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Assessment on the Consequences of Liquefied Petroleum Gas Release Accident in the Road Transportation via GIS Approaches

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Abstract: Transporting of hazardous substance inviting a catastrophic potential, depending on the amount of transported product, its hazardous characteristics and the features of the surrounding environment. In view of the above factors, an efficient intervention is essential to minimize the impacts from transportation hazards. This study will provide analytical techniques on estimation of hazardous risk from Liquefied Petroleum Gas (LPG) transportation by integrating results from several risk consequences models to the latest Geographic Information System (GIS) tool. The advantage of this GIS map is that the point of accident can be moved to any location on it, hence a new result will be displayed for a new potential damage of LPG accident.

Key words: Accident, ArcGIS, Consequences model, road transportation

INTRODUCTION

The transportation of hazardous material for the manufacturing and distribution of products is a very common industrial activity. However, the transportation of dangerous goods is highly potential to cause hazard for the people present on and along the routes (road users and surrounding population) and for the environment (RSPA, 2003; TRB, 2005). Historical evidences have shown that incidents due to hazardous materials (HazMat) releases during transportation can lead to severe consequences (Zulkifli *et al*., 2009a-c). As a matter of fact, a number of accidents occurred in the past years have demonstrated that this activity can involve a large number of people and damage a major number of building construction, comparable and even larger than in accidents occurred at fixed installations (Zulkifli *et al*., 2010; Purdy, 1993; Bubbico *et al*., 2000).

For instances, it is well known that in 1978, at San Carlos de la Rapita, Spain, the occurrence of a fireball of a tanker containing 23.5 t of propylene caused about 200 fatalities. Meanwhile, in 22 April 1992, Guadalajara, Mexico, the occurrence of a gasoline transmission pipeline leaked owned by the Mexican State oil company and migrated into the sewer system caused a series of vapor cloud explosions, which led to the demolition of 20 blocks along sewer‘s path and caused about 252 people perished in the blasts. In contributed to that interest, Malaysia also had experience in some major accidents for instance explosion and fire at km 20.8 New Klang Valley Expressway (carrying 21,600 L of petrol), North South highway near Damansara Perdana (LPG tanker), Jalan Sg Besi, at a roundabout of Taman Billion, Cheras (carrying 38,000 L of petrol) and Batu Klawang Ulu Klawang, truck carrying 33,000 L (21,000 L of petrol and 10,000 L of diesel), caused 3 fatalities and property damaged.

Most of the major industrial road accident databases have recorded the LPG major transportation accidents in various countries, across different modes of transportation and its impacts (CCPS, 1995, 1999, 2009; Lees, 2005; UNEP, United Nations Environment Program DTIE, 2009; MARS, 2008; HSE, 2009; NTSB, 2008; Esri Arcgis Desktop 9.3 Help, 2009).

Liquefied Petroleum Gas (LPG) is a very importance fuel and chemical feedstock. The material has been involved in many major fires and explosions. From a historical survey performed by the authors using information contained in several major accident databases showed that the occurrence of 111 road accidents of LPG transportation from 1654-2008. Out of 111 cases of major accidents, 34 (22.52%) cases caused fatalities, 33 (21.85%) cases caused injured consequences and 52 (33.11%) cases caused traffic interruptions (Zulkifli *et al*., 2009b).

In risk assessment several researchers have used GIS, by integrating GIS with mathematical and simulation models, to necessary databases and expert systems.

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Besides, it would be easier to understand risk information systems; if a common and interactive graphical user interface could be made in order to be more powerful and easier to use. The GIS technology integrates common database operations such as query and statistical analysis with unique visualization and geographic analysis capabilities. These functions make GIS distinguish from other information systems and make it valuable for explaining events, predicting outcomes and planning strategies. Geographic information can be divided into two classes: location and spatial data, which records the location of a given object (point, line, or polygon) and attribute or non spatial data which describes characteristics of the object.

