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Review of the event tree structure and ignition probabilities used in HSE's pipeline risk assessment code MISHAP

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Review of the event tree structure and ignition probabilities used in HSE's pipeline risk assessment code MISHAP

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The Health and Safety Executive (HSE) uses the MISHAP01 (Model for the estimation of Individual and Societal risk from HAzards of Pipelines) model to calculate the risks associated with Major Accident Hazard (MAH) pipelines in Great Britain. The risks calculated are used to determine the distances to land-use planning (LUP) zones around the MAH pipeline. The UK Onshore Pipeline Operators Association (UKOPA) has queried some of the assumptions and methods currently used within the tool and has compiled a briefing note outlying areas of concern. In response to the briefing note, HSE asked the Health and Safety Laboratory to review the MISHAP tool. The review examined the natural gas and non-natural gas event tree structures used by the tool as well as the probability values used to populate them. The review proposes replacing the generic natural gas and non-natural event trees with three event trees that take into account the minimum ignition energy of the substance and the substance reactivity. The derived event trees will feature in future versions of the MISHAP tool.

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HSE Books

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EXECUTIVE SUMMARY

At present the Health and Safety Executive (HSE) utilises the computer program MISHAP to calculate the level of risk around pipelines, particularly in land use planning (LUP) assessments. However, UKOPA (UK Onshore Pipeline Operators Association) has questioned some of the principles the tool is based on as it regards current procedures as lacking in transparency as well as following an illogical approach though little scientific evidence was presented to support this viewpoint. In particular, the event trees and probabilities within MISHAP were highlighted.

To present its concerns, UKOPA compiled a briefing note[a] where ethylene and propane were used as exemplar substances for non-natural gas. However, the majority of UKOPA's assumptions in the note were based on the original HSE event trees and then amended to suit, rather than using the most up to date knowledge and experience to create new values. This investigation mainly covers natural gas and ethylene pipelines as a basis for comparison with some reference to propane and other materials.

Overall, this project is part of a larger project, outlined in the "Pipeline RISKAT – Project Brief", which aims to improve the current MISHAP based pipeline risk assessment methodology. The project brief should be referred to for further explanation.

Objectives

The objectives of this study were to:

- Review the basis of the event tree structure for non-natural gas;
- Review the basis of the probabilities used in the non-natural gas event tree;
- Review the comments raised by UKOPA in relation to the non-natural gas event tree; and
- Make recommendations for changes (if required) to the event tree structure and probabilities for non-natural gas.

Main Findings

- The MISHAP event tree structure appears to be well founded, as all suitable event sequences and most final scenarios have been included. The inclusion of Vapour Cloud Explosions (VCEs) may be required at a later date due to the implication from the events at Buncefield;
- The probability values used in the MISHAP event tree were based on the best judgment available at the time but there is limited documented supporting evidence from HSE;
- UKOPA has put forward a number of reasonable arguments for changing HSE's non-natural gas event tree, but no detailed written supporting evidence has been provided;

[a] *McConnell R A, UKOPA Briefing Note HSE Issue 07 – HSE Event Trees for Non-Natural Gas Major Accident Hazard Pipeline, 22nd April 2007*

- Using properties such as the minimum ignition energy to construct event trees was considered suitable, though users should bear in mind that the minimum ignition energy can vary from site to site;

- It is accepted that the probability of an obstructed (or unobstructed) release is not substance dependent, so the probability values should be the same for natural and non-natural gas. A value of 0.63 was identified from literature, rather than UKOPA's proposed value of 0.8. Note that changing this value does not affect the overall ignition probability or the totals for each scenario for the current natural gas event tree, though it does have an impact on the non-natural gas event tree by increasing the overall ignition probability compared to the tree proposed by UKOPA;

- There was little evidence to suggest why the value for delayed local ignition of obstructed non-natural gas releases was set to 0, though using this setting converts the MISHAP event tree to the earlier PRAM event tree, which has been used to model ethylene in the past. It could be a precautionary decision made by HSE for conservatism, but there is no corroborating evidence;

- Due to the difference in minimum ignition energies, it is accepted that as ethylene is twice as likely as methane to ignite, the unobstructed, delayed local ignition event probability should be twice that of methane. This assumption cannot be applied to immediate ignition as during this period, the release rate is higher and there are other factors (e.g. stoichiometry of the fuel/air mixture, temperature etc) present which can greatly influence the ignition probability. A value of 0.35 for immediate ignition probability was applied for substances with a similar flammability to ethylene. For substances not grouped with ethylene it is assumed that the immediate ignition probability is the same as the delayed local ignition probability until better evidence can be found;

- Literature relating directly to pipelines was not available in some cases so other relevant literature was used as support. This is particularly the case for natural gas where appropriate offshore data were used. On the whole, the review identified overall ignition probabilities which are comparable to the values proposed, though further evidence would be preferable;

- Rather than representing all non-natural gas materials with the same event tree, as is current practice, the idea of using physical properties was expanded upon to include the flammability (by way of risk phrases), as this is also a measure of the ease of ignitability;

- Based on the literature, physical properties such as minimum ignition energy and flammability as well as some judgement, three new event trees have been constructed:

    - Event tree 1 – R12 materials with a minimum ignition energy < 0.22 mJ;

    - Event tree 2 – R12 materials with a minimum ignition energy ≥ 0.22 mJ;

    - Event tree 3 – natural gas and other buoyant materials. R11 and low reactivity materials are also appropriate provided the delayed remote ignition probability is amended to suit.

Recommendations

The recommendations are:

- The unobstructed release probability should be independent of the material released. A value of 0.63 has been derived in this report based on recent work by HSL;
- To use a set of event trees based on physical properties such as minimum ignition energy and flammability;
- Further work is required to determine if VCE should be included as an event, and what the implications would be;
- Sensitivity studies should be carried out to identify the implications, in terms of hazard footprints and risk, from moving from two event trees to three;
- Further validation by experiment or analysis of historical data would be useful for completeness. This could include small scale experiments using common MISHAP materials, e.g. natural gas and ethylene, and performing immediate, delayed local and delayed remote ignition trials as well as obstructed releases, to try to compare the theoretical values proposed here with practical results. However, it is appreciated that any experimental set up would be complicated and costly to run; and
- The event trees should be made available to industry for comment.

1 INTRODUCTION

At present the Health and Safety Executive (HSE) utilises the computer program MISHAP to calculate the level of risk around pipelines, particularly in land use planning (LUP) assessments. However, UKOPA (UK Onshore Pipeline Operators Association) has questioned some of the principles the tool is based on as it regards current procedures as lacking in transparency as well as following an illogical approach [2] though little scientific evidence was presented to support this viewpoint. In particular, the event trees and probabilities within MISHAP were highlighted.

The main concerns UKOPA has relate to the ignition probabilities used within MISHAP, as well as the event tree sequences. Currently, the MISHAP event tree is based on windspeed, ignition and obstructed release probabilities and, depending on which branch is followed through the event tree, different resulting events are possible such as fireballs and jet fires etc.

HSE requested the Health & Safety Laboratory (HSL) to review the basis of the non-natural gas event tree in MISHAP, taking into account the comments and concerns raised by UKOPA. The focus of the investigation was on the non-natural gas event trees, but also included examination of the natural gas event trees as a comparison where appropriate. Overall, the objectives were to:

- Review the basis of the event tree structure for non-natural gas;
- Review the basis of the probabilities used in the non-natural gas event tree;
- Review the comments raised by UKOPA in relation to the non-natural gas event tree; and
- Make recommendations for changes (if required) to the event tree structure and probabilities for non-natural gas.

This project is part of a larger project, outlined in the "Pipeline RISKAT – Project Brief" [1], which aims to improve the current MISHAP based pipeline risk assessment methodology. The project brief should be referred to for further explanations.

The remainder of the report is structured as:

- Section 2 discusses the concerns [2] UKOPA has with the event trees and probabilities used in HSE's current pipeline risk assessment approach;
- Section 3 assesses the appropriateness of the current HSE event tree, in terms of structure and possible outcomes;
- Section 4 summarises the results from a literature search;
- Section 5 compares the MISHAP event tree probabilities with UKOPA's proposed values and also those found in the literature to check for commonality;
- Section 6 presents the proposed event trees. An in depth discussion of why they were chosen as well as supporting evidence is also given; and
- Section 7 presents overall conclusions and recommendations.

This report has been reformatted for public viewing, but no changes to the results or conclusions have occurred.

2 UKOPA CONCERNS REGARDING THE HSE METHOD

This section discusses the current HSE method and highlights the areas in which UKOPA has concerns, i.e. the probability values and the non-natural gas event tree structure.

2.1 CURRENT HSE METHOD

At present, the MISHAP code used by HSE contains default event trees for both natural and non-natural gas, as illustrated in Figures 1 and 2 respectively; the depicted values are the default event tree probabilities.

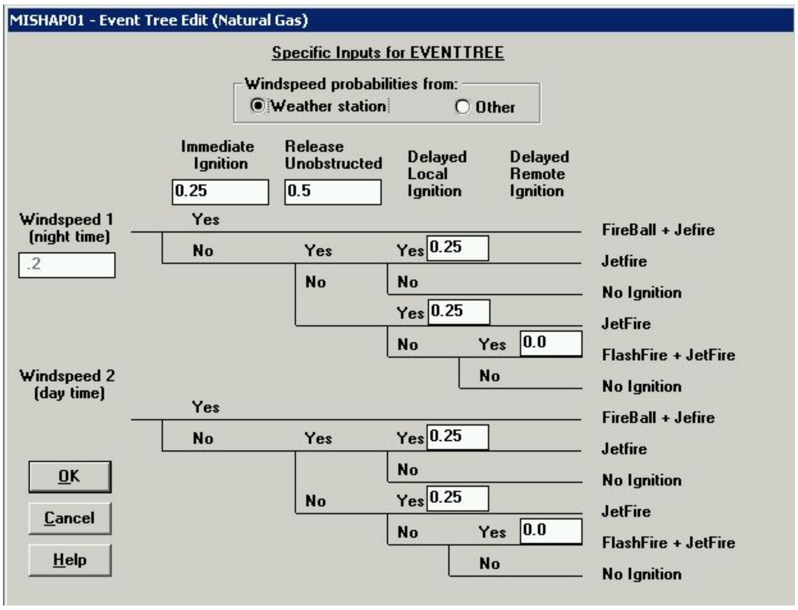

Figure 1 MISHAP natural gas event tree

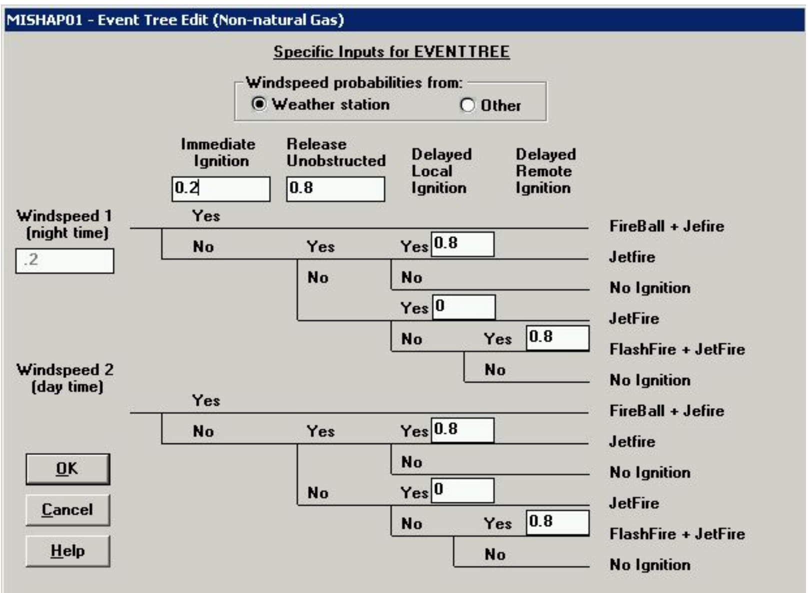

Figure 2 MISHAP non-natural gas event tree

HSE's Major Hazard Assessment Unit (MHAU) (now HID CI5) originally developed two similar pipeline risk assessment methodologies, PRAM for pipelines conveying flammable substances and TPRAM for pipelines carrying toxics. Over time, PRAM was developed and was eventually replaced by MISHAP98, and then by MISHAP 01, also known as MISHAP.

