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Uncertainty quantification in the health consequences of the boiling liquid expanding vapour explosion phenomenon

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Abstract

A methodology for estimating the risk owing to the phenomenon of boiling liquid expanding vapour explosion (BLEVE) in the presence of uncertainties both in the model and in the parameters of the models is presented. BLEVE takes place when a tank containing liquefied petroleum gas (LPG) is exposed to fire and fails catastrophically. Two models have been used in the estimation of the intensity of thermal radiation from the resulting fireball, namely the solid-flame model assuming an emission power independent of the combustion mass and the point-source model that estimates the emissive power as a function of the combustion mass. Three measures of the BLEVE consequences, the intensity of thermal radiation, the dose of thermal radiation and the probability of loss of life as a result of the exposure to the thermal radiation and as a function of the distance from the center of the tank have been considered. Uncertainties in the exact values of the parameters of the models have been quantified and the resulting uncertainties in the three consequence measures have been assessed. A sensitivity analysis on the relative contribution of the uncertainty in each of the input variables to the uncertainties of the consequence measures has been performed. One conclusion is that the uncertainties in the probability of loss of life are mainly due to the uncertainties in the model of the physical phenomenon rather than to the uncertainties of the dose–response model. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: BLEVE; Uncertainty; Risk assessment; Chemical industry; LPG; Consequences; Thermal dose–response; Individual risk

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1. Introduction

Boiling liquid expanding vapour explosion (BLEVE) occurs when there is a sudden loss of containment of a pressure vessel containing a superheated liquid or a liquefied gas. The primary cause is usually an external flame impinging on the shell of a vessel above the liquid level weakening the container and leading to sudden shell rupture. If the released liquid is flammable, a fireball may result. The resulting thermal radiation is intense and has the potential to cause severe health-damage even loss of life as well as other material damage.

At an increasing rate, decisions concerning the safety of installations with equipment having the potential for a BLEVE have to be made. In the European Union, for example, the so-called SEVESO directive II [1], requires member states to take measures to protect the public from accidents through emergency response plans and policies for uses of land around installations handling hazardous materials. Quantitative risk assessment (QRA) provides, in the opinion of the authors, a systematic and self-consistent framework for making risk-informed decisions concerning safety issues of such installations. One quantitative measure of risk is the probability that an individual located at a point in the vicinity of the installation will die as a result of an accident in the installation. Such a measure incorporates all the constituents of risk, namely what can go wrong in the installation and how probable it is, what are the adverse phenomena that follow and their intensity, what are the consequences of these phenomena and how probable they are [2]. Regardless of the advertised advantages of QRA, it does not receive universal acceptance and the main body of criticism it receives is on the subject of uncertainty. It is claimed that QRA has not been applied because of lack of necessary information and data to quantify the relevant models. What is proposed in those cases are the so-called ‘deterministic’ models yielding the intensity or other characteristics of an adverse physical phenomenon that follows an accident. It is then claimed that meaningful decisions can be made on the basis of these results. In the case of BLEVE, this approach would calculate the intensity of the resulting thermal radiation as a function of the distance from the tank and would establish safety distances on the basis of a limit in the intensity of thermal radiation. Such safety distances might refer to distances within which certain uses of land or other activities are not allowed, or to distances within which certain protective actions have to be taken in the event of an emergency, or simply distances within which certain equipment should not be located to avoid material damages or even accident propagation to higher scales. QRA on the other hand accepts that in addition to the intensity of thermal radiation the effects depend on the duration of the exposure and on the strength of the exposed individual (or material accordingly) to the exposure. QRA accepts that what determines the consequences of a BLEVE are the dose of the thermal radiation and response of the exposed to this dose. There are uncertainties associated with these two latter steps. Some of the models and/or their parameters are not known with enough precision to consider them as deterministically known. The same is true, however, with the models concerning the physical phenomena. It is not established that the uncertainty about the estimation of the intensity of physical phenomena like thermal radiation is less than the uncertainty in establishing the effect of an exposure to such a phenomenon. Even if this is the case, the question to guide the choice of the appropriate criterion to support decisions should not be which criterion is characterized by a smaller degree of uncertainty, but rather which criterion is more relevant to the decision at hand. The challenge is then to quantify the existing uncertainties and incorporate them in the decision-making process.

The objective of this paper is to present a methodology for assessing the uncertainties in the estimation of the consequences of the BLEVE phenomenon. The consequences are considered conditional on the BLEVE occurring. That is the probability with which such an accident might occur is not included in the analysis. Three quantitative measures of consequence are considered, namely the intensity of thermal radiation, the dose of thermal radiation for the duration of the phenomenon, and the probability for loss of life as a result of the dose. All three quantities are calculated as a function of the distance from the tank. The approach taken is to consider the consequence as a function of the parameters of the various models. Uncertainties in the values of the parameters are quantified by assuming them as random variables distributed according to known probability density functions (pdfs). The latter are determined from the physically possible ranges of the parameters and the available experimental evidence. Consequences now being functions of random variables are themselves random variables and their pdfs can be determined via a number of techniques. In this paper, the Monte Carlo approach using a Latin-Hypercube Sampling [3] scheme has been followed. Uncertainties in the BLEVE phenomenon have been assessed in a benchmark exercise [4] and the results have shown that the results are not affected significantly by the specific technique and/or the particular computer program implementing it. In this paper, the calculations have been performed using the @Risk Code [5].

The paper is organized as follows. Section 2 presents two different models for the thermal radiation of the BLEVE phenomenon and quantifies the uncertainties about the various parameters as well as the resulting uncertainties for the intensity of the thermal radiation. Sections 3 and 4 do the same for the quantitative measures of dose and individual risk (IR). Finally, Section 5 presents the results of a sensitivity study and the main conclusions of this work.