Tools for GIS spatial risk assessment can externally generated risk contours results (by displaying as buffer and multiple ring buffer and others) and links to models describing accidental, continuous atmospheric releases and dispersion spills into surface water systems and transportation risk analysis. Therefore by using GIS, hazards from transportation LPG accident, can be viewed and evaluated the potential consequences at any points and locations based on computer maps generated. Results of consequences such as fire, explosion, fireball, BLEVE from transportation of LPG accidents will be more accurate, precise and more details, depending on how far the very comprehensive maps (spatial and nonspatial) informations can be generated. To perform an accurate Transportation Risk Analysis (TRA), the knowledge of territorial information of comparable accuracy is of paramount importance. In particular, data are needed about local distribution of population, incident rates and weather conditions. Lepofsky *et al*. (1993) first proposed to integrate GIS into TRA to manage those kinds of information. In another research, Bubbico *et al*. (2000, 2004) have pointed out that the TRA tool developed based on the GIS approach allows risk assessment for various transportation modes and permits to rapidly investigate possible benefits resulting from changes of routes. However, the methodology needs further improvements, because of several factors such as computer strength, software evolution and etc.

This study presents the most recent analytical techniques on estimation of hazardous risk from Liquefied Petroleum Gas (LPG) transportation by integrating results from several risk consequences models to the latest Geographic Information System (GIS) tool (advance ArcGIS 9.3.1 update version).

MATERIALS AND METHODS

Description of the accident case study: In this case study, risk analysis assessment is implemented, to estimate and to evaluate the risk impact of an accident involving LPG trucks. In order to estimate the risk related to LPG truck accident, the actual accident scenario is taken. To make this case study relevant, the selection of accident scenario is based on the actual events that occurred in Malaysia, according to information gathered from database in NIOSH, Bangi Malaysia. Based on review of the report from NIOSH, a specific accident scenario can be created according to the truck condition, time and features of the accident scene. The truck accident scene is analyzed at Jln. Sungai Besi near Taman Billion, Cheras at 6.30 a.m. During that accident, a truck with the composition 30950L (tank volume 11995×2480×3500 mm), which carries liquid nitrogen is skidded and hit hard object by the roadside, resulting in a fire. With an efficient action from Fire and Rescue Department, the fire is successfully controlled in 30 min.

Following the event, has resulting in traffic jam (3 lanes per side) till 5 km long starting from Jalan Istana Baru and Jalan Sri Petaling to the scene. Traffic interruptions lasted about 1.5 h. In the case study involving hazardous substance, the accident scenario was changed from carrying liquefied nitrogen to truck carrying LPG and there are considerations must be undertaken such as Malaysia climate is hot and wet, temperature ranging from 28-32°C, humidity level about 70%. LPG usually comprise of two major components, butane and propane. In this case the ratio of butane to propane is 70:30 by percentage.

Accidental scenarios: In case of a loss of containment of a hazardous material, the possible damages are due to its toxicity and/or its flammability and the evolution of the accident depends on a number of parameters. For example, the physical properties of the substance, its physical conditions during transport (pressure, temperature, degree of filling), location and size of the release hole, determine whether the spill will be liquid, vapor or two-phase. The amount of material released is a function of:

- The total amount of transported material. It depends on the size of the tank and its amount and therefore also on the transportation (by road or rail) and on the filling degree
- The size of the release area (leak from the relief valve, from a pinhole, from a larger fracture in the vessel wall, etc.)
- The release duration, whether it is continuous or instantaneous

In case of immediate ignition, a flammable material will form a jet fire, whose consequences will be limited to a