Initially the event tree present in PRAM (illustrated in Appendix 3 [6]) included weather conditions and hole sizes (represented by jets or passive releases) as part of a node on each branch. The event tree was consequently changed by splitting the event tree into two for each weather type and taking account of the hole size elsewhere in MISHAP, e.g. the failure frequency. In addition, immediate ignition was moved to the start of the MISHAP event tree and remote ignition added.

Despite the changes in the event tree structure, MISHAP yields exactly the same scenario probabilities and consequences as PRAM. Both are based on a minimal representative set of events.

2.2 UKOPA CONCERNS AND PROPOSALS

UKOPA has a range of concerns associated with the non-natural gas event tree that HSE uses to determine the level of risk around pipelines carrying hazardous substances [2]. These are detailed below.

1. The ignition probability of 0.84 (84 %) that is currently used by HSE for non-natural gas including ethylene, spiked crude, NGLs (Natural Gas Liquids) and propane (see Table 1), is not comparable to that of natural gas, where a lower value of 0.4375 (43.75 %) is used. The land use planning (LUP) zones produced for non-natural gas are significantly larger than those for natural gas as the probability of ignition is much greater. This is a concern, especially as there are no references to explain the logic behind the ignition probability values as they were based on the best available judgement at the time.

2. There are concerns as to why there is a difference between the probabilities of an unobstructed release between dense phase ethylene and methane gas. HSE assumes that 50 % of delayed ignition events for natural gas releases are unobstructed and 80 % of delayed ignition events for other substances are unobstructed.

   UKOPA argues that the contents of the pipeline should not influence the location of the puncture, or the probability of jet impingement. They go on to state that the top of the pipeline is most likely to experience third party damage (though other possible failure causes do exist, e.g., corrosion holes are most likely to occur at the bottom of the pipeline), so implementing an 80 % probability of unobstructed releases for both natural gas and ethylene seems sensible.

3. UKOPA also question the difference between the probabilities for local ignition for an unobstructed natural gas jet (25 %) and an unobstructed ethylene jet (80 %).

   UKOPA argues that the physical dimensions of a resultant gas jet are similar for both natural gas and non-natural gas, assuming the dimensions of the hole size are also similar. They go on to discuss that the difference in minimum ignition energy between the two substances is the only probable factor that could affect the ignition probability. As a result, they propose an ignition probability of 50 % (twice that of natural gas) as this value is in proportion to the substances' minimum ignition energies.

4. HSE's decision to assume that the remaining obstructed non-natural gas releases result in flash fires due to remote ignition does not seem appropriate.

   UKOPA state that local ignition is more likely than assumed by HSE with some obstructed releases, as opposed to the gas cloud dispersing downwind, reaching the lower flammable limit (LFL) and then igniting to cause a flash fire. UKOPA proposes that 50 % (twice that of methane) of releases that do not ignite immediately are ignited locally, and 80 % of the remaining releases ignite remotely.

UKOPA prepared two approaches for non-natural gas in its briefing note [2], one for propane and one for ethylene. As ethylene pipelines are the most common pipelines in the UK, after natural gas, it is appropriate to focus on the ethylene event tree, though propane and other substances will be discussed as appropriate. From the proposals put forward by UKOPA, the event tree illustrated in Figure 3 is obtained.

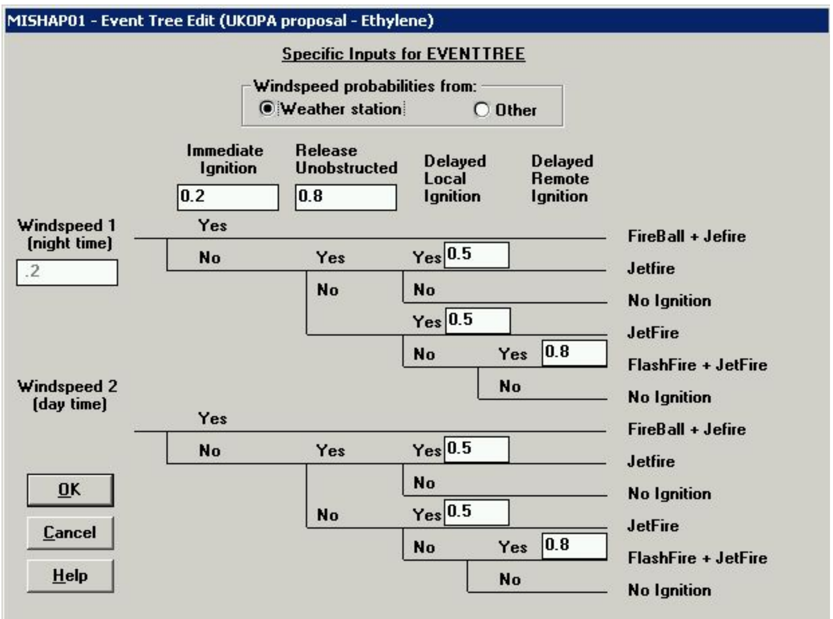

Figure 3 Proposed UKOPA event tree for ethylene

It is important to note that HSE uses a generic non-natural gas event tree whereas UKOPA's proposals are for ethylene, so caution must be applied when making comparisons.

Table 1 illustrates the percentage of all releases that lead to a given outcome for HSE (non-natural gas) and UKOPA (ethylene).

Table 1 Current and proposed fractions for non-natural gas and ethylene releases that lead to a given outcome

Outcome	HSE – current (non-natural gas)	UKOPA – proposed (ethylene)
Fireball + jet fire	0.20	0.20
Jet fire	0.512	0.40
Flash fire + jet fire	0.128	0.064
Ignition probability	0.84	0.664

Table 1 shows that HSE and UKOPA agree that 20 % of all releases result in a fireball followed by a jet fire. The UKOPA method shows a smaller instance of jet fires, and flash fires followed by jet fires, than HSE. As a result of these lower estimates, UKOPA proposes that un-ignited releases (33.6 %) are twice as likely as assumed by HSE (16 %).

2.3 INITIAL ANALYSIS OF UKOPA PROPOSALS

From the points outlined above, UKOPA put forward reasonable arguments questioning the differences between HSE's natural and non-natural gas event trees. It is accepted, by HSL, that the contents of a pipeline should not influence the location of a hole or the probability of jet impingement, therefore the probability of an unobstructed release should be the same for natural and non-natural gas. However, UKOPA does not explain why it has chosen the HSE non-natural gas event tree value of 0.8 as opposed to suggesting a different one based on new knowledge.

UKOPA's reasoning behind the probabilities of an unobstructed jet experiencing delayed local ignition needs further investigation. It is probable that the near-field dimensions of a jet release are comparable between natural and non-natural gas, thus leaving the minimum ignition energy (MIE) as the main factor affecting the ignition probability. The minimum ignition energy is defined as: 'that which is required to bring the minimum volume to a temperature that will allow combustion' [13]. As the minimum ignition energy of methane (0.22 mJ) is approximately twice that of ethylene (0.12 mJ), it is therefore plausible that methane is half as likely as ethylene to ignite. The feasibility of using the minimum ignition energy to estimate the ignition probability will be investigated later in the report. However, UKOPA has based its ethylene probability (0.5) on twice that of HSE's natural gas value (0.25), rather than devising a new value based on new judgement and/or research.

UKOPA has misgivings with the HSE approach that assumes all obstructed, non-natural gas releases result in flash fires (followed by a jet fire) due to delayed remote ignition. While HSE sets the probability of delayed local ignition of an obstructed, non-natural gas release to zero, UKOPA proposes a value of 0.5 for ethylene. Again, this probability value is proposed due to methane having twice the ignition energy of ethylene. Provided the gas is between the upper flammable limit (UFL) and the LFL, it seems appropriate to have a non-zero probability value for local ignition.

The majority of UKOPA's assumptions are based on the original HSE event trees and then amended to suit, rather than using the most up to date knowledge and experience. Further analysis of the HSE and UKOPA proposed event trees is presented later in this report, which is used to judge the validity of UKOPA's proposals.

3 MISHAP EVENT TREE ANALYSIS

This section presents the history behind the evolution of PRAM into MISHAP01, and goes on to examine the logic behind the sequence of events within the MISHAP event trees. The aim of this review is to determine whether the current HSE approach is suitable.

3.1 HISTORY

This section aims to capture information regarding the evolution of the event tree from the format available in early PRAM, through MISHAP98 to the version that is currently used in MISHAP01.

A detailed discussion of the event tree layout is given in Section 3.1.3.

3.1.1 Safety evaluation of the Trans-Pennine Ethylene Pipeline (TPEP) and booster station

A safety evaluation of the TPEP (Trans-Pennine Ethylene Pipeline) was carried out by MHAU (now HID CI5). Appendix 1 contains the MHAU event tree and the corresponding probability values for pipeline ruptures while Appendix **Error! Reference source not found.** contains the event tree and corresponding probability values for pipeline punctures. The ignition probability given in Appendix 1 is 0.84, so despite changes to the structure of the event tree, this value is still currently used by HSE for non-natural gas.

Table **Error! Reference source not found.** gives the full range of ignition probabilities based on hole size that were extracted from the given event trees.

Table 2 Ignition probabilities used for the TPEP assessment

Hole size (mm)	Urban release	Rural release
Rupture	0.512	0.128
50	0.712	0.128

Sometime between 1988 (the publication date of R4813) and 1998, the PRAM event tree evolved from the form in Appendix 1, to the form given in Appendix 3, which is the basis for MISHAP98. Section 3.1.2 discusses MISHAP98 in more depth.

3.1.2 Risk assessment for pipelines using MISHAP98 (flammables) and TRAM (toxics)

The MISHAP98 event tree is available publically [5], but there is no discussion to indicate why the default probability values were chosen; it is probably because they have been extracted from the earlier PRAM event tree. Figures 4 and 5 show the structure of the event tree used in MISHAP98.

Figure 5 is similar to the tree given in Appendix 3 and is a more up-to-date version of the original PRAM event tree given in Appendix 1, and discussed in section **Error! Reference source not found.**. Table 3 shows how the branch probabilities changed after the conversion to the new PRAM event tree structure.

Table 3 Event tree changes for PRAM

Ignition type	Original PRAM	New PRAM
Immediate	0.20	0.20
Local	0.64	0.64
Remote	N/A	0.0256
No ignition	0.16	0.1344

The immediate and local ignition values are unchanged but the original PRAM probability for no ignition was split to take into account the possibility of remote ignition. The sum of remote ignition and no ignition in the new scheme equals the value for no ignition in the old scheme (0.1344 +0.0256=0.16).

After the adoption of MISHAP98 (and redundancy of PRAM), a template event tree for natural gas was produced after discussions with Transco and was based on the best knowledge available at the time; again there is no paper record of why the changes were made. Table 4 gives the probability values that were available in MISHAP98. The PRAM values were also carried over from the original PRAM set up to the new MISHAP98 tool.

