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Modelling Ignition Probabilities within the Framework of Quantitative Risk Assessments

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The calculation and modeling of ignition probability of a flammable gas cloud and of flammable vapors is a fundamental step within a Quantitative Risk Assessment (QRA). The numerical quantification of these probabilities can substantially change the resulting scenarios and events likelihood assessment, and consequently the assessed level of risk. Calculation and modeling of ignition probabilities is frequently approached with very simple models, widely used despite the fact that the same authors often declared their methods as "highly speculative". A critical review on the commonly used data and methodologies reveals that, in most cases, these models are based on small data populations, highly localized, thus giving rise to doubts about their general applicability and validity. Moreover most methods lack capability of predicting differences between immediate and delayed ignition with a reasonable accuracy. On this basis, the focus of the present paper is to develop a more sophisticated framework, still simple and quick to apply, for calculating immediate and delayed ignition probabilities on a sounder manner than currently allowed by the "traditional" methods.

1. Introduction and background

Modeling of the ignition probability is a key step within the framework of risk assessment. A quite comprehensive summary description of the ignition probability models applied in modern Risk Analysis is provided by Lees (1996) and, more recently, by the Energy Institute (2006). In this paper we initially develop a critical review of the most significant and applied models, subsequently we develop a novel theoretical framework and finally we present an applicative case-study referred to a fictive process plant.

2. Theoretical background

In the earliest works, modeling of ignition probabilities tended to be based on small sets of incidents data, very case-specific, and sometimes heavily relying on at least "debatable" expert estimates. In the Eighties several methods were developed, and over the next decades they were fine-tuned, without any real breakthrough.

2.1 Cox method

Cox et al. (1990) estimated ignition probability for gases and liquids as a step-function of the leak flowrate, starting from the previous work of Kletz (1997) and on the basis of data from Dahl et al. (1983), providing the method which is most widely used in modern Risk Analysis. The method by Cox

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(Cox, 1990) is relatively easy and pragmatically quick to be applied, but it is also possibly lacking sensitiveness relevant to Plant-specific factors, and does not provide a way to distinguish between immediate ignition and delayed ignition. However, the method is based on statistical data too sparse to allow a conventional evaluation of confidence limits (Lees, 1996), so that it provides only a rather simple estimate of the probabilities of ignition and of following explosion scenario, as summarized in Table 1.

2.2 Energy Institute Method

The method proposed by the Energy Institute (2006) relies on concentric Areas structure around the release point where different ignition source types and densities exist. The ignition contributions from all the four considered areas are then combined to give the overall probability of ignition. The model requires basic information on the release and then a significant effort in defining the ignition characteristics of each area as well as in the dispersion modelling. By comparing, in selected cases, results with other methods, including Cox et al. (1990) and E&P Forum (1992), it can be evidenced a slight underestimation of the ignition probability for largest flow rates.

To simplify the method use, the authors developed 28 simple look-up correlations for assigning ignition probabilities in the framework of Quantitative Risk Assessments. These look-up correlations relate ignition probabilities to release rates for typical industrial scenarios both onshore and offshore. The correct correlation shall be selected for each application, and the method provides a "selection guide" according to the release type and release environment, listed in Table 2.10 of Energy Institute (2006).

These correlations provide a pragmatic approach for use in typical QRA studies, both offshore and onshore. In OGP (2010), the Energy Institute look-up correlations method is considered an advance with respect to other more simplified formulations relating only the release rate to the probability of ignition, and it is suggested as preferred method versus the more widely used Cox et al. (1990). On the negative side, it is worth remarking that the Energy Institute look-up correlations method gives poor indications on how to differentiate between early and delayed ignition.

2.3 Other Widely Used Methods

In E&P Forum Method (E&P Forum, 1992), the ignition probability of a flammable gas cloud is associated to the Cloud Volume and, eventually, to the release rate, by means of a direct correlation. In Simmons (Simmons, 1974) and other Aerial Methods (Spencer and Rew, 1997), Cloud Area is defined as a function of the distance from the ignition point, and the Ignition Probability is calculated from an error function of the Cloud Area based on statistical data.

2.4 Critical Review

The available models show a wide range of different approaches: most of the methods rely on relatively small data sets of accidental releases, highly site-specific, and are heavily based on the analyst expert judgment. Despite their specificity to particular cases, the inferred methods are extensively used also in different context, with consequent hazardous underestimation, or conservative overestimation of the ignition probability, depending on the selection of the approach.