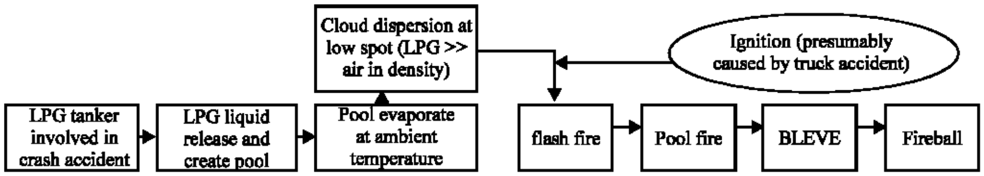

Fig. 1: The sequence of the events based on LPG road tanker accident case study at Jln Sg. Besi at 6.50 am

relatively small area near the release site. Even in this case, serious consequences can occur, either because of the presence of many people nearby, or because of secondary effects (domino effect), such as the heating effect on the tank itself or the impingement of the flame on other objects (collapsible structures, other vessels containing hazardous materials, buildings, cars. buses and so on). In the absence of immediate ignition or for nonflammable materials, also depending on the external (ambient) conditions, the liquid spill may or may not generate a liquid pool. In both cases a vapor cloud will be produced, either directly or from pool evaporation. The whole sequence of events is shown in Fig. 1. The consequences flow of LPG transportation accident are followed, according to steps of quantitative risk assessment models as shown in Appendix.

Development of GIS application: In this case study, the information on surrounding locations in the model is treated by adopting raster GIS framework. The raster framework transforms a continuous space into a discrete one by modeling it as a tessellation of square grid cells called pixels. Tessellation refers to a finite number of objects/cells that cover the surface as discrete partitions. Raster is commonly used to approximate continuous surfaces in GIS. Raster GIS are organized as a number of layers, one assigned to each characteristic of interest. Raster data stored as raster datasets as matrix of square cells.

Arc Map 9.3.1 Update version was used to model the LPG release incident and the impact of the release of this toxic, hazardous chemical in the area surrounding at Jln Sungai Besi, near to Taman Billion Cheras. Layers including landuse information (such as recreational area, industrial area, institutional area, development area, tourist area, settlement area, forest, airport and agricultural area), population density and roads were included in the map for the 3 states of Selangor, W. Persekutuan Kuala Lumpur and Negeri Sembilan. Satellite images, connected to a database with millions of satellite of photographs from Google earth were used, to visualize actual map view of LPG accident case. Since data from different sources need to be combined and then used in an ArcGIS 9.3.1 update application, it is essential to have a common referencing system. Georeferencing tasks are undertaken because the authors want to produce a new map by overlaying two or more different datasets together to the same geographic locations. For reference, georeferencing is a crucial task in making satellite imagery useful for GIS mapping application. To georeference an images, 4 major steps were involved, first establish control points, secondly input the known geographic coordinates of establish control points, then choose the coordinate system and other projection parameters and finally minimize residuals. Residuals are the difference between the actual coordinates of the control points (used by Google Earth) and the coordinates predicted by the geographic model created using the control points (into WGS 1984 Mercator coordinate system).

RESULTS AND DISCUSSION

Consequences of LPG transportation accident: Unconfined Vapor Cloud Explosion (UVCE) is common consequences in transportation and other unconfined area. Explosions effect modeling is generally based on TNT equivalence and TNO. The TNT model is easy to use for a known energy of a combustible fuel to an equivalent mass of TNT. The approach is based on the assumption that an exploding fuel mass behaves like exploding TNT on an equivalent energy basis (Crowl and Louvar, 2002). TNT is the easier model and it is based on the assumption of equivalence between the flammable material and TNT, factored by an explosion yield term (CCPS, 1994; Crowl and Louvar, 2002). The procedure of TNT calculation model is shown in Appendix (Crowl and Louver, 2002; Fay and Lewis, 1977; Martinsen and Marx, 1999; Pieterson and Huaerta, 1985; Roberts, 1981; Birk, 1995; Clancey, 1972; Casal, 2008; Cuchi and Casal, 1998). The TNT equivalence predicts peak overpressure with distance. Crowl and Louvar (2002), provides an equation for the scaled overpressure over scaled distance. It can be noted that the pressure depends strongly on the distance between the place of the explosion and the structure. The consequence is that the explosion of the same explosive charge can cause different overpressures depending on the location of the explosive charge. Pressure depends also on the location of the explosive charge above the ground. Table 1 shows the peak overpressure results for different distances for material release and (Fig. 2) shows the peak overpressure in multiple buffer zones around LPG tank using the TNT method using the ArcGis 9.3.1 Update version software. The results of the atmospheric transmissivity (t) between the fireball and the target are estimated by using the equations as described in the Appendix (Crowl and Louvar, 2002; Casal, 2008; Davenport, 1998; Eisenberg *et al*., 1975; Prugh, 1994; Buettner, 1951; Fugelso *et al*., 1972; Considine and Grint, 1985; Abramowitz and Steung, 1972; Finney, 1971; Schubach, 1995; Vilchez *et al*., 2001; Weber *et al*., 1990; TNO, 1989, 1992, 2005). The persons who are exposed to excessive radiation heat from the fires may receive fatal burns. Combustible structures might be ignited by exposure to a radiant heat flux of 31.5 kW m^{-2} or more. Therefore, it is conservatively assumed that all persons within the 31.5 kW m^{-2} isopleths are fatalities.

