporated to preserve the internal pressure (*i.e.* the vapor pressure at the liquid temperature). The evaporation subtracted energy to the liquid fraction that cooled down.

To determine the liquid flow rate discharged from the hole, it is necessary to model the dynamics of both the liquid and vapor phases inside the tank car, *i.e.* to write the mass and energy balances (see Fig. 3 for the symbols).

Table 1
Technical data of the 462R rail tank car (www.gatx.eu/en/leaflets).

Tare weight [t]	33.5
Maximum speed loaded [km/h]	100
Maximum speed unloaded [km/h]	120
Maximum load per axle [t]	20
Maximum loads [t] at the operating speed of 100 km/h	*A* = 30.5, *B* = 38.5, *C* = 46.5[a]
Total tank capacity [m^3]	110
Design pressure [bar]	25
Working pressure [bar]	25
Test over-pressure [bar]	25
External over-pressure [bar]	1

[a] Categories *A*, *B*, *C* are referred to RIV international regulations for freight transportation where *A* is a railway line that can bear a burden of 16 t/axle, *B* of 18 t/axle, and *C* of 20 t/axle. Therefore, when we find *C* = 46.5 t, the tank car can transport an overall freight weight of 46.5 t if the train runs on a C-type railway line, which can bear a maximum burden of 20 t/axle.

With reference to Fig. 3, the liquid holdup ($\dot{m}_L$) inside the tank car changed due to both the internal evaporation ($\dot{m}_{evap}$) and the discharge from the hole ($\dot{m}_{disch}$), whilst the vapor holdup ($\dot{m}_V$) changed due to the evaporation only:

$$\begin{cases} \dfrac{dm_L}{dt} = -\dot{m}_{disch} - \dot{m}_{evap} \\ \dfrac{dm_V}{dt} = \dot{m}_{evap} \end{cases} \tag{1}$$

According to van der Bosch and Duijm [6], the discharge rate can be evaluated as:

$$\dot{m}_{disch} = \rho_L A_h c_D \sqrt{\frac{2}{\rho_L}(P - P_a) + 2gh_L} \tag{2}$$

where P is the pressure of the gaseous phase over the liquid, *i.e.* its vapor pressure (it is assumed to be always at the thermodynamic equilibrium). From the images of the crack (Fig. 4) and the witness of a person who could examine the punctured car, it was assumed that the effective hole dimensions were 40 cm × 2.5 cm (*i.e.* a hole area, A_h, of 100 cm^2).

This value is also in agreement with the estimates of the experts that reported a hole area of 90–220 cm^2. Since the hole had sharp and irregular edges, the discharge coefficient (c_D) was assumed 0.62 [6]. The internal evaporation rate can be derived imposing the volume conservation:

$$V = \frac{m_L}{\rho_L} + \frac{m_V}{\rho_V} \tag{3}$$

By neglecting the variation of the physicochemical properties with time, and by deriving this equation it is possible to find:

$$\frac{dm_v}{dt} = -\frac{dm_L}{dt}\frac{\rho_V}{\rho_L} = \dot{m}_{evap} \tag{4}$$

and then:

$$\frac{dm_L}{dt} = -\frac{\dot{m}_{disch}}{(1 - (\rho_V/\rho_L))} \tag{5}$$

The assumption that the densities do not vary with time, *i.e.* with temperature, is reasonable due to its rather small variation (as will be discussed in the following).

Fig. 4. The first derailed car at Viareggio station (on the left) and a detailed image of the crack in the LPG tank (on the right).

Table 2
Meteorological conditions of the night of June 29, 2009 measured at about 1.7 km from the epicenter of the accident between 11 and 12 PM.

Wind direction	NEE
Wind speed [m/s]	<1
Air temperature [°C]	23
Ambient pressure [mbar]	1008
Relative humidity	80%

The energy balance can be written as:

$$(m_L cp_L + m_V cp_V)\frac{dT}{dt} = -\dot{m}_{evap}\,\Delta H_{ev} \qquad (6)$$

Eq. (6) implies that the system is adiabatic, *i.e.* there is no heat exchange with the environment. This is a reasonable hypothesis due to the short time required to discharge all the liquid in the damaged tank car and the fact that the range of LPG temperatures inside the tank car is close to the ambient conditions. It is assumed that the LPG was initially at the ambient temperature (*i.e.* 296 K, see Table 2) because, even if it warmed during the day due to the sun radiation, in our opinion it also had sufficient time after the sunset to cool down thanks to the forced convection between the running train and the surrounding air. In fact, approximately four hours passed between the sunset (at 8.04 PM) and the accident (at 11.48 PM).

The evaluation of the dynamics of the LPG inside the tank car, in terms of liquid and vapor masses, and temperature, calls for the solution of the following ordinary differential equation (ODE) system:

$$\begin{cases} \dfrac{dm_L}{dt} = -\dfrac{\dot{m}_{disch}}{(1-(\rho_V/\rho_L))} \\ \dfrac{dm_v}{dt} = \dot{m}_{evap} \\ \dfrac{dT}{dt} = -\dfrac{\dot{m}_{evap}\ \Delta H_{ev}}{m_L cp_L + m_V cp_V} \end{cases} \qquad (7)$$

where $\dot{m}_{disch}$ can be evaluated with Eq. (2) and $\dot{m}_{evap}$ with Eq. (4).

The level of the liquid inside the tank car (h_L) can be evaluated from the volume of liquid (V_L) and from the tank car geometrical dimensions by considering it as a horizontal cylinder with flat sides [7]:

$$V_L = L\left[R^2 \mathrm{acos}(1-h_L/R) - (R-h_L)\sqrt{2Rh_L - h_L^2}\right] \qquad (8)$$

where R is the radius of the tank car (*i.e.* 1.52 m), and L is its length (*i.e.* 15.95 m). At each time step, the volume of the liquid is inferred from its mass, evaluated by solving the ODE system (7), and from its density. The level of liquid can be determined by finding the roots of Eq. (8).