Table 4 PRAM and Transco default data for MISHAP98

	PRAM	Transco
Probability of immediate ignition	0.20	0.25
Probability of delayed ignition	0.6656	0.22
Probability of no ignition	0.1344	0.53

Figures 4 and 5 show the event trees that were used to derive the values in Table 4 for the Transco and PRAM columns respectively. The Transco event tree is similar to the tree currently used for natural gas except for the delayed remote ignition values for flash fires which were set to 0.1 for MISHAP98 and then to the current value of 0 for MISHAP01. Even though the flash fire assessment should not be carried out for natural gas pipelines, the values were included in the event tree and the assessor normally ignored the flash fire input windows.

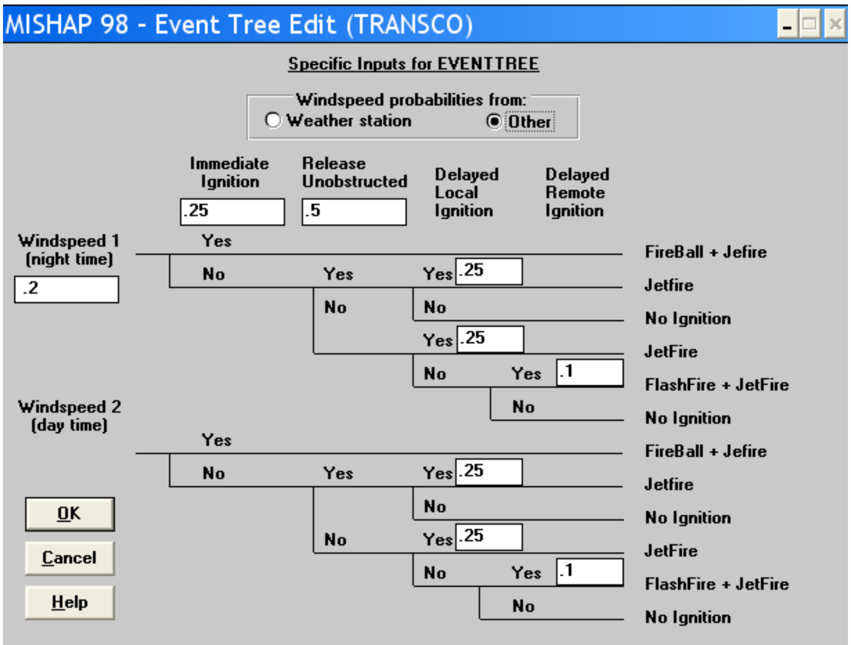

Figure 4 Default MISHAP98 event tree values for natural gas using the template agreed with Transco

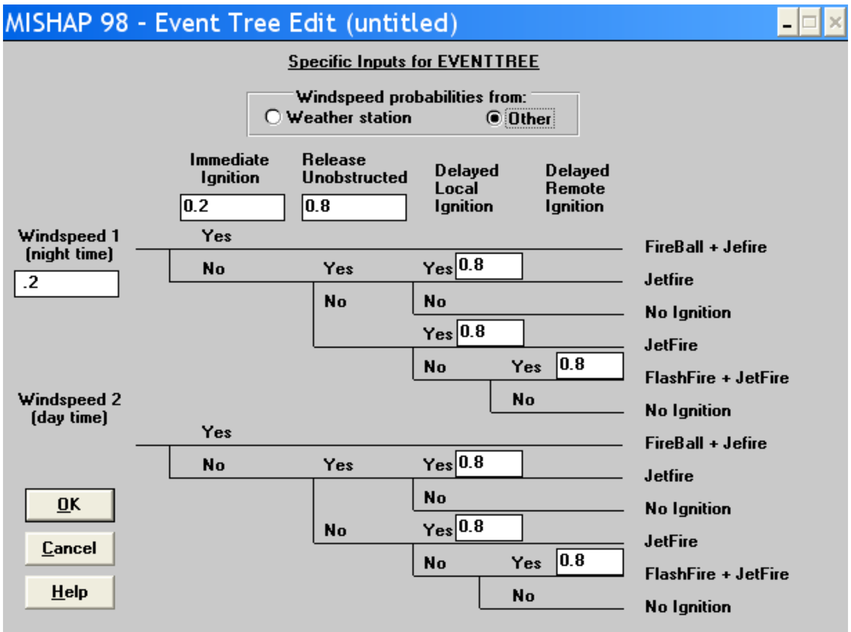

Figure 5 Default MISHAP98 event tree values when no template is selected – PRAM values

The PRAM event tree in Figure 5 is constructed in a similar manner to the tree currently used by HSE to represent non-natural gas pipelines except for delayed local ignition of obstructed releases which is set to 0.8 for MISHAP98 and then to the current value of 0 for MISHAP01. Setting the delayed local ignition probability to 0 makes the MISHAP event tree equivalent to the PRAM event tree.

It is likely that the probability values were modified during the conversion from MISHAP98 to MISHAP01, though no changes were noted explicitly in published literature. Changes to the fire models between the two versions have been published [36].

3.1.3 Review of MISHAP event tree sequences

Whenever a natural or non-natural gas pipeline failure occurs, the resultant gas cloud travels downwind from the source and can be affected by local and far-field conditions, which in turn, affect the possible consequences. The nature of the failure and the consequences are discussed below.

3.1.4 Nature of failure

A variety of factors can influence the state of the released cloud as it moves away from the source, thus affecting the final event. They are:

- Immediate/delayed ignition

  In the case where a metal structure, such as a pipeline, is broken on impact, the frictional sparks that may be generated often act as an ignition source, thus resulting in immediate ignition. This is often the case for rural pipelines suffering third party damage (note that third party damage is one of many possible causes of release). Overall, immediate ignition is often incident generated [13]. Even though the term immediate ignition is used, in reality 'prompt ignition' is a better description as it represents ignition due to a nearby source that occurs before an appreciable vapour cloud is produced.

  If immediate ignition does not occur, the released cloud will continue to travel downwind until it encounters a sufficient source of ignition. Furthermore, if ignition sources are located within a building, there may be a substantial time delay until the gas is able to permeate the walls of the building. However, if there are sufficient ignition sources located outdoors, indoor sources may be ignored [13]. Indoor ignition sources such as household appliances may only be in use for half the time the house is inhabited.

  In most cases, it is assumed that immediate ignition occurs within 30 s of a release and delayed ignition occurs after 30 s [16].

- Obstructed/unobstructed releases

  A significant puncture near the top of a pipeline, giving what is termed an unobstructed release, would be expected to give rise to a narrow high-velocity, near-vertical jet. In contrast, the gas escaping from a significant side or bottom puncture would be obstructed by impact with the crater formed in the blast [5], and may have some influence on the jet, possibly affecting its width, velocity and direction. Holes and ruptures on the underside of the pipeline can produce a crater that is almost 10 pipeline diameters in size [4].

- Delayed local ignition

  Delayed local ignition implies that there are sufficient ignition sources close to the release point but the gas plume does not meet the requirements for ignition. This could occur if the plume is outside the UFL and LFL (Upper and Lower Flammability Limits) range.

- Delayed remote ignition

Remote ignition can occur if there are insufficient ignition sources close to the release point. It can also occur if the gas plume requires a period of time to disperse to a concentration below the UFL (usually downwind and therefore remote from the site) that has an appropriate fuel to oxygen ratio for ignition.

The flammability of a cloud is not uniform throughout as fuel rich or fuel deficient pockets may exist, and may affect ignition.

3.1.5 Consequences

A number of different events can occur after the release of flammable gas from high-pressure pipelines; these include:

- Fireball;
- Jet fire;
- Trench fire;
- Flash fire; and/or
- Vapour cloud explosion (VCE).

Obstructed jet fires are usually labelled as trench fires or crater fires, while unobstructed jet fires are referred to as jet fires. MISHAP is unable to model non-vertical jets so horizontally obstructed releases are modelled vertically (MISHAP cannot model the situation where a rupture generates two jets within the crater that are directed towards each other, instead it models a narrow high-velocity vertical jet) [5].

With the exception of a VCE, all these events are possible after the failure of a highly pressurised pipeline containing substances such as natural gas. VCEs occur when overpressure is produced as a result of combustion in the presence of obstacles, structures and/or partial confinement [3]. For MISHAP, the risk associated with VCE events is negligible because the development of MISHAP (and its predecessors) was based on areas with low congestion and confinement (e.g. rural pipelines), which are not conducive for creating the large flammable clouds required by VCE. [5]. In addition, the likely non-ideal location of the cloud and probable lack of strong ignition sources in the medium range also inhibits this event [5], and possibly helps explain its exclusion from MISHAP. VCE is available for event trees from other sources, e.g. [27]. There is evidence to suggest that the reasons behind the exclusion of VCE from MISHAP should be re-examined.

An unobstructed jet has high initial momentum, and is rapidly dispersed to levels below the LFL (while still in the momentum phase), so as a result, the flash fire option is not available in MISHAP. The puncture release rate is usually insufficient to generate the conditions required for a significant fireball [5, 6]. Furthermore, computational fluid dynamics (CFD) calculations and experimental work carried out at Loughborough University indicate that ground-level flash fires are unlikely for high pressure pipeline releases of methane, therefore, it is HSE's policy not to run the flash fire model for pipelines conveying natural gas [5].

The nature of an ignited event can be greatly influenced by the ignition timing. A pool fire (for a liquid release) or a jet fire is assumed to occur following early ignition, but it is dependent on whether the material is in liquid or gaseous form. Whenever delayed ignition takes place, it is assumed that the initial ignition would generate either a flash fire (and subsequently a jet fire) or an explosion [7].

With small holes, the fireball scenario is ignored as it is not considered possible, however, a jet fire may occur but it is usually small and obstructed. Gas escaping from a larger hole or rupture has considerable energy, which can cause a crater to form in the ground surrounding the breakage in the pipeline. MISHAP deals with buried pipelines, so if the puncture is located near the top of the pipeline, earth will be projected to one side of the pipeline, in the direction of the flowing gas. If the puncture is on the side, a horizontal jet will result which will excavate a curved channel on the same side of the pipeline as the hole (however, this option is not currently available in MISHAP). If the puncture is located on the bottom of the pipeline, a large crater in excess of 10 pipeline diameters in diameter may form [4].

3.1.6 Structure of event tree

The structure of MISHAP is based on that of PRAM [6], its predecessor (see Appendix 1). However, while the PRAM event tree allows for a rupture as well as a puncture, MISHAP uses one generic event tree. This is because the first calculation in MISHAP is rupture by default, followed by three puncture releases of sizes defined by the user, so the size of the hole does not need to be taken into account within the MISHAP event tree [4].

Of all the possible significant events that could occur in relation to a hazardous pipeline, four possible outcomes are illustrated in the MISHAP structure:

- Fireball plus vertical jet fire;
- Vertical jet fire alone;
- Flash fire plus vertical jet fire; and
- No ignition.

Note that the vertical jet fire is subsequently tilted by the wind in the downwind direction. Currently, angled jet fires, overpressure, crater formation, etc. are not included in MISHAP [5, 36].

Figures 1 and 2 illustrate the full event trees for both natural and non-natural gas respectively. Each branch has an associated consequence that is discussed below.

<u>Branch 1 – fireball and jet fire</u>

Pipeline rupture may be associated with immediate ignition resulting in a fireball, and as this is a momentum release, a jet fire may result. This consequence is therefore appropriate for this branch.

<u>Branch 2 – jet fire</u>

This release is unobstructed and experiences delayed local ignition. Local to the source, concentrations of the released material are generally still high enough to ignite, and as the jet has momentum, a jet fire ensues.

Branch 3 – no ignition

Neither immediate nor delayed ignition takes place so there are no consequences associated with ignition for this event.

Branch 4 – jet fire

This release is obstructed and undergoes delayed local ignition. As mentioned in Section 3.1.4, an ignited, obstructed release produces a jet fire in a similar way to an unobstructed release, but the width, velocity and direction of the jet fire may differ[b].

