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EVALUATION OF THE EFFECTS OF FIRES AND EXPLOSIONS IN THE TRANSPORT OF HAZARDOUS MATERIALS

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Abstract: *Transportation of liquid and gaseous fuels and chemicals, albeit not frequent, can lead to serious dangers for humans, the environment and property due to fires and explosions. The two most common transportation modes on land are tanker trucks and pipelines. The effects of fires and explosions in such transportations can be modelled successfully to describe observed damages, as discussed here for three different types of accidents, namely tanker trucks carrying liquefied natural gas (LNG) or liquefied petroleum gas (LPG), and a gas pipeline, resulting in ignition and explosion. The effects of overpressure due to explosion and of radiated heat by fires are effectively modelled. The methodology and the developed e-platform are valuable teaching tools for engineers and civic personnel in order to foresee and assess risk and accident consequences near inhabited areas, and/or to predict alternate routes.*

Key words: *hazardous materials, fires, explosions, road transport, ADR vehicles, pipelines*

1. Introduction

Hazardous goods include all fuels (solid, liquid or gas), chemicals which are flammable, toxic, poisonous, oxidizing and explosive, materials that are radioactive or corrosive, etc. Transportation of such dangerous materials by road, rail, sea, inland waterways, or air are regulated by the corresponding international treaties ADR (European Agreement concerning the International Carriage of Dangerous Goods by Road), RID (European Agreements Concerning the International Carriage of Dangerous Goods by Rail), IMDG (International Maritime Dangerous Goods Code), ADN (European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways), and ICAO (International Civil Aviation Organization), respectively, which have been endorsed by almost all European countries.

Although a number of databases provide some information on the transportation of goods, their analyses on dangerous materials and the impact of related accidents are often incomplete. For the movements of hazardous materials in the USA, a good source is the annual reports of the National Transportation Board (NTSB, 2014). In 2004, over 1.5 billion tons of hazardous materials were shipped by truck, rail, water, and air in the USA. Reports on accidental releases numbered about 13 fatalities, 289 injuries and $52.6 million in reported damages (NTSB, 2014).

For the UK, a corresponding good source of information on the road transportation of hazardous materials is given in *Transport Statistics Great Britain* 2014 an annual report published by the Department of Transport (2014). In the UK, historical records show that the transportation of hazardous chemicals by road is not a real problem. Kletz (1986) showed that from 1970 to 1982, an average of 1.2 people per year were killed by road accidents involving the transportation of chemicals or gasoline. Though this is a 1.2 too many, it has to be compared with 6,000 deaths per year from road accidents of all sorts. However, incidents killing many people have happened in many other countries (Sinton, 1983 and Lees, 2003).

An alternative to road transport for the high volumes of petroleum, natural gas and liquid or gaseous chemicals is pipeline transport. Only for the transmission of natural gas in 2014, EU has a pipeline network of 143 000 km, up to 120 cm in diameter, with an incident rate of 0.33 per year and 1000 km (EGIG, 2015). Pipeline accidents can be devastating, with scores of fatalities and injuries. and high property damage costs.

In assessing the risk of accidents involving dangerous materials, a vital step is the evaluation of the hazard nature and zone analysis

(Sakellaropoulos et al., 2014; Assael and Kakosimos, 2010b). This paper addresses the accidents occurring during the transport by road or pipeline, and concentrates on the evaluation of the effects of fires and explosions in the case of hazardous materials. It is our intention to show that today one can relatively easily calculate such effects on humans and property, train engineers and civic personnel to evaluate alternatives and minimize probable losses.

In the following sections first a brief description of the quantification of hazardous effect of fires and explosions will be presented. Following this, accidents related to road and pipeline transport will be discussed in turn, each described with a typical case study.

2. Quantifying Hazardous Effects

In order to quantify the hazardous effects of leaks from tanker trucks carrying fuels or from a pipeline we examine below the possible development of fire or explosion following a leak. A risk assessment procedure involves the following steps:

1. Hazard identification
2. Failure case definition
3. Failure frequency
4. Hazard zone analysis
5. Public risk quantification
6. Risk Assessment (acceptable risk values)

An event tree analysis followed by statistical data of previous accidents and suitable algorithms permits the evaluation of the consequences of such events.

Figure 1 shows the probable consequences resulting from a gas or liquid fuel leak from a tank truck (or road tanker in the UK), or a pipeline. With the exception of the flash fire (sudden ignition of a cloud of flammable gases, where the flame is not accelerated by the presence of obstacles or turbulent dispersion), the effects from the other three type of fires and from explosions can be calculated.