When all the liquid was released from the crack, the tank car was still under pressure and the vapors were emitted through the hole in the choked-flow regime. In fact:

$$\left(\frac{P}{P_a}\right) \geq \left(\frac{\gamma+1}{2}\right)^{\gamma/(\gamma-1)} \qquad (9)$$

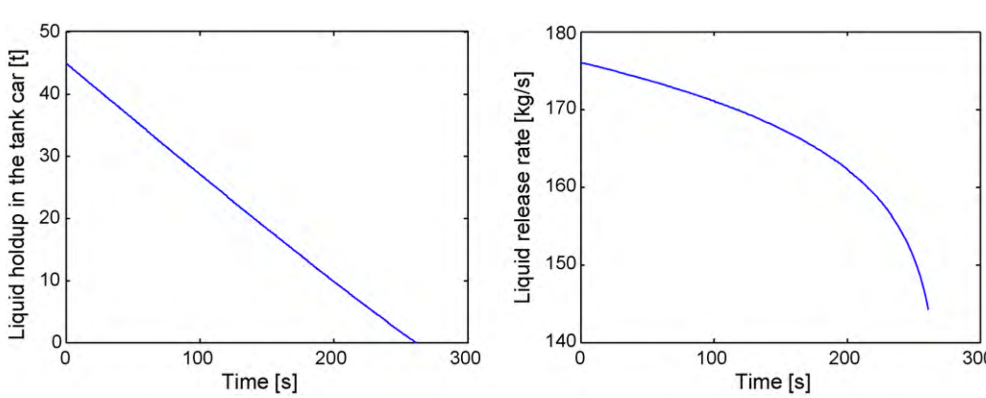

Fig. 5. Dynamics of the liquid holdup from the tank car (on the left) and the corresponding liquid release rate (on the right) under the assumption that the ignition occurred after the end of the release.

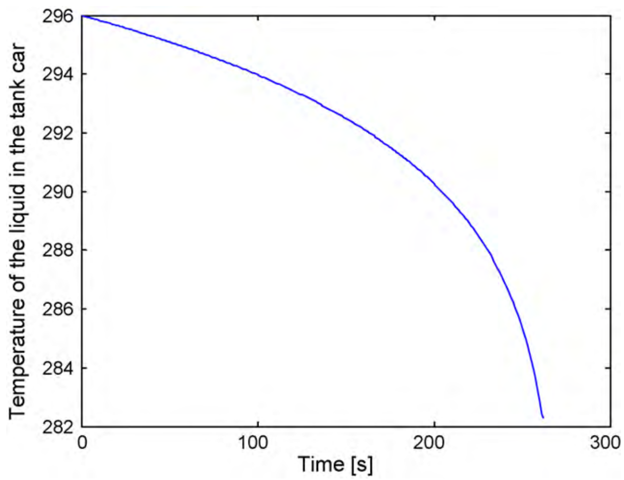

Fig. 6. Dynamics of the liquid temperature in the tank car due to the internal evaporation.

where the adiabatic constant for LPG is $\gamma = 1.13$. The gaseous discharge rate can be evaluated as [6]:

$$\dot{m}_{disch} = A_h c_D \sqrt{\rho_V P \gamma \left(\frac{2}{\gamma - 1}\right)^{(\gamma+1)/(\gamma-1)}} \tag{10}$$

Fig. 5 shows the dynamics of the liquid holdup, and the corresponding discharge rate. It follows that about 45 t of LPG were released in 262 s, *i.e.* 4 min and 22 s. After this time, only gas was emitted.

The vapor still in the tank car after the end of the liquid release was 1273 kg, *i.e.* 2.8% of the total initial holdup.

Fig. 6 shows the decrease of the temperature of the liquid fraction inside the tank car due to evaporation. The minimum temperature reached was ~282 K, corresponding to a decrease of ~14 K.

This analysis is valid if the ignition of the pool that was spreading on the ballast occurred after the release of all the LPG from the punctured car. Otherwise, the dynamics illustrated in Fig. 5 would change because of the radiative flux from the pool-fire to the damaged tank car. In this case, the heat balance becomes:

$$(m_L c p_L + m_V c p_V)\frac{dT}{dt} = -\dot{m}_{evap}\,\Delta H_{ev} + \alpha Q_{irr} A \tag{11}$$

where Q_{irr} is the heat flux emitted by the burning propane pool (250 kW/m^2 [8]), and α is the fraction of the incident energy that is absorbed by the tank car ($\alpha = 0.7$ for rusted steel). By assuming that the pool spread on one side of the tank car and, consequently, the flames licked it only on that side, the tank car area engulfed by the fire, A, was half of its total external area. Eq. (11) adopts a rather conservative approach and neglects the heat exchanged by radiation and convection between the tank car and the environment. A more detailed analysis can be found in [9–11].

As reported by some witnesses, the ignition occurred probably between 2 and 5 min after the derailment. If it is assumed that the ignition occurred after 2 min, it is possible to find that the pressure inside the tank car would have increased during the release up to 18 bar (Fig. 7), a value decidedly lower than the maximum allowable pressure, *i.e.* 25 bar (see Table 1). Under these assumptions, the release time falls to 236 s, *i.e.* 2 min and 54 s. If the pressure had risen to higher values or the flame had compromised the tank car metal resistance, a BLEVE would have occurred.

The liquid release rate increased after the ignition according to Eq. (2) because the internal pressure rose (Fig. 8).

As aforementioned, the dynamics showed in Figs. 5 and 6 can be representative of an ignition beyond 262 s, when the release was already over.