2. Intensity of thermal radiation

The intensity of thermal radiation $Q(r)$ which an individual may receive in case of a fireball is given by the following equation, according to CCPS/AIChE [6] and TNO [7]:

$$Q(r) = E\tau_{\alpha}v_{\mathrm{F}} \tag{1}$$

where: $Q(r)$, radiation (kW/m^2); E: emissive power per unit area (kW/m^2); τ_{α}: atmospheric transmissivity; v_{F}: view factor.

2.1. Emissive power

Emissive power is the power that is radiated per unit surface at the surface of the fireball. As it is obvious from Eq. (1), E controls the intensity of thermal radiation a receptor is receiving at a distance r from the center of the trace of the fireball to the ground. The value of surface-emissive power has been estimated from experiments by various researchers and the results are summarized in CCPS/AIChE [6] and TNO [7]. There is a great variability in the reported results. In addition, two major models have been proposed for this quantity:

(a) Solid-flame model described in CCPS/AIChE [6] and in TNO [7];
(b) Point-source model described in CCPS/AIChE [6].

2.1.1. Solid-flame model

According to this model, the fireball is represented by a solid sphere and all thermal radiation is emitted from its surface. The important assumption made by those using this model for the BLEVE phenomenon is that the emissive power E is constant and does not depend on the mass of the flammable substance involved in the combustion. This value has been estimated from experiments. Three sets of experiments have been reported in the literature and their results appear in Table 1. TNO [7] proposes 180 kW/m^2 while CCPS/AIChE [6] proposes 350 kW/m^2 as the constant value of the emissive power.

2.1.2. Point-source model

According to this model, a selected fraction f of the heat of combustion is emitted as radiation in all directions. Assuming further that heat is radiated at a constant rate during the phenomenon, the emissive power is a function of the fuel mass, of the radius and of the duration of the fireball and it is given by the following equation:

$$E = \frac{MH_c f}{\pi D^2 t} \tag{2}$$

where: E, emissive power (kW/m^2); M, mass of combustion (kg); H_c, heat of combustion (kJ/kg); f, fraction of heat release due to combustion that is radiated from the fireball; D, diameter of fireball (m); and t, duration of fireball (s).

The radiated fraction of the combustion heat f is a function of pressure in the tank and it is estimated according to Roberts [11] by:

$$f = f_1 P^{f_2} \tag{3}$$

where: P is the pressure in tank in MPa and f_1, f_2 parameters.

According to Roberts [11] parameters f_1 and f_2 are constant and take the values $f_1 = 0.27$, $f_2 = 0.32$. In this analysis, they have been considered as uncertain parameters.

Table 1
Experimental results for the emissive power (E)

References	Fuels	Fuel mass (kg)	E (kW/m^2)
(a) Hasegawa and Sato [8]	C_5H_{12}	0.3–30	110–413
(b) Johnson et al. [9]	C_4H_{10}, C_3H_8	1000–2000	320–375
(c) Roberts et al. [10]	C_3H_8	279–1708	320–415

2.2. View factor

Given a radiation surface and a receptor, not all the points of the radiating surface can radiate in straight line to the receptor. The view factor in Eq. (1) takes into consideration the fact that a receptor does not 'see' all the points of a radiating surface and hence, he receives only a fraction of the radiated power. The faction of the radiating surface that can be viewed by a receptor is called the view factor. The view factor of a point on a plane surface located at a distance L from the center of a sphere with diameter D depends not only on L and D but also on the orientation of the surface with respect to the fireball. The simplest and most conservative case is when the surface is vertical to the line between the receptor and the center of the fireball. Then the view factor is given by Ref. [12]:

$$\upsilon_F = \frac{D^2}{4L^2} \tag{4}$$

where: υ_F, view factor; D, fireball diameter; and L, distance from the center of the fireball.

For a point on the ground and at a distance r from the trace of the fireball on the ground, the distance L from the center of the fireball is given by:

$$L = \sqrt{(\gamma D)^2 + r^2} \tag{5}$$

where: D, fireball diameter; L, distance from the center of the fireball; and γD, height of the center of the fireball from the ground.

The height of the center of the fireball from the ground (liftoff) has been expressed as a fraction γ of the diameter of the fireball.

2.3. Diameter of the fireball

Regardless of the model used to estimate the surface emissive power, an estimation of the diameter of the resulting fireball is needed. Empirical estimations of the diameter are given in Table 2 and all are provided as a function of the mass involved in the combustion through an equation of the form:

$$D = b_1 M^{b_2} \tag{6}$$

where: D, diameter of fireball (m); M, mass of fireball (kg); and b_1, b_2, parameters.

Parameters b_1 and b_2 are not precisely known. In this analysis, they have been considered as random variables.

2.4. Duration of the BLEVE phenomenon

The duration of the fireball is an important factor in the assessment of the emissive power E in the point-source model (Eq. (2)) and of the dose in both models as will be

Table 2
Data for parameters b_1, b_2, c_1, c_2 of the empirical relationships for fireball diameter and duration

References	b_1	b_2	c_1	c_2
Data values				
Lihou and Maund [13]	3.51	0.33	0.32	0.33
Roberts [11]	5.8	0.33	0.45	0.33
Pietersen [14], TNO [7]	6.48	0.325	0.825	0.26
Williamson and Mann [15]	5.88	0.333	1.09	0.167
Moorhouse and Pritchard [16]	5.33	0.327	1.09	0.327
Hasegawa and Sato [8]	5.28	0.277	1.1	0.097
Fay and Lewis [17]	6.28	0.33	2.53	0.17
Lihou and Maund [13]	6.36	0.325	2.57	0.167
Raj P.K. (Ref. 5 of Chapter 6) in TNO [7]	5.45	0.333	1.34	0.167
Statistics				
Mean value	5.60	0.323	1.26	0.224
Standard deviation	0.90	0.018	0.80	0.089
Skewness	−1.39	−2.48	−0.40	0.003
Kyrtosis	4.29	7.28	1.03	1.13
Correlations				
b_1	1	0.08	0.57	−038
b_2	0.08	1	0.04	0.49
c_1	0.57	0.04	1	−0.59
c_2	−0.38	0.49	−0.59	1

discussed in the next section. Empirical relationships similar to those for the diameter have been proposed:

$$t = c_1 M^{c_2} \tag{7}$$

where: t, duration of fireball (s); M, mass of fireball (kg); and c_1, c_2, parameters.