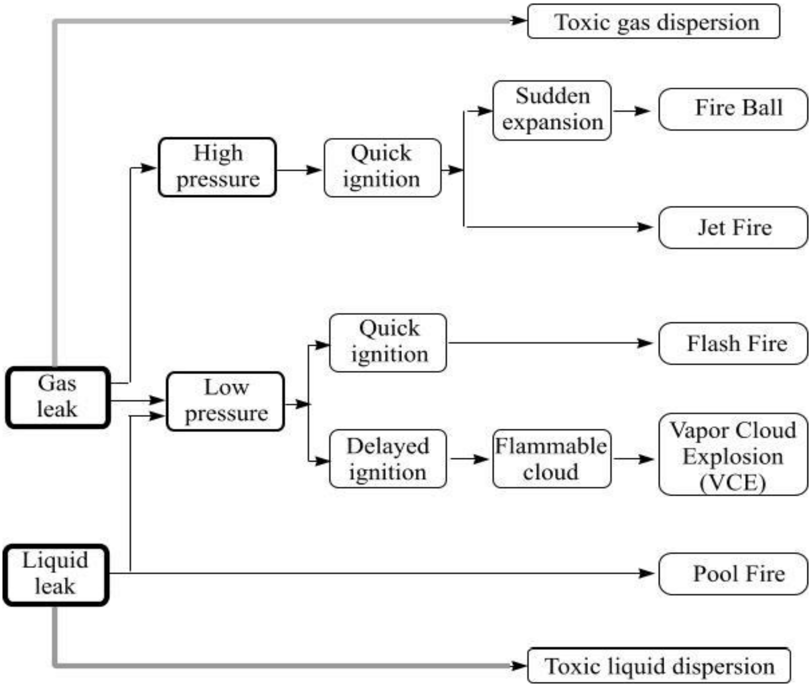

Fig. 1. Probable consequences resulting from a gas or liquid fuel leak
Source: Assael and Kakosimos (2010b).

In the case of fires, damages are a direct consequence of the generated heat flux. There are many models to calculate the generated heat flux. However, the solid-flame model is the most widely used today, as it can, with care, easily be applied in most cases. In the "solid-flame" approach the flame is treated as a solid object that radiates heat from its visible surface. The heat flux q' (W/m^2) in a certain distance, is obtained from:

$$q' = SEP_{\mathrm{act}}\, F_{\mathrm{view}}\, \tau_{\alpha} \tag{1}$$

where, SEP_{act} (W/m^2) denotes the actual surface emitting power, F_{view} (-), the view factor, and τ_{α} (-) the atmospheric transmissivity. In the above relation, the surface emitting power is calculated empirically as a function of the burning rate and takes into consideration the fraction of the flame covered by soot, while the view factor depends upon the shape of the flame, the presence of wind and the distance of the receptor from the external flame surface. Finally, the atmospheric transmissivity takes into consideration the part of the heat flux absorbed by the air which is between the flame and the receptor of the radiation. Having obtained the heat flux as a function of the distance, empirical probit functions are employed (Assael and Kakosimos, 2010b) to calculate the probability of injury or death and the effects of radiation on materials.

While in the case of fires, one calculates the heat flux as a function of distance, **in explosions one calculates the resulting overpressure as a function of distance**. A simplified method usually employed to characterize the power of an explosion, is the Equivalent TNT Method. According to this method, the power of the explosion equates to an equivalent mass of TNT (tri-nitrotoluene) that would produce the same explosive power. First, the mass of the flammable gas in the cloud with concentrations between the lower and the upper flammability limits is estimated. This mass is consequently multiplied by the heat of combustion to obtain the total available energy of combustion. This energy is multiplied by a parameter (0 to 1) that accounts for the non-ideality of the explosion, and then divided with the heat of combustion of TNT, in order to calculate the equivalent TNT mass. The equivalent TNT mass is employed for the calculation of the shock wave in a specific distance from the source.

Unconfined vapor cloud explosions (VCE), are usually calculated by the Multi Energy Method (Assael and Kakosimos, 2010b). The method assumes that the VCE is composed of a number of subexplosions taking place inside the cloud. Initially the dimensions of the cloud, based upon the amount of leaked flammable gas, is estimated, and the probable explosion sources are identified. Following this, a series of empirical criteria are employed in order to identify the obstructed regions, to calculate the volume they occupy and thus to obtain the space left free for the vapor cloud to spread.

Consequently the energy of the explosion is calculated, and thus from empirical expressions the resulting overpressure in specific distances from the explosion center, as well as the duration of the positive phase, are obtained. The calculation of the overpressure is directly dependent upon the type of region where the explosion took place, i.e., if it is an obstructed region or not. From the overpressure, the effects to humans or material damages can easily be calculated with the use of probit functions.

3. Road Transport of Dangerous Goods

Road transport of dangerous goods in European Union amounted to 78.7 Bt·km in 2010, or 4.5% of the total goods traffic (1775 Bt·km). Only in Germany road transport of dangerous goods in 2010 led to 8 deaths and 159 injuries, representing 0.9% and 0.5%, respectively, of total deaths and injuries in goods transportation (Kirchnawy, 2012).

In Asian and African countries, 13 accidents were reported in 2012 related to truck transport of fuels or chemicals with 375 persons killed and 156 injured. In China, accidents related to hazardous materials transport involved 708 tanker trucks, between 2004 and 2011, with 55.5% leading only to a spill, 7.7% releases leading to fire and 2.5% to an explosion (Shen et al., 2014).

