CHEMICAL ENGINEERING TRANSACTIONS
VOL. 31, 2013
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at: www.aidic.it/cet
Guest Editors: Eddy De Rademaeker, Bruno Fabiano, Simberto Senni Buratti

ISBN 978-88-95608-22-8; **ISSN** 1974-9791
DOI: 10.3303/CET1331005

Critical Exposure Time and Population Density for Cost Effective Application of Thermal Protection on LPG Road Tankers

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Thermal protections (TP) applied to road tankers for the transportation of pressurized liquefied flammable gases are able to postpone or even avoid boiling liquid expanding vapor explosions (BLEVEs) and the following fireball. Their presence delays mechanical failure and provides more time to emergency responders. However, installation and maintenance costs of TP, as well as difficulties in inspections and maintenance of the protected steel tank limited its implementation. Actually TP is applied only where it's mandatory due to technical standards or national regulations.
In the present study a Cost Benefit Analysis (CBA) model is presented for the application of TP on road tankers. A simplified risk analysis is performed to determine the benefits of risk reduction by thermal fire protections, which are compared to the costs of applying them. If the average population density in the areas crossed by road tankers is higher than a critical density threshold, or if the time spent by the road tankers along the route is higher than a critical time limit, the TP results convenient. The application of the CBA model to some case studies confirmed the validity of the proposed approach.

1. Introduction

From time to time road tankers and rail cars carrying pressure liquefied flammable gases are exposed to accidental fire impingement and suffer catastrophic failures resulting in BLEVEs (Birk and Cunningham, 1994). These BLEVEs produce hazards including fireball, blast overpressure and far reaching projectiles (Landucci et al. 2009). Many studies have been conducted (Droste and Schoen, 1988, , Gomez-Mares et al., 2012a) and it has been clearly demonstrated that TP can dramatically reduce the likelihood of a fire-induced BLEVE (Gomez-Mares et al. 2011; Gomez-Mares et al. 2012b).
However, the use of TP is not widely implemented because of cost considerations: many tanks must be protected to mitigate one single BLEVE (Paltrinieri et al., 2009, Tugnoli et al., 2012). Though, since BLEVE incidents continue to occur around the world, some countries continue to consider the application of TP as a possible safety measure. The decision to use these protection strategy has to be based not only on technical consideration, but also on the results of CBA (USEPA, 2010, HSE, 2001)
This paper presents a simple CBA model that removes some of the complexities that appear to stall discussions. After the description of the theoretical basis of the model, its application to some case studies is described.

2. Cost Benefit Analysis Model

The presence of TP reduces the occurrence probability of the fireballs following hot BLEVEs, turning out in a decrease of overall risk indexes. This turns out also in a lower Expectation Value *EV*, that is the average annual predicted frequency of deaths represented by the area beneath the plot of the cumulated frequency against the number of fatalities (Carter and Hirst, 2000). In particular, assessing the *EV* in the case of both uncoated and coated tankers, the difference among these two values, ΔEV, can be evaluated. An

immediate meaning may be associated to the term ΔEV, since it represents the decrease in the number of yearly fatalities i.e. the number of persons saved per year adopting TP (Paltrinieri et al., 2012).
The EV due to a fireball caused by a single tank truck (conservatively assumed without pressure relief valve) traveling on an established route can be calculated as:

$$EV = \cdot \sum_{j=1}^{N_s} f_j \cdot N_j \qquad (1)$$

where N_s is the number of segments (indexed with j) of the route, f_j is the occurrence frequency of the fireball on segment j and N_j is the number of fatalities caused by the fireball on segment j.
The frequency f_j can be expressed as:

$$f_j = f' \cdot p_{rel} \cdot p_{inst} \cdot p_{FB} \cdot L_j \cdot N_t \qquad (2)$$

where f' is the accidental frequency per unit length, p_{rel} is the release probability in case of accident, p_{inst} is the probability of the release being instantaneous, p_{FB} is the probability of the fireball after the instantaneous release, L_j is the segment length, N_t is the number of yearly times the truck travels on the route. The terms f', p_{rel}, p_{inst}, p_{FB} are assumed uniform along the route.
The number of fatalities N_j if the accident happens on segment j (assuming a uniform population density ρ_j along the segment) is:

$$N_j = 2\pi \cdot \rho_j \cdot p_{pres} \cdot p_{out} \cdot \int_0^{\infty} V(r) \cdot r \cdot dr \qquad (3)$$