The mathematical framework of ignition probability models has developed from early years to sophisticated approaches such as the one by Energy Institute (2006), which embeds in the model not only the release rate or the size of the released mass but also, through the use of proper look-up correlations, the nature of the released fluid and the plant layout. However, the available models are still affected by a large degree of uncertainty (which can be pragmatically reduced only by wider peer review and testing) and nearly all of them lack capabilities of predicting differences from immediate/early ignition to delayed ignition probabilities. This specific aspect will be extensively discussed in the next chapter.

3. A Framework for Calculating Immediate and Delayed ignition probabilities

Starting from the overall ignition probabilities calculated with a reliable existing method e.g. (Energy Institute, 2006), it is proposed to consider selected parameters of the release scenario and of the plant area affected by the release dispersion to evaluate, respectively, the fraction of the overall probability that contribute to immediate ignition, and the fraction that shall contribute to delayed ignition.

Table 1: Estimated Probability of Ignition for Leaks of Flammable Fluids (Cox et al., 1990)

Leak Size	Probability of ignition		Probability of explosion given ignition
	Gas	Liquid	
Minor (≤ 1 kg/s)	0.01	0.01	0.04
Major (1-50 kg/s)	0.07	0.03	0.12
Massive (≥ 50 kg/s)	0.3	0.08	0.3

Table 2: Minimum Immediate Ignition Probability (Low Fluid Temperature)

Substance Group	$T_R \leq (T_{AI} - 27\ °C)$		
	P ≤ 2 barg	2 barg > P > 50 barg	P ≥ 50 barg
IIA	5 %	10 %	20 %
IIB	10 %	20 %	30 %
IIC	20 %	30 %	40 %

Table 3: Minimum Immediate Ignition Probability (Medium Fluid Temperature)

Substance Group	$(T_{AI} - 27\ °C) < T_R < (T_{AI} + 27\ °C)$		
	P ≤ 2 barg	2 barg > P > 50 barg	P ≥ 50 barg
IIA	60 %	70 %	80 %
IIB	70 %	80 %	90 %
IIC	80 %	90 %	95 %

We consider three different contributors to the overall ignition probability, namely: (1) the “Minimum Probability of Immediate Ignition”, calculated on the basis of conditions of the processed fluid at the release point (temperature, pressure and fluid properties); (2) the “Maximum Delayed ignition Probability”, connected to the density and properties of the ignition sources potentially engulfed by the dispersed release; (3) the “Residual Probability”, a variable contribution.

3.1 Minimum Immediate Ignition Probability

The Minimum Probability of Immediate Ignition is a percentage of the Overall Probability of Ignition, calculated on the basis of the released substance properties (the "Substance Group") and of the processed Fluid Temperature and Pressure.

The Substance Group of the released substance can be of Type IIA, IIB or IIC. This property is related to the minimum ignition energy required to ignite the substance and represents the fluid tendency to ignite. Each substance is assigned a value based on CEI 31-35 (CEI, 2007).

The Fluid Temperature at Release (T_R) is classified according to three ranges (low, medium and high), on the basis of its difference from the Fluid Auto-Ignition Temperature (T_{AI}). As suggested in API 581 (API, 2000), when the processed fluid temperature is at least 27 °C higher than the Auto-Ignition temperature of the substance, 100 % of the Overall Ignition Probability contributes to the Minimum Immediate Ignition Probability. For other cases, the values shown in Table 2 and Table 3 apply.

The processed Fluid Pressure at release influences the orifice exit velocity and the kinetic energy that can be converted to heat by friction. High release pressures lead to larger energies and therefore to higher Immediate Ignition probabilities.

3.2 Maximum Delayed Ignition Probability

The Maximum Delayed Ignition Probability (C_R) is a fraction of the difference between the Overall Probability of Ignition and the Minimum Immediate Ignition Probability. This parameter is modeled by equation (1) on the basis of the potential ignition sources that can be engulfed by the dispersed flammable cloud.

$$C_R = Max\left[\varepsilon_i \cdot P_{pi} \cdot P_{di}\right]_{i=1}^{N} \tag{1}$$

ε_i is the Efficiency of the "i"-th ignition source engulfed by the dispersed flammable cloud;

P_{pi} is the presence factor over a year time of the of the "i"-th ignition source (days of presence/365);
P_{di} is the directional factor on the 360° full rotation of the "i"-th ignition source. It depends on the mutual position of the release point and of the ignition source, and it can consider prevalent wind direction. For point sources in a specific position its default value is 0.25 (single quadrant).
N is the overall number of different ignition sources (with different efficiency, presence or position) reached by the flammable cloud (or the average density of ignition sources, for homogeneous areas).