Three recent accidents in Greece with LPG carrying tanker trucks, fortunately without fatalities, show the importance of proper training of drivers and civic personnel.

- On April 22, 2013 an LPG truck, unloading to a hotel storage tank in Grete, exploded resulting in severe burns of the driver.
- On May 15, 2014 an LPG truck skidded in a country road close Ioannina, resulting in a leak

which was combated by firefighters from a dangerously close distance of 3-5 meters. The road was closed for several hours.

- On May 26, 2014 an LPG truck was irresponsibly parked on a densely populated village road close Trikala. A leak developed and police and firefighters tried to isolate the area and move the truck.

It is only by luck that these incidents did not develop to major disasters with fatalities, injuries and property damage, as had happened 15 years before on a main Greek highway.

Consider the following two cases:

CASE 1. Explosion of a road tanker containing liquefied natural gas (LNG)

Natural gas (NG) is the second most important energy source in Europe, after oil, representing 23% of total energy content. Most NG reaches Europe via pipelines (86%), as discussed in Section 4. However, more than 14% is transported by ships and stored as liquefied natural gas (LNG) (Eurogas, 2014). LNG is transported to end users by tanker trucks as a cryogenic liquid (at -162 ^{o}C) or as a compressed gas (CNG). The former is preferable since its volumetric energy density is about 2.5 times that of CNG. Both LNG and CNG are used, among others, to power light and heavy duty vehicles and buses. It is noteworthy that the natural-gas vehicle (NGV) fleet is steadily growing to over 20 million NGV worldwide. Major players in NGV are the Asian and South American countries, where such vehicles exceed 15 million. Europe had a total of 1.2 million NGVs in 2014, of which 22100 were medium and heavy duty vehicles and buses. Italy had the largest share, with 885000 NGVs (NGVA, 2015). Many countries, including Italy, France, Spain, Poland and Greece, have significant fleets of municipal buses operating on CNG or LNG to reduce city pollution by conventional diesel engines.

Transportation of LNG by tanker trucks complies with the ADR International treaty. Tankers are insulated or double-walled, to protect liquid methane from boiling off. Because of the relatively low number of LNG tanker trucks and the infrequent catastrophic rupture of such vessels, relevant data are limited. On October 7, 2012, a tanker carrying 20 tons LNG exploded on a Chang Ji highway in China, killing 5 people, including 3 firemen, and causing the destruction of 7 cars. On October 20, 2011 and on June 22, 2002 the Spanish transportation industry suffered two major incidents involving LNG tankers, with fires, explosions and death of drivers, while another 12 accidents between 1999 and 2012 led to leaks and property damage. Buses operating on LNG or CNG have had occasional minor accidents, usually during maintenance, due to improper handling. The June 22, 2002 accident will be evaluated below as an accident analysis example.

The accident took place at 13:30, on June 22, 2002, on the C-44 road near Tivissa, Catalonia, Spain. A tanker containing natural gas, lost control on a downhill section of the road, probably due to high speed. It turned over, tipped on its left side and stopped besides a sandy slope. Full description is given by Planas-Cuchi et al. (2004). Immediately very high flames appeared between the cabin and the trailer (see Fig. 2). The flames could be fed by the diesel oil from the truck tank or by a broken pipe to the LNG. Approximately 20 min after the road accident, the tank exploded giving rise to a fireball. The driver died, and two persons that were in a distance of about 200 m were injured (burned).

The tanker, built 28 months earlier, was made of AISI 304, in cylindrical shape and insulated, and it was designed for a working pressure of 7 bar. It had a volume of 56 m^3, 85% of it was filled with liquid LNG at a temperature slightly below -160 ^{o}C and the pressure slightly below 1 bar. There were five safety valves all connected to a discharge pipe located at the top of the vessel. The truck had a 0.5 m^3 aluminium diesel oil tank.

Fig. 2. The tanker 2 min after the road accident The car was left by one of the witnesses that ran away

Source: Planas-Cuchi et al. (2004).

Initial flames

The initial flames most likely are attributed to the puncture of the 0.5 m^3 aluminium diesel oil tank. A pool lake was probably formed. Assuming a typical pool depth of 2 cm, this will give a pool diameter, D, of about 5.6 m. Since the burning rate, m', of diesel fuel is about 0.055 $kg \cdot m^{-2} \cdot s^{-1}$, the height of flames, L, generated can be obtained by (Thomas, 1963):

$$L = 42 D \left(m' / (\rho_{\mathrm{air}} \sqrt{g D}) \right)^{0.61} = 11 \text{ m} \qquad (2)$$

In the above relation, ρ_{air} (1.21 kg/m^3), is the air density and g (9.81 m/s^2), the acceleration due to gravity. The pool diameter of 5.6 m and the flame height of 11 m, seem logical according to observations.

