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Benefits of Time Dependent Ignition Probability Models within the Framework of Quantitative Risk Analysis

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The evaluation of ignition probabilities is a fundamental step within the calculation of hazardous phenomena frequencies associated to a loss of containment of a flammable product (explosion, pool fire, jet fire). An error on this step can substantially change quantitative risk analysis conclusions.

It is important to keep in mind that quantitative risk analysis are increasingly used to design facilities. In other words, facilities (equipment, structures and buildings) are designed to withstand accidental loads up to down a certain frequency. Three main approaches are commonly used for ignition probabilities calculation: tabulated values from databases, semi-quantitative methods or more or less sophisticated mathematical models.

Nowadays, time dependent models are implemented to predict the evolution of the ignition probability as function of time. These models are particularly useful when combined with Computational Fluid Dynamics (CFD) calculations to provide flammable gas volume build up as function of time. Thus, it is possible to predict the evolution of the delayed ignition probability as function of time. Main interest of these models is to propose a discretization by time intervals of the delayed ignition probability. This approach is particularly relevant for performing explosion risk analysis.

1. Introduction

To take into account ignition probabilities within the calculation of hazardous phenomena frequencies, a flat-rate approach consists to apply a single ignition probability to different flammable volumes. This probability is generally associated with the maximum observed volume over the flammable cloud persistence time. However, for short duration leakage (isolated by a mitigation system or leak with a limited inventory), the maximum volume is not present over the entire persistence time. The use of a time dependent ignition model coupled with CFD gas dispersion results allows to define a range of potential explosion scenarios with different criticality levels and thus to refine conclusions in terms of risk rating and / or to define design constraints more precisely.

In this paper, after a brief review of the most significant approaches to estimate ignition probabilities, an applicative case-study referred to a fictive process unit is presented. For this case, benefits of applying an ignition time dependent model will be highlighted.

2. Theoretical background

2.1 Immediate ignition versus delayed ignition

In an industrial plant, there are many possible sources of ignition including electrical sparks, static electricity, naked flames, hot surfaces, etc. Following a loss of containment of flammable product (for example after a piping rupture), three outcomes must be considered:

- Ignition occurs immediately, commonly known as immediate ignition or prompt ignition;
- Ignition occurs in a delayed time, commonly known as delayed or differed ignition;
- The flammable cloud is not ignited.

Immediate and delayed ignition must be distinguished because leading to different hazardous phenomena. For example, consequently to a flammable gas release, immediate ignition will tend to give rise to a jet fire

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whilst delayed ignition will lead to an explosion or flash fire, depending on the degree of congestion. So, knowledge of the overall ignition probability is insufficient. Hence, each contributor to the overall ignition probability must be estimated. The overall ignition probability can be assessed using the following equation (1):

$$P_I = P_{IM} + (1 - P_{IM}) \times P_{DEL} \tag{1}$$

With:
P_I : overall ignition probability
P_{IM} : immediate ignition probability
P_{DEL} : delayed ignition probability

2.2 Approaches to estimate ignition probabilities

Ignition probabilities can be assessed with two main approaches:

- Values extracted from databases;
- Mathematical models (more or less sophisticated).

The use of values from databases is the simplest and quickest way to estimate ignition probabilities. However, sometimes, there may remain some doubts about their applicability and validity. Indeed, these values are commonly based on small data populations or heavily based on expert judgment. Otherwise, a large number of assumptions are implicit. In a great part of databases, it is worth noticing that it is difficult to establish a clear differentiation of the immediate and delayed ignition probabilities. The value is generally an overall ignition probability. So, the analyst must introduce an additional assumption by applying a flat-rate split between immediate and delayed ignition. The most commonly apportionments are:
50% for immediate and 50% for delayed;
30% for immediate and 70% for delayed.

The review of mathematical models reveals a wide range of different approaches. Two famous models which are most widely used in quantitative risk analysis are proposed by:
Cox et al. (1990): model for gases and liquids, the ignition probability is simply related to the leak flowrate;
Energy Institute (2006): 28 simple look-up correlations were developed for typical onshore and offshore modules giving ignition probability as function of the leak flow rate. A full model is also available based on four concentric areas around the release point (which could be reached by any flammable cloud) with different ignition source types, densities and intensities.

2.3 Time Dependent Ignition Model

When flammable gas is dispersed, the flammable volume builds up. During the growth phase, the cloud will come into contact with different ignition sources. Depending on their location, the flammable cloud could be ignited at different time and their contact time with the dispersed flammable cloud will be different. Indeed, sources quickly engulfed by the cloud staying in contact more longer.

Following the detection, for example by safety systems such as gas detection, it is possible to remove some ignition sources (example: shutdown of pumps or compressors). If this type of strategy is deployed quickly enough, a reduction of the ignition probability can be expected.