Efficiency ε for different fluids depends on the type of ignition source and its "strength". Spencer and Rew (1997) identify 6 categories of Ignition Strength ranging from Negligible Ignition Potential to Certain Ignition Potential (potential=1). Free flames are typically associated with "Certain" ignition potential, and other examples of ignition sources are associated to other potentials. Based on the Source Strength and the Substance Group (the fluid tendency to ignite), Efficiency factors have been defined, as reported in Table 4.

In API 2216 (API, 1991) it is suggested that hot surfaces (even without sparks or free flames) can be considered efficient in the ignition of a flammable mixture, granted that the Surface Temperature (T_S) exceeds the Auto-Ignition temperature (T_{AI}) of the substance. When T_S exceed T_{AI} by more than 105 °C, Efficiency is considered 100 %, as reported in Table 5.

3.3 Residual Probability

if the sum (Minimum Immediate Ignition Probability + Maximum Delayed Ignition Probability), calculated as described at Paragraphs 3.1 and 3.2, is lower than the Overall Ignition Probability, then the difference to reach overall (Residual Probability) shall be added to the Minimum Immediate Ignition Probability.

4. Applicative case-study

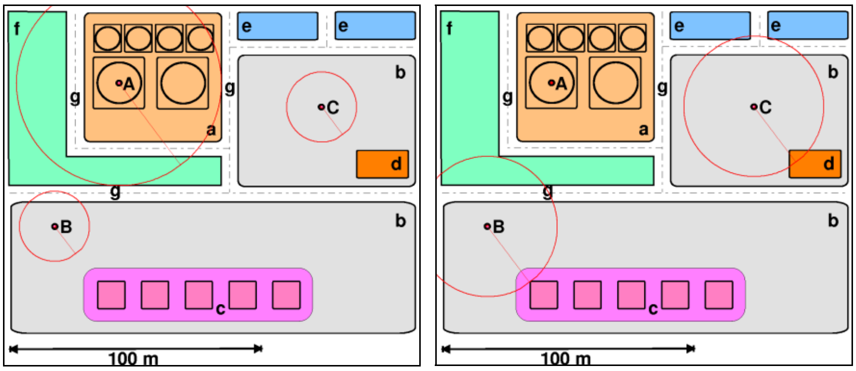
In order to verify the application of the method, a fictive industrial facility was set-up, as shown in Figure 1. The facility has been modelled in order to represent a variety of potential ignition sources, and was tested for different release scenarios with different fluids, different operating conditions and in different locations. The summary description of the Cases analyzed is reported in Table 6; each of the presented cases was analyzed for two release scenarios (equivalent hole size of 25 mm and equivalent hole size of 100 mm). To model the release and the consequent flammable gases and vapors dispersion the PHAST Package release 6.54 was used (DNV, 2007), in a 2F meteorological condition (wind speed 2 m/s, Pasquill Stability Class F). Gas releases have been modelled as turbulent free jets at 45° from horizontal. Liquid releases as horizontal. Release and Dispersion results are reported in Table 7. Interference of dispersed flammable clouds with facility areas are shown in Figure 1 for selected scenarios. Distances to dispersion levels are calculated and plotted for the LFL/2 concentration at a maximum height from ground of 20 m.