Overpressure estimation

The explosion was very violent, breaking the tank and tanker into several pieces, ejecting them into large distance and causing a pressure wave. As not enough information is available to consider it as a BLEVE, an easy way to get a good idea of the extent of the pressure wave is to deduce it from the effects observed. There was a house at a distance of 125 m, where the glass windows remained intact. Hence at 125 m, the maximum pressure wave would have to be less than 0.03 bars (Assael and Kakosimos, 2010b). Employing this constraint to a TNT equivalent curve or equation, and since the enthalpy of combustion, ΔH_c, is approximately 55 MJ/kg, one can easily calculate that this corresponds to a 60 kg TNT equivalent mass. Hence the full overpressure vs distance curve can be calculated (see Fig. 3). It should be remembered that for buildings destruction, an overpressure of 1 to 2.6 bars is necessary, while for deaths an overpressure higher than 3 bars is required (Assael and Kakosimos, 2010b).

Thermal effects

Assuming that all the mass initially contained in the tank was involved in the fireball, results in a mass M = 20,000 kg (density of 421 kg/m^3, at about 113 K and say 10 bar pressure in the tank before explosion). TNO (2005) proposed that the maximum diameter, $D_{\max}$ (m), and the total time duration, $t_{\max}$ (s), of the fire ball can be calculated from the following empirical expressions:

$$D_{\max} = c_4 M^{0.325} \quad \text{and} \quad t_{\max} = c_5 M^{0.26} \qquad (3)$$

where, $c_4 = 6.48 \; m \cdot kg^{-0.325}$ and $c_5 = 0.852 \; s \cdot kg^{-0.26}$.

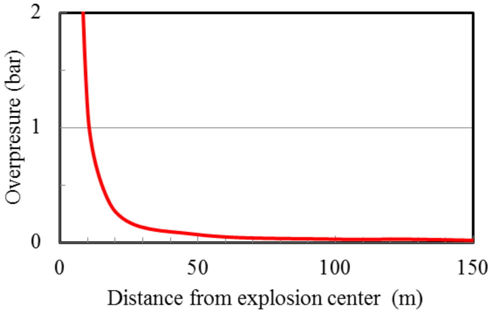

Fig. 3. Estimated overpressure as function of distance

Thus the maximum diameter and time duration of the resulting fireball is $D_{\max}$ = 162 m, and $t_{\max}$ = 11 s. Finally, the height of the fire ball center from the ground, H (m), is usually considered equal to the maximum diameter, $D_{\max}$, and therefore, H = 162 m. The heat flux, q' (kW/m^2), in a specific distance from the center of the fire (the distance enters the calculations through the view factor and the atmospheric transmissivity), is calculated according to the solid-flame model (Assael and Kakosimos, 2010b; TNO, 2005), from the product of the actual surface emitting power, SEP_{act} (kW/m^2), the view factor, F_{view} (-), and the atmospheric transmissivity, τ_α (-), as:

$$q' = SEP_{\mathrm{act}} \, F_{\mathrm{view}} \, \tau_{\mathrm{a}} \qquad (4)$$

a) The actual Surface Emitting Power can be obtained (TNO, 2005) from:

$$SEP_{\mathrm{act}} = F_{\mathrm{s}} \, m' \Delta H_{\mathrm{c}} \qquad (5)$$

where the radiation fraction, F_s (-), is given by (TNO, 2005):

$$F_{\mathrm{s}} = c_6 \, P_{\mathrm{sv}}^{0.32} \qquad (6)$$

where $c_6 = 0.00325 \; Pa^{-0.32}$, and P_{sv} (Pa), denotes the vapor pressure inside the vessel. The burning rate, m' (kg/m^2s), can be calculated as a function of the mass, M (kg), of the flammable substance and the total fire ball duration, t_{max} (s), as:

$$m' = \frac{M}{(0.888\pi D_{max}^2)\, t_{max}} \tag{7}$$

where $(0.888\pi D_{max}^2)$ is the time-average surface of the fire ball sphere.

Assuming that the pressure before the explosion rose to 10 bars, and that for LNG, ΔH_c = 55 MJ/kg, by substituting in the above expressions we obtain, m' = 0.025 kg·m^{-2}·s^{-1}, F_s = 0.27, and SEP_{act} = 371 kW/m^2.

b) In the case of a fireball, it can easily be shown (Assael and Kakosimos, 2010b) that the **view factor**, F_{view} (-) that a receptor, standing at a distance X (m) from the center of the explosion, faces, can be calculated from:

$$F_{view} = \left(R/\sqrt{X^2+H^2}\right)^2 \tag{8}$$

c) Finally, for the calculation of **atmospheric transmissivity**, τ_a (-), the following empirical expression (Bagster and Pittblado, 1989) can be employed:

$$\tau_a = c_7\left[P_w(X-R)\right]^{-0.09} \tag{9}$$

In the above expression, P_w (Pa), denotes the partial water vapor pressure in air (usually about 1620 Pa), while X (m) is the distance of the receptor from the center of the fire of radius R (m) (meaningful only for $X > R$). The constant c_7 is equal to 2.02 Pa$^{0.09}$m$^{0.09}$.

