APPENDIX 12

Probabilistic aspects in the event tree

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1. Introduction

When the frequency of the critical event has been calculated from the fault tree or assessed from generic frequencies, the rough levels of probability for each branch of the event tree (which start from the critical event) must be evaluated in order to calculate the frequencies of dangerous phenomena.

So, the probabilities of transmission from the critical event to the dangerous phenomena, namely ignition probabilities, must be deeply investigated.

The probabilities studied in this appendix are the following ones:

- ✓ The *probability of immediate ignition*, which depends on the flammability of the substance, the source term, the presence of ignition sources around the equipment, the safety barriers to prevent the ignition (explosion proof area,…), …
- ✓ The *probability of delayed ignition*, which depends on the flammability of the substance, the source term, the direction in which the cloud disperses, the presence of ignition sources and the type of ignition sources inside the flammability limits of the cloud (function of meteorological conditions), the safety barriers to prevent the ignition (explosion proof area,…),…
- ✓ The *probability of VCE*, which depends on the obstruction of site in the direction in which the cloud will be dispersed. This probability is higher for a zone with strong obstruction.

It should be noted that prevention safety barriers in the event trees mainly influence the value of the ignition probabilities. These barriers will not be represented in the trees, but will serve qualitatively to estimate the ignition probabilities.

A bibliographic review on these probabilities has been realised. From values found in the literature, some orientations are given in order to assess the probabilities of ignition and VCE in the event tree according to the actual situation on site and the presence of safety barriers.

These orientations must not be used rigorously because the probabilities of ignition and of VCE depend on a lot of parameters. They can be used as basis for discussion.

2. Probability of immediate ignition

It can be the immediate ignition of a liquid or of a gas:

The immediate ignition of a liquid can occur in the case of:

- a pool from a continuous release of liquid or two-phase substance
- a pool from an instantaneous release of liquid or two-phase substance
- or a pool inside a tank

The immediate ignition of a gas can occur in the case of:

- a gas or two-phase jet
- or a gas or aerosol puff

2.1.1 PROBABILITY OF IMMEDIATE IGNITION OF A LIQUID

2.1.1.1 Data found in the literature

Purple Book [1]

Probability of immediate ignition for stationary installations

Source		***Substance***
Continuous (CE7, CE8)	*Instantaneous (CE10, CE11)*	*K1 - liquid*
< 10 kg/s	< 1000 kg	0.065
10 - 100 kg/s	1000 - 10000 kg	0.065
> 100 kg/s	> 10000 kg	0.065

Probability of immediate ignition for transport units in an establishment

Source	***Probability of immediate ignition***
Road tanker continuous (CE7, CE8)	0.1
Road tanker instantaneous (CE10, CE11)	0.4
Tank wagon continuous (CE7, CE8)	0.1
Tank wagon instantaneous (CE10, CE11)	0.8

HSE - Canvey report [2]

Source of ignition	***Probability of ignition***
None "None readily identifiable" e.g., limited release of liquid hydrocarbon into a bund after overfilling a tank.	0.1
Very few Large release of gas liquefied under pressure after catastrophic failure of a tank farm.	0.2

Source of ignition	***Probability of ignition***
Few Release of flammable material near to non-continuous operations, e.g. LPG release from a tank near to road/rail facilities.	0.5
Many Release of flammable material near to a plant or a release resulting from a nearby fire or explosion.	0.9

<u>SAI study (Canvey report)</u>

The SAI study covers 59 incidents involving small spills (typically a few Tons) of LPG and flammable liquids. The analysis concludes that there is a 0.9 probability that ignition of large spills will occur within a few hundred meters of the source of the release.

<u>MHIDAS [3]</u>

For the liquids, the probability of immediate ignition is equal to 0.74

According to the activity,

Activity	***Immediate ignition probability***
Process	0.85
Storage	0.73
Load/unload	0.67

<u>LEES [4]</u>

R.L. Browning (1969) has given a set of estimates of the relative probability of ignition. <u>For ignition under conditions of no obvious source of ignition and with explosion-proof electrical equipment he gives the following probabilities of ignition:</u>

	Relative probability of ignition
Massive LPG release	0.1
Flammable liquid with flashpoint below 43°C or with temperature above boiling punt	0.01
Flammable liquid with flashpoint 38 - 93°C	0.001

Canvey report

Leak	***Probability of ignition for a liquid***
Minor (< 1kg/s)	0.01
Major (1-50 kg/s)	0.03
Massive (> 50 kg/s)	0.08

SAFETI software

Probability of immediate ignition of a leak is equal to 0.3 per default.