Table 1: Peak overpressure vs. scaled distance for blast wave pressure from an explosion (TNT equivalent model)

r (m)	Ze (m $kg^{-1/3}$)	P^s	P^o	r (m)	Ze (m $kg^{-1/3}$)	P^s	P^o
25	1.067	17.302	876.355	525	22.398	0.077	3.886
50	2.133	3.532	178.902	550	23.465	0.073	3.697
75	3.200	1.412	71.502	575	24.532	0.070	3.526
100	4.266	0.779	39.455	600	25.598	0.067	3.370
125	5.333	0.514	26.036	625	26.665	0.064	3.228
150	6.400	0.378	19.127	650	27.731	0.061	3.098
175	7.466	0.297	15.046	675	28.798	0.059	2.978
200	8.533	0.245	12.392	700	29.864	0.057	2.867
225	9.599	0.208	10.540	725	30.931	0.055	2.764
250	10.666	0.181	9.180	750	31.998	0.053	2.669
275	11.732	0.161	8.138	775	33.064	0.051	2.580
300	12.799	0.144	7.315	800	34.131	0.049	2.496
325	13.866	0.131	6.648	825	35.197	0.048	2.418
350	14.932	0.120	6.096	850	36.264	0.046	2.345
375	15.999	0.111	5.632	875	37.331	0.045	2.276
400	17.065	0.103	5.236	900	38.397	0.044	2.211
425	18.132	0.097	4.893	925	39.464	0.042	2.150
450	19.199	0.091	4.594	950	40.530	0.041	2.092
475	20.265	0.085	4.330	975	41.597	0.040	2.037
500	21.332	0.081	4.095	1000	42.664	0.039	1.985