Branch 5 – flash fire and jet fire

The released gas plume experiences delayed, remote ignition. If the plume concentration is above the LFL but below the UFL, it is still possible for ignition sources to ignite the plume. As the upwind parts of the plume are also fuel and oxygen rich, the entire plume ignites backwards to the source creating a jet fire.

Branch 6 – no ignition

As with branch 3, neither immediate nor delayed ignition takes place so there are no consequences associated with this event.

The description of the branches discussed above supports the selection of possible events (e.g. jet fire) that can occur. However, it could not be determined in the documentation reviewed why the need arose to change the sequences between the PRAM event tree (Appendix 1 [6]) and the current MISHAP event tree. Further investigation into the inclusion of VCE may be required.

The PRAM event tree uses the following sequence:
Rupture → unobstructed release → immediate ignition → neutral weather → delayed ignition

The current MISHAP event tree uses the following sequence:
Immediate ignition → unobstructed release → delayed local ignition → delayed remote ignition

It is appropriate that neutral weather and rupture are not included in the MISHAP event tree sequence (as illustrated above), as MISHAP takes them into account in other ways. However, there is no record as to why the order of unobstructed release and immediate ignition are swapped. It is assumed that delayed ignition is split into local and remote to provide better detail. Despite the changes in order, the overall branch probabilities are unaffected. This is because the MISHAP non-natural gas event tree can be made equivalent to the PRAM event tree by setting the branch probability for delayed local ignition in the case of an obstructed release to zero for both daytime and night-time.

[b] *Note that MISHAP cannot distinguish between a narrow high-velocity vertical jet and a wider lower-velocity vertical jet, and it cannot model a non-vertical jet at all [5].*

3.1.7 Summary

The main findings concerning the generation of the MISHAP event tree are as follows:

- A fireball results from immediate ignition;
- A jet fire results from delayed local ignition;
- A flash fire results from delayed remote ignition; and
- If a release has momentum, a jet fire is possible with each ignited case.

Further examination is presented in Section 4.11 which will determine, from the literature, if the structure currently used by MISHAP is appropriate or needs revising.

4 REVIEW OF RELEVANT LITERATURE

This section summarises a review of literature that was carried out to determine the basis of the probabilities used in the MISHAP event tree and to identify wider sources of ignition probabilities. This information is used in Section 5 to review and compare the probabilities currently used in the MISHAP event tree against other values which are currently available from other sources.

A variety of HSE literature was explored to identify the origin of the PRAM/MISHAP event tree probabilities. However, all the literature examined accepted the default probability values without question. As a result, the same literature and other references were reviewed to highlight common ignition probability values that are used external to HSE.

The wider literature did not sufficiently cover ignition probabilities of similar scenarios to those used in MISHAP for natural and non-natural gas pipelines. However, as offshore ignition probabilities have been thoroughly researched, these have also been considered. The most appropriate probability values are included in the literature summary below, so that cautious comparisons can be made with the current HSE values and the proposed UKOPA values. However, it should be noted that offshore natural gas may be slightly less pure than natural gas present in the onshore pipeline network.

4.1 IGNITION PROBABILITY OF FLAMMABLE GASES

This report [13] describes the initial preparation that was carried out to develop a model, or at the very least a methodology to estimate the ignition probability of flammable gas clouds that is based on a better approach than the models available at the time of writing. Background information such as: ignition sources, ignition probability and the nature of the release involved are discussed, and are based on a literature review. Reference will be given to the sources the authors obtained information and data from.

The physics of ignition in terms of ignition energy, autoignition temperature and electrostatic discharge, etc., are discussed as well as the ignition sources, e.g. open flames, which can cause them. Predicting when ignition will occur in practice is fraught with difficulties as ignition is sensitive to the following: temperature, concentrations of fuel and oxygen, volume of flammable mixture and pressure, though this list is not exhaustive.

The ease of ignition can be estimated based on the physical characteristics of the flammable material in question, for example, the minimum volume, minimum ignition energy, autoignition temperature and ignition lag time are all factors which can be measured and compared for a range of materials. However, these characteristics can also be influenced by external factors; the ignition energy is dependent on: the mixture temperature, pressure and composition. The minimum ignition energy is usually obtained close to or below stoichiometry for a given set of conditions.

The minimum ignition energy is usually used as a measure of ignitability as opposed to the minimum ignition temperature (which is largely dependent on the volume of the gas/air mixture) as the results are less sensitive to the experimental setup. The energy of the ignition source can then be compared against the minimum ignition energy of the gas, thus estimating the likelihood of ignition.

This report also discusses incident generated ignition, which is said to be a fairly common cause of releases from gas pipelines located in rural areas that experience third party damage.

The report provides a number of tables listing a variety of ignition data from other references. The most useful are listed here.

Table 5 [14] lists a summarised set of 59 accidents involving LPG and other flammable liquids that occurred in the open. The report explicitly states that immediate ignition resulted for 12 out of the 59 cases (5 for industrial and 7 for non-industrial). Treating industrial and non-industrial separately, the associated delayed value given in Table 5 is the sum of the number of ignitions corresponding to a range of ignition sources, such as open flames, for which delayed ignition is assumed.

Table 5 Immediate and delayed ignition

Industrial		Non-industrial	
Immediate	5	Immediate	7
Delayed	12	Delayed	32
Proportion of ignitions that are immediate	0.29	Proportion of ignitions that are immediate	0.18

Taking both industrial and non-industrial accidents into account, the proportion of ignitions that are immediate is 0.21. Most of the immediate cases listed were due to transportation accidents. From Table 5, 56 events are listed and it is not clear what happened to the remaining 3 releases.

Another report [15] that was reviewed by the authors listed the ignition probabilities for LPG releases that resulted from rail accidents. They were based on incident data and engineering judgement. Table 6 lists the data that were obtained.

Table 6 Ignition probabilities of LPG as a result of rail accidents

Spill size	Immediate	Delayed	None
Small	0.1	0	0.9
Large	0.2	0.5	0.3

This gives a total ignition probability of 0.1 for small releases and 0.7 for large releases. The proportion of all ignitions that are immediate is 0.38 (0.3/(0.5+0.3)).

The most appropriate data is given in Table 7, which lists overall ignition probabilities for natural gas pipelines from three different sources. The values vary significantly for a number of reasons:

- The probability is based on the size of the release, bigger releases experiencing a higher likelihood of ignition;

- The exact sources of the data are unknown and could be based on offshore or other transportation data, though it is likely that rural pipelines account for a large proportion; and

- Immediate ignition is included.

Table 7 Ignition probabilities for natural gas pipelines failures

Data source	Ignition probability	
World-wide, Townsend & Fearnehough (1986)	Leaks	0.1
	Ruptures	0.5
US Gas, Jones (1986)	Ruptures	0.26
	All sizes	0.16
European Gas, European Gas Pipeline Incident Data Group (1988)	Pinholes/cracks	0.02
	Holes	0.03
	Ruptures < 16”	0.05
	Ruptures ≥ 16”	0.35
	All sizes	0.03

4.2 A REVIEW OF IGNITION PROBABILITIES FOR USE IN OFFSHORE INSTALLATION QUANTIFIED RISK ASSESSMENTS

This report [8] was written by AEA Technology on behalf of HSE and reviews both onshore and offshore ignition data and models. The ignition probabilities proposed are based on limited available data and take release size, material and confinement into consideration.

Offshore analysis yields information on obstructed and unobstructed releases, which can aid assessment of pipeline ignition probabilities in the presence of confinement. Table 8 contains information on gas/condensate releases.

Table 8 Proposed generic offshore hydrocarbon ignition probabilities for unobstructed and obstructed releases

Situation	Release Rate	Nominal ignition probability
Confined	Massive	0.50
	Major	0.15
	Minor	0.05
Semi-confined	Massive	0.30
	Major	0.05
	Minor	0.01
Open	Massive	0.20
	Major	0.03
	Minor	0.0025

Table 9 shows the probability of a gas explosion given ignition. This data is based on historical offshore data from the North Sea and worldwide locations.

Table 9 Probability of explosion given ignition

Event	North Sea data	Worldwide data
	Number of events	
Fire (no explosion)	142	343
Explosion	38	95
	Probability	
Probability of explosion	0.21	0.22

Ignition timings for onshore LPG releases are illustrated in Table 10.

Table 10 Ignition timings – based on an analysis of LPG pipeline releases

	Relative probability of ignition within time, t (s)					
Time	1	10	30	100	1000	>1000
Probability	0.24	0.30	0.31	0.39	0.61	1.0

4.3 CLASSIFICATION OF HAZARDOUS LOCATIONS

The authors of this book [9] explore onshore and offshore flammable gas ignition data and base the probability values on the mass release rate. Table 11 depicts the estimated probability values.

Table 11 Estimated probability of ignition of leaks of offshore flammable gas

Release rate category	Release size	Ignition probability
Minor	<1 kg/s	0.01
Major	1-50 kg/s	0.07
Massive	>50 kg/s	0.3

4.4 IGNITION PROBABILITY REVIEW, MODEL DEVELOPMENT AND LOOK-UP CORRELATIONS

This paper [7] consists of a detailed literature review of ignition probabilities for offshore and onshore releases so that they can be better understood and therefore modelled more appropriately in quantified risk analysis (QRA).

The model that is developed throughout the report yields ignition probabilities of 0.1 for LPG and less for natural gas/methane.

4.5 A GUIDE TO QUANTITATIVE RISK ASSESSMENT FOR OFFSHORE INSTALLATIONS

This report [10] reviews historical offshore ignition probabilities in relation to the ratio of leaks to ignitions. Table 12 illustrates the dependence of ignition probability on leak size. The larger release sizes are shown here as these can be compared more easily to a pipeline failure.

Table 12 Generic offshore ignition probabilities

Release size and type	Ignition probability
5-25 kg/s gas leak	0.10
25-200 kg/s gas leak	0.30
>200 kg/s gas leak	0.50

The report [10] also covers ignition delay probabilities, again for offshore releases, that could be useful when compared to delayed and immediate ignitions for pipeline failures. They are given in Table 13.

Table 13 Ignition delay probabilities

Time interval (min)	Probability of ignition within interval	Probability of ignition by end of interval
0 (immediate)	0.10	0.10
0-5	0.20	0.30
5-20	0.37	0.67
20-60	0.29	0.96
>60	0.04	1.00

4.6 IGNITION PROBABILITY FOR HIGH PRESSURE GAS TRANSMISSION PIPELINES

This paper [12] updates a previous analysis reported at IPC2002 (International Pipeline Conference 2002) that derived a function for the ignition probability of an underground, high-pressure natural gas pipeline based on the pipeline operating pressure and the square of the diameter. Observation data indicated that releases from such pipelines can ignite in remote locations even if there are limited ignition sources present. The authors state that ignitions are therefore generated by the failure itself. The following data was combined to derive the new function.

- Transmission pipeline incident data recorded between 1970 and 2004; and
- US Office of Pipeline Safety Office (OPS) data between 2002 and 2007

The paper [12] focuses on rupture releases, but proposes that the same correlation can be used for puncture releases if the ignition probability is halved. This accounts for the release being from a single hole, while ruptures are double ended. Table 14 lists the combined data used to obtain the function.

Table 14 Variation of overall ignition probability with pd^2 for the full dataset from a rupture (where p is the operating pressure in bar and d is the pipeline diameter in m)

pd^2 range (bar m^2)	Mean [pd^2] (bar m^2)	Number of incidents	Number of ignited incidents	Ignition probability
0-5	1.3	183	11	0.06
5-15	9.8	51	11	0.22
15-30	19.7	52	16	0.31
30-45	35.7	18	10	0.56
45-80	57.0	21	17	0.81

Equations 1 and 2 are based on the full combined dataset.

$$P_{(ign)} = 0.0555 + 0.0137pd^2 \qquad 0 \leq pd^2 \geq 57\text{, and} \qquad (1)$$

$$P_{(ign)} = 0.81 \qquad pd^2 > 57 \qquad (2)$$

The paper [12] also makes references to a generic cause of the failure and its effect on the ignition probability. For example, the authors state that the ignition probability for releases caused by external interference, such as excavating machinery, is much lower than releases caused by other means. Table 15 is a reproduction of the supporting data.