2.1.1.2 Orientations

According to the values found in the literature, the following values can be proposed.

Case 1 (case the most unfavourable):

If around the equipment,

- ✓ the material is not "explosion proof" and the systems are not earthed
- ✓ and there is no retention pool,
- ✓ and there are no safety barriers to prevent the ignition (setting up and maintenance of "no smoking" areas, injection of foam,…)

the proposed value for the immediate ignition of a pool is **0.9** (maximum value found in the literature).

Case 2

If around the equipment,

- ✓ the material is "explosion proof" and the systems are earthed
- ✓ and there is no retention pool,
- ✓ and there are no safety barriers to prevent the ignition (setting up and maintenance of "no smoking" areas, injection of foam,...)

or

If around the equipment,

- ✓ the material is not "explosion proof" and the systems are not earthed
- ✓ and there is a retention pool
- ✓ and there are no safety barriers to prevent the ignition (setting up and maintenance of "no smoking" areas, foam injection,...)

or

If around the equipment,

- ✓ the material is not "explosion proof" and the systems are not earthed
- ✓ and there is no retention pool
- ✓ and there are safety barriers to prevent the ignition (setting up and maintenance of "no smoking" areas, foam injection,...)

the proposed value for the immediate ignition of a pool depends on the type of unit in which the equipment is installed.

Unit	*Immediate ignition probability*
Process	0.9
Storage	0.7
(Un)loading	0.7

Table 1: Probabilities of immediate ignition in different units

Commentaries:

For the **process** unit, the values found in the literature are:

0.9 HSE - Canvey report

0.85 Statistic study on the accident data from the MHIDAS database

Proposed value : **0.9** (there are a lot of possible ignition sources (hot pipes,…)

For the **storage** unit, the value found in the literature is:

0.73 Statistic study on the accident data from the MHIDAS database

Proposed value : **0.7**

For the **(un)loading** unit, the values found in the literature are:

0,4 (Road tanker); 0.8 (Tank wagon) Purple book

0.5 HSE -Canvey report

0.67 Statistic study on the accident data from the MHIDAS database

Proposed value : **0.7**

There are no distinction between a storage unit and an (un)loading unit. In the storage unit, the cause of ignition can be works done in the storage zone or other circumstances which provoke the leak and the ignition. In the (un)loading unit, the cause of ignition can be the thermal engines or circumstances which provoke the leak and the ignition.

Case 3 (case, the most favourable):

If around the equipment,

- ✓ the material is "explosion proof" and the systems are earthed
- ✓ and there is a retention pool,

- ✓ and there are safety barriers to prevent the ignition (setting up and maintenance of "no smoking" areas, quick foam injection,...)

the proposed value for the immediate ignition of a pool depends on the reactivity of the substance (in inspiring of values given by Browning (1969)).

Flammability	***Immediate ignition probability***
Flammable (R10: flashpoint between 21°C and 55°C)	0.01
Highly flammable (R11: flashpoint lower than 21°C)	0.1
Extremely flammable (R12: flashpoint lower than 0°C)	0.1

Table 2: Probability of immediate ignition according to the flammability of the substance

Between the maximal values of ignition probability when there are no safety barriers and the minimum values when everything is done in order to avoid and to prevent the ignition, the ignition probability of a pool depends on:

- The pool area.

  The larger is the pool area, the higher is the ignition probability (the probability to meet an ignition source is higher).

  The pool area depends on the leak rate for a continuous leak or on the released quantity for an instantaneous leak, depends on safety barriers put in (valve, diaphragm to limit the release rate, emergency isolation valve, retention pool,…)

- The energy necessary to ignite the substance.

  The lower is the energy necessary to ignite the substance, the higher is the ignition probability.

- The presence of ignition sources around the equipment

  The higher is the number of ignition sources, the higher is the ignition probability.