Equations (8) and (9), together with the calculated value of SEP_{act} = 371 kW/m^2, can be employed in equation (4) to obtain the heat flux q' (kW/m^2) as a function of the distance X (m). Results are shown in Figure 4. We note that at the distance of 200 m where the two men were, the heat flux was equal to 24 kW/m^2.

The probability, P (-), of injury (1st or 2nd degree burns) or death, can be obtained as a consequence of a specified dose, D (W$^{4/3}$s·m$^{-8/3}$), from the following equations:

$$P = F_k \frac{1}{2}\left[1 + \mathrm{erf}\left(\frac{Pr-5}{\sqrt{2}}\right)\right] \tag{10}$$

where the probit function, Pr (-), is given by the empirical expression,

$$Pr = c_1 + c_2 \ln D \tag{11}$$

and the dose D (W$^{4/3}$s·m$^{-8/3}$), is defined as a function of the heat flux, q', and the actual time, t_{eff}, of exposure to the particular heat flux, as:

$$D = t_{eff}\,(q')^{4/3} \tag{12}$$

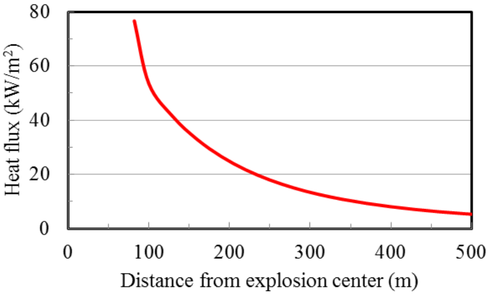

Fig. 4. Heat flux as function of distance.

In equation (10), the probability, P (-), refers to injury (1st or 2nd degree burns) or death, depending on the values of the coefficients c_1 and c_2 that are chosen from Table 1.

The parameter, F_k (-), refers to the influence of clothes, and it constitutes a correction factor, provided there is no ignition of the clothes. Its values range from 0.14 for winter clothes (large coverage of skin area) to 0.95 for summer clothes (small coverage of skin area).

Table 1. Coefficients c_1 and c_2

Effect	c_1	c_2
1st degree burn	-39.83	3.0186
2nd degree burn	-43.14	3.0186
Deaths	-36.38	2.56

Source: Assael and Kakosimos (2010b); TNO (1989).

From equation (12), and for time equal to the duration of the fireball, that is 11 s, $D = 7.6\times10^6$ W$^{4/3}$s·m$^{-8/3}$. Employing equation (10) and (11), with the corresponding values from Table 1, we obtain that at 200 m, the probability of 1st degree burns is 95%, of 2nd degree burns 36% and of death 20%, which agrees well with what really happened.

In Figure 5, equations 10 to 12 are plotted. For a particular effective time and heat flux, the probability of death can easily be found.

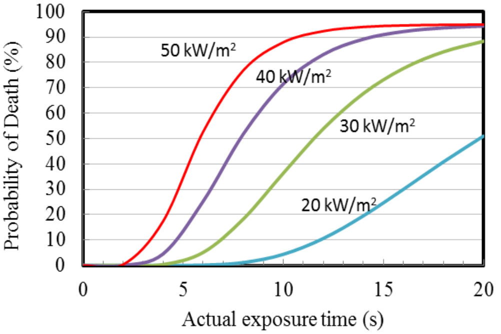

Fig. 5. Probability of death as a function of the actual exposure for different heat fluxes (F_k =0.95).

The frequency of a rupture and fuel release is 1×10^{-8} incidents/km yr (EIA, 2006). If this tanker operates in a city for 5 days per week, on a 100 km route daily, and say 10% of such accidents are catastrophic, the estimated frequency of such a fire is ($1\times10^{-8}\times0.1\times5\times52\times100$ =) 26×10^{-6} incidents/yr. This number of fatalities is unacceptable in most countries, with an upper risk limit of 10^{-6} fatalities/yr.

CASE 2. Vapor Cloud Explosion from a leak in a road tanker containing LPG

The case of vapor cloud explosion can be exemplified by a leak of a tanker truck carrying liquefied petroleum gas (LPG), usually propane. LPG is derived from petroleum refining (53% in EU) or natural gas processing (47%) (Argus Consulting Services, 2013). About 50% of LPG is used as an energy source in the private and public sector and 25% for light duty vehicles and cars. For instance, Poland has one of the largest fleets of about 2.5 M LPG driven cars, with 5700 filling stations state-wide. Italy is also a major player in LPG driven vehicles with about 1.8 M cars and 3000 stations. Although the fraction of LPG cars is currently small (~4% in EU, or 10M vehicles), it is expected to increase to 10% by 2020, because of the insignificant emissions of particulates and NO_x, the reduced CO_2 emissions and the low fuel cost (about half) compared with gasoline or diesel.