Table 15 Variation of ignition probability with cause of failure for pipeline rupture incidents (1970-2004)

Cause of failure	Number of incidents	Number of ignited incidents	Ignition probability
External interference	123	14	0.11
Other causes	105	39	0.37

The main point noted by the authors [12] is that the derived function does not take the location of the pipeline (e.g. rural or urban) or the cause of failure (e.g. external) into consideration.

4.7 COMPARISON OF RISKS FROM CARBON DIOXIDE AND NATURAL GAS PIPELINES

This aim of this report [17] was to determine if carbon dioxide (CO_2) used for carbon capture and storage (CCS) has sufficient toxicity to be regulated as a dangerous fluid under the Pipeline Safety Regulations (PSR). Therefore, the results and method used are not wholly applicable to the purpose of the MISHAP examination; however, a method was given to calculate the probability of a jet fire based on the size of the crater angle.

A number of crater angles were obtained from the literature [22] and then averaged to give a value of 19º (θ) from the horizontal, which is essentially the angle for an obstructed jet.

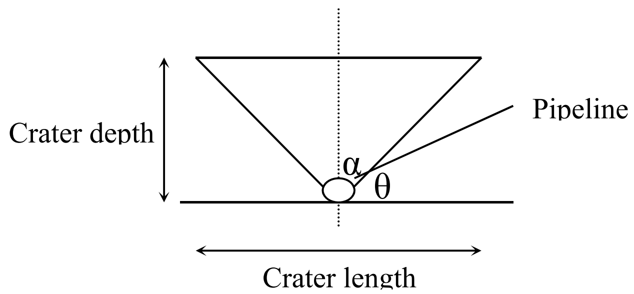

Figure 6 Calculation of crater angle

From Figure 6, the crater angle is given by θ so an unobstructed jet is represented by the angle (90-θ) otherwise known as α, which is equal to ±71° from the top of the pipeline. From UKOPA data there are 71[c] events with 'hole circumferential position' recorded, assuming that the top of the pipeline is 0°. Of these 71 events, 45 have angles of less than ± 71° so:

$$\text{Proportion of unobstructed releases } = \frac{45}{71} = 0.63$$

Therefore, the obstructed proportion can be taken as 1-0.63 = 0.37.

4.8 DEVELOPMENT OF ALGORITHMS FOR PREDICTING IGNITION PROBABILITIES AND EXPLOSION FREQUENCIES

This reference [20] lists a number of algorithms that can be used to calculate the ignition probability for immediate ignition and delayed ignition as well as the probability that delayed ignition results in an explosion. The author suggests a set of default conditional probabilities, as given in Table 16, which are conservative estimates for the majority of possible events. However, there may be situations where the probability is not representative, so fine-tuning of the default value is required.

The data are mainly based on studies of chemical process operations, but there may be some contribution from nuclear and offshore oil/gas production. It appears that the constructed algorithms may be used for generic substances by amending the default probability based on site-specific information.

The calculated overall ignition probability of 0.405, reproduced for illustration in Appendix 4 of this report, is based on the default event tree by Moosemillar [20].

[c] *Note that it is coincidental that there are 71 events as well as an angle of ± 71°.*

Table 16 Default conditional probabilities for immediate ignition, delayed ignition and explosion

Event	Default probability
Immediate ignition	0.15
Delayed ignition (given absence of immediate ignition)	0.30
Explosion (given delayed ignition)	0.2

4.8.1 Immediate ignition

The author assumes that immediate ignition is more accurately described as 'prompt ignition' where ignition occurs close to the release point but before any substantial vapour cloud is produced.

The default value for immediate ignition is 0.15, but other factors such as the potential for autoignition (Pai) and the potential for static discharge (Psd) should be considered, where:

- Pai is related to the release temperature (T) relative to the autoignition temperature (AIT); and
- Psd is related to the minimum ignition energy (MIE) and the 'release energy' for the released material. After a compromise between varying expert opinion, the 'release energy' was defined as the cube root of the source pressure ($P^{1/3}$).

The following relationship for $P_{imm.ign}$ (probability of immediate ignition) was proposed:

$$P_{imm.ign} = Pai + Psd \tag{3}$$

$$P_{imm.ign} = \left[1 - 5000e^{-9.5\left(\frac{T}{AIT}\right)}\right] + \left[\frac{0.0024 \times P^{1/3}}{MIE^{2/3}}\right] \tag{4}$$

where AIT and T are in ºF, P is in psig and MIE is in mJ. There are a number of constraints on this relationship:

- 0 ºF is the minimum value allowed for T;
- If $\frac{T}{AIT} < 0.9$, Pai = 0;
- If $\frac{T}{AIT} > 1.2$, Pai = 1; and
- The maximum value allowed for $P_{imm.ign}$ is 1.

The model assumes there is the possibility of non-immediate ignition if T is no more than 200 ºF higher than the AIT (this is required as AIT values vary throughout literature) and thus $P_{imm.ign} \leq 0.98$.

For mixtures, Le Chatelier's mixing rule can be applied to T and AIT.

4.8.2 Probability of delayed ignition

The author assumes that delayed ignition occurs for instances that do not meet the requirements for immediate ignition, i.e., an appreciable vapour cloud is allowed to develop which is then ignited by a remote ignition source such as fired heaters or rotating equipment etc.

The default value for the probability of delayed ignition is 0.3, and requires refinement due to variable influencing conditions at the time of release. The modifiers listed in Table 17 do not generate new probability values directly, they need to be used along with the default probability value; the details of which are discussed fully below.

Table 17 Modifiers for calculating the probability of delayed ignition in terms of the material being released, the magnitude of the release and the strength of the release

Modifier	Description
$[M_{mat}] = 0.6 - 0.85\log(MIE)$ MIE is in mJ.	*Material being released [M_{mat}]* The following limit is in place: $0.1 \leq [M_{mat}] \leq 3$. This assumes that even if a material is notoriously difficult to ignite, eventually a situation will arise where ignition occurs.
$[M_{mag}] = 7 \times e^{[0.642 \times \ln(FR) - 4.67]}$ FR is the flowrate from the hole in lbs/sec.[d]	*Magnitude of the release [M_{mag}]* The following limit is in place: $[M_{mag}] \leq 2$.
$M_{dur} = \frac{1}{0.3}\left[1 - \left(1 - S^2\right) \times e^{-(0.015 \times S)t}\right]$ t is in seconds. S is a pre-defined 'strength' value (in other words the probability of ignition in one minute) which can be found in Appendix 5.	*Duration of the release and the numbers/density and 'strength' of ignition sources M_{dur}* The likelihood of ignition increases: • The longer the cloud is exposed to the ignition source; and • The strength of the ignition source. $P_{ign}=1-(k \times e^{-at})$ is a commonly used algorithm which has been adapted for the purposes of this model, as shown in the multiplier column[e].

The paper also presents modifiers for probability of explosion given delayed ignition and indoors vs. outdoors operation, which have not been included here.

In some situations, the product of the default probability and the modifier can be greater than 1, which is not possible under mathematical rules. Therefore, the probability is set to be between 0 and 1, and for a particular scenario, the modifiers act as an aid for positioning the probability

[d] *This equation is based on a version from Cox, Lees and Ang*
[e] *k is the strength constant and t is the time constant. A similar version of this equation is given in the Purple Book [23]*

somewhere between these two values. For example, if the product of the multipliers (ΠM_i) is greater than 1, the 'new' probability lies between 0.3 (the default probability) and 1, the bias swinging towards 1 for greater product values. If the product of the multipliers is less than 1, the 'new' probability lies between 0 and 0.3, the bias swinging towards 0 for smaller products.

The algorithms are as follows:

If the product of the multipliers is > 1, then $P_{del.ign} = 1 - \left(\frac{0.7}{\Pi M_i} \right)$ (5)

If the product of the multipliers is < 1 , then $P_{del.ign} = 0.3 \times \Pi M_i$ (6)

4.9 GUIDELINE FOR QUANTITATIVE RISK ASSESSMENT, PART 2: TRANSPORT – PURPLE BOOK

Section 2 of the Purple Book [24] discusses IPORBM (Dutch acronym for Inter Province Committee for Risk Calculation Methodology), which is a software program that determines the risks involved when transporting hazardous substances by roads, waterways, pipelines etc.

The section on pipelines is the most useful; Table 18 lists the pipeline diameters and operating pressures for a set of substances for which IPORBM can be used.

Table 18 Pipeline operating conditions at which the IPORBM software tool can be run

Substance category	Diameter (inches)	Operating pressure (bar)
Natural gas	2, 4, 6, 8, 10, 12, 14, 16, 18, 24, 30, 36, 42, 48	40, 60, 90
Ammonia	4, 6, 8	10, 14, 20
Chlorine	2, 3, 4	12 through 20
Ethylene (ethene)	6, 8, 10	50, 75, 100
Ethylene oxide	6 through 10	5 through 10
K1[f]	4, 6, 8, 10, 12	All pressures
K2[g]	4, 6, 8, 10, 12, 14, 16, 18, 24, 30, 36	All pressures
Carbon monoxide	6, 8, 24	20, 30
Propane	6, 8, 10	50, 75, 100
Vinyl chloride	8, 10	50, 75, 100

Within the IPORBM tool, there is a set of default ignition probabilities which are listed in Table 19.

[f] *There is no description of what a K1 substance is.*
[g] *A flammable liquid with flash point < 21°C and a vapour pressure at 50°C which is < 1.35 bar (pure substances) or < 1.5bar (mixture).*

Table 19 Default ignition probabilities for pipelines in IPORBM

Ignition probability scenario	Immediate ignition	Delayed ignition
Natural gas – rupture	0.09	0.91
Ethylene/propane/vinyl chlorine leak	0.14	0.86
Ethylene/propane/vinyl chlorine rupture	0.30	0.7
Ethylene oxide	0.10	N/A
K1 liquids	0.10	N/A
K2 liquids	0.01	N/A

The document goes on to present a populated event tree for road transportation of pressurised materials and gives an overall ignition probability of 0.3 (See Appendix 6). The structure of the event tree is dependent on the type of release, i.e. instantaneous or continuous and direct and delayed ignition are also taken into account. It is not clear what the 'relevant release' option represents, but it is likely that all relevant releases result in ignition and all non-relevant releases result in no ignition, so it is a novel way of presenting the overall ignition probability.

4.10 GEXCON GAS EXPLOSION HANDBOOK

This website [25] introduces the concepts of explosion safety and was written by a multidisciplinary team (including BP and HSE) as part of the 'Gas Safety Programme 1990-1992'. Chapter 4 focuses on the 'Combustion properties of fuel-air mixtures' and outlines factors that can affect ignition.

4.10.1 Flammability limit

It is only possible to ignite a cloud if the concentration lies within the flammability range. For hydrogen, this range extends between (approximately) 5-75%, so there is a high likelihood that the gas will be somewhere in this range on release and will stay within it for some time. Other substances have much narrower ranges: ethylene is between 4-38%, methane is between 5-15% and propane is between 2-10%, so the ignition source may have to 'wait' until the cloud reaches the required conditions, which may not last very long.

4.10.2 Laminar flame speed

This property is determined though experiment and represents: 'the propagation velocity of the flame normal to the flame front into the reactants under laminar flow conditions'. For hydrocarbon-air mixtures, this can be taken as a measure of reactivity, for example, hydrogen has a flame speed of 28 m/s but methane has a much lower speed at 3.5 m/s. Other substances of note are ethylene, which has a laminar flame speed of 6.5 m/s and propane, which has a speed of 4.0 m/s.