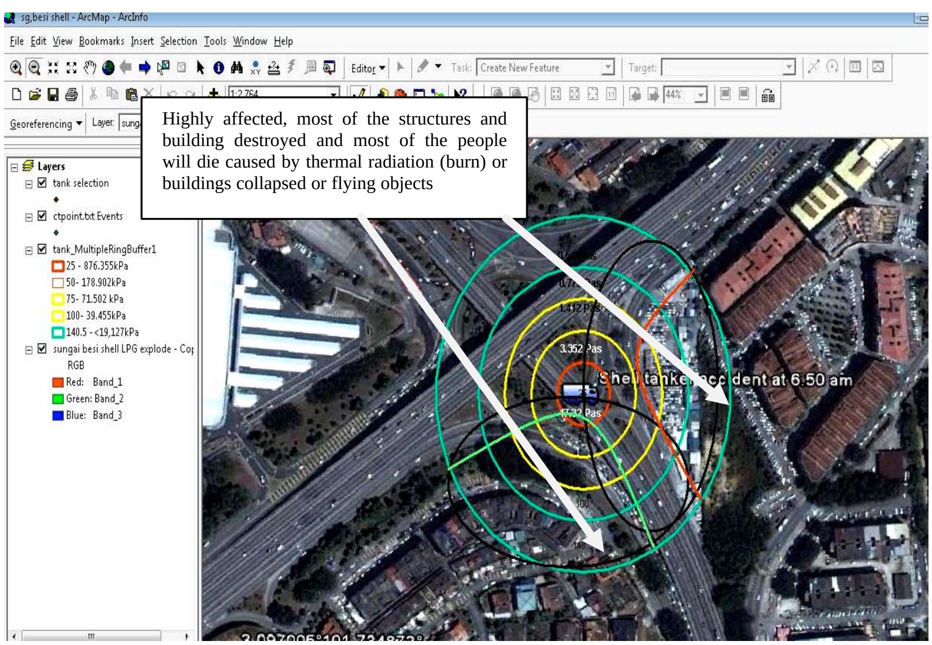

Fig. 2: Peak overpressure vs. distances as a result of LPG tanker accident with scale, North direction and diagnostic features as a result of explosion damage

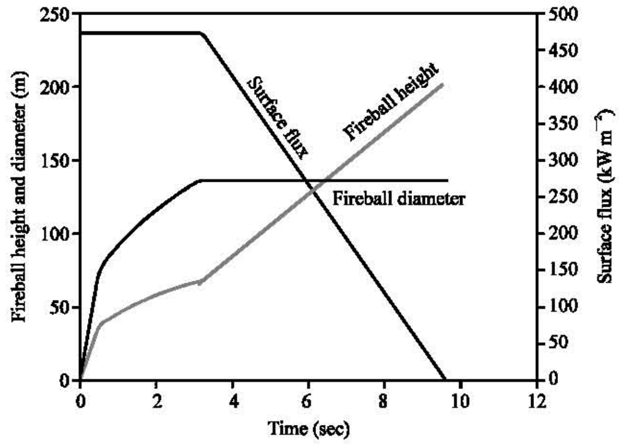

Fig. 3: Emissive power, fireball height and fireball diameter as a function of time, for BLEVE of 13,000 kg of LPG (1195×2480×3500 mm) truck tanker

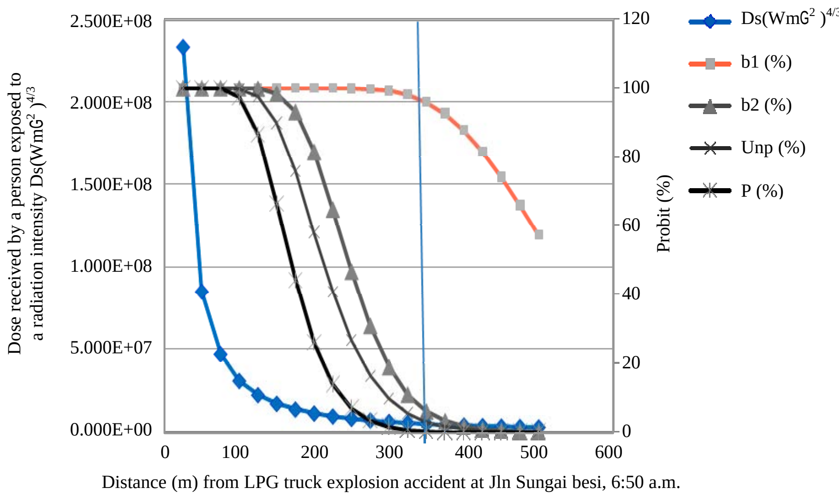

Fig. 4: Effects of LPG transportation accident to human and percentage of area affected, b1: First degree burn, b2: Second degree burn, unP: Unprotected exposed to radiation intensity and P: Protected to expose of radiation intensity

Unprotected skin might severely be burned if it is exposed to a radiant flux of 5.0 kW m^{-2} for 30 sec or more. In the area between the 31.5 and 5.0 kW m^{-2} isopleths, persons who are indoors are protected by the structure, but persons who are outdoors and cannot reach shelter quickly may receive fatal burns. Figure 3 shows the surface flux, fireball diameter and fireball height which are dependent on the time for a BLEVE of LPG tank. Upon rupture tanks containing LPG fragment into a number of parts. Birk (1995) has suggested the approximate guide for estimating projectile range.