Table 4: Efficiency Factor for different Ignition Sources generating potential sparks

Substance Group	Ignition Source Strength				
	Certain	Strong	Medium	Weak	Negligible
IIA	1	0.60	0.05	0.01	0
IIB	1	0.75	0.27	0.025	0
IIC	1	0.90	0.50	0.04	0

Table 5: Efficiency Factor for Hot Surfaces

Temperature	Efficiency Factor Value
$T_S < T_{AI}$	$\varepsilon = 0$
$T_{AI} \leq T_S \leq (T_{AI} + 105\ °C)$	$\varepsilon = 0.5$
$T_S > (T_{AI} + 105\ °C)$	$\varepsilon = 1$



Plot of LFL/2 distance
Scenarios A1, B1, C1 - 100 mm leak size

Plot of LFL/2 distance
Scenarios B3, C3 - 100 mm leak size

● Release Point (A, B, C)

Area of Plant	**Source Strength (ε)**
a. Tank Farm	0.01
b. General Process Area	0.05
c. Area with hot surfaces	0.6
d. Area with free flames	1
e. Building	0.01
f. Free Field	0
g. Road	0.05

Figure 1: Fictive Plant used in Application & Plot of selected scenario's Dispersion (Flammable Clouds)

The Ignition Probability for immediate and delayed ignition has been assessed with the proposed method, starting from the overall ignition probability calculated with the Look-up correlations No. 5 (cases B and C) and No 7 (Case A) reported in Energy Institute (2006), and then applying the procedure described at Chapter 3. For Comparison, the Probability of ignition was also calculated with the classic method by Cox. Results from the three methodologies – look-up correlations by Energy Institute (2006) and Cox et al. (1990), and the proposed method are compared in Table 8.
Results from the proposed method are evidently following the expected trends, and are very consistent with the other methods values, as it was expected. A clear differentiation of the immediate and delayed ignition probabilities has been obtained, and the values are consistent with the distribution of ignition sources in the fictive plant used for the application. The actual validity of the numerical values shall be however tested and benchmarked against known data, for validation.

5. Conclusions

The existing approaches to Ignition Probability modelling show large uncertainties in their application, and somehow lack capabilities which are essential in Risk Analysis, such as the possibility to differentiate between immediate and delayed ignition. We proposed a framework for a more sophisticated method, based on more rigorous appraisal of the released fluids properties, releases conditions, presence and characteristics of ignition sources. The method was tested on a fictive industrial facility on typical release scenarios, calculating immediate and delayed ignition probabilities and comparing results with the application of main "traditional" methods. Results show a robust ability to differentiate among scenarios of immediate and delayed ignition. The proposed approach still lacks testing and validation on real applications, and to this end we are currently investigating these items more rigorously.

Table 6: Summary Description of Application Release Cases

Case	Description	Group	Conditions at Release	
			T (°C)	P (barg)
A1	Release of liquid Iso-Octane from bunded Tank	IIA	25	1.5
B1	Release of Methane from Process Area	IIA	100	1.5
B2	Release of Methane from Process Area	IIA	100	30
B3	Release of Methane from Process Area	IIA	100	55
C1	Release of Methane from Process Area	IIA	100	1.5
C2	Release of Methane from Process Area	IIA	100	30
C3	Release of Methane from Process Area	IIA	100	55

Table 7: Summary Release and Dispersion Results from PHAST 6.54 (DNV, 2007)

Case	Release Rate (kg/s)		Distance (m) to LFL/2 concentration (below 20 m height)	
	25 mm leak size	100 mm leak size	25 mm leak size	100 mm leak size
A1	5	76	19	41
B1	< 1	2.5	< 5	14
B2	2	34	14	27
B3	4	61	16	28
C1	< 1	2.5	< 5	14
C2	2	34	14	27
C3	4	61	16	28

Table 8: Classic methods and Proposed Method results comparison for all scenarios and leak sizes

Case	Cox et al., 1990 Overall Ignition Probability (-)		Energy Institute, 2006 Overall Ignition Probability (-)		Proposed Method Immediate Ignition Probability (-)		Proposed Method Delayed Ignition Probability (-)	
	25 mm	100 mm	25 mm	100 mm	25 mm	100 mm	25 mm	100 mm
A1	0.03	0.08	0.008	0.08	0.00762	0.0762	0.00038	0.0038
B1	0.01	0.07	0.001	0.01	0.00095	0.0095	0.0000475	0.000475
B2	0.07	0.07	0.008	0.08	0.00764	0.0368	0.00036	0.0432
B3	0.07	0.3	0.017	0.129	0.01632	0.0671	0.00068	0.06192
C1	0.01	0.07	0.001	0.01	0.00095	0.0095	0.0000475	0.000475
C2	0.07	0.07	0.008	0.08	0.00764	0.0080	0.00036	0.072
C3	0.07	0.3	0.017	0.129	0.01632	0.0258	0.00068	0.1032

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