4.11 EVENT TREE STRUCTURE

This section is a brief summary to confirm that the event tree structure used by HSE is appropriate based on the literature review.

The event tree structure has not changed significantly since PRAM as all the components are there but in some cases they have been amalgamated or split into other nodes (the split into delayed local and delayed remote being the obvious example).

The immediate ignition is required to account for ignitions, e.g. fireballs, which result as a consequence from the release impact. This component is relevant to all the event trees identified and is an integral part of the event tree so its removal is not an option.

Most documentation from the literature review did not include the effects of obstructed releases (see the Appendices) including the early PRAM tree. However, if the pipeline is punctured at the side, the crater caused by the blast will reduce the momentum of the released cloud, which disperses in a different manner to a jet release. The obstructed release scenario is still valid and should be retained in the event tree.

Some sources ([24] being the most notable) only refer to delayed ignition and do not specify the proximity to the release point. Splitting into different forms of delayed ignition has its advantages, for example, ignition sources may be better controlled closer to the pipeline than in the far field, and as it spreads, the cloud has a bigger area in which to find a remote ignition source (see Table 10) thus affecting the probability. Appendix 4 gives the event tree for another source [20] which specifies delayed ignition in terms of a release than results in an explosion (VCE) or a release that results in a fire, (the fire scenarios would cover jet fires and flash fires for this reference).

A number of references ([20] and [24]) where the event tree is explicitly given in this report and others that are not ([27] and [26]) seem to include vapour cloud explosions as an option. A variety of HSE literature (e.g. [5]) states that VCEs were originally neglected from the MISHAP event tree (and its predecessors) because the tool was based on areas where the degree of confinement and congestion were minimal. This means the risk associated with the VCE was small when compared to the risk from an ideally burning flash fire [6] and was thus neglected (the TPEP event tree value may support this). As VCE is currently widely used as a possible event, it may be worth exploring the effects of including it in MISHAP as an option in the future.

On the whole the current MISHAP event tree is valid but further investigation into the inclusion of VCE may be required, particularly considering the events at Buncefield.

5 COMPARISON OF CURRENT EVENT TREE PROBABILITIES

The following sub-sections consider each of the MISHAP event tree nodes in turn, and compare the probabilities assumed with UKOPA suggestions and values found in the literature.

5.1 OVERALL IGNITION PROBABILITY

Table 20 lists the current HSE ignition probability values and the proposed UKOPA ignition probabilities for ethylene and propane. From some sources, it was possible to obtain overall ignition probability values, which are listed in Table 21.

Table 20 HSE and UKOPA overall ignition probability values

Model	Substance	Ignition probability
HSE	Non-natural gas	0.84
	Natural gas	0.44
UKOPA	Ethylene	0.66
	Propane	0.498

Using equation (1) from section 4.6, the overall ignition probability can be estimated from a correlation developed [12] for high-pressure natural gas pipelines. A typical natural gas pipeline has an operating pressure of 32 barg with an external pipeline diameter of 0.762 m [17] (the paper does not clarify if the pipeline diameter is internal or external so external has been assumed). Applying these values to equation (1) yields an ignition probability value of 0.31, which is similar to the value of 0.44 which is currently used.

Table 21 Overall ignition probabilities from literature

Reference	Comments	Ignition probability
Ignition probability of flammable gases [13]	Ignition probabilities for LPG releases that resulted from rail accidents (non-natural gas)	Large release – 0.7 Small release – 0.1
	Ignition probabilities for natural gas failures (Data are from three sources referenced by [13])	Ruptures – 0.5[h], 0.26[i] and 0.35[j] Leaks – 0.1[i], 0.16[j] and 0.03[k]
Safety evaluation of the Trans-Pennine Ethylene Pipeline (TPEP) and booster station	Average of the ignition probabilities used (Based on 50 mm, 20 mm and 5 mm holes for ethylene)	Urban – 0.77 Rural – 0.43
A review of ignition probabilities for use in offshore installation quantified risk assessments [8]	Confined – massive release Semi-confined – massive release Open – massive release (Based on hydrocarbons so comparable to natural gas)	0.5 0.3 0.2
Development of algorithms for predicting ignition probabilities and explosion frequencies [20]	Generic probabilities based on oil and chemical process operations, with some input from offshore oil/gas production. See Appendix 4 for the event tree. This is based on the default probability values.	0.405
Ignition probability for high pressure gas transmission pipelines [12]	High pressure natural gas pipeline	0.31

For natural gas, the probability values for a significant release range from 0.26 to 0.5; the current value of 0.44 for natural gas lies comfortably within it. Reference [8] is useful as it indicates how increasing levels of confinement affect the overall ignition probability for typical gaseous offshore hydrocarbon releases. The size of release is not taken into consideration in the MISHAP event tree, so these values are only useful as a way to determine the upper and lower limits of a range.

For non-natural gases, a value of 0.77 was found for ethylene as shown by Table 21, which lies in the middle of the value proposed by UKOPA (0.66) and the value currently used by HSE (0.84). For propane, a value of 0.498 was proposed by UKOPA, which is considerably different to the literature value of 0.7 for LPG.

As there are more references to natural gas, the overall ignition probability can be estimated with greater confidence than that of non-natural gas. As natural gas pipelines are the most prevalent, this is where most of the research is focussed. Further work is required to derive non-natural gas probabilities.

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[h] *World-wide, Townnsend & Fearnehough (1986)*
[i] *US Gas, Jones (1986)*
[j] *European Gas, European Gas Pipeline Incident Data Group (1988)*

5.2 IMMEDIATE IGNITION

Table 22 gives the overall immediate ignition probabilities that are used by HSE for natural and non-natural gas as well as the ethylene and propane values proposed by UKOPA. The literature examined did not discuss immediate ignition probabilities for ethylene as most onshore ignition probabilities identified were for LPG. The literature probability values are listed in Table 23.

Table 22 HSE and UKOPA immediate ignition probability values

Model	Substance	Probability
HSE	Non-natural gas	0.2
	Natural gas	0.25
UKOPA	Ethylene	0.2
	Propane	0.2

Table 23 Immediate ignition probabilities from literature

Reference	Substance	Probability
A review of ignition probabilities for use in offshore installation quantified risk assessments [8]	LPG	0.24 to 0.31
	Natural gas	0.2 (massive open release)
Ignition probability review, model development and look-up correlations [7]	LPG	0.1
	Natural gas/methane	<0.1
A guide to quantitative risk assessment for offshore installations [10]	Natural gas[k]	0.1 (immediate) 0.2 (within 0-4 mins)
Classification of hazardous locations[l] [9]	Offshore flammable gas	0.3 (massive release)
Ignition probability of flammable gases [13]	LPG and other flammable substances	Industrial – 0.29 Non-industrial – 0.18
	LPG (rail car accidents)	Large release – 0.29 Small release – 1.0
Guideline for Quantitative Risk Assessment, Part 2: Transport – Purple Book [24]	Natural gas – rupture	0.09

The probability of natural gas ignitions that are immediate vary between 0.1 and 0.3, so retaining the current value of 0.25 seems appropriate based on the limited literature. The large releases are chosen for comparison because it is assumed that a leak from a pipeline will result in a significant release.

For LPG, the immediate ignition probabilities are slightly higher than for natural gas and lie between 0.24 and 0.31, which suggests the value for propane should be higher than natural gas

[k] Document states the substance as being gas. As the release is offshore, natural gas has been assumed.
[l] This release was not stated as immediate in the document, but it is assumed to be immediate here.

despite the similarities in minimum ignition energy, and higher than the value of 0.2 proposed by UKOPA. The probability values from 'Ignition probability review, model development and look-up correlations' should be treated with caution as these values are obtained from a model that requires further peer review and testing so they have been ignored from the LPG range given previously.

For ethylene, no information was available for immediate ignition. Using the minimum ignition energy, it is evident that the ethylene ignition probability value should be greater than natural gas/methane and propane, as ethylene requires less energy to ignite than either of these substances. A value of 0.2 for immediate ignition of non-natural gas (HSE method) and ethylene (UKOPA method) compared with the natural gas/methane value of 0.25 does not appear reasonable. A value above 0.35 is more appropriate for ethylene (the reasons for this value are discussed more fully in 6.2.1).

5.3 UNOBSTRUCTED AND OBSTRUCTED RELEASES

Table 24 lists the overall probability of an unobstructed release occurring when immediate ignition does not take place. Table 25 depicts the available information that was obtained from the literature review. The majority of documented event trees identified did not consider the effects of obstructed releases, which is an important factor especially if the puncture to the pipeline occurs at the side. Impingement on the crater produced in the blast is likely to reduce the momentum of the cloud, which in turn, affects the dispersion. Even though the literature review does not support the use of obstructed releases, the impact it will have on the state of the cloud is too important to ignore.

Table 24 HSE and UKOPA unobstructed release probability values

Model	Substance	Probability of unobstructed release
HSE	Non-natural gas	0.8
	Natural gas	0.5
UKOPA	Ethylene	0.8
	Propane	0.8
	Natural gas	0.8

Table 25 Unobstructed and obstructed release probability values from literature

Reference	Situation	Proportion of unobstructed releases
Comparison of risks from carbon dioxide and natural gas pipelines [17]	Unobstructed	0.63

UKOPA believe the probability of unobstructed releases should be the same for both ethylene and natural gas as the contents of a pipeline should not influence the probability of jet impingement, thus UKOPA proposes a value of 0.8 [2]. HSE's current non-natural gas event tree agrees with this value.

The literature review could not identify any sources to support the current use of 0.8, or any historical evidence to suggest why it or 0.5 for natural gas was adopted in the first place. As the value chosen should be independent of the substance released, recent work by HSL on carbon dioxide pipelines is the most up to date documented material available; this gives the proportion of unobstructed release as 0.63 based on available data [17].

Changing the value from 0.5 to 0.63 for natural gas has no impact on the overall ignition probability or the summed probabilities of each scenario (i.e. fireball + jet fire or jet fire etc.). This is because HSE assumes that no flash fire occurs for natural gas, as shown in Figure 1. For non-natural gas, the overall ignition probability and the sum of the scenario totals change. As the unobstructed contribution reduces, the overall ignition probability rises which is due to the 'flash fire and jet fire' scenario increasing at the cost of the 'no ignition' scenario.

5.4 DELAYED IGNITION

The majority of the literature examined focused mainly on the probability of the release igniting immediately or not, and did not take into account whether ignition occurred locally or remotely. It is likely that these probability values will be largely case dependent because the density of ignition sources surrounding a release is not easy to predict.

The Dutch purple book [24] gives the probability of delayed ignition as 0.86 for ethylene leaks and 0.7 for ethylene ruptures. The data were not split into remote and local sources. For LPG, the ignition probability increases over time [8 and 10], which is applicable to other substances.

5.4.1 Delayed local ignition

Table 26 summarises the delayed local ignition probability values used by HSE and proposed by UKOPA for obstructed and unobstructed releases.

Table 26 HSE and UKOPA delayed local ignition probability values

Model	Substance	Release type	Probability
HSE	Non-natural gas	Unobstructed	0.8
		Obstructed	0
	Natural Gas	Unobstructed	0.25
		Obstructed	0.25
UKOPA	Ethylene	Unobstructed	0.5
		Obstructed	0.5
	Propane	Unobstructed	0.25
		Obstructed	0.25

UKOPA proposes that as ethylene has a lower minimum ignition energy than natural gas/methane (half), it should be twice as likely to ignite, thus giving a probability of 0.5 which is twice that of natural gas/methane (0.25).