It was recognised that it is often impossible to design assets or buildings against the worst-case overpressure. The overpressure is sensitive to the size of the ignited flammable cloud. Thus, it is necessary to be able to predict the probability of ignition at different time and not only the overall ignition probability.

The first initiative to develop a methodology for the prediction of the ignition probability versus time was conducted through a joint industry project (DNV/Scandpower AS, 1999). This model, for offshore application, was developed by incorporating:

- Two different types of ignition sources reflecting operational modes: continuous and discrete sources.
- Different ignition sources: electrical equipment, pumps, compressors, personnel, hot work, etc.
- The effect of the shutdown of ignition sources.

More recently, new researches have been conducted to develop a new time dependent ignition model for potential ignition sources located in offshore oil and gas installations named MISOF (2016), which is short for Modelling of Ignition Sources on Offshore oil and gas Facilities. This model was calibrated for installations located in the North Sea.

3. Modelling of ignition versus time

3.1 Proposed model

Nowadays, with the “democratization” of dispersion calculations with CFD software, evolution of the flammable volume versus time can be easily modelled. In the model described hereafter, two outputs of FLACS® software are used to predict the ignition probability versus time:

- The flammable volume (FLAM);
- The new flammable volume (Q6).

In the proposed model, the ignition probability calculation is performed as integration in time. The both types of ignition sources (continuous and discrete) are combined with the FLACS® outputs as shown in the following equation (2):

$$P_{ign}(\Delta t)=\int_{t1}^{t2}\left[\left(\sum_{i=1}^{n} Ic_i^v \times Q6(t)\right).dt\right]+\int_{t1}^{t2}\left[\left(\sum_{j=1}^{m} Id_j^v \times FLAM(t)\right).dt\right] \tag{2}$$

With :

FLAM(t): Flammable volume at time t (m^3)

Q6(t): New flammable volume at time t (m^3/s)

Ic^v_i: Volume ignition intensities for continuous sources ($/m^3$)

Id^v_j: Volume ignition intensities for discrete sources ($/m^3.s$)

Continuous sources are permanently present and could ignite a flammable cloud as soon as it reaches the source. In the proposed model, these sources are therefore associated with the new flammable volume. Discrete ignition sources may occur randomly in time and could ignite a flammable cloud at any moment. In the proposed model, these sources are therefore associated with the flammable volume.

Considering the ignition source intensities extracted from the Guidelines for use of JIP Ignition Model (Table 1) and a volume of reference (V_{REF}), volume ignition sources intensities could be calculated. The volume V_{REF} represents the volume which could be exposed to the flammable cloud.

Table 1: Ignition source intensities

Ignition source	Discrete sources	Continuous sources
Electrical equipment	2.70E-08/m^2.s	2.60E-06/m^2
Pump	2.10E-07/pump.s	9.60E-05/pump
Compressor	5.10E-06/compressor.s	2.30E-03/compressor
Other equipment	2.10E-09/m^2.s	2.60E-06/m^2
Other	1.70E-08/m^2.s	1.30E-06/m^2
Personnel	4.00E-08/m^2.s	3.00E-06/m^2

3.2 Applicative case study

The model described paragraph 3.1 was applied on a fictive process unit composed of three levels (three floors marked in yellow on Figure 1), four pumps and three compressors.

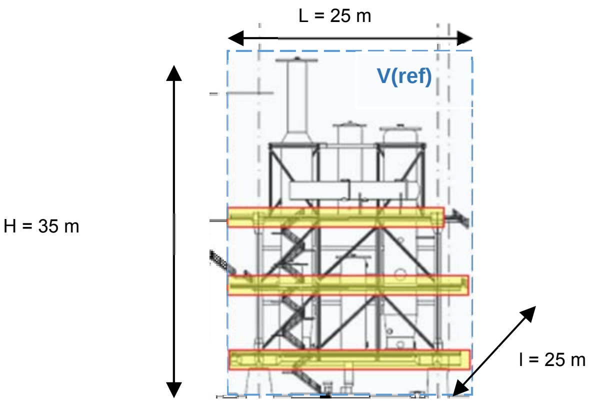

Figure 1: Unit’s sizes

In this unit, dispersion associated with a major flammable gas leakage scenario (flow rate around 200 kg/s) was modelled. Both evolutions of the flammable volume and the new flammable volume obtained using a CFD modelling (via FLACS®) are presented in Figure 2. For the purposes of this example, the dispersion was deliberately stopped after 190 s.