The effects of dose received by a person can be shown from Fig. 4. From the graph it can be concluded that people who are staying within a radius of 100-210 m from the incident were highly potential to cause fatalities of 100-60% burn of body (with dose received more than $(1\times10^{10}\ Wm^{-2})^{4/3}$.

CONCLUSIONS

The objective of this work is to estimate the impacts and effects from the LPG transportation accident and display the affected area or zones results via ArcGis 9.3.1 version was achieved. For the case study evaluated, a 13,000 kg (34.5 m^3) LPG road tanker filled to 80% capacity was assumed to be involved in a series of events, started from the LPG tank truck hit the hard object by the roadside and as a result the LPG liquid release and caused fire and explosion. The blast effects associated with the case study indicate that the building damage may occur up to 425 m from the event, depending upon the building type. Personnel within a building may suffer serious injury. At 300 to 400 m it were estimated that the direct exposure of personnel to the blast may cause second degree burns after 20 sec. By applying the probit equations for thermal radiation in Appendix, the percentage of the population affected is found. Approximately 99.239% of the people will suffer first-degree burns, 18.867% will suffer second-degree burns, 1.569% will protect and 9.640% will die. The time dependent flux approach estimates that the distances to second-degree burns is approximately up to 252 m. It is known that 80-90% of the missiles fragments associated with BLEVE event would fall within 563 to 588 m. In authors opinion, the flying fragments have a potential cause of major scale damages with an increased in the total area affected if another LPG tanker was also exist within 563 to 588 m. This impact is known as domino phenomenon. Based on Clancey (1972), the diagnostic features of explosion damage, it was shown that most of the structures such as cars and building constructions between North-East (NE) to South-East (SE) and between South-West (SW) to South-South East (SSE) (within the range of 75 to 150 m radius) will sustained almost complete destruction and damage by the accident. The advantage of this map is that the point of accident can be moved to any location on it, hence a new result will be displayed for a new potential damage of LPG accident.

ACKNOWLEDGMENT

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NOMENCLATURE

A_p = Pool area (m^2)
a = Empirical constant in Eq. 38
b = Empirical constant in Eq. 38; units depend on the type of accident
b_1 = Constant in Eq. 39
b_2 = Constant in Eq. 39
b_3 = Constant in Eq. 39
b_4 = Constant in Eq. 39
b_5 = Constant in Eq. 39
C = Concentration of toxic gas in the atmosphere (ppm)
c_0 = Constant in Eq. 42
c_1 = Constant in Eq. 42
c_2 = Constant in Eq. 42
d_1 = Constant in Eq. 42
d_2 = Constant in Eq. 42
d_3 = Constant in Eq. 42
D = Pool diameter (m)
$D_{initial}$ = Diameter (m)
D_{max} = Peak fireball diameter (m)
E = Surface emitted flux (kW m^{-2})
E_{max} = Maximum surface emitted flux (kW m^{-2})
E_{TNT} = Energy of explosion of TNT (kJ kg^{-1})
E(t) = Surface emitted flux at exposure time (kW m^{-2})
f = Radiant heat fraction (-)
F_{rad} = Radiation fraction, typically (0.25-0.4) (-)
$F_{21}(xt)$ = View factor (-)
$H_{BLEVE}(t)$ = Center height of fireball at time t (m)
H_W = Jet flame conical half-width at flame tip (m)
k = Constant specific for each fuel (m^{-1})
l = Path length, distance from flame surface to target (-)
L_f = Flame height (m)
M = Initial of flammable liquid (kg)
m = Intermediate variable defined by Eq. 39
m = LPG release rate (kg sec^{-1})
$\dot{m}$ = Mass burning rate per unit area (kg/m^2/sec)
$\dot{m}_\infty$ = Mass burning rate per unit area for an infinite pool (kg/m^2/sec)
m_{TNT} = Equivalent mass of TNT (kg)
P_w = Water partial pressure (N m^{-2})
P^0 = Peak overpressure (kPa)
Q = Percentage of people which undergo a certain injury (%)
Q_R = Radiation received by a black body target (kW)
Q_T = Total rate of heat release (kW)
$\tau(x,t)$ = The atmospheric transmissivity between the fireball and the target (-)
r = Distance from the ground-zero point of the explosion (m)
$r_{s,50\%}$ = Side-on hazard range to 50% lethality (m)
s = Intermediate variable defined by Eq. 38
t = Exposure time ($10 < t < 300$) (sec)
t_{BLEVE} = Fireball duration (sec)
t_d = Exposure time (s)
u = Intermediate variable defined by Eq. 43 and 44
V = Intensity or dose associated to the effects of an accident; units depend on the type of accident
Y = Probit variable
Z_e = Scale distance (m $kg^{-1/3}$)