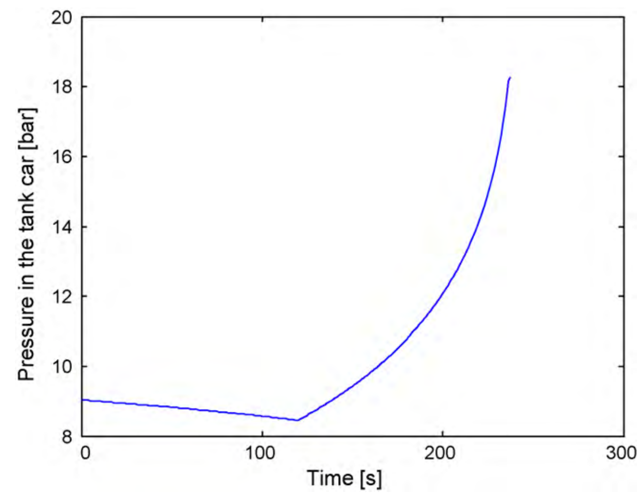

Fig. 7. Dynamics of the pressure inside the tank car in case of ignition after 2 min. For times larger than 2 min (*i.e.* 120 s) the pressure increased due to the heat radiated by the pool-fire.

3. Flash of the liquid jet stream in the atmosphere

Once emitted to ambient conditions, the liquid stream flashed and produced a two-phase jet. According to Hanna and Drivas [12], the vapor fraction can be evaluated as:

$$x_V = \frac{c p_L (T - T_{eb})}{\Delta H_{ev}} \tag{12}$$

where T is the temperature of the jet (Fig. 6) and $T_{eb} = 231.1$ K is the boiling temperature of pure n-propane.

Eq. (12) allows evaluating the liquid and vapor mass fractions and the corresponding flow rates in case of ignition after 2 and 5 min. In both cases, since the temperature changed during the discharge, the vapor and liquid fractions changed accordingly (Figs. 9 and 10). The sum of the vapor and liquid discharge rates in Figs. 9 and 10 (on the left) corresponds to the flow rates showed in Figs. 8 and 5, respectively.

For the ignition after 2 min, there is a sharp increase in the vapor fraction, and the corresponding flow rate, because of the rise in the internal tank car temperature that reached 326 K, *i.e.* 53 °C (Fig. 11).

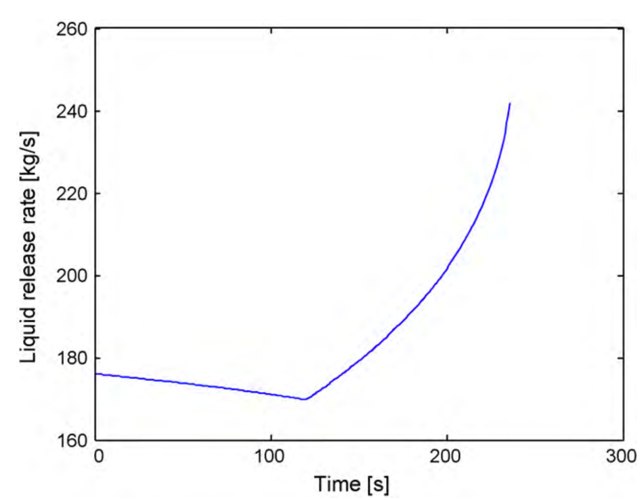

Fig. 8. Discharge rate of the liquid from the crack in the tank car in case of ignition after 2 min. For times larger than 2 min (*i.e.* 120 s), there was a sharp rise of the release rate because the pressure inside the tank car increased.

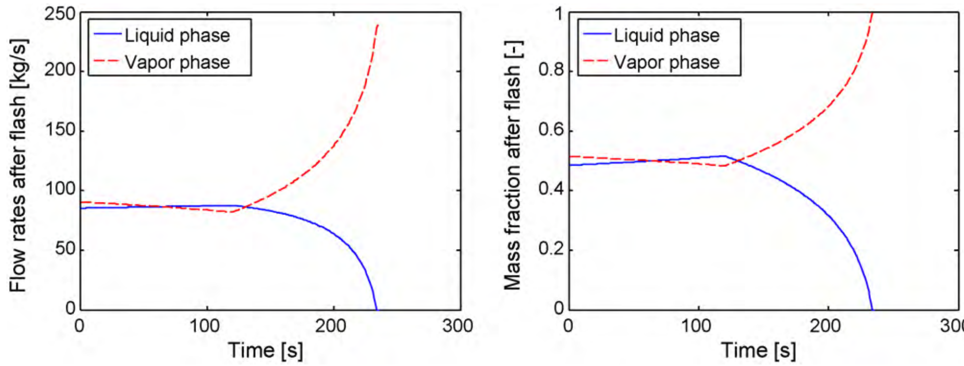

Fig. 9. Mass flow rates (on the left) and mass fractions (on the right) after the flash of the liquid jet emitted by the crack in case of ignition after 2 min.

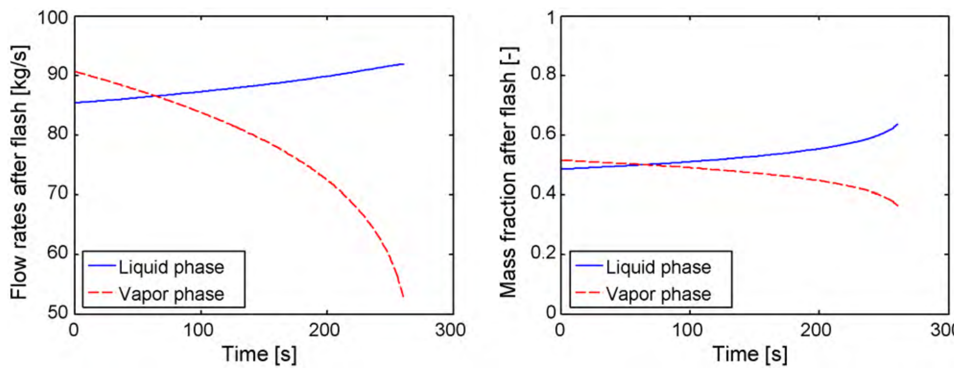

Fig. 10. Mass flow rates (on the left) and mass fractions (on the right) after the flash of the liquid jet emitted by the crack in case of ignition after 5 min.