LPG is usually delivered to private or industrial premises and to filling stations by tanker trucks; Poland is a major producer of such vehicles. Statistically (Caumont and Ponthieu, 2000), leaks occur primarily during the loading/unloading of the tanker, and albeit rare, they lead to 20% jet or pool fires which can turn to an explosion (VCE, 24% and BLEVE 36%). Only 20% of gas leaks do not ignite. Next, we consider the rupture of a 5 ton LPG truck, resulting in the formation of a vapor cloud and a VCE. Assuming that 3,000 kg of propane are released, and a heat of combustion of 46 MJ/kg, one can calculate that a cloud volume of 32,200 m^3 will be formed, resulting in an energy of explosion of 140 GJ. Hence in say, 50 m the overpressure will be approximately 0.3 MPa and its positive phase time duration will be 50 ms. Following an equivalent analysis employing probit functions as in Case 1, these numbers will result in 100% probability of fatality of people in that distance, and major structural damages to two-floor houses.

Vapor release from an LPG tanker truck during loading or unloading can result to an explosion if the gas is trapped in partly enclosed spaces. A ‘flame return’ can result in a BLEVE. If an LPG truck like the one above delivers fuel to 10 customers per day on a route of 500 km per week, we can estimate the probability of gas release with subsequent ignition and explosion to be: ($500\times52\times2.4\times10^{-9}$) = 6.24×10^{-5} incidents/yr, and for BLEVE’s 7.0×10^{-8} incidents/yr, using the incident rates given in Table 2 (OGP, 2010).

Table 2. LPG Incidents

Phenomenon	%	Release frequency per km·yr
Gas phase leak/No ignition	20	2.6×10^{-9}
Jet or pool fire	20	2.1×10^{-9}
Vapor cloud explosion	24	2.4×10^{-9}
BLEVE	36	2.7×10^{-12}
Failure Type	%	
Tanker component	18	
Hose/Coupler/Connection	21	
Human error	18	
Other	43	

Source: Caumont and Ponthieu (2000), OGP (2010).

4. Pipeline Transport of Natural Gas

For the bulk transportation of gases, liquids or chemicals over long distances, pipeline transport is a very effective and economic way. The world wide network of pipelines in 2014 exceeded 3.5 Mkm in 120 countries, with USA, Russia and Canada in the first three positions. Although oil pipelines are the longest and have a high percentage of spills and accidents, natural gas pipeline incidents lead to more destructive effects. Therefore, in this section we outline possible accidents and their impact involving gas pipelines, especially in Europe.

Table 3. Pipeline Distribution Network Length per Country (in km)

Country	Length (km)	Country	Length (km)
Austria	37,495	Norway	125
Belgium	69,687	Poland	125,800
Czech Rep.	72,868	Portugal	16,296
Denmark	18,175	Romania	17,218
France	203,092	Slovakia	33,079
Finland	1,911	Slovenia	4,342
Germany	371,000	Spain	64,115
Greece	6,087	Switzerland	18,762
Italy	249,180	Turkey	69,800
Ireland	11,137	UK	126,335
Netherlands	124,073		
		TOTAL=**1,640,577**	

Source: Marcogaz (2013).

The European Union has an extensive network of pipelines for the transmission and distribution of natural gas. Some typical characteristics are given in Table 3 for selected countries that participate in the Technical Association of the European Natural Gas Industry, Marcogaz (2013), totaling 1.64 Mkm of pipelines and 115 M consumers.

Table 4 shows the network of major gas pipelines to Europe (NEEDS, 2007; Friedrich and Neumüller, 2007). Natural gas imports from the Russian pipelines in 2013 were 39% of total, for EU-28, with Norway and Algeria having a 34% and 13% share, respectively (Pongas et al., 2014). Sixteen EU countries depend over 90% on Russian imports.

The dependence of EU on imports of natural gas, the shear length of the pipeline network, the aging of Russian and European pipelines and the geopolitical instability in some of the major supply routes make gas transmission quite sensitive to accidents, with tens of release or fire or explosion incidents per year.

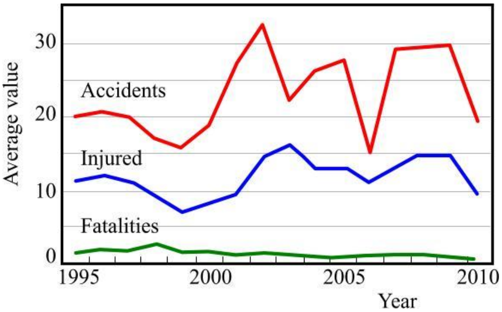

Fig 6. Ratio of accidents/injuries/fatalities to 1 million customers for each year from 1995 to 2011

Source: Marcogaz (2013).

The Marcogaz Association (Marcogaz, 2013) reports 20-25 accidents per million customers per year (or 150 accidents per 1000 km per year), with 1.42 fatalities per million customers (or 9.3 fatalities per 1000 km per year), see Figure 6. These numbers refer to all pipeline grades.

For steel pipelines, see Table 5 (EGIG, 2015), the incident frequency is 22/yr in the last 5 years or 0.158 failures/1000 km·yr. However, large pipelines (> 40 cm diameter) have a very high probability of 32% to ignite and explode, with occasionally devastating effects.