  The number of ignition sources depends on the type of unit in which the equipment is installed (e.g., in a process unit, the number of ignition sources is higher), and also on safety barriers put in. The prevention barriers of the ignition can be "Use of explosion-proof apparatus", "Use of earthed systems (to avoid the static electricity, the sparks,…)", "Setting up and maintenance of "no smoking" areas", "Prohibition of pumps and other electrical apparatus within the bunded areas of storage tanks (the pump should be located in its own containment area in case of leakage)",…

- The cause of the critical event

  If the cause of the critical event is tied to an energy source or a high temperature, the probability of immediate ignition will certainly be equal to 1.

  If the cause of the critical event is due to a hot work near the equipment, the probability of immediate ignition will certainly be equal to 1.

2.1.2 PROBABILITY OF IMMEDIATE IGNITION OF A GAS

2.1.2.1 Data found in the literature

Purple Book

Probability of immediate ignition for stationary installations

Source		***Substance***	
Continuous	*Instantaneous*	*Gas, low reactive*	*Gas, average/high reactive*
< 10 kg/s	< 1000 kg	0.02	0.2
10 - 100 kg/s	1000 - 10000 kg	0.04	0.5
> 100 kg/s	> 10000 kg	0.09	0.7

Probability of immediate ignition for transport units in an establishment

Source	***Probability of immediate ignition***
Road tanker continuous (CE7, CE8)	0.1
Road tanker instantaneous (CE10, CE11)	0.4
Tank wagon continuous (CE7, CE8)	0.1
Tank wagon instantaneous (CE10, CE11)	0.8

HSE - Canvey report

Source of ignition	***Probability of ignition***
None "None readily identifiable" e.g., limited release of liquid hydrocarbon into a bund after overfilling a tank.	0.1
Very few Large release of gas liquefied under pressure after catastrophic failure of a tank farm.	0.2

Source of ignition	***Probability of ignition***
Few Release of flammable material near to non-continuous operations, e.g. LPG release from a tank near to road/rail facilities.	0.5
Many Release of flammable material near to a plant or a release resulting from a nearby fire or explosion.	0.9

Wilson (Canvey report)

The ignition probability of cloud within a few hundred meters is less than 0.8.

There are insufficient data to support the view that large clouds are very unlikely to drift unignited off-site.

MHIDAS

For the gas, the probability of immediate ignition is equal to 0.766.
According to the activity,

Activity	***Immediate ignition probability***
Process	0.85
Storage	0.73
Load/unload	0.67

Canvey report

Leak	Probability of ignition for a gas
Minor (< 1kg/s)	0.01
Major (1-50 kg/s)	0.07
Massive (> 50 kg/s)	0.3

<u>EDF [5]</u>

	%		*% cumulated*
No ignition	5		
Not specified	21		
Periphery of the cloud	29	Periphery	39
Immediate nearby	45	Nearby	61

The ignition occurs at the place of the rupture or nearby (61%). The ignition at the periphery of the cloud is frequent (39%).

<u>SAFETI software</u>

Ignition probability of a horizontal jet = 0.4 (probability of a horizontal jet = 0.6)

Ignition probability of a vertical jet = 0.2

2.1.2.2 Orientations

In the literature, according to the size of the leak, the flammability of the substance (flammable, highly flammable, extremely flammable) and the equipment type where the leak occurs, the probability of an immediate ignition of a gas can vary from 0.01 to 0.8.

We have chosen to consider the values of "Purple Book" as reference. Indeed, when comparing the different source data, the scale of these values is plausible. Moreover, the data are given according to the reactivity of gas, for a continuous and an instantaneous release and for different ranges of flow rate.

Source		***Substance** [9]*	
Continuous (gas jet)	***Instantaneous (gas puff)***	***Gas, low reactive***	***Gas, average/high reactive***
< 10 kg/s	< 1000 kg	0.02	0.2
10 - 100 kg/s	1000 - 10000 kg	0.04	0.5
> 100 kg/s	> 10000 kg	0.09	0.7

Table 3: Probability of immediate ignition of a gas

There are other parameters which influence the probability of immediate ignition for a gas:

- The presence of ignition sources around the equipment

  The higher is the number of ignition sources, the higher is the ignition probability.