4. Spreading, evaporation, and burning of the liquid pool

Since the crack in the tank car was close to the ground, the liquid jet impacted directly on the ballast and did not have the time and space to break up into drops (as it happens after a typical flight in air). Therefore, it is reasonable to assume that the vapor fraction did not entrain any liquid. Consequently, the liquid fraction spread onto the ground and formed a pool.

The spreading of the LPG on the ballast, its evaporation, and delayed ignition were simulated with AXIM^{TM}, a software tool for the dynamic simulation of chemical accidents [13]. This simulator can account for the dynamics of both the temperature and the flow rate of the released LPG. In addition, it allows simulating a pool-fire triggered at any arbitrary time after the beginning of the release.

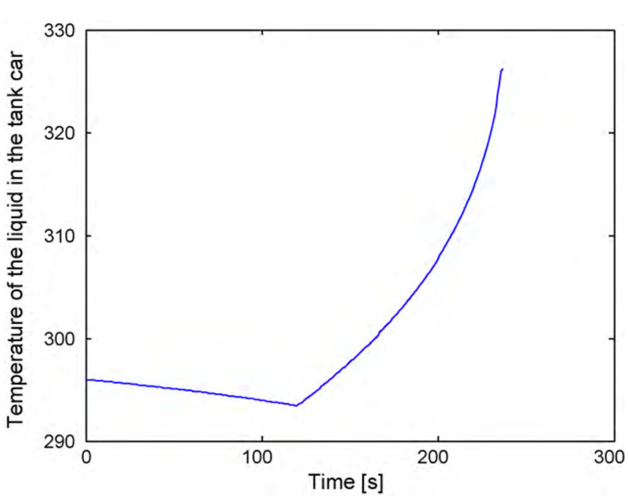

Fig. 11. Temperature dynamics inside the tank car in case of ignition after 2 min.

By assuming that the pool was free to spread and expand, AXIM^{TM} determined that, in case of ignition after 2 min, the pool reached a diameter of ~20 m, whilst the flame reached a maximum drag diameter of ~22 m and a height of ~40 m (Fig. 12). In case of ignition after 5 min, the pool reached a maximum diameter of ~23 m, whilst the flame reached a drag diameter of ~25 m and a height of ~44 m (Fig. 13).

The pool-fire model in AXIM^{TM} is based mainly on [8,14–17]. These models determine the flame dimensions (drag diameter, height, and tilt) from experiments related to the ignition of confined liquid pools (*i.e.* liquids in a bund). The accidental conditions in Viareggio differed from that situation because the vapor fraction that flashed from the liquid stream was set on fire too. The aforementioned models are not able to account for this additional burning mass in the computation of the flame geometrical dimensions. Consequently, AXIM^{TM} accounts only for the combustion of the liquid evaporated from the pool and not for the combustion of the vapors flashed from the liquid stream. We expect that, by considering also this contribute, the evaluated flame height would be even higher.

Moreover, the data presented in Figs. 12 and 13 overestimate the pool and flame dimensions because the liquid permeation into the ground and the presence of objects acting as a confinement were not modeled. A (reduced) flame height of about 25 m, as reported by some eyewitnesses, would have been possible only if the pool spreading had been inhibited at a certain extent by the morphology and features of the ground. Fig. 14 shows that the ballast was not a flat ground of pebbles. Instead, there were piles of pebbles, depressions, and some obstacles that probably played the role of a fortuitous bund.

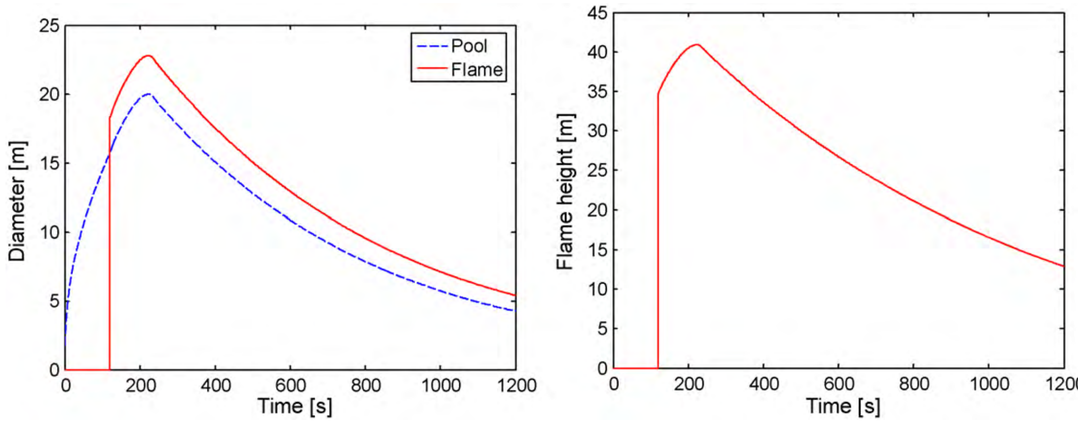

Fig. 12. Pool diameter and flame drag diameter (on the left). Pool-fire height (on the right) if the ignition occurred after 2 min.