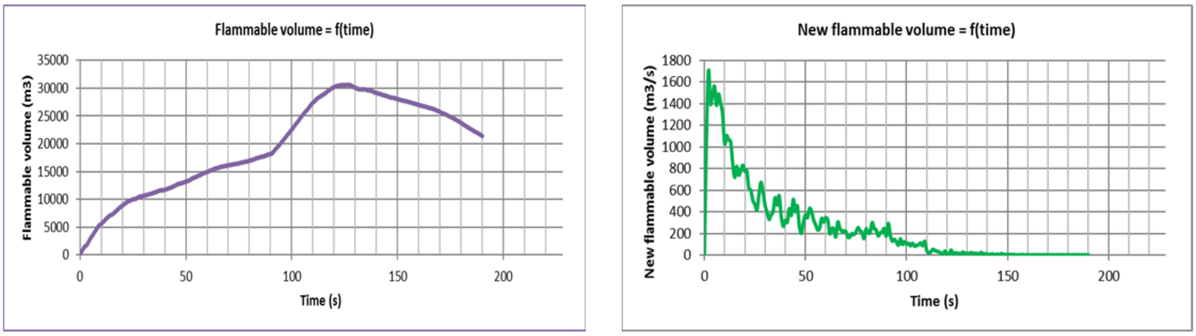

Figure 2 : Flammable volume and new flammable versus time

Considering unit's sizes, values for volume ignition intensities for continuous and discrete sources are presented in Table 2. Except for the "Other" category, for which only one floor area is considered (assumption in accordance with the Guidelines for use of JIP Ignition Model (1998)), other sources are considered to be present on the three floor areas.

Table 2: Volume ignition intensities for continuous and discrete sources

Ignition source	Number of equipment or surface (m²)	Ic^v (/m^3)	Id^v (/m^3.s)
Electrical equipment	1875	2.23E-07	2.31E-09
Pump	4	1.76E-08	3.84E-11
Compressor	3	3.15E-07	6.99E-10
Other equipment	1875	2.23E-07	1.80E-10
Other	625	3.71E-08	4.86E-10
Personnel	1875	2.57E-07	3.43E-09

Figure 3 shows the development of the cumulative delayed ignition probability versus time, obtained by applying equation (2), distinguishing the contribution for both types of ignition sources (continuous and discrete).

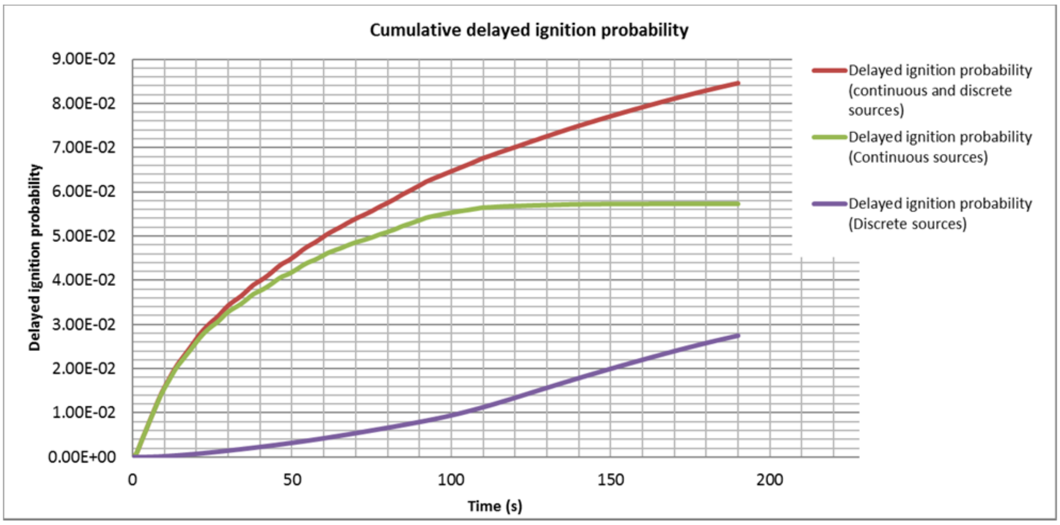

Figure 3: Delayed ignition probability versus time

As can be seen from Figure 3, the probability that the cloud ignites is equal to 8.5E-02 (at t = 190 s).
The maximum flammable volume observed over the persistence time of the cloud considered (t = 190 s) is around 30 000 m^3 for a unit of 21875 m^3. Above 100 s, the flammable cloud completely fills the unit. If only one explosion scenario was assessed, the maximum flammable volume should be considered with a probability of 8.5E-02. As argued above, this approach sounds very conservative because the unit is progressively engulfed by the cloud (as shown in Figure 2 by the flammable volume evolution versus time).
In order to refine results, the ignition probability can be discretized by time intervals as shown in Table 3.

Table 3: Discretization of the ignition probability by time intervals

t1(s)	t2(s)	PDEL	FLAM(t1) (m^3)	FLAM(t2) (m^3)	% of unit volume filled at t2
0	50	4.51E-02	0	13212	60
50	100	1.96E-02	13212	22556	100
100	130	7.93E-03	22556	30128	100
130	190	1.20E-02	30128	21404	97

Regarding results of Table 3, it would be relevant to consider two explosion scenarios. A first one, considering a flammable volume around 60% of the unit volume (observed at t = 50 s) and a second one, considering that the unit is entirely filled.
The cumulative delayed cumulative ignition probabilities associated to these scenarios are:

- 4.51E-02 for the first one;
- 3.96E-02 for the second one.