being p_{pres} the probability of the population being present along the segment, p_{out} the probability of the population being outdoors, $V(r)$ the death probability distribution with distance r (p_{pres}, p_{out}, $V(r)$ are assumed uniform along the whole network). Complete protection is assumed for people being indoors. Eq. (3) can be written as:

$$N_j = \rho_j \cdot p_{pres} \cdot p_{out} \cdot A_{FB} \qquad (4)$$

having introduced the term A_{FB} (which can be interpreted as the impact area of the fireball) as follows:

$$A_{FB} = 2\pi \int_0^{\infty} V(r) \cdot r \cdot dr \qquad (5)$$

By substituting Eq.s (2) and (4) in Eq. (1), EV becomes:

$$EV = p_{rel} \cdot p_{inst} \cdot p_{FB} \cdot p_{pres} \cdot p_{out} \cdot A_{FB} \cdot L \cdot N_t \cdot f' \cdot \sum_{j=1}^{N_s} \rho_j \cdot x_j \qquad (6)$$

with x_j ratio between the length L_j of segment j and the total length L of the route. The reduction in EV due to TP can now be calculated:

$$\Delta EV = p_{rel} \cdot p_{inst} \cdot p_{pres} \cdot p_{out} \cdot L \cdot N_t \cdot f' \cdot \sum_{j=1}^{N_s} \rho_j \cdot x_j \cdot A_{FB} \cdot \left(p_{FB}^{unpr} - p_{FB}^{pr}\right) \qquad (7)$$

referring the superscript ^{unpr} to unprotected tankers and ^{pr} to tankers with TP. As obvious, in the case of TP there is a reduction of the occurrence probability of the fireball, p_{FB}.
Yearly Benefits YB can be calculated on the basis of the reduction of fatalities and of the Value of a Statistical Life, VSL (HSE, 2001):

$$YB = \Delta EV \cdot VSL \qquad (8)$$

The Yearly Costs YC of TP can be evaluated as a function of the Unitary Cots of Coating UCC, the lifetime of TP $ULtime$ and the percentage discount rate i (USEPA, 2010):

$$YC = UCC \cdot \left[\frac{(1 + i/100)^{ULtime} \cdot i/100}{(1 + i/100)^{(ULtime-1)} - 1} \right] \qquad (9)$$

When the Yearly Benefits *YB* deriving from TP are higher than the Yearly Costs *YC* (HSE, 2001, USEPA, 2010), TP is convenient:

$$YB \geq YC \qquad or \qquad \frac{YB}{YC} \geq 1 \tag{10}$$

By substituting eq. (7) in eq. (8) and eq. (8) in eq. (10), eq. (11) is obtained:

$$\sum_{j=1}^{N_s} \rho_j \cdot x_j \geq \frac{YC}{f' \cdot p_{rel} \cdot p_{inst} \cdot p_{pres} \cdot p_{out} \cdot N_t \cdot L \cdot A_{FB} \cdot \left(p_{FB}^{unpr} \cdot - p_{FB}^{pr}\right) \cdot VSL} \tag{11}$$

The first member of eq. (11) represents the average effective population density along the route:

$$\bar{\rho}_{eff} \equiv \sum_{j=1}^{N_s} \rho_j \cdot x_j \tag{12}$$

while the second member can be interpreted as a critical population density ρ_C:

$$\rho_c \equiv \frac{YC/VSL}{f' \cdot p_{rel} \cdot p_{inst} \cdot p_{pres} \cdot p_{out} \cdot N_t \cdot L \cdot \left(p_{FB}^{unpr} - p_{FB}^{pr}\right) \cdot A_{FB}} \tag{13}$$

Thus TP results convenient if:

$$\bar{\rho}_{eff} \geq \rho_c \qquad or \qquad \frac{\bar{\rho}_{eff}}{\rho_c} \geq 1 \tag{14}$$

Though eq. (11) can be written also in another form. Route length may be expressed as follows:

$$L = v \cdot t \tag{15}$$

where *v* is the average speed of the road tanker (in *km/hours*) and *t* is the time (in *hours*) required to travel along the route, eq. (11) becomes:

$$\frac{t \cdot N_t}{52} \geq \frac{YC \cdot N_t}{f' \cdot p_{rel} \cdot p_{inst} \cdot p_{pres} \cdot p_{out} \cdot N_t \cdot v \cdot \left(p_{FB}^{unpr} - p_{FB}^{pr}\right) \cdot A_{FB} \cdot \bar{\rho}_{eff} \cdot VSL \cdot 52} \tag{16}$$