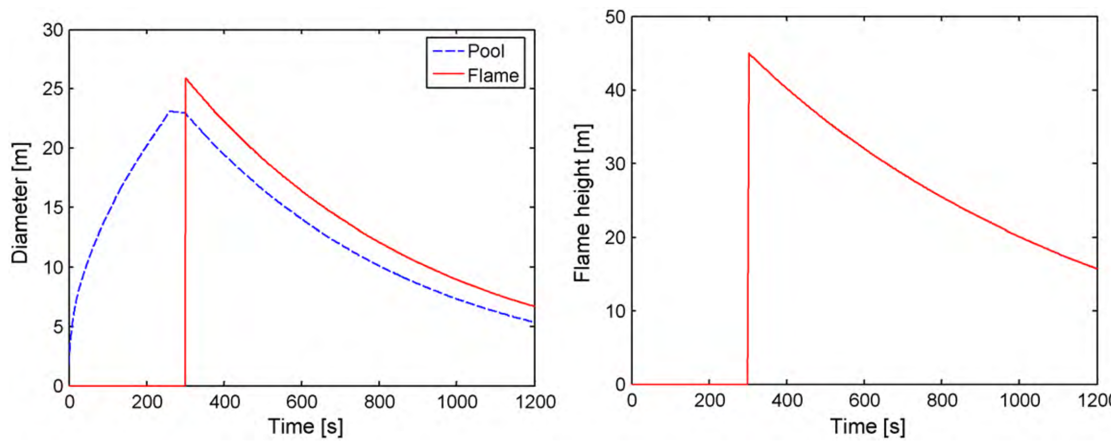

Fig. 13. Pool diameter and flame drag diameter (on the left). Pool-fire height (on the right) if the ignition occurred after 5 min.

Rosmuller [18] experimented the spreading of colored water on the railway ballast close to a noise shield and demonstrated that it influenced significantly both the pool shape and height. In fact, in his experiments the pool was not circular because the released water flowed into the depression between the ballast and the noise shield. This portion of the pool was about 90 m long and 1 m wide, whilst the remaining part of the liquid formed a rather circular pool 15–20 m in diameter. According to Rosmuller measures [18], close to the noise shield, the pool reached a depth of about 15 cm. In the simulation, it was assumed that the depth of the pebbles was 10 cm and the pool spread through them reaching a depth of 6 cm. This value, which is lower than the one reported in [18], is justified by the absence of a macroscopic depression/containment. Actually, the aforementioned obstacles, acting as an irregular confinement of about 10 m in diameter, together with the permeable ballast, could have led to flames as high as 25 m (Fig. 15).

Another open issue is related to the hypothesis that all the liquid discharged from the crack in the tank car contributed to the pool. Fig. 16 shows that separate pool-fires formed on the ballast near the derailed and punctured tank car, and they could not be ascribed to the combustion of the sleepers. On the contrary, this phenomenon could be due to the spray of the released liquid to different places and directions because of the unevenness of the ballast, and the release velocity (30 m/s). This explanation is supported by the statement of the train drivers, who told that they ran away from the locomotive trampling on the LPG pools on the ballast [1]. The locomotive head was approximately at 35 m from the punctured tank car and Figs. 12 and 13 show that the single-pool

Fig. 14. The images show that the Viareggio ballast was not flat. On the contrary, the ground was irregular, with some piles of pebbles, depressions, and obstacles.

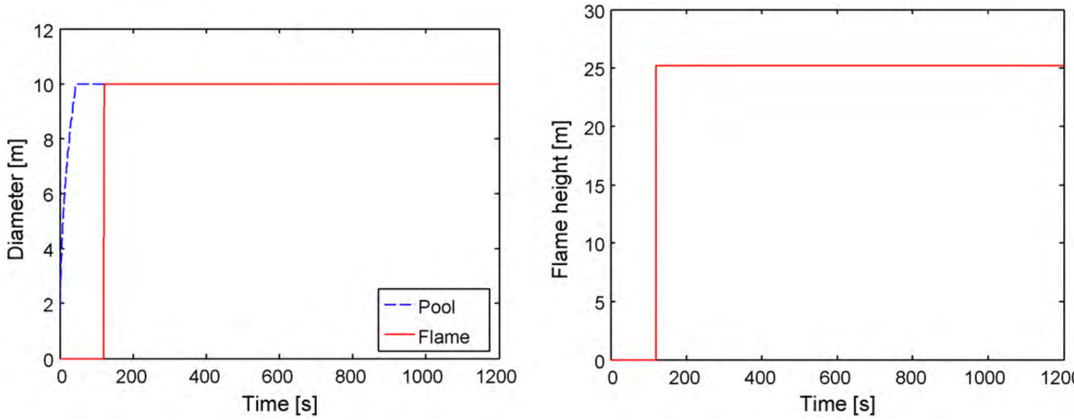

Fig. 15. Pool and flame diameters (on the left) and pool-fire height (on the right) in case of confinement of the pool and if the ignition occurred after 2 min.

Fig. 16. Formation of smaller and isolated fires in the surroundings of the damaged tank car.

did not reach so far. Possibly, the liquid discharged from the crack did not form only one pool. Instead, it formed a main pool, and a set of isolated and smaller pools.

By forcing the LPG pool to a bund diameter of about 10 m, it is possible to obtain the maximum radiative heat flux that arrived on a person (supposed 1.8 m high and 0.4 m wide) as a function of his/her distance from the pool epicenter (Fig. 17).