For non-natural gas there is no documentation to support the selection of zero for obstructed releases experiencing delayed local ignition. However, using zero here generates the original PRAM event tree (and thus PRAM probability values), which has been used in the past for ethylene, a non-natural gas.

For non-natural gas, it is likely that delayed local ignition for obstructed releases was set to zero as a cautious approach because there was insufficient data available to suggest an alternative value.

5.4.2 Delayed remote ignition

The MISHAP event tree assumes that delayed remote ignition and therefore a flash fire cannot occur when a natural gas release is unobstructed. Table 27 lists the delayed remote ignition probabilities when a release is obstructed.

Table 27 HSE and UKOPA delayed remote ignition probability values

Model	Substance	Probability
HSE	Non-natural gas	0.8
	Natural Gas	0
UKOPA	Ethylene	0.8

HSE proposes a value of 0.8 for non-natural gas while UKOPA also propose a value of 0.8, this time for ethylene. As HSE and UKOPA agree, it may be appropriate to maintain this value in MISHAP.

The delayed remote ignition probability should be kept at zero because during a release of high-pressure methane, initially the cloud cools significantly during the expansion process so local ignition of the cold, dense cloud is possible. Further downwind, buoyant behaviour becomes apparent so ignition by remote ignition sources at ground level is not possible so flash fires are excluded for natural gas [5].

5.4.3 Time of ignition

Tables 10 and 13 illustrate, based on the literature reviewed, how the ignition probability varies as a function of time, though using a different time interval scale. The literature in which the tables were found [8 and 10] do not state whether the release at the time of ignition was local or remote, though assuming immediate ignition occurs within 30 s, the data could be used to make very rough estimates of immediate and delayed ignition. As the probability values used by HSE and UKOPA are not time dependent it does not seem appropriate to compare them against this literature.

Overall the literature review has been compiled based on event trees and probability values that are relevant to MISHAP. When this has not been possible, information relating to other relevant substances has been used as a guide and should therefore be treated with caution. Other sources do not fully explain where their data comes from, so again caution is required when using the literature results.

Section 6 uses the results of the literature review to assemble and analyse suggested conditional probability values in terms of each node on the event tree, i.e. immediate ignition, release unobstructed etc. Event trees based on the results are then suggested.

6 DISCUSSION

The previous sections have focused on identifying ignition probability and conditional probability values that are currently used in industry to assess how appropriate the current HSE MISHAP event trees are. UKOPA [2] lists a number of physical properties, which may influence the ignitability of a substance; for example, using the minimum ignition energy, ethylene (0.12 mJ) requires less energy to ignite than methane (0.22 mJ) so correspondingly, it should have twice the ignition probability. The validity of this concept will be explored further in the following sections.

Sources citing immediate ignition probability values for highly flammable substances such as ethylene and hydrogen could not be found, so using the difference in minimum ignition energy is a logical first step.

6.1 MINIMUM IGNITION ENERGY AND OTHER PHYSICAL PROPERTIES

The minimum ignition energy is defined as: 'that required to bring the minimum volume to a temperature that will allow combustion' [13] and can be measured experimentally using spark ignition. This is a repetitive technique that measures the spark energy required to ignite a fuel/O_2 or fuel/air mixture, the minimum value being taken as the minimum ignition energy [18]. Ignition energy is often used to measure the ignitability of a substance though it is dependent on many factors, including: mixture temperature, pressure and composition etc.

The majority of the alkane family (e.g. ethane to heptane) have minimum ignition energies that are comparable in size, but methane has a slightly larger minimum ignition energy because it consists of carbon-hydrogen bonds which are harder to break than the carbon-carbon bonds present in ethane etc. Natural gas is a mixture of methane and 'impurities' from the carbon-hydrogen bonded higher alkanes. The presence of these differently bonded substances is enough to lower the minimum ignition energy of natural gas to a similar, though still slightly larger, value to that of the other alkanes [13]. The domination of methane means it can still be used to represent natural gas. Despite being labelled as extremely flammable under CHIP [28], methane is regarded as low reactive by other sources [25 and 26] which means flame acceleration is inhibited (methyl chloride is another low reactive R12 substance) unlike the other members of the alkane family.

Spencer and Rew [13] reference Britton [19] where a more detailed analysis of ignition energy in terms of substance was carried out; the review can be found in Table 28. Five ignition energy ranges are defined, from 0.01 to 1000 mJ, which correspond to a particular material and type of ignition source. Ethylene and hydrogen require the least amount of energy for ignition to occur, so ignition could arise from weak sources such as radio frequency pick-up to strong sources such as flames. Methane requires slightly more energy to ignite, and sources such as mechanical sparks and flames will be of sufficient energy, whereas radio frequency-pick up will not. This list suggests that substances with small minimum ignition energies are more likely to ignite than materials with higher ignition energies due to a wider range of suitable ignition sources.

Table 28 Illustration of ignition energy ranges

Minimum ignition energy (mJ)	Explosive mixture	Examples of explosive gas and dust mixtures	Ignition source
100-1000	Coarse dusts and mists, very insensitive gases	Methylene chloride, ammonia	Flames, chemical sources, large hot spots, propagating brushes
10-100	Typical sub-200 mesh dusts, typical mists, insensitive gases	Lycopodium	Personal spark limit, bulking brush limit
1-10	Sensitive dusts, fine mist, some gases in air	Acetone	Brush limit
0.1-1	Typical gases in air, very sensitive dusts, very fine mists	Methane, methanol	Mechanical sparks, stray current sparks, ungrounded conductors, small hot spots
0.01-0.1	Sensitive gases, primary explosives and oxygen enriched air	Ethylene, hydrogen	Discharges from textiles, weak inductive coupling, weak radio frequency pick-up.

Spencer and Rew [13] also reference Jeffreys *et al* [21] who state that probabilities are dependent on fuel type and will thus be higher for materials such as propane and butane than for methane, due to smaller values of minimum ignition energy.

Moosemiller [20] discusses the development of algorithms for predicting the explosion frequencies for a variety of process and environmental conditions based on frequencies of initiating events and conditional probabilities associated with immediate and delayed ignition. Equations 3 and 4 (which are given below as a reminder) show the relationship that was explored for immediate ignition which was constructed based on the potential for autoignition (P_{ai}) and the potential for static discharge (P_{sd}). P_{ai} is related to the ratio between the release temperature and the autoignition temperature and P_{sd} is related to the process pressure and the minimum ignition energy. As the minimum ignition energy decreases P_{sd} increases as shown in Figure 7.

$$P_{imm.ign} = P_{ai} + P_{sd}$$

$$P_{imm.ign} = \left[1 - 5000e^{-9.5\left(\frac{T}{AIT}\right)}\right] + \left[\frac{0.0024 \times P^{1/3}}{MIE^{2/3}}\right]$$

The first term (P_{ai}) can be ignored as it is set to either 0 or 1 depending on the ratio of T and AIT. The second term (P_{sd}) is more useful as the dependence of minimum ignition on immediate ignition can be explored. The pink line was derived using a fixed source pressure of 1350 psig and a MIE ranging from 0.01 mJ (scenario 1) to 0.4 mJ (scenario 9). The blue line was derived using a constant MIE of 0.12 mJ and source pressures that vary from 200 psig (scenario 1) to 2000 psig (scenario 9).

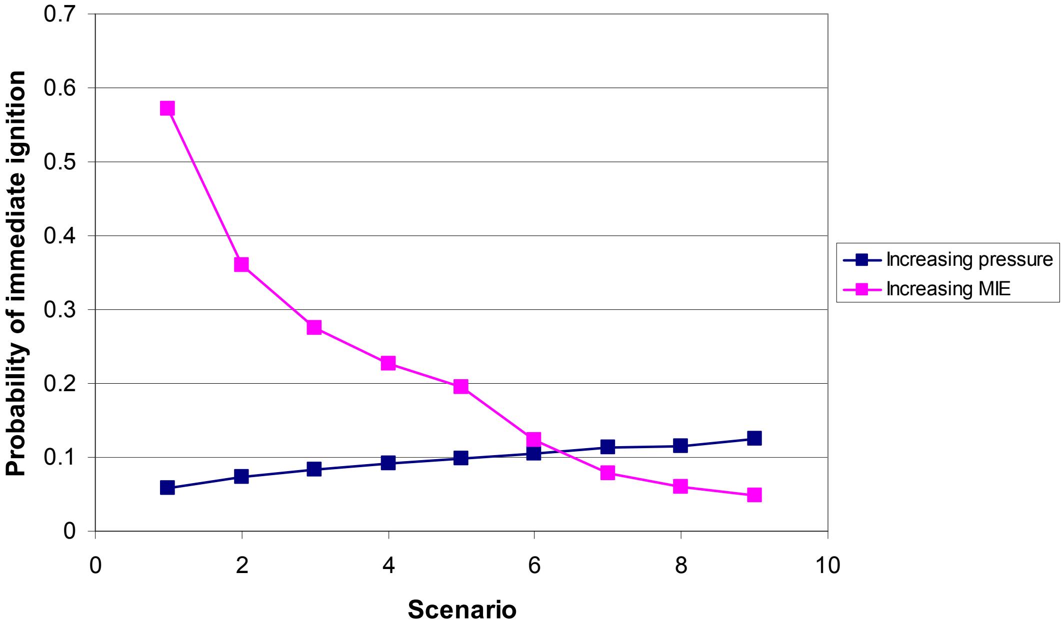

Figure 7 The blue line illustrates how the probability of immediate ignition varies with increasing pressure (constant minimum ignition energy) and the pink line with increasing minimum ignition energy (constant source pressure). Note that the pink line is completely independent from the blue line, i.e., the pink scenario 1 does not correspond to the blue scenario 1 and so on.

Figure 7 shows that varying the source pressure does not have a significant effect on the probability of immediate ignition, provided the MIE remains constant. The minimum ignition energy is shown to have an influence on the probability of immediate ignition and thus the overall ignition probability value.

Table 29 lists the minimum ignition energies for a range of materials, most of which belong to the alkane family and have very similar minimum ignition energies. Using the minimum ignition energy as a basis for determining ignition probability, it follows that substances with similar characteristics can be grouped together and represented by the same event tree in MISHAP, rather than individual event trees that are substance specific.

Table 29 Minimum ignition energies for selected substances in air from various literature

	Minimum ignition energy (mJ) [3]	Risk phrases [29, 30, 31 and 32]
Carbon disulphide	0.01-0.02	R11
Carbon monoxide	-	R12 – low reactive
Hydrogen	0.019	R12
Acetylene	0.02	R12
Ethylene	0.12	R12
Benzene	0.22	R11 – high reactive
Ethane	0.24	R12
Propane	0.25	R12
n-Butane	0.25	R12
n-Hexane	0.25	R11
n-Heptane [30]	0.24	R11
Methane[m]	0.29	R12 – low reactive
Ammonia	Up to >100	R10 – low reactive

Table 29 also lists the risk phrase[n] for each substance, which is also an indicator of flammability. R12 materials are classed as extremely flammable, R11 materials are highly flammable and R10 materials are flammable. The following are extracts from CHIP [28]:

- R12 – 'Chemicals that have an extremely low flash point and boiling point, and gases that catch fire in contact with air.' The flash point is usually < 0 ºC and the boiling point is ≤ 35 ºC [35];

- R11 – 'Chemicals that may catch fire in contact with air, only need brief contact with an ignition source, have a very low flash point or evolve highly flammable gases in contact with water.' The flash point is usually < 21 ºC [35]; and

- R10 – Materials that have a flash point between 21 ºC and 55 ºC [35].