The first member of eq. (16) represents the time, expressed as Hours Per Week, the road tanker effectively spends on the route:

$$HPW_{eff} \equiv t \cdot N_t / 52 \tag{17}$$

while the second member can be interpreted as a critical time:

$$HPW_c \equiv \frac{YC/VSL}{f' \cdot p_{rel} \cdot p_{inst} \cdot p_{pres} \cdot p_{out} \cdot v \cdot \left(p_{FB}^{unpr} - p_{FB}^{pr}\right) \cdot A_{FB} \cdot \bar{\rho}_{eff} \cdot 52} \tag{18}$$

TP results convenient if:

$$HPW_{eff} \geq HPW_c \qquad or \qquad \frac{HPW_{eff}}{HPW_c} \geq 1 \tag{19}$$

Eqs (11) and (19) represent different forms of Eq. (10). It can be easily demonstrated that:

$$\frac{\bar{\rho}_{eff}}{\rho_c} \equiv \frac{HPW_{eff}}{HPW_c} \equiv \frac{YB}{YC} \tag{20}$$

3. Case studies

The presented approach was applied to some case studies for validation purposes. In all cases a road tanker carrying 23,000 kg of pure propane was assumed. The physical effects of the fireball following the BLEVE of the tanker were evaluated with the models proposed by the Yellow Book (TNO, 1996): first the dimensions of the fireball were estimated, than the radiation profile with distance was obtained. By means of the damage model described in the Green Book (TNO, 1992), the death probability profile was calculated and thus the impact area was estimated with eq. (5). The main results of the consequence analysis are summarized in Table 1, while other data common to all case studies are reported in Table 2.

Table 1: Results of the consequence analysis of the fireball

Fireball Diameter - Fireball Height (*m*)	169 - 169	
Fireball Duration (*s*)	11.6	
Distance *r* (*m*)	Radiation (*kW/m²*)	Death probability *V(r)*
0	/	1.0
125	35.0	1.0
126	34.7	$3.99 \cdot 10^{-1}$
150	30.1	$2.23 \cdot 10^{-1}$
200	22.0	$3.33 \cdot 10^{-2}$
300	12.3	$6.76 \cdot 10^{-5}$
325	10.8	$1.00 \cdot 10^{-5}$
A_{FB} (*km²*)	$6.25 \cdot 10^{-2}$	

Table 2: Input data common to all case studies

Variable	Unit measure	Value	Source
p_{rel}	/	0.05	TNO, 1999
p_{inst}	/	0.105	
p_{FB}^{unpr}	/	0.80	
p_{FB}^{pr}	/	0.11	Paltrinieri et al., 2009
v	(*km/h*)	50	Paltrinieri et al., 2012
VSL	*€/fatality*	$0.48 \cdot 10^{6} \div 11.3 \cdot 10^{6}$	Paltrinieri et al., 2012
UCC	*€/tanker*	$3 \cdot 10^{3} \div 5 \cdot 10^{4}$	
ULtime	*y*	10	
i %	/	3.5	
$k_{exp}=p_{pres} \cdot p_{out}$	/	$0.01 \div 1$	Bonvicini et al., 2012

The difference among the fireball occurrence probability without and with TP - i.e. the term (p_{FB}^{unpr}-p_{FB}^{unpr}), which is equal to 0.69 basing on the data of Table 2 - represents the risk reduction factor due to TP.
As discussed in detail in (Paltrinieri et al., 2012), very different estimates of *VLS* are adopted worldwide by Public Authorities; a range spanning over an order of magnitude is associated also to the unitary cost of TP, *UCC*. For this reason variability ranges, as proposed in (Paltrinieri et al., 2012), were adopted for both parameters. As a consequence, through eq. (9) a variability range of the Yearly Cost of TP *YC* corresponding to 322 ÷ 5,367 €/tanker was estimated. By combining the extreme values of the ranges of *UCC* and *VSL,* the variability range of *UCC/VSL* was obtained, corresponding to $2.65 \cdot 10^{-4} \div 1.04 \cdot 10^{-1}$ *fatality/tanker*. The term $p_{pres} \cdot p_{out}$ - i.e. the product of the presence probability of people and the probability of people being outdoor - represents the population exposure factor k_{exp}, whose estimate is affected by great uncertainty (Bonvicini et al., 2012): thus a range was assumed for it too, as reported in Table 2. The Dutch guidelines (TNO, 1992) suggest for k_{exp} a value of 0.04.
The remaining data necessary to run the CBA model are route specific. The first case study refers to a fictitious Canadian LPG path; its data are reported in Table 3. For case study 1 single-point values of the *VSL* (*VSL*=$6.5 \cdot 10^{6}$ *\$/fatality)* and for the *YC* (*YC*=$2 \cdot 10^{3}$ *\$/tanker*) were adopted. Both values are inside the ranges reported or derived from the data of Table 2. Basing on the above reported values of the variables of the CBA model, an effective exposure time (estimated through Eq. (17)) of HPW_{eff} = 19.2 *h/week* can be evaluated. The critical exposure time HPW_c depends on the exposure factor and the population density along the route. Assuming different values of k_{exp}, HPW_c was evaluated as a function of ρ_{eff}, as shown in Figure 1.