There was a man who was walking on the pedestrian crossing over the railroad that "evaporated" due to the high heat radiation. He was at approximately 45 m from the fire epicenter, and it is possible to see from Fig. 18 that the heat radiation to which he was exposed was about 1.4 kW/m^2 if it is assumed that the pool was confined. Conversely, it could have been as high as 5 kW/m^2 if

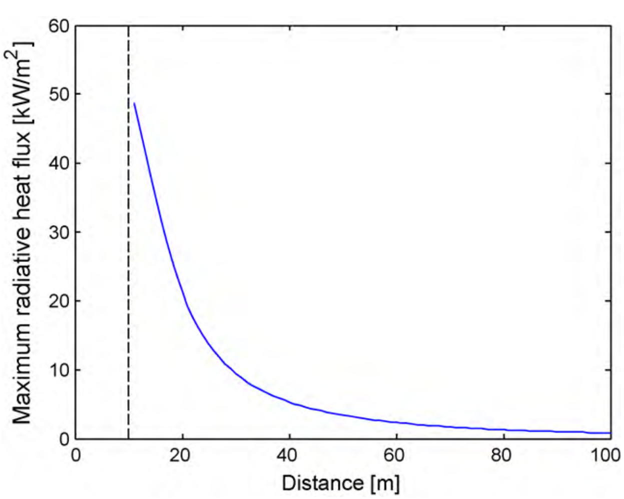

Fig. 17. Maximum radiative heat flux to a person as a function of the distance from the pool-fire epicenter. The vertical dashed line shows the maximum pool radius.

the pool was free to spread and the ignition occurred after 2 min. However, these values cannot explain the real "vaporization" of that man.

To determine the effects of the aforementioned thermal radiations on a person, let us consider the thermal load defined as [19,20]:

$$TL = \int_0^{\bar{t}} I^{4/3} dt \quad [s(W/m^2)^{4/3}/10^4] \tag{13}$$

where I is the radiative heat, t is the time, and $\bar{t}$ is the exposure time. According to Lees [20], second-degree burns occur for a thermal load of 1200, third-degree burns for 2600, unpiloted clothing ignition for 3000, and lethality for 4500 $s(W/m^2)^{4/3}/10^4$. Fig. 19 shows that, for the confined pool, the person was not supposed to suffer any injuries, even for a long exposure time. On the contrary, for the ignition after 2 min, the thermal load approached the threshold for second-degree burns. Nonetheless, the time to reach such threshold is quite long, *i.e.* about 10 min of exposure.

From this analysis, the person walking on the pedestrian crossing over the railroad should have suffered at most second-degree burns. His death could be ascribable to the inhalation of the hot smoke and air [21]. In fact, when inhalation injuries are combined with external burns the chance of death increases significantly. Consider also that 60% to 80% of fatalities resulting from burn injuries can be attributed to smoke inhalation (www.burnsurvivor.com). Nonetheless, it was not possible to find any reasonable justifications to his "evaporation" if only the radiative contribute from the pool-fire is accounted for. Possibly, a portion of the dense-gas cloud (see also Section 5) moved towards the pedestrian crossing and the man was caught in the path of the flash fire when the cloud was ignited. According to [19], this situation would lead to severe injuries because the direct contact with the flame would cause deep burns over the major part of the body. In our opinion, this is the cause of the man "evaporation". Even the

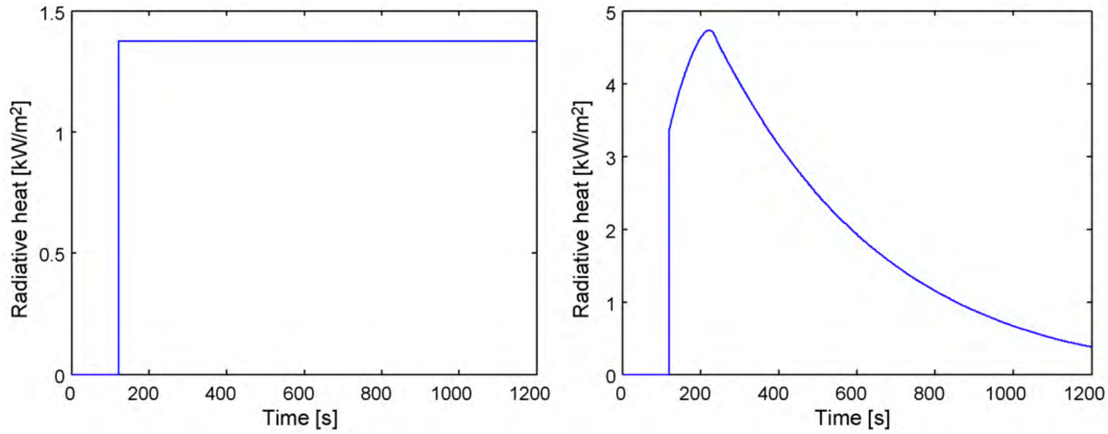

Fig. 18. Radiative heat absorbed by the person on the pedestrian crossing over the rail road (∼45 m from the fire epicenter) in case of confined pool (on the left) or unconfined spreading with ignition after 2 min.

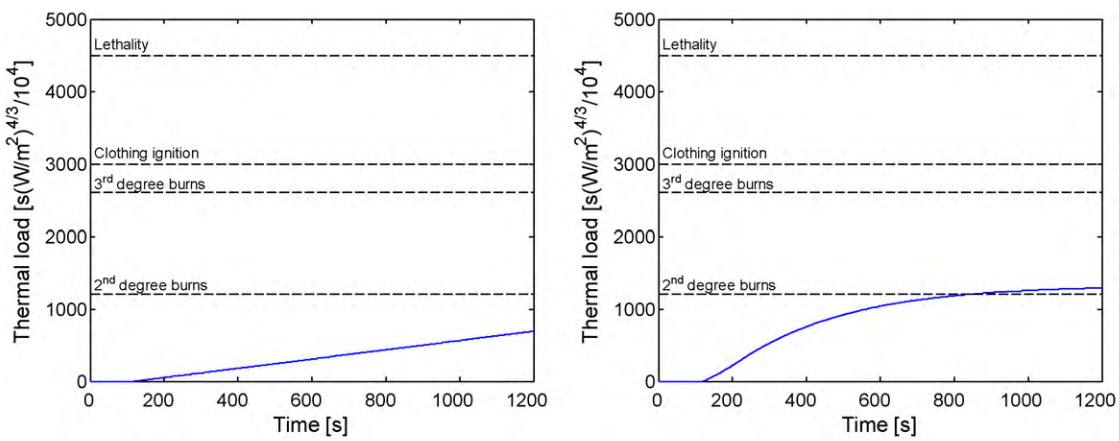

Fig. 19. Thermal load on the person walking on the pedestrian crossing over the railroad (under the hypothesis of radiation from the pool-fire) in case of confined pool (on the left) or unconfined spreading (on the right) with ignition after 2 min.