Reported values for parameters c_1, c_2 are given in Table 2. Again, it is noticed that the values of these parameters are not precisely known. In this analysis, they have been considered as random variables.

2.5. Quantification of uncertainties in the thermal radiation intensity

Given the range of the reported values for the various parameters, it follows that the estimation of the thermal radiation intensity at a point in the vicinity of a fireball is characterized by a substantial degree of uncertainty. This uncertainty is either due to lack of knowledge about the exact model to be applied, or about the exact value of certain parameters, or because some of the conditions under which the event might happen are characterized by stochastic variability. Following the general approach discussed in Section 1, these uncertainties are quantified by assuming the various parameters as random variables characterized by a range of possible values and associated probabilities. Table 3 gives the pdf and the associated values of the

Table 3
Probability density function characteristics of input variables

Symbol in text	Type of distribution	Mean	Standard deviation	Standard deviation / mean	1st parameter	2nd parameter
τ_α	Beta	7.00E − 01	8.23E − 02	1.18E − 01	2.10E + 01	9.00E + 00
f_1	Lognormal	2.70E − 01	2.70E − 02	1.00E − 01	2.70E − 01	2.70E − 02
f_2	Normal	3.20E − 01	3.20E − 02	1.00E − 01	3.20E − 01	3.20E − 02
b_1	Lognormal	5.62E + 00	9.62E − 01	1.71E − 01	5.62E + 00	9.62E − 01
b_2	Normal	3.22E − 01	1.84E − 02	5.73E − 02	3.22E − 01	1.84E − 02
c_1	Lognormal	1.25E + 00	8.57E − 01	6.87E − 01	1.25E + 00	8.57E − 01
c_2	Normal	2.31E − 01	9.22E − 02	3.99E − 01	2.31E − 01	9.22E − 02
γ	Uniform	7.50E − 01	1.44E − 01	1.92E − 01	5.00E − 01	1.00E + 00
d_{50}	Lognormal	2.32E + 03	7.74E + 02	3.34E − 01	7.68E + 00	3.70E − 01
y	Normal	9.50E − 01	2.00E − 02	2.11E − 02	9.50E − 01	2.00E − 02
E	Uniform	3.10E + 02	6.85E + 01	1.57E − 01	2.00E + 02	4.20E + 02

parameters of these pdfs for each of variable considered random in the analysis. In addition, Table 3 gives the implied mean value and standard deviation for each variable, as well as, the ratio of standard deviation to the mean value which provide a measure of the assumed spread of the values for each parameter. Uncertainty assessment for the parameters τ_α, f_1, f_2 and γ are generic to this analysis. Uncertainties for parameters b_1, b_2, c_1, c_2 and E are quantified in such a way that the assumed mean and standard deviation are those implied by the data in Tables 1 and 2.

Table 2 gives some of the statistics of the sample of the nine data points for the parameters (b_1, b_2, c_1, c_2), namely the mean, the standard deviation, the skewness and the kyrtosis. Table 2 also gives the cross correlations among the parameters (b_1, b_2, c_1, c_2) implied by the sample values. The pdfs in Table 3 for parameters (b_1, b_2, c_1, c_2) were selected so that they span the region of values suggested by the data in Table 2, while having the same mean and standard deviation with the sample. Variables b_1 and c_1 were assumed lognormally distributed to avoid numerical problems with potential negative values that the sampling procedure might generate in large samples. The sampling scheme took into account the correlation coefficients given in Table 2. The normal and lognormal distributions considered for the parameters b_2 and b_1 do not exhibit the negative skewness characteristic of the data for these two parameters. As it will be discussed in the sensitivity section, this assumption does not affect the conclusions of this analysis. Since there were only three sources for data for the constant emissive power E (see Table 1), the pdf of E has been assumed uniform spanning the internal [200–420 kW/m^2]. Any function of some or all of these parameters being a function of random variables is itself a random variable distributed according to a pdf with characteristics depending on the nature of the function and the pdfs of the input variables.

The uncertainties in the intensity of thermal radiation as a function of the distance r have been calculated and are shown in Fig. 1 for both models of the emissive power. Fig. 1 gives the 5, 50 and 95% percentiles of the intensity of thermal radiation Q at various distances r for a tank storing 2500 ton of LPG at a pressure of 0.5 MPa.