The horizontal line represents the effective exposure time HPW_{eff} of the route. It can be noted that eq. (19) is verified, i.e. TP is convenient, for population densities greater than 71 *pers/km²* whatever the value of k_{exp} is (within the considered range). Though, the lower k_{exp}, the higher the population density along the route required to justify TP: for instance, if k_{exp}=0.3, the critical population density value is ρ_c=237 *pers/km²*, if k_{exp}=0.01, ρ_c=7100 *pers/km²*. Thus for the route of case study 1 (having k_{exp}=0.3 and ρ_{eff}=450 *pers/km²*) TP is cost effective. The same conclusion can be obtained by evaluating the critical exposure time, equal to HPW_c =10 *hours/week* and thus lower than HPW_{eff}.
The second case study considers two Italian real-life LPG transportation routes. Specific data for them, extracted from national data-bases and statistical reports (Fiani, 2012), are summarized in Table 4.

Table 3: Case study 1: route specific data

Variable	Unit measure	Value
L	*km*	210
N_t	*trips/y*	238
f'	*ev/tanker/y*	$3.8\cdot10^{-7}$
k_{exp}	/	0.3
ρ_{eff}	*pers/km²*	450

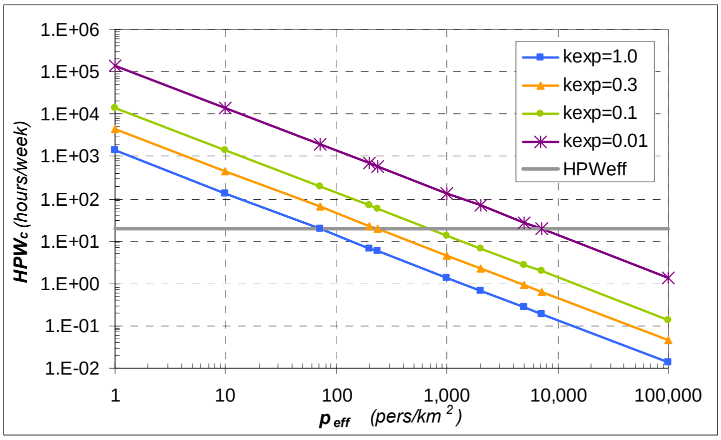

Figure 1: Case study 1: critical exposure time HPW_c versus average effective population density ρ_{eff} for different values of the exposure factor k_{exp}

Table 4: Case study 2: route specific data

Variable	Unit measure	Route A	Route B
L	*km*	257	944
N_t	*trips/y*	238	79
f'	*ev/tanker/y*	$5.9\cdot10^{-8}$	$1.6\cdot10^{-7}$
ρ_{eff}	*pers/km²*	227	502

The exposure factor k_{exp} was taken equal to 0.04, as suggested in (TNO, 1992). By means of eq. (13) the benefit-to-cost ratio, expressed as ρ_{eff}/ρ_c was evaluated for both routes as a function of *UCC/VSL*. Results are reported in Figure 2. The vertical lines are plotted at the extreme values of the range of *UCC/VSL* previously defined, while the horizontal line corresponds to a $\rho_{eff}/\rho_c=1$: only above this line TP is cost effective. It can be noted that for route A, which has a rather low ρ_{eff}, there is no value of *UCC/VSL* (within the defined range) for which TP is convenient. Instead, in the case of route B, which has a higher ρ_{eff}, TP is justified for *UCC/VSL* values lower than $4.4\cdot10^{-4}$ *fatality/tanker*.