highest value of the radiative heat flux from the pool-fire (Fig. 17) equal to 50–60 kW/m^2 cannot explain the sudden "evaporation" of that man.

5. Dense-gas dispersion

To simulate the dispersion of the dense-gas flashed from the liquid jet emitted by the punctured tank car and evaporated from the boiling liquid pool (up to the ignition time), it is necessary to consider the following phenomena:

- the gravity slumping, due to the high density of the gas cloud (about two times that of air);
- the entrainment of fresh air that dilutes and heats up the gas cloud;
- the dynamics of the gas cloud temperature due to the heat exchanged with the ground;
- the motion of the gas cloud with the local wind.

The heat exchanged by the gas cloud with the ground was neglected. This phenomenon is modeled only by DISPLAY-2 [22]. In addition, since there were rather calm weather conditions (see Table 2), the motion of the gas cloud by the wind was negligible respect to the gravity slumping. In addition, a remarkable feature, common to all the accident simulators, is that the model included in AXIM^{TM} [13] does not account for the dilution of the jet due to the impact with the ground in the proximity of the release.

To simulate the gas dispersion, the balance equations involve the conservation of mass, and of momentum. The gas dispersion on the railroad, the ballast, and finally through the rows of the surrounding buildings was simulated. The dense-gas cloud was modeled by means of the shallow water equations. In particular, the model of TWODEE [23] was adapted to simulate congested environments, *i.e.* to account for the presence of buildings and/or other manmade obstacles (*e.g.*, fences, cabins, pylons). The simulations were run with a grid of 250 × 200 cells, in a domain of 250 m × 270 m, with non-reflective, or open, or wave-permeable boundary conditions. On a Dual Core AMD Opteron processor at 2 GHz with 2 GB of RAM, with Windows XP Professional Service Pack 3, the code requires about 15 min to simulate 180 s (as a matter of fact the code was not parallelized, therefore the Dual Core feature was not exploited).

The positions of the buildings in the surrounding of the accident were determined with a georeferenced program (Google Earth^{TM}, version 5.0.11733.9347), see Fig. 20 and Table 3. For the sake of simplicity, it was assumed that all the buildings are 10 m high (this assumption is reasonable since it refers to two/three-story buildings).

Fig. 21 shows the 3D reconstruction of the building in the proximity of the accident.

Fig. 22 shows the dispersion of the gas cloud in the area close to the accident and its spreading over the buildings and in the street canyons. It is possible to notice that the gas cloud arrived at the closest building after about 18 s, then at the second rows of buildings after about 41 s. Afterwards, the gas cloud reached the buildings on

Fig. 20. Identification of the main buildings in the surroundings of the accident location, corresponding to the (0, 0) coordinates within the chosen reference frame.

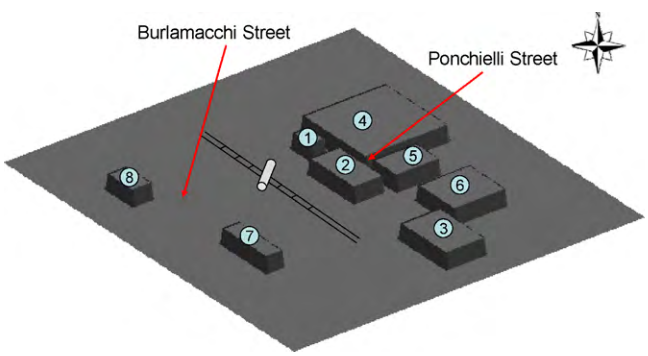

Fig. 21. Simplified 3D reconstruction of the main buildings in the surroundings of the accident.

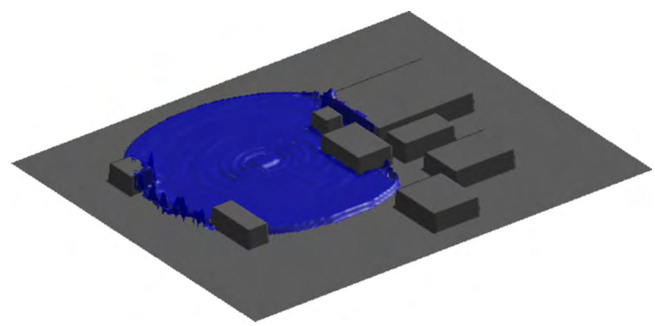

Fig. 23. 3D representation of the gas cloud motion through the streets of Terminetto quarter at 66.6 s after the beginning of the release.