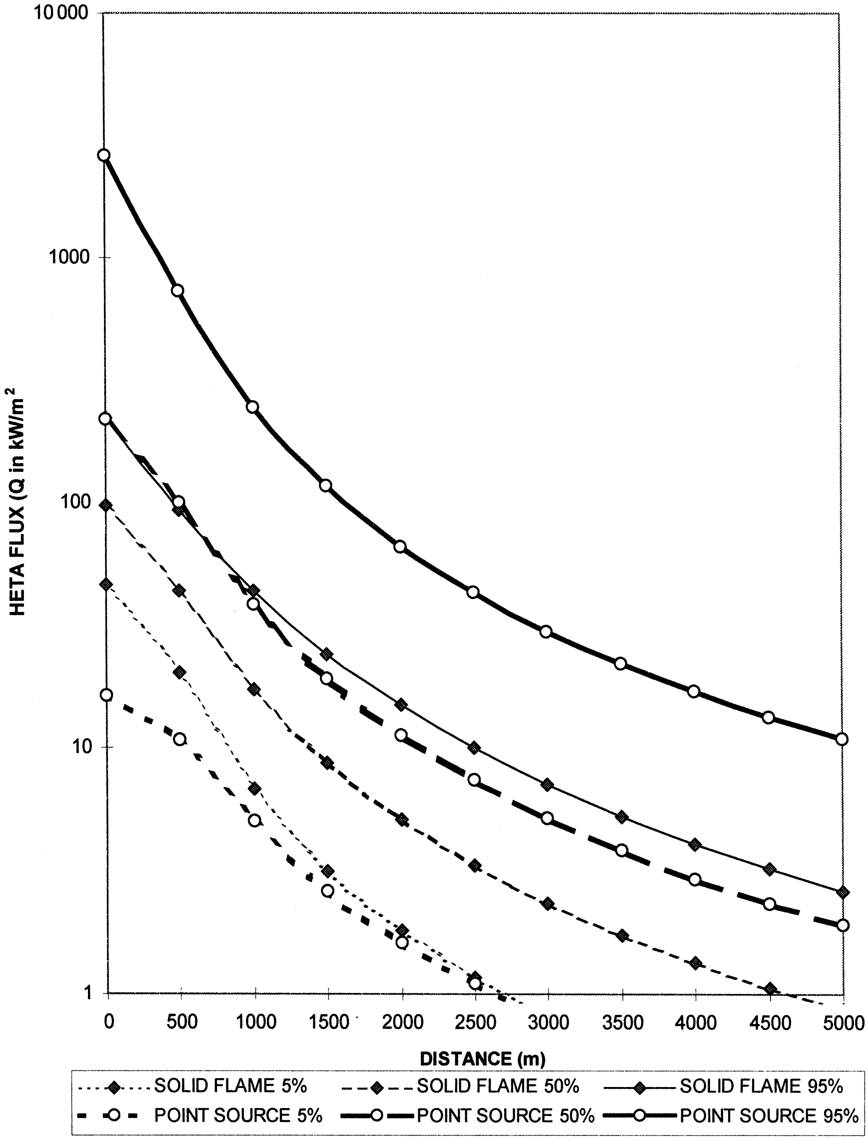

Fig. 1. Uncertainties in the intensity of thermal radiation as a function of distance for the solid-flame and the point-source models (5, 50 and 95% percentiles), for a BLEVE in a tank containing 2.5×10^{6} kg LPG.

The point-source model is characterized by a larger degree of uncertainty than the solid-flame one. For example, at 2000 m from the center of the tank, the point-source model gives that the intensity of thermal radiation will lie in the interval [1.6–65 kW/m^2] with probability 90%, and Q will be greater than 11 kW/m^2 with probability 50%. The corresponding figure for the solid-flame model are [2–15 kW/m^2] for the 90% probability interval and 5 kW/m^2 for the median value.

Uncertainties in the point-source model are larger since the emissive power in this model depends on the duration of the phenomenon, which in turn depends on the combustion mass (see Eqs. (1)–(4)). The uncertainty in the empirical coefficients in the duration equation are rather substantive (see Eq. (7) and Table 3) resulting in a large uncertainty in the emissive power for the point-source model. The 90% probability interval for the equivalent emissive power of the point-source model is [88–4900 kW/m^2] with a median value of 660 kW/m^2 and a mean value of 1407 kW/m^2. This is a significantly broader range than that for the solid-flame model (see E in Table 3).

Both models yield uncertainty ranges for the value of $Q(r)$ that could be considered as large for decision-making. This is particularly true if seen from the point of view of the distance at which a particular level of radiation intensity is achieved. If a safety distance is to be defined in terms of the level of the thermal radiation intensity, the point-source model can only tell us, for example, that this distance for $Q = 10$ kW/m^2 could be in the range [550–5200 m] with probability 90%. On the other hand, the solid-flame model provides a safety distance for which $Q = 10$ kW/m^2 as [800–2500 m].

3. Dose of thermal radiation

Whenever health consequences are to form the basis of a decision concerning the effects of an accident involving a BLEVE, knowledge of the intensity of thermal radiation is not sufficient. The effect on human health of the exposure to thermal radiation depends not only on the intensity of the radiation but also on the duration of the exposure. A quantitative measure of the severity of the effect of a particular exposure is given by the so-called dose function for thermal radiation given by the relationship [6,17,18]:

$$d(r) = [Q(r)]^{4/3} t \tag{8}$$

where: $Q(r)$ is the thermal flux at a distance r (kW/m^2); t is the duration of the exposure (s); and $d(r)$ is the level of adverse exposure or dose at point r.

The unit of thermal dose is called TDU (thermal dose unit) and its dimensions are 1 TDU $= 1$ $(kW/m^2)^{4/3}$ s.

The exponent $4/3$ in Eq. (8) measures the non-proportional effect of the level of radiation intensity. There is widespread agreement in the literature on the value of the exponent [6,17,18]. In any event, any uncertainty on the actual effect of a particular dose on the human health can be taken into consideration through the concept of IR as discussed in the next section. All the uncertainty in the estimation of thermal dose owing to a BLEVE stems, therefore, from the uncertainties in the intensity of thermal radiation and the duration of the phenomenon.

Since no new uncertain variable has been introduced in the definition of the dose, the uncertainties in this quantity can be quantified in terms of the input variables used in the calculation of Q given in Table 3. The results are given in Fig. 2.

A complete reversal of the behavior determined for the intensity of thermal radiation is observed. For the thermal dose received by a receptor during the duration of the