4. Conclusions

An approach was developed to carry out a cost-benefit analysis for the application of TP on road tankers. The model allows to identify critical values of average population density or of time spent by the road tankers along the route in densely populated areas above which there is an economic convenience of TP application,

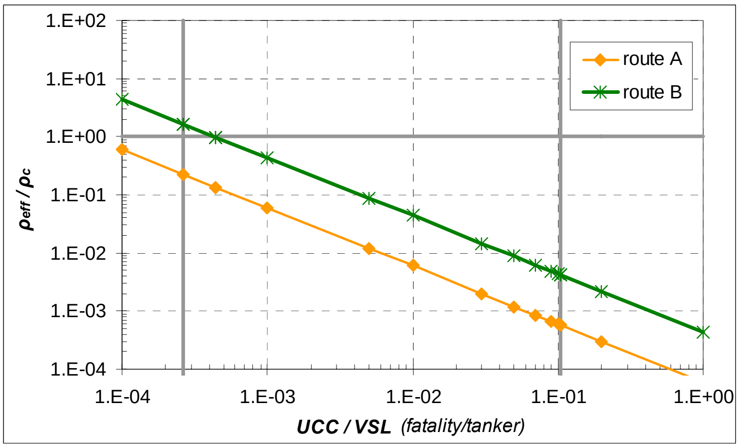

Figure 2: Case study 2: benefit-to-cost ratio (expressed as ρ_{eff}/ρ_c) vs UCC/VSL

References

Birk A.M., Cunningham M.H., 1994, The BLEVE. Journ. Loss Prev., 7, 474-480.

Bonvicini S., Ganapini S., Spadoni G., Cozzani V., 2012, The Description of Population Vulnerability in Quantitative Risk Analysis, Risk Analysis, 32(9), 1576-1594.

Carter D.A., Hirst I.L., 2000, “Worst case” methodology for the initial assessment of societal risk from proposed major accident installations, Journ. of Hazar. Mater., 71, 117-128.

Droste B., Schoen W., 1988, Full Scale Fire Tests with Unprotected and Thermal Insulated LPG Storage Tanks. Journal of Hazardous Materials, 20, 41-54.

Gómez-Mares M., Tugnoli A., Larcher S., Landucci G., Cozzani V., 2011, Experimental study and numerical simulation of epoxy intumescent passive fire protection performance. Chem.Eng.Trans. 24, 1159-1164.

Gomez-Mares M., Tugnoli A., Landucci G., Cozzani V., 2012a, Performance assessment of passive fire protection Materials, Industrial & Engineering Chemistry Research, 51, 7679 – 7689.

Gomez-Mares M., Tugnoli A., Larcher S., Landucci G., Barontini F., Cozzani V., 2012b, Enhanced modelling of exposed PFP coatings based on bench-scale fire-tests, Chem.Eng.Trans. 26, 321-326.

HSE, 2001, Reducing Risk Protecting People (R2P2), HSE decision-making process, Health and Safety Executive, HSE Books, UK.

Fiani N., 2012, Cost-benefit analysis of passive fire protections in LPG road transport, MSc Graduation Thesis in Chemical Engineering, University of Bologna, 2012, Bologna, I (in Italian).

Landucci G., Molag M., Cozzani V., 2009, Modeling the performance of coated LPG tanks engulfed in fires, Journal of Hazardous Materials, 172, 447-456.

Paltrinieri N., Bonvicini S., Spadoni G., Cozzani V., 2012, Cost-Benefit Analysis of Passive Fire Protections in Road LPG Transportation. Journ. Risk Analysis, 32, 200-219.

Paltrinieri N., Landucci G., Molag M., Bonvicini S., Spadoni G., Cozzani V., 2009, Risk Reduction in Road and Rail LPG Transportation by Passive Fire Protection. Jour. of Hazar. Mater., 167, 332-344.

TNO, 1992, Methods for the determination of possible damage (“Green Book”, CPR16E), TNO Department of Industrial Safety, Sdu Uitgevers, The Hague, NL.

TNO, 1996, Methods for the calculation of Physical Effects (“Yellow Book”, CPR14E), TNO Department of Industrial Safety, Sdu Uitgevers, The Hague, NL.

TNO, 1999, Guidelines for quantitative risk assessment (“Purple Book”, CPR18E), TNO Department of Industrial Safety, Sdu Uitgevers, The Hague, NL.

Tugnoli A., Cozzani V., Di Padova A., Barbaresi T., Tallone F., 2012, Mitigation of fire damage and escalation by fireproofing: A risk-based strategy, Reliability Engineering & System Safety, 105, 25-35.

USEPA, 2010, Guidelines for Preparing Economical Analysis, EPA 240-R-10-001, Washington DC, USA.