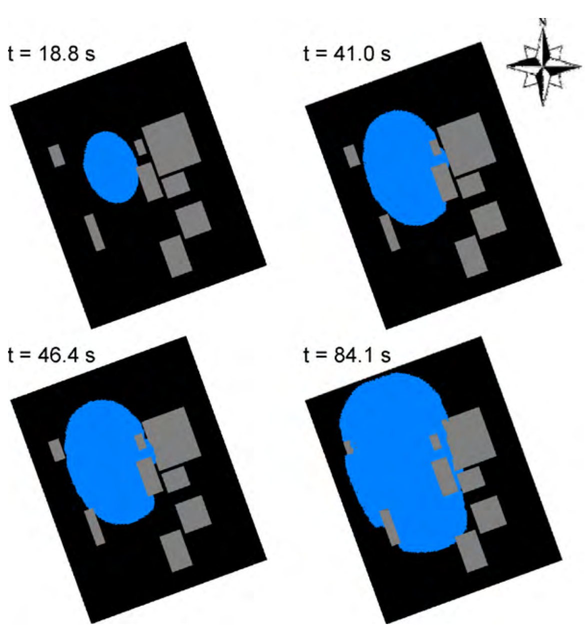

Fig. 22. Dispersion of the dense-gas cloud at different times from the release start. It is possible to observe the channeling of the gas cloud through the houses and its spreading on the roofs of some buildings.

the west side of the gas cloud at approximately 46 s. The picture on the right bottom corner shows that after about 77 s the gas cloud arrived also at the farthest building on the right bottom (*i.e.* at about 100 m from the derailed tank car) with a concentration higher than the lower flammability limit.

Fig. 22 shows the aerial view of the gas cloud, whilst Fig. 23 shows the 3D reconstruction of the gas cloud at a given instant (*i.e.* 66.6 s). It is possible to observe the splash of the dense-gas cloud on some houses.

The modeling of the dense-gas dispersion motion through the streets of Terminetto neighborhood shows that in less than two minutes the gas cloud reached all the locations where the explosions occurred. This is in agreement with the witnesses who reported that the explosions occurred after only a couple of minutes from the train derailment. This point highlights the difficulty to protect people by implementing any emergency plans and actions in case of chemical accident. In the Viareggio accident, only one tank car out of fourteen broke and released LPG. The consequences could have been even worse if more tank cars had broken due to the heat radiation from the pool-fire or to the impact with any obstacles on the ballast.

This accident highlights the necessity for implementing/installing *ad hoc* mitigation measures close to towns and cities to contain the consequences of chemical accidents due to the rail transport of hazardous substances. Probably, a noise shield as

Table 3
Coordinates and dimensions of the main buildings marked in Fig. 17 (on the right) respect to the reference frame positioned where the accident occurred.

Building ID	Coordinates of the lower left corner [m]	Transversal (x) distance from the origin [m]	Longitudinal (y) distance from the origin [m]
1	(45, 7)	11	17
2	(35, −46)	22	41
3	(31, −136)	29	42
4	(61, −23)	60	59
5	(62, −50)	32	22
6	(65, −100)	38	35
7	(−52, −78)	13	41
8	(−66, 27)	15	23

high as a couple of meters could have diluted the gas cloud under the lower flammability limit. Actually, the Thorney Island trials demonstrated the effectiveness of walls in diluting a dense-gas cloud [24]. In fact, downwind of the wall, the concentration was halved respect to that measured in similar meteorological conditions when there were no barriers.

6. Explosion

The evidence tells us that the explosions occurred inside the houses due to the penetration of the dense-gas cloud through the open windows in the basements and ground floors.

Generally speaking, buildings are not very resistant to overpressures when the explosions are triggered from inside. In fact, an overpressure of 7 kPa is often enough to destroy a typical brick building [20]. At the same time, the presence of weaker elements in the walls (such as windows), which fail first, provides vents to the explosion, and results in lower overpressures. Conventional windows fail at overpressures of 3–4.6 kPa, strained windows at 0.2–1 kPa, brick walls (114 mm thick) at 35 kPa, and brick walls (228 mm thick) at 105 kPa [20].

The dense-gas dispersion model discussed in Section 5 cannot simulate the penetration into buildings. Consequently, we did not determine the amount of LPG that diffused through the openings and eventually exploded. In addition, we assumed that there were no explosions external to the houses. Consequently, conventional models such as the TNT equivalent method and the multienergy method [20,25] do not apply to this quantitative assessment.

7. Conclusions

The analysis reported in this manuscript showed that it is possible to reconstruct the sequence of events that led to the catastrophic accident of Viareggio on June 29th, 2009. The accident was described in detail according to a number of information sources, ranging from the eyewitnesses to the newspapers, television programmes, pictures, and the opinion of experts.

The paper presented and discussed suitable models to relate the observed consequences (in terms of damages, and injuries) to the evolution of specific physical phenomena. Some uncertainties were highlighted and different accidental scenarios were also simulated to assess the differences and confirm or discard the corresponding hypotheses. In particular, it was shown that there is a large uncertainty related to the time of ignition. To overcome this difficulty, different ignition times were simulated, being representative of two antithetic cases: the ignition during the release of LPG from the tank car (after 2 min), and the ignition once the release was already over (after 5 min). The analysis showed that the release rate is influenced by the presence of a fire licking the punctured tank car, especially in terms of vapor flash fraction.

Another source of uncertainty was related to the shape of the pool and its possible confinement due to the ballast morphology and the presence of obstacles. It was shown that a flame height of 25 m was not possible if the pool was free to spread, for both the ignition times of 2 and 5 min. On the contrary, a flame height of 25 m was possible if the effective spreading area corresponded to an equivalent pool diameter of only 10 m (*i.e.* limited by the surrounding features of the ballast).

In addition, it was not possible to justify the evaporation of the person walking on the pedestrian crossing. In fact, the simulated radiative heat flux and the thermal load from the pool-fire were far too low to produce such a consequence. Probably, the man died because he was caught in the flash fire.

The modeling of the dense-gas dispersion showed that in approximately 77 s the gas cloud reached all the locations where the explosions occurred. This is in agreement with the witnesses who reported the occurrence of some explosions after only a couple of minutes after the train derailment. This evidence confirms the need to develop effective mitigation and preventive measures because, in case of this kind of accidents, there is no time to apply any emergency response plans/actions.

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