Tables 6-8 give some typical failure types and their frequency or percent of occurrence and percent of fatalities or injuries (EGIG, 2015). Small size cracks or pinholes less than 2 cm in diameter occur most frequently, primarily due to metal corrosion, but they are not capable to give rise to a jet fire. Larger holes and pipe rupture are usually the result of third party interferrences (e.g. digging, maintenance, arsony etc). Although such events are 30 times less frequent than pinholes, they have a higher frequency of ignition; especially large diameter ruptures in pipelines over 40 cm in diameter lead to 32% ignition and subsequent explosion. In even larger diameter pipelines such as the ones used in the major networks feeding EU countries, the very limited, statistically, incident frequency shows almost sure ignition in the case of rupture.

Table 4. Major Gas Pipelines to Europe

Pipeline	Origin	Via/To	Year	Capacity (Mm^3/d)	%	km on shore	km Offshore
N. Afica to Europe				**218**	**20.8**	**5377**	**1530**
Transmed(E.Matei)	Algeria	Tunisia Sicily	1983 1997	99		2315	170
Maghreb	Algeria	Morocco	1996	23		1575	45
Greanstream	Libya	Sicily	2004	30			540
Galsi	Algeria	Sardinia	2015	22		940	565
Medgaz	Algeria	Spain	2008 2011	44		547	210
Russia to Europe				**707**	**67.6**	**>7000**	**1200**
Uzhgorod and other	Russia	Ukraine	1983	390		>2800	
Yamal and other	Russia	Belarus Poland	1999 2005	105		4196	
Nord Stream(NEGB)	Russia	Germany	2010 2012	151			~ 1200
Other	Russia	Finland Turkey		60			
Norway to Europe				**121**	**11.6**		**1606**
Norpipe	Norway	Germany	1977	44			440
Langeled	Norway	UK	2006 2007	70			1166
TOTAL				**1046**	**100**	**12377**	**4336**

Source: NEEDS (2007), Friedrich and Neumüller (2007).

Table 5. Failure Incidents and Their Frequency in Gas Pipelines

Interval	Years	Number of Incidents	Failure Frequency per (1000 km yr)
1970-2013	44	1309	0.329
1974-2013	40	1179	0.307
1984-2013	30	805	0.249
1994-2013	20	426	0.177
2004-2013	10	209	0.157
2009-2013	5	110	0.158

Source: EGIG (2015).

Table 6. Cause of Pipeline Incidents (2009-2013)

Third party interference	28%
Corrosion	26%
Construction/material failure	16%
Hot tap	6%
Natural events	16%
Other	8%

Source: EGIG (2015).

Table 7. Pipeline Failure Frequency and Ignition with Leak Size (2013)

Leak size	Typical Size (cm)	Average failure Frequency /1000km.yr	Cause	Ignition (%)
Pinhole /crack	≤ 2	0.105	corrosion	4.4
Hole	~ 5	0.030		2.3
Rupture (all diam.)	≥ Pipe dia.	0.016		13.9
Rupture	≤ 16 inch		Hot tap or third party interference	10.3
Rupture	> 16 inch			32.0

Source: EGIG (2015).

Table 8. Fatalities and Injuries from Pipeline Incidents (EGIG, 2015)

Personnel	Injuries (%)	Fatalities* (%)
Employee/Contractors	0.08	0.08
Personnel causing incident	0.61	0.46
Fighting personnel	0.15	0.08
Public	0.23	0.15

* Mostly from pipe rupture
Source: EGIG (2015).

Before analyzing gas pipeline explosions we report some recent incidents in EU.

- In October 2014 a pipeline feeding gas to a BASF plant exploded in the city of Ludwigshaffen, Germany, with one person killed, 26 injured, 7 seriously, and 25 buildings damaged at a distance of 100m.
- In April 2014, a high pressure pipeline 2.2 m in diameter was ruptured in Cerville, France, creating a crater of 4m diameter and 1.5 deep, without injuries.
- In December 2007, a 63 mm dia. pipeline at Noisy le Sec, France, leaked natural gas, followed by two explosions 45 minutes later, leading to 8 injuries and 36 apartments destroyed (ARIA Database, 2015).
- In June 2014 two explosions occurred in the largest gas pipeline from Russia to Europe through Ukraine (EEGA, 2015). A 20 km section was sealed off. The aging pipeline had four such accidents in the last 10 years. However the incident rates per 1000 km and year are 0.120 - 0.180, similar to European pipelines.
- In November 2013, an “empty” gas pipeline under maintenance exploded in the village of Jankow Przygodzki, Poland, killing three and injuring 13 more, some seriously. A dozen houses were destroyed by the flames.

Major gas leak accidents have occurred also in other continents.

- In July 2014, 32 people died and 321 were injured in an explosion in Kaohsiung, China, from a leak of gas in the sewer system of the city.
- In June 2014, a gas pipeline exploded in Nagaran India, killing 16 persons and destroying scores of houses.
- In September 2011, a high pressure, 76 cm dia. pipeline exploded in San Bruno, San Francisco, USA, killing 8 persons, injuring 58 and destroying 35 houses.