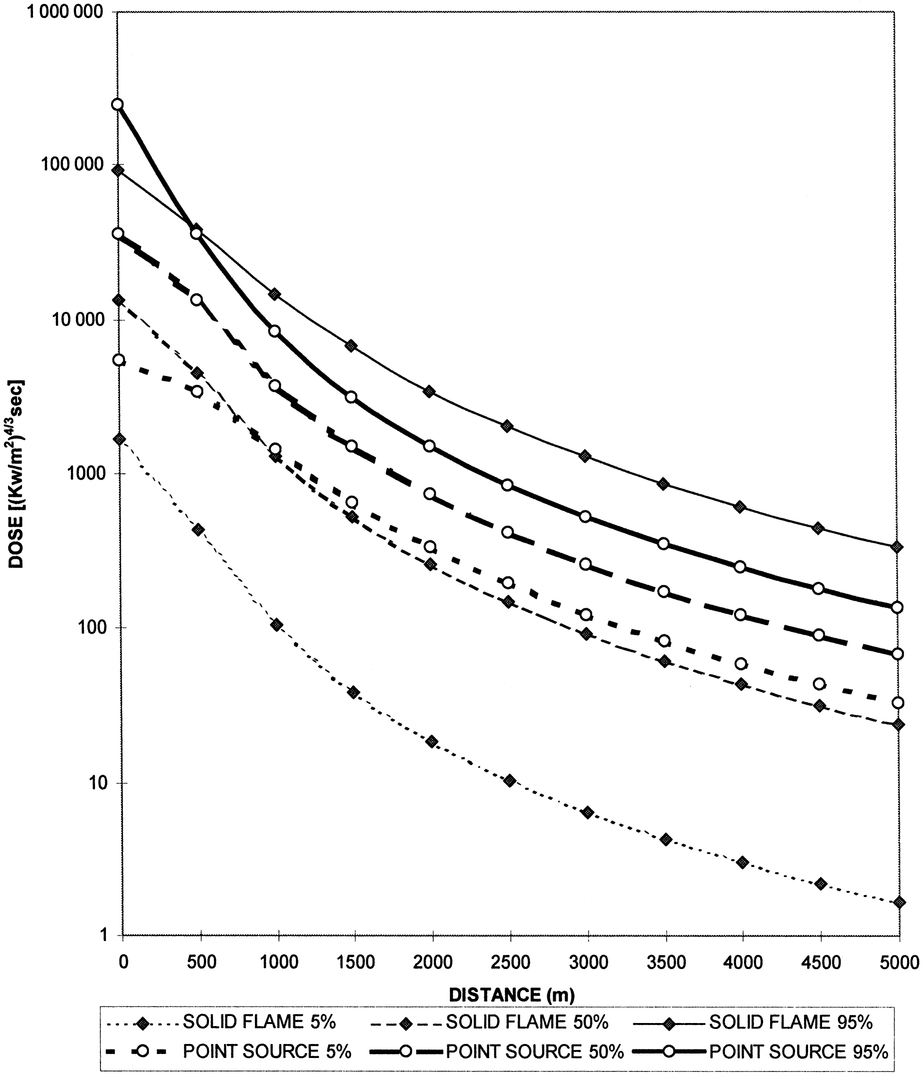

Fig. 2. Uncertainties in the dose of thermal radiation as a function of distance for the solid-flame and the point-source models (5, 50 and 95% percentiles), for a BLEVE in a tank containing 2.5×10^6 kg LPG.

BLEVE phenomenon, the point-source model yields a much narrower range of uncertainty than the solid-flame model. For example, the distance at which a thermal dose of 1000 TDU will be received for the solid-flame model is characterized by a 90% probability interval of [270–3300 m] with a median value of 1130 m. The corresponding values for the point-source model are [1225–2350 m] 90% probability interval and 1770 m median value. This reversal is due to the different dependence of the two models on the duration of the phenomenon. (see Eqs. (1)–(8)). The solid-flame model estimates the dose as being proportional to the duration of the BLEVE (Eq. (8)) since the intensity of thermal radiation does not depend on it (see Eq. (1) and Section 2.1.1). In the point-source model on the other hand, $Q(r)$ is inversely proportional to the duration (see Eqs. (1) and (2)). This strong dependence is partly offset in the dose relationship (see Eq. (8)) leaving the dose $d(r)$ to be inversely proportional to the cubic root of duration t (see Eqs. (1), (2) and (8)).

4. Individual risk

Thermal dose is a measure of the effect a particular exposure to thermal radiation has on human health and hence, it provides a basis for systematic comparison of different exposures. This comparison is possible in the sense that a larger dose has a more severe health effect than a smaller one. When knowledge of how much more severe are the health consequences of different thermal doses is needed or when comparison of exposures to different types of phenomena is necessary, thermal dose in itself is not an adequate measure anymore. Two large thermal doses, both of them lethal, are from the point of view of the health consequence equivalent even if one is many times larger than the other. The same is true for two thermal doses both below the threshold for irreversible health damage. Furthermore, doses from different phenomena (e.g., thermal and toxic doses) are not directly comparable. On the other hand, the type of health damage that an exposure might cause provides a common basis that allows direct comparison. In this paper, we will consider only one type of health effect namely, loss of life.

The effect of subjecting a number of people to the same dose of thermal radiation is not identical, presumably because the strength of the human body to the stresses imposed by thermal radiation varies among the general population. A quantitative measure of the health consequence is, therefore, the probability of loss of life as a result of a given thermal dose. This quantification is achieved through the so-called Probit function defined as a linear transformation of the logarithm of the dose:

$$P = A + B \ln d \tag{9}$$

On the assumption that the strength of the human body to thermal radiation is normally distributed with mean value of five and standard deviation of one, the probability of loss of life conditional on receiving a dose d is given by:

$$\mathrm{IR}(P) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{P-5} \exp\left(-\frac{u^2}{2}\right) du. \tag{10}$$

This probability is also called IR of loss of life. The assumption of normality in the distribution of human strength should not be considered as restrictive since the particular form of the function for the dose (see Eq. (8)) and the values of parameters A, B in Eq. (9) are chosen so that the transformed random variable of the difference of the strength and the logarithm of the dose is distributed according to the standard normal distribution. Parameter A controls the mean value of the distribution or the dose that causes 50% of the exposed population to die. Parameter B controls the spread of the distribution, for example the dose that causes death to 1% of the exposed population. Parameters A, B are determined from experiments on animals and possibly from existing data of accidents and are of course characterized by uncertainty.