To highlight the interest to refine the analysis, overpressure distances for the both explosion scenarios were estimated using the Multi-Energy method by considering an explosion severity level of 6 (product: propane). Distances for commonly used thresholds depending on the considered flammable volume are presented in Table 4.

Table 4: Overpressure distances versus filled unit volume

Threshold (mbar)	Distance (m) FLAM = 13212 m^3 (60 % of the unit volume)	Distance (m) FLAM = 21850 m^3 (100 % of the unit volume)
500	37	44
200	122	144
140	162	192
50	398	471

As expected, the overpressure distances for the first scenario are lower than those of the second one. Hence, the proposed approach permits to minimize the probability allocated to the worth case scenario.

4. Conclusions

The presented model is based on CFD modelling and incorporate the most important ignition sources present on onshore and offshore facilities. It allows to test the influence of parameters on the ignition probability (such as unit size, ignition sources isolation, number of equipment). However, it is worth noticing that CFD modelling is valuable for existing facilities or when reliable inputs about design are available for the definition of the congestion levels. Hence, the proposed model turns out relevant for application in end of detailed engineering phase.
The model was tested on a fictive industrial facility. On a typical release scenario modelled with CFD software (FLACS ®), the delayed ignition probability was assessed. Results show the relevance and the benefits to take into account the development of the cumulative ignition probability versus time and not only a single value. Indeed, the modelling of ignition probability for different time intervals permits to split explosion scenarios and to reduce the probability allocated to the worth case. The event trees hereafter summarize results from the proposed model.
As shown in Figure 5, the proposed approach permits to reduce the frequency of the worth case explosion scenario by introducing a new scenario associated with a partial filling of the unit (60 % of the unit volume).
In the example previously provided, benefits of this approach include the increase of analysis accuracy (relevant recommendations to select explosion scenarios) and potential cost savings by designing facilities (equipment, structures) on hard data.

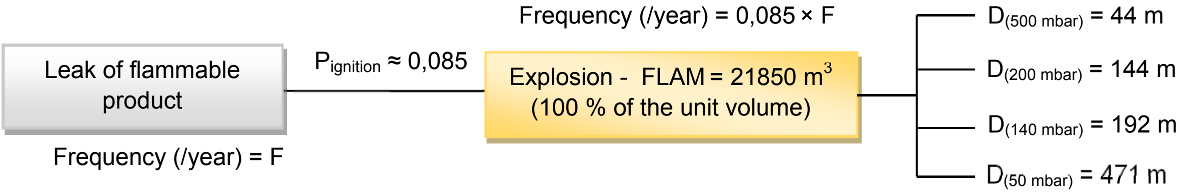

Figure 4 : Event tree without discretization of the ignition probability versus time

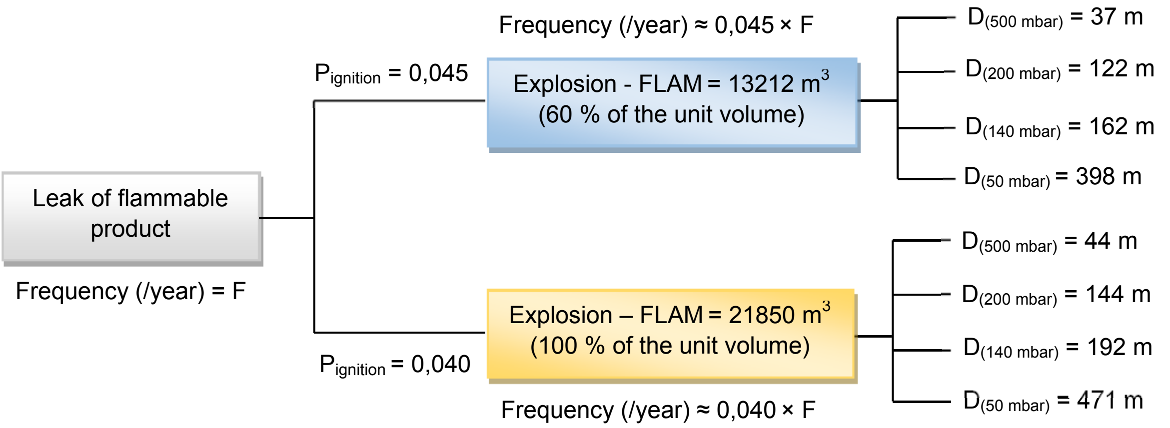

Figure 5 : Event tree with discretization of the ignition probability versus time

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