Greek Letters

Δh_c = Heat of combustion (kJ kg^{-1})
τ = Atmospheric transmissivity (-)
α = Angle above a horizon ($\theta°$)
ξ = Efficiency of combustion, (it can be assumed 95%)

APPENDIX

Selection of release incident such as:

Selection of release incident such as:
- Tank rupture
- Fire external to vessel
- Hole in a tank and other

Selection of source model to describe release incident.
Result may include:
- Total quantity release
- Relase rate
- Material phase

Selection of dispersion model.
Result may incident:
- Downwind concentration
- Area affected
- Duration

Selection of fire and explosion model.
- TNT equivalency
- TNO multi energy explosion
- Flash fire
- Pool fire
- BLEVE
- Fireball

Result may include:
- Blast overpressure:
- Radiant heat flux

Selection of effect model.
- Response vs. dose
- Probit model
- and other

Result may include:
- Toxic response
- No. of invividuals affected
- Property and Envirmental damage

Mitigation factors

Risk calculation

Selection of release incident are based on available database such as:
- CCPS 2004, LEES 2005, FACTS, AS and other.

Results such as:
- Statistic type of incident consequences have reported by the authors

Source model to describe release incident are based on:
- Various investigation reports, e.g.: NSTB, NIOSH, HSE(UK) and other.
- Published literature (HAZMAT Transportation Accident)
- Interview from the eyewitnesses

Despersion model are depending on Hazardous substances and properties (density, pressure, temperature, etc.), meteorology conditions.

Vulnerability to thermal radiation can be measured by using Probit model as below:

1st degree burns: $Y = -39.83+3.02 \ln (Q_{4/3}t)$ Eq. (31)

2nd degree burns: $Y = -43.14+3.02 \ln (Q_{4/3}t)$ Eq. (32)

Protected:

$Y = -37.23+2.56 \ln (Q_{4/3}t)$ Eq. (33)

Unprotected:

$Y = -36.38+2.65 \ln (Q_{4/3}t)$ Eq. (34)

from $Q = I_{av} (x) = \int_0^t I_{th} (x, t)dt$ Eq. (35)

The bove equations are proposed by Eisenberg *et al*. (1975), CCPS (1999, 2005), Prugh (1994) and $t_p = [35/Q]_{1.33}$ (Eq. (36), time) required for pain by Butter (1954). Fugelso (1974), Considine *et al*. (1982) proposed effect to overpressure

Probit equation Y can be predicted as a percentage of individual by using equation below.

$$P = \frac{1}{\sqrt{2n}} \int_{-\infty}^{Y-5} \exp[-v_2/z]\, a'v, \quad Y = a+b \ \ln V, \quad s = 1/1+\gamma|Y-5|$$

$$m = (b_1s+b_2s_2+b_3s_3+b_4s_4+) \left| \frac{1}{\sqrt{2\pi}} \exp\left[-\frac{(Y-5)_2}{\sqrt{2}}\right]\right|$$

$$P_r = 50 \left[1+ \frac{Y-5}{|T-5|} \operatorname{erf}\left[\frac{|Y-5|}{\sqrt{2}}\right]\right], \operatorname{erf}(x) \approx 1-(a_1\phi+a_2\phi_2+a_3\phi_3) \exp(-x_2)+\varepsilon$$