A comprehensive assessment of the present state of knowledge on the fatality causing levels of dose are given by Rew and McKay in Ref. [19]. They summarize the experience of various researchers on these effects not directly through the parameters A, B but rather in terms of the level of dose causing fatalities to 50 and 1% of those exposed. Given Eqs. (9) and (10) parameters A, B can be determined from these dose levels as follows:

$$A = P_{50} - \frac{\ln(d_{50})}{\ln(d_{50}) - \ln(d_{01})}(P_{50} - P_{01}) \tag{11}$$

and

$$B = \frac{P_{50} - P_{01}}{\ln(d_{50}) - \ln(d_{01})} \tag{12}$$

where d_x is the dose that through Eq. (9) provides P_x which in turn gives from Eq. (10) x% probability of dying. By virtue of Eqs. (11) and (12), it follows that A, B can be defined in terms of two other variables namely, d_{50} and y where:

$$y = \ln(d_{50}) - \ln(d_{01}) \tag{13}$$

since, P_{50}, P_{01} are known (from the standard normal distribution) and equal to 5 and 2.673658, respectively.

Ref. [19] provides available estimations of d_{50} and d_{01} reproduced here in Table 4. Uncertainties in the estimation of IR can therefore be quantified by assuming the parameters d_{50} and y as random variables distributed with the characteristics given in Table 3. For the dose causing death with probability 50%, it has been assumed that it is lognormally distributed so that d_{50} lies with probability 95% in the range [1050–4440]. Similarly variable y has been assumed distributed normally and that the range of the reported values [0.90–0.986] forms the 95% probability interval (see Table 4). It is noteworthy that while the reported values for d_{50} vary considerably, the reported values for d_{01} are such that the difference of the logarithms of d_{50} and d_{01} present very small variation (see Table 3).

Quantification of the uncertainties of the IR as a function of the distance from the center of the tank gives the results presented in Fig. 3. As expected, the behavior of the

Table 4
Comparison of current methodologies

Methodology	Dosage $(kW/m^2)^{4/3}$ s for probability of fatality of:		
	1%	50%	$y = \ln(d_{50}) - \ln(d_{01})$
Eisenberg et al. [20]	960	2380	0.908
Tsao and Perry [21]	420	1050	0.916
TNO [7]	520	–	–
Lees [22]	1655	4440	0.987

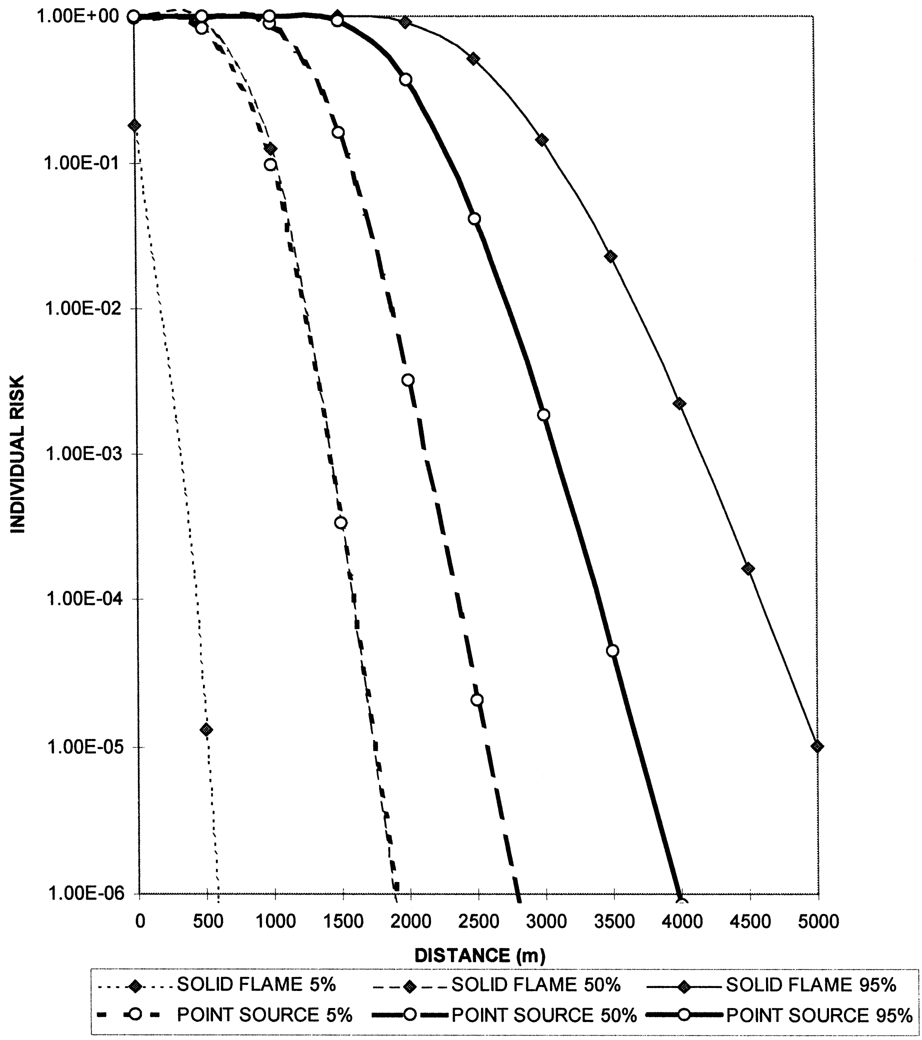

Fig. 3. Uncertainties in the IR as a function of distance for the solid-flame and the point-source models (5, 50 and 95% percentiles), for a BLEVE in a tank containing 2.5×10^{6} kg LPG.

two models is similar to that observed for the dose, the solid-flame model being characterized by a greater degree of uncertainty than the point-source model. Again, the uncertainties are rather large to provide uncontroversial support to relevant decisions. For example, the 90% probability interval for the distance at which the IR is equal to 10^{-2} is [285 m, 3700 m] for the solid-flame model, and [1240 m, 2750 m] for the point-source model. Since the thermal dose of 1000 TDU is closely equivalent to an IR of 10^{-2} (using mean values for parameters A and B in Eq. (9)), it follows that the uncertainty in the IR is only slightly higher than those in the dose. In other words, the uncertainty in the parameters A, B of the Probit (Eq. (9)) does not contribute significantly to the uncertainty in the estimation of the IR. This point is further discussed in the following section.