Grouping solely in terms of minimum ignition energy may not capture the flammability or reactivity of a substance; likewise, grouping solely in terms of R-phrase may not be straightforward or appropriate. For example, hexane and heptane have similar minimum ignition energies to the lighter alkanes such as butane and propane, however the former are classed as R11 substances and the latter as R12 substances. As the R11 substances are considered not as flammable as R12 substances, it follows that the ignition probability should be slightly lower. The same issue arises with methane, which is classed as an R12 material but has been labelled as low reactive [26 and 27] and has a slightly larger minimum ignition energy than other alkanes. It follows that methane could be grouped along with R11 materials,

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[m] *UKOPA use a minimum ignition energy of 0.22 mJ for methane, which shows that varying results can be obtained due to the experimental set up which can be heavily influenced by the surroundings.*

[n] *Note that risk phrases are being phased out and will be replaced byH-phrases under GHS. See http://www.hse.gov.uk/ghs/implications.htm for details.*

however, as methane is less dense than air the flash fire probabilities will have to be different. The same event tree can be used for buoyant materials such as methane and R11 materials (including other low reactives), provided the delayed remote ignition probability is amended to suit whether a flash fire can occur or not.

The R12 category includes materials such as hydrogen and ethylene, which have significantly lower minimum ignition energies to other members of the R12 family so it would not be appropriate to represent these substances using the same event tree. Despite having a low minimum ignition energy, carbon disulphide is classed as an R11 material as it has a boiling point of 46ºC, as opposed to other R12 materials which have a boiling point below 35ºC [35]. It may be more appropriate to combine the minimum ignition energy and the flammability to create three representative event trees:

- Event tree 1 - R12 materials with a minimum ignition energy < 0.2 mJ;
- Event tree 2 - R12 materials with a minimum ignition energy ≥ 0.2 mJ; and
- Event tree 3 - natural gas and other buoyant materials event tree. R11 and other low reactive materials are appropriate provided the delayed remote ignition probability is amended to suit [26 and 27].

Table 33 in Appendix 7 contains a list from the Dutch Purple Book [23] indicating the reactivity of a substance. The first column for low reactivity corresponds well with Event Tree 3, as methane is common to both. The average reactivity column corresponds well with Event Tree 2, as butane and propane are common to both. The final column indicates high reactivity substances, as does Event Tree 1, and acetylene is common to both[o].

There are some caveats that should be considered when using the proposed event trees as a number of issues, which may or may not be site-specific, can affect the ignition probability (these issues have been identified from the literature review unless otherwise stated):

- As shown with natural gas, impurities can lower the minimum ignition energy;
- The stoichiometry of the fuel/air mixture can affect the minimum ignition energy;
- A narrow flammability range means the ignition source may have to 'wait' for the cloud to dilute to the required concentration. This is important for delayed ignition.
- The density of ignition sources can affect the ignition probability [34]. The strength of the ignition source will have to be larger than the minimum ignition energy;
- An increase in temperature and pressure can increase the minimum ignition energy [33], making the material less susceptible to ignition;
- The probability of immediate ignition increases as the release rate (or size of release) increases. This may not be important for MISHAP as the hole size and thus release rate is accounted for in the failure frequency (see the PRAM event trees in Appendix 1);
- The ignition probability seems to increase as the duration of the release increases;
- High laminar flame speeds indicate the material is reactive. Methane has a low flame speed compared to ethylene; and
- The ignition probability increases with confinement.

[o] *Note that the majority of the substances labelled as high reactive in Appendix 7 have little or no substance information readily available, so they have been labelled as high reactive for conservatism.*

6.2 PROPOSED EVENT TREES

Taking into account the literature review and proposals based on the minimum ignition energy and the flammability, a number of event trees can be constructed. The following event trees use the current natural gas event tree as a basis, though values are changed to suit the type of material.

6.2.1 Event Tree 1 – R12 materials with a MIE < 0.2 mJ, e.g. ethylene

UKOPA quote a minimum ignition energy of 0.22 mJ for methane and 0.12 mJ for ethylene, so a simple assumption would be that the ignition probability for ethylene is roughly twice the value for methane.

Using the current HSE event tree for natural gas (immediate ignition of 0.25) this would yield an ignition probability of 0.5. Initially, flow rates are high and during this time it is likely that 'other factors' (i.e. the caveats given in section 6.1) which lower the ignitability are more evident. A value of 0.35 for immediate ignition seems more appropriate.

Eventually the release rates will stabilise so doubling the ignition probability from 0.25 to 0.5 is more applicable for delayed ignition. A value of 0.5 for delayed local ignition is considered appropriate.

The density of ignition sources may be different in the near and far field, but as this is a site-specific parameter it can't be included in the event tree.

Work by HSL identified in the literature review used an unobstructed release probability of 0.63 for carbon dioxide pipelines. UKOPA has stated that the type of material in the pipeline should not affect the probability of an unobstructed release; this is a sensible approach to adopt so it follows that the unobstructed release probability should be set to 0.63. The literature search did not yield a convincing amount of evidence to support any value, but the value proposed is based on the best available knowledge at the time of writing.

For delayed remote ignition most sources did not further categorise into local and remote ignition though the values suggested for ethylene leaks (0.86) and ruptures (0.7) are not too dissimilar from the values currently used (0.8) for remote ignition of non-natural gas. The current value is based on best judgement so it seems prudent for it to remain at 0.8 until improved knowledge becomes available.

Based on the literature review and suggestions from UKOPA, the event tree in Figure 8 is proposed for use when modelling extremely flammable materials with low minimum ignition energies in MISHAP. This applies to substances such as ethylene and acetylene. Hydrogen is intrinsically buoyant meaning the logic of ignoring flash fires is applicable, so this event tree would not be appropriate despite hydrogen's tendency to ignite.

6.2.2 Event tree 2 - R12 materials with a MIE ≥ 0.2 mJ

This event tree can be used to model substances such as butane, ethane and propane which are extremely flammable substances, and which have a minimum ignition energy above 0.2 mJ. According to the literature search, methane tends to have a minimum ignition energy slightly higher than other members of the alkane family. As discussed in section 6.2.1, the current immediate ignition probability of 0.25 for methane should be retained, so to take into account the low reactivity and higher minimum ignition energy of methane, the immediate ignition probability proposed for R12 (with MIE ≥ 0.2 mJ) materials should be slightly higher. The literature review found immediate ignition probabilities for propane between 0.1 and 0.29, but mostly biased towards the 0.29 end of the range, which supports a slightly higher probability for Event Tree 2 type substances. An immediate ignition probability of 0.3 is proposed.

The unobstructed release probability of 0.63 remains valid. The delayed local ignition probability has been set to the same as the immediate ignition probability and the delayed remote ignition probability value has also been retained until better knowledge is available.

Based on the literature review and suggestions from UKOPA, the event tree in Figure 9 is proposed for use when modelling extremely flammable materials with minimum ignition energies ≥ 0.2 mJ in MISHAP.

6.2.3 Event tree 3 – Natural gas, R11 and low reactive materials

This event tree can be used for buoyant, R11 and low reactive materials provided the delayed remote ignition probability is amended to suit the chosen substance.

Natural gas

On the whole, the current natural gas event tree does not need to be overhauled based on the findings of the literature review, which yielded immediate ignition probabilities for natural gas between 0.1 and 0.5 depending on the size of the release, so the immediate and delayed local probability values of 0.25 can be retained.

UKOPA propose an unobstructed release probability of 0.8 while the literature review identified 0.63 as a more appropriate choice. The overall ignition probability for the natural gas event tree as well as the total probabilities for each scenario (i.e. fireball + jet fire, jet fire etc) remain unchanged on adoption of 0.63.

The conditional probability value for delayed remote ignition has been kept at zero to take into account the reasoning that natural gas is unlikely to form a significant vapour cloud due to its buoyant nature. There may be additional buoyant substances, which may be better represented using this event tree rather than one of the other trees, this is a decision which will be based on the judgement of the user.

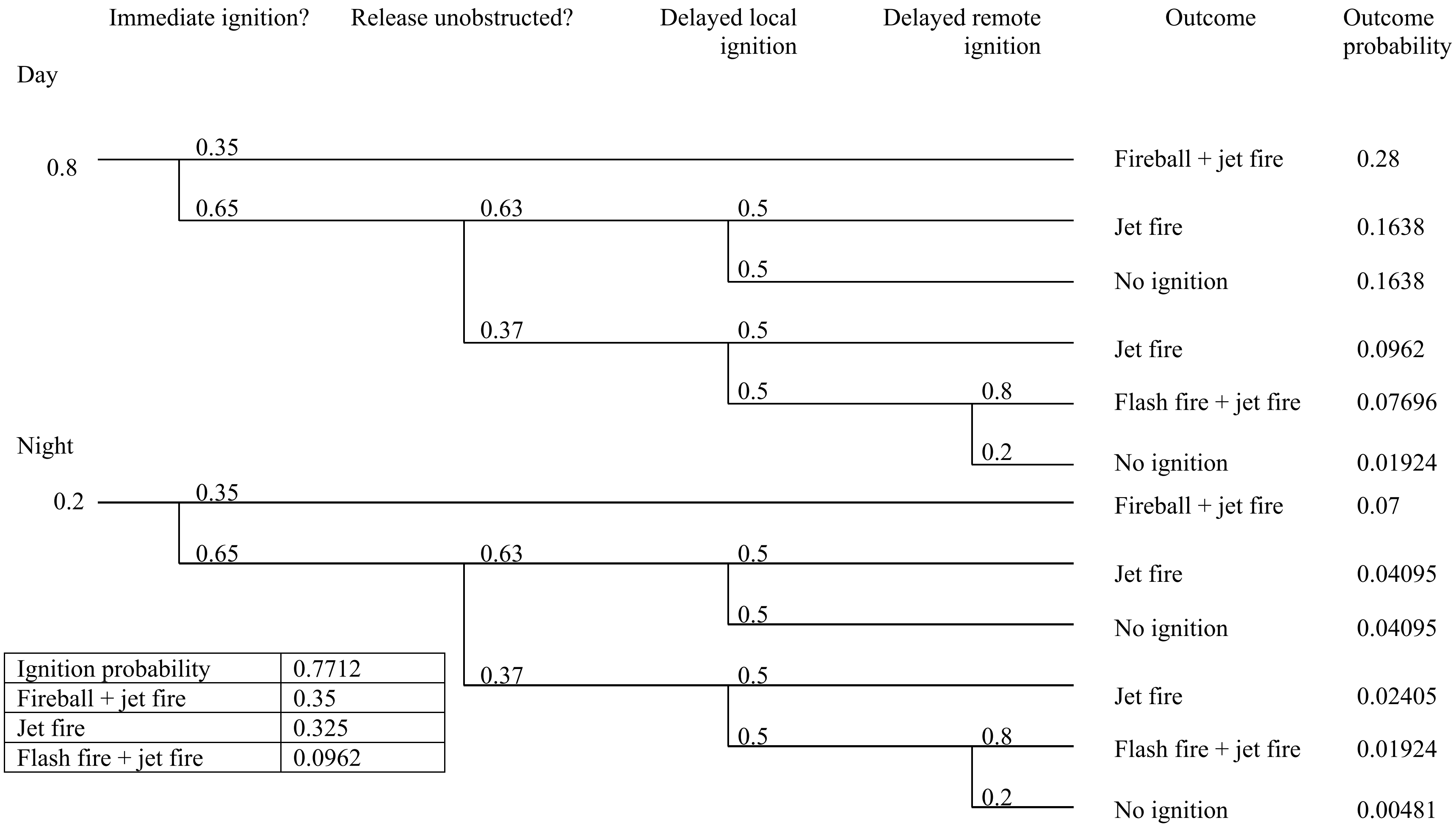
The proposed natural gas event tree is given in Figure 10, and has an overall ignition probability of 0.44.

R11 and low reactive materials

This event tree is also suitable for materials such as the flammable elements of ammonia (low reactive) and carbon monoxide (R12 but low reactive) or other flammable gases that would be transported by pipeline, provided the delayed remote ignition energies are amended.