Or

$$\phi = \frac{1}{(1+ax)} \quad \alpha = 0.47047 \quad \alpha_1 = 0.34802 \quad \alpha_2 = 0.09587$$

$a_3 = 0.74785$ and $\varepsilon \leq 2.5\times10^{-5}$ Eq. (37-46)

The above equations proposed by Finney (1971), Crowl and Louvar (2002), Abramowitz and Steung (1972), TNO (1990); Weber *et al*. (1990); Schubach (1995); Casal *et al*. (1999) and Vílchez *et al*., (2001).

Risk assesment contours display on AreGis 9.3.1

Sequence of LPG tanker accident:
- TNT equivalency calculation involved

$$m_{TNT} = \frac{\eta m \Delta H_c}{E_{TNT}}, \quad Z_e = \frac{r}{(m_{TNT})_{1/3}}$$ Eq. (1-2)

TNT overpressure curve or by equation
- TNO multi energy explosion

$$\bar{R} = \frac{R}{(E/P_o)_{1/3}}, \quad P = \Delta\bar{P}_{P_o}$$ Eq. (3-4)

- BLEVE

$D_{max} = 6.48\, M_{0.325}$, $H_{BLEVE} = 0.75\, D_{max}$

$D_{initial} = 1.3\, D_{max}$, $t_{BLEVE} = 0.825\, M_{0.26}$

Eq. (5-8)

(a) Point source model:

$Q_R = \tau E F_{21}$

Eq. (9)

$\tau = 2.02(P_w l)^{-0.09}$, depend on the temperature and atmospheric humidity.

$$l = (H_{BLEVE}^2 + r_2)_{0.5} - (0.5 D_{max})$$

$$E = \frac{F_{rad}\, M \Delta H_c}{\pi (D_{max})_2\, t_{BLEVE}}$$

$$F_{21} = \frac{D_{max}^2}{4r_2}$$ Eq. (10-12)

The above BLEVE equation is given by Pieterson and Huaerta (1985), Robert (1981) by considering the radiation received by a target for the duration of the BLEVE accident.

(b) Solid model:

$t_d = 0.9\, M_{0.25}$, $D(t) = 8.664\, M_{0.25}\, t_{(1/3)}$

$D_{max} = 5.8\, M_{(1/3)}$, $R_{flash} = 0.65\, D_{max}$

$H_{BLEVE}(t) = \frac{D(t)}{z}$, $H_{BLEVE}(t) = \frac{Z D_{max}}{z t_m}$

$E_{max} = 0.0133\, f H_c M_{0.25}$, $f = P_{0.32}$

$E(t) = E_{max}(3/2(1-t/t_d))$

$$F_{22}(x,t) = \frac{D(t)_2}{4(H_{BLEVE}(t)_2+x_2)}$$

$\tau(x,t) = 2.02\, (RP_v(\sqrt{H_{BLEVE}(t)_2+x_2} - D(t)/2))^{-0.09}$

$Q = \tau e F_{22}$

The above BLEVE equation is given by Martinsen and Marx (1999), AIChE (1999), Fay and Lewis (1977), Robert (1991), by considering the thermal radiation generated from a BLEVE fireball- fireball is assume as a spherical ball that rises into the air as the flammable material is burned.

- Pool fire model:

$Q_r = \xi m \Delta H_c A_p$, $\dot{m} = \dot{m}_{max}(1-\exp(-kD))$

$A_p = \frac{V}{t_p}$, $D = \sqrt{(4/\pi)\times A_p}$

$\frac{L_f}{D}\ 42 \left(\frac{m}{p_{air}\sqrt{nD}}\right)_{0.61}$, $Q_R = kQ_r$

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