From the analysis in Sections 2 and 3 and this section, it follows that the uncertainty characterizing the distances at which a particular level of thermal radiation is reached, is greater than the uncertainty characterizing the distances at which the corresponding levels of thermal dose and IR are reached. For an LPG tank containing 2500 ton of flammable material, the duration of the BLEVE phenomenon is such that the levels of IR 10^{-2} and thermal radiation dose 1000 TDU are generated by an intensity of thermal radiation at the level of 15 kW/m^2. Given the uncertainties as they are quantified in Table 3, and regardless of the model for the emissive power, it can be stated that the distance at which the IR is 10^{-2} will not be greater than 3700 m with probability 95% while the distance at which the dose of thermal radiation is 1000 $(kW/m^2)^{4/3}$ s is not greater than 3300 m also with probability 95%. For the same tank, the distance at which the intensity of thermal radiation will be less than 15 kW/m^2 with probability 95% is 4200 m.

5. Sensitivity analysis and conclusions

A sensitivity analysis of the contribution to the uncertainty of the various outputs of the uncertainties of the input parameters has been performed. This analysis provides a ranking of the relative importance of the uncertainty in each of the input parameters with respect to the uncertainty in various outputs. This ranking would indicate the most efficient way to reduce the uncertainties in the calculated quantities (i.e. $Q(r)$, $d(r)$, $IR(r)$). It should be emphasized that the results discussed here, although they reflect the general functional dependencies of the various outputs to the input parameters, are conditional on the assessed uncertainties of the input parameters as they are presented in Table 3. The contribution of each input distribution to the output distribution has been measured in terms of a multivariate stepwise regression analysis performed on the sample of the outputs and their associated inputs. The results are given in Table 5. The higher the overall coefficient (RSqr) the more stable the results of the analysis. This means they are not expected to change if the sample in the Monte Carlo approach changes. The very high degree of ‘R-squared’ achieved in all six cases shown in Table 5 indicates a high degree of stability of the results that are going to be discussed in the remaining of this section.

5.1. Intensity of thermal radiation

The first two columns in Table 5 give the regression coefficients of the various input parameters with respect to the distance r at which the intensity of thermal radiation achieves the value of 5 kW/m^2, for the two models examined in this paper. For the solid-flame model, the most important parameters are the two coefficients b_1, b_2 determining the diameter of the fireball (Eq. (6)) followed by the emissive power E and the coefficient of atmospheric transmissivity τ_α. The diameter of the fireball becomes

Table 5
Multiple regression coefficients of the input variables to three output quantities

	$r(Q=5$ kW/m2)				$r(d=1000$ TDU)				$r(\mathrm{IR}=10^{-2})$			
	Solid-flame RSqr = 0.949		Point-source RSqr = 0.844		Solid-flame RSqr = 0.844		Point-source RSqr = 0.952		Solid-flame RSqr = 0.827		Point-source RSqr = 0.922	
Rank	Name	Sens. Coef.	Name	Sens. Coef.	Name	Sens. Coef.	Name	Sens. Coef.	Name	Sens. Coef.	Name	Sens. Coef.
#1	b_2	0.76	c_2	−1.02	c_2	0.72	c_2	−0.71	c_2	0.67	c_2	−0.69
#2	b_1	0.46	c_1	−0.38	b_2	0.39	τ_α	0.34	b_2	0.38	d_{50}	−0.62
#3	E	0.31	τ_α	0.09	c_1	0.25	c_1	−0.33	b_1	0.24	τ_α	0.28
#4	τ_α	0.18	b_2	−0.08	b_1	0.25	f_1	0.29	c_1	0.23	c_1	−0.26
#5	γ	−0.04	f_1	0.07	E	0.17	b_2	−0.19	d_{50}	−0.21	f_1	0.23
#6	f_1	0.00	b_1	−0.05	τ_α	0.08	b_1	−0.12	E	0.17	b_2	−0.15
#7	f_2	0.00	γ	−0.03	γ	−0.04	γ	−0.10	τ_α	0.08	b_1	−0.08
#8	c_1	0.00	f_2	0.00	f_1	0.00	f_2	−0.07	γ	−0.03	f_2	−0.07
#9	c_2	0.00	d_{50}	0.00	f_2	0.00	d_{50}	0.00	f_1	0.00	γ	−0.07
#10	d_{50}	0.00	y	0.00	d_{50}	0.00	y	0.00	f_2	0.00	y	0.02
#11	y	0.00	E	0.00	y	0.00	E	0.00	y	0.00	E	0.00

The regression coefficient indicates the contribution of the particular input variable to the variation of the output variable.

important since it affects the view-factor (Eq. (4)). It is noteworthy that owing to the relatively large distance (with respect to the fireball diameter) at which $Q=5$ kW/m^2, the role of the liftoff high coefficient γ is insignificant.

Different results are obtained for the point-source mode. Here, the coefficients (c_1, c_2) determining the duration of the phenomenon are the most important. With substantially smaller contribution following are the coefficient of atmospheric transmissivity τ_α; the coefficients (b_1, b_2) affecting the diameter of the fireball; and the coefficient f_1 affecting the fraction of the combustible mass involved in the BLEVE phenomenon. A negative coefficient indicates a negative dependence of the $r(Q)$ on the specific coefficient, i.e., an increase in the coefficient results in a decrease in the distance $r(Q)$. Here, the diameter of the fireball is of no significance since it is canceled out (see Eqs. (2) and (4)) remaining only in the factor L where soon it is dominated by the distance r (See Eq. (5)). Again, the coefficient γ determining the liftoff height is of no importance.

5.2. Dose of thermal radiation

The contribution of the various parameters to the uncertainties about the distance at which thermal radiation dose achieves the value 1000 TDU is given in the third and fourth columns of Table 5. The factor contributing the most in the uncertainties of the dose in the solid-flame model is parameter c_2 affecting the duration of the phenomenon (see Eq. (7)). Next comes parameter b_2 affecting the diameter of the fireball followed by the remaining parameters c_1, b_1 of the duration and the diameter, respectively (see Eqs. (6) and (7)). Following are parameters E and τ_α. This change in the order of importance of the parameters from that observed for the intensity of thermal radiation is due to the fact that duration does not affect Q in the solid-flame model. On the contrary, the relative importance of the various parameters with respect to the uncertainty in the distance at which a particular dose level is obtained for the point-source models remains practically the same as for the intensity of thermal radiation.