One of the most serious industrial disasters occurred in a pipeline near the city of Ghislenghien, Belgium, in July 2004 (ARIA Database, 2004). We can examine this in more details as CASE 3 below.

CASE 3. Rupture and ignition of a gas pipeline in Ghislenghien, Belgium (ARIA Database, 2004).

The accident took place on July 30th, 2004. A 70 bar, 100 cm diameter pipeline of 1.6 million m^3/h flowrate, was damaged during excavation resulting in the following chronological sequence of events:

- 8:15 to 9:00 in the morning a gas leak appeared.
- 9:00 the gas exploded creating a crater of 10 m diameter and 4 m deep.
- 9:02 further ignition of the gas from a pipe section, resulted in a fireball.
- A jet fire was consequently formed, with flames rising to 150-200 m, lasting for twenty min until the gas supply was shut off.

Twenty four persons died, including 5 firefighters, 1 police officer and 5 employees, 132 persons were injured, and an industrial zone in a 200 m radius sustained total devastation. Molten plastic material on cars was observed even at a distance of 400 m. A calculation based on the volume of gas contained in the damaged pipe section of 15 km long, estimated the gas quantity lost to about 700 tons (i.e. a volume of approximately 1 million m^3 of natural gas). The accident was qualified as Belgium’s most serious industrial disaster in half a century.

Modelling of the accident will be based upon the small amount of facts available.

Jet fire

All observations indicated a flame height of 150-200 m. Assael and Kakosimos (2010b) described a full step by step procedure to model a jet flame. The main parameter that influences the flame’s height, is the gas flowrate. To produce an average flame length of 175 m, the quantity of natural gas required is about 300 kg/s – which corresponds to a total gas quantity for the 20 minutes leak equal to 360 tons of natural gas. Such a jet flame will produce a heat flux of 2.4 kW/m^2 even at 150 m, which also agrees with observations of damages.

Explosion Overpressure estimation

The gas exploded creating a crater of 10 m diameter and 4 m deep. Observations of damages showed overpressure of 20 mbar at 390 m, and 10 mbar at 890 m (Zarea, 2006). If one employs the Multi Energy technique or the TNT equivalent (Assael and Kakosimos, 2010b), with the mass as unknown, and tries to calculate the observed overpressure, a mass of about 5,000 kg of natural gas (or a 2,000 kg TNT equivalent mass) is calculated to produce the observed overpressure.

Fire ball

The accident report estimated that the total mass of gas contained in the sealed section of the pipeline was about 700 tons. We have already calculated that 360 tons were burnt in the jet fire and 5 tons in the explosion. It is thus most probable that the remaining 335 tons were burnt in the fireball. Employing equations (3) we obtain that the maximum diameter and time duration of the resulting fireball is $D_{\max} = 400$ m, and $t_{\max} = 23$ s. The height of the fire ball center from the ground, H (m), is usually considered equal to the maximum diameter, $D_{\max}$, and therefore, $H = 400$ m. This explains why there was total devastation in a 200 m zone, with so many people dying, and car plastic material melting at a distance of 400 m.

In conclusion, the approximate calculations indicate that the fireball and the resulting jet fire created the major damages, mostly due to the very large amount of natural gas involved. If the initial gas leak had been detected earlier from the pressure loss, and the gas supply was restricted immediately, the large human and property damages would have been prevented.

5. Conclusions

Effects from fires and explosions can today, easily be calculated. This knowledge is very valuable in designing alternative transport paths across the country or through inhabitant places. If we can model a disaster, we can also predict how to avoid it.

The field of Risk Assessment requires holistic engineers whose understanding of the process phenomena is coupled by a knowledge of assessment techniques and models, and who are themselves also actively involved in the assessment procedure (Kletz, 2003). This latter characteristic is quite significant for educators, since it is hard to quantify and teach it.

Thus in order to attract students and engineers to an otherwise sidelined area of study, we developed a course applying a more modern pedagogical approach, using a wide range of multimedia teaching tools, videos and in-class exercises. In a recent paper (Assael and Kakosimos, 2010a) the development of a course on Risk Assessment aiming to enhance awareness and comprehension of the procedures was described; it was also intended to make the subject attractive and enjoyable to students and engineers. Extra care was undertaken to employ multimedia tools and videos during the teaching of the course. A new multimedia e-platform was developed, which includes all teaching material that encompasses Hazard Identification - Event Frequency, Outflow, Effects and Consequences Analysis and Probable Causes of Destruction. The feedback was very positive for both the method of teaching and delivery (e-platform) and the peer assessed project, which indicates that in many respects the aims have been achieved. In addition, the authors recently had the opportunity to discuss the details of the course itself in the "European Workshop on Teaching Safety in Chemical Engineering (Kakosimos and Mihailidi, 2010), where again the overall comments were very positive.

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