- The cause of the critical event

  If the cause of the critical event is tied to an energy source or a high temperature, the probability of immediate ignition will certainly be equal to 1.

3. Probability of delayed ignition of a gas dispersion

3.1 Data found in the literature

IPO [6]

Source of ignition	*Probability of delayed ignition*
Industrial site	0.9
Process installations	0.5
Road, N < 50 vehicles per hour (*)	0.5
Road, N > 50 vehicles per hour (*)	1

(*) The length of the road is set equal to 100m, the velocity of a vehicle to 50 km/h.

MHIDAS

Sources of ignition	*Probability of ignition*
Process	0.85
Storage	0.73
(Un)loading	0.67

Canvey report

The probability of ignition of a vapour cloud was taken as 0.1 or 1, depending on whether ignition was regarded as improbable or probable, taking into account the ignition sources between the point of release and the population group.

Canvey report

Ignition of a cloud in transit

Once an unignited cloud begins to disperse towards areas of population, there is still a chance of ignition prior to its reaching them. Again judgement values are used viz.:

Cloud passes over	*Ignition probability*
Open land	0
Industrial site	0.9

Ignition of a cloud over a population

Type of ignition	***Ignition probability***
Edge/edge: edge of unignited cloud just reaches edge of populated area when ignition occurs	0.7
Central: unignited cloud right over population when ignition occurs	0.2
Non-ignition	0.1

LPG study [8]

It was assumed that the probability of the dispersing cloud igniting is 0.5 when the edge of the cloud (i.e. the place at which its concentration corresponds to the lower explosion limit) comes into contact with a source of ignition.

In calculating the effects of the delayed ignition of a LPG cloud, the following alternatives have been considered:

- Ignition occurs fairly soon after the LPG escapes
- Ignition occurs when the explosive quantity is greatest
- Ignition occurs later (with account taken, inter alia of the maximum distance over which the cloud drifts)

3.2 Orientations

In the literature, the probabilities of delayed ignition are given by type of ignition source. According to the found values, the probability can vary from 0 (open land) to 1 (Road, with more than 50 vehicles per hour).

The following values can be proposed for the probability of delayed ignition of flammable gas dispersion according to a given area:

Sources of ignition	***Probability of delayed ignition***
Unit of combustion (furnace, flare,…)	1
Technical premises or remote-controlled boxes	1
Building no equipped with explosion proof devices and no submitted to the interdiction of open flame	1

Sources of ignition	***Probability of delayed ignition***	
Utility zone		
– With explosion-proof devices	0.5	
– With explosion-proof devices in all the zone	0.1	
– Without explosion-proof devices	1	
Habitation zone	1	
Construction site	1	
Neighbouring industrial site (distant from the leak)	0.9	
Process unit		
– With explosion-proof devices	0.8	
– With explosion-proof devices in all the zone	0.1	
– Without explosion-proof devices	1	
Storage unit		
– With explosion-proof devices	0.5	
– With explosion-proof devices in all the zone	0.1	
– Without explosion-proof devices	1	
(Un)loading unit	Day	Night (*)
– Lorry	0.7	0
– Wagon	0.6	0
– Ship	0.6	0
Parking and manoeuvre areas with vehicles with thermal engines	Day	Night
– Work with 1 shift	0.4	0.1
– Work with 2 shifts	0.8	0.2
– Work with 3 shifts	1	1
Roads with two lanes and more	1	

Sources of ignition	***Probability of delayed ignition***	
Roads with low size	Day: 0.6	Night: 0.2
Railway and tram	Day: 0.6	Night: 0.1

Table 4: Probability of ignition according to the ignition sources

(*) If there are no loading/unloading during the night

Commentaries:

- Utility zones are air cooler (the ventilators are equipped with engines), zones with pumps and/or compressors,…
- For the **process** units, the found values are the following ones:

  0.5 delayed ignition (reference: IPO)

  0.85 immediate ignition during a leak in a process zone (reference: MHIDAS)

  Value proposed : **0.8**

- For the **storage** units, the found value is the following one:

  0.73 immediate ignition during a leak in a storage zone (reference: MHIDAS)

It is probable that this high value is strongly dependent on the "immediate ignition" aspect. It involves that we are in the case of a leak in the storage zone and that the leak ignites immediately. These accidents are due to works done in the storage zone or other circumstances which provoke the leak and the ignition. But in the case of a delayed ignition, studied here, the probability must be lower because the leak does not occur always in the storage zone where it ignites. So there are fewer activities in the zone and the ignition probability is lower.