The strong negative dependence on the duration is somehow diminished, since for the point-source model the $Q(r)$ is inversely proportional to the duration while $d(r)$ is proportional to the cubic root of the duration (see Eqs. (1), (2) and (8)). The atmospheric transmissivity τ_α is significant for the point-source model.

5.3. Individual risk

The fifth and sixth columns in Table 5 give the regression coefficients of the various input parameters to the uncertainty about the distance at which the probability of fatality from the thermal radiation of a BLEVE is equal to 10^{-2}. Since the probability of fatality or IR is a monotonically increasing function of the dose (see Eqs. (9) and (10)), the only changes from the case of dose are due to the introduction of uncertainties in the parameters A and B in Eq. (9) or the equivalent parameters d_{50} and y (see Table 3 and Section 4). It is noteworthy that the uncertainty about the parameters of the physical model is much more important than the uncertainty about the parameters of the Probit function. For the solid-flame model, parameters d_{50} ranks fifth in importance substantially behind the parameters c_2, b_2 of the BLEVE duration and the diameter of the fireball, and slightly behind parameters c_1, b_1. Furthermore, d_{50} is only slightly ahead of the emissive power E (see fifth column of Table 5).

For the point-source model, parameter d_{50} ranks second in importance behind parameter c_2 affecting the duration and ahead of atmospheric transmissivity τ_α and parameters c_1, f_1 and b_2. Similar results were obtained for different levels of IR.

The calculations and the analysis of Sections 5.1 and 5.2 and this section have been repeated with a mass of combustion $M = 200$ ton. Similar results have been obtained concerning the relevant importance of various parameters.

5.4. The role of the pdfs of the input variables

All the results presented in Sections 2–5 depend of course on the assumed range of uncertainty of the input variables and the associated pdfs. To investigate the effects of the assumed pdfs, all of the analysis has been repeated assuming that input parameters given in Table 3 are distributed according to uniform pdfs as follows. For parameters (b_1, b_2, c_1, c_2, E, d_{50}, y), for which there were available data, the limits were the smaller and larger reported values (see Tables 1, 2 and 4). For parameters τ_α, f_1, f_2, the ranges considered were [0.5–1], [0.1–0.4] and [0.3–0.4], respectively.

The effect of these changes was minor. No significant qualitative change in the results of the range of the uncertainties has resulted, e.g. Figs. 1–3 were practically unchanged. Practically the same results were obtained also for the sensitivity analysis of Sections 5.1, 5.2 and 5.3.

Finally, no effect on the results has been observed when the pdfs of parameters b_1, b_2 were changed to pdfs negatively skewed as indicated by the data in Table 2.

5.5. Conclusions

Based on the analysis presented in this paper and on the assumption that the uncertainties in the state of knowledge of the various parameters are quantified as given in Table 3, the following general conclusions can be drawn about the uncertainties in the consequences of the BLEVE phenomenon.

- To reduce the uncertainties in the estimation of the intensity of thermal radiation, it is important to reduce the uncertainties in the estimation of the size of the diameter of the fireball and in the emissive power E for the solid-flame model, while reduction in the uncertainties in the estimation of the duration of the phenomenon and in the fraction of the combustion heat that is radiated is required for the point-source model. In general, reduction of the uncertainties in these parameters can be achieved with additional experimentation. Of course, this reduction will be possible only if the present uncertainty is due to lack of knowledge and not to an inherently stochastic behavior of the BLEVE phenomenon. In the latter case, additional experimentation will better define the nature of the random variation of the parameters rather than decrease their range of possible values and their corresponding variance. An indirect reduction in the uncertainty can be also achieved if some of the data in Tables 1 or 2 are discarded as originating from experiments not representing the particular situation under analysis. This is particularly true for simulating BLEVE phenomena involving large masses since the data in Tables 1 and 2 are generated by experiments involving very small masses. It should be noticed that 'reduction' in the uncertainties means reduction in the variance of the unknown parameters and hence, in the variance of the dependent variables and not necessarily reduction in the upper limits, mean values, etc.
- In both models, the atmospheric transmissivity τ_{α} is significant.
- In both models, the liftoff height of the fireball is not significant.
- The diameter of the fireball plays no role in the uncertainties of any of the outputs (Q, d, IR) for the point-source model.
- The most important contributor to the reduction of the uncertainties about the dose of thermal radiation is the uncertainty about the duration of the phenomenon regardless of the model used to estimate the emissive power of thermal radiation.
- The uncertainties about the IR of loss of life as a result of the exposure to the thermal radiation of a BLEVE are mainly due to the uncertainties in the received dose rather than to the uncertainties of the effect of a particular level of dose. The uncertainties in the received dose are mainly due to the uncertainties about the duration of the phenomenon and to a lesser effect to the uncertainties about the model estimating of the emissive power E.
- Whenever consequences on human health are of importance in a decision concerning establishing safety distances the quantitative measures of thermal dose and/or IR of loss of life are characterized by significantly lower uncertainty than the intensity of thermal radiation.
- Finally, it should be emphasized that these uncertainties are not due to the fact that risk is quantified. These are uncertainties existing regardless of whether IR is estimated or not; at least in their greatest part. Before trying to reduce these uncertainties, one should ask whether they are actually important for decision-making purposes. Population

distribution around the site and potential mitigation measures might play an important role, and when taken into account they might provide a different picture. Obviously, the calculated uncertainties will became less important in a scarcely populated site than in a densely populated one. A decision-theoretic approach could be followed where the 'relative value' of the additional knowledge expected form additional experimentation could be weighted against the cost of such experimentation.

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