Value proposed : **0.5**

For the process units, the value is higher because there are more possible ignition sources (hot pipes,…)

- For the **(un)loading** units, the found values are the followings ones:

  0.67 immediate ignition during a leak in a process zone (reference: MHIDAS)

  Proposed value for the lorries (thermal engines): **0.7**

  Proposed value for the other transport means: **0.6**

During the night, the value can be zero if there are no loading/unloading.

For the **process, storage and (un)loading** units, the proposed value is equal to 0.1 if there are explosion - proof devices in the entire unit.

For the **process, storage and (un)loading** units, the proposed value is equal to 1 if there are no explosion - proof devices.

- For the roads, IPO proposes :

  0.5 if less than 50 vehicles per hour

  1 if more than 50 vehicles per hour

  Proposed values: 1 if road with two lanes or more, and 0.6 (day) or 0.2 (night) for the roads with low size.

To estimate the probability of delayed ignition, it is necessary to known the relative position of the flammable zone in order to determine the ignition sources covered by the flammable cloud.

This relative position of the flammable zone depends on:

- The released quantity of gas or the vaporised quantity of gas (source term)
- Meteorological conditions
- The direction of the wind

So, it is not possible to give a value for the delayed ignition because it depends on a lot of parameters, it will be determined on site.

4. Probability of a VCE

4.1 Data found in the literature

Rijnmond report [7]

	Probability of VCE
Low obstruction	0.1
Medium obstruction	0.5
Strong obstruction	2/3

Canvey report

The probability of explosion, i.e. overpressure in the vapour cloud, was taken as unit only for larger clouds (1000T), 0.1 for smaller clouds (cloud size 10-100T, (LNG 0.01)) and 0 for cloud size < 10T.

Probability of explosion of large LPG release (+/- 1000T) is 1 for a significant delay to ignition and 0.1 for rapid ignition.

LPG study [8]

Following an analysis of past accidents, TNO assumed the probability of a pressure wave occurring in addition to combustion to be 2/3.

LEES

Estimates of probability of explosion given ignition for leaks of flammable gas (A.W. Cox, Lees and Ang, 1990):

Leak	***Probability of explosion given ignition***
Minor (< 1kg/s)	0.04
Major (1-50 kg/s)	0.12
Massive (> 50 kg/s)	0.3

The table was adjusted to fit better to the historical data as the frequency of plant fires and vapour cloud explosions:

Leak	***Probability of explosion given ignition***
Minor (< 1kg/s)	0.025
Major (1-50 kg/s)	0.12
Massive (> 50 kg/s)	0.25

Kletz concludes that although it may not be correct to assume a threshold quantity, a minimum size of cloud below which an explosion will not occur, the probability of an explosion certainly appears to be much less if the quantity is small. He suggests that if there are 10t of vapour, the probability of explosion is at least 1 in 10, whereas there is 1t or less the probability of explosion is of the order of 1 in 100, or more likely, 1 in 1000.

Wiekema (1984) has carried out a statistical study on some 165 vapour cloud ignitions. Incidents were not included when no ignition occurred or when ignition was virtually simultaneous with the release, as in a BLEVE. In nearly 60% of these cases the ignition resulted in an explosion; in the other cases a flashfire occurred. The amount spilled did not influence the probability of an explosion in the spill range 1-100 t.

SAFETI software

The probability of a VCE is equal to 0.4 (default value).

4.2 Orientations

The probability of a VCE depends on the obstruction of the zone where the ignition occurs. This probability is higher for a zone with strong obstruction. So, the probability of a VCE depends on the direction in which the cloud will be dispersed.

When the delayed ignition occurs, the following values can be proposed for the probability of a VCE according to the obstruction of the zone where the cloud is flammable:

	Probability of a VCE (13)
Low obstruction	0.1
Medium obstruction	0.5
Strong obstruction	2/3

Table 5: Probability of VCE according to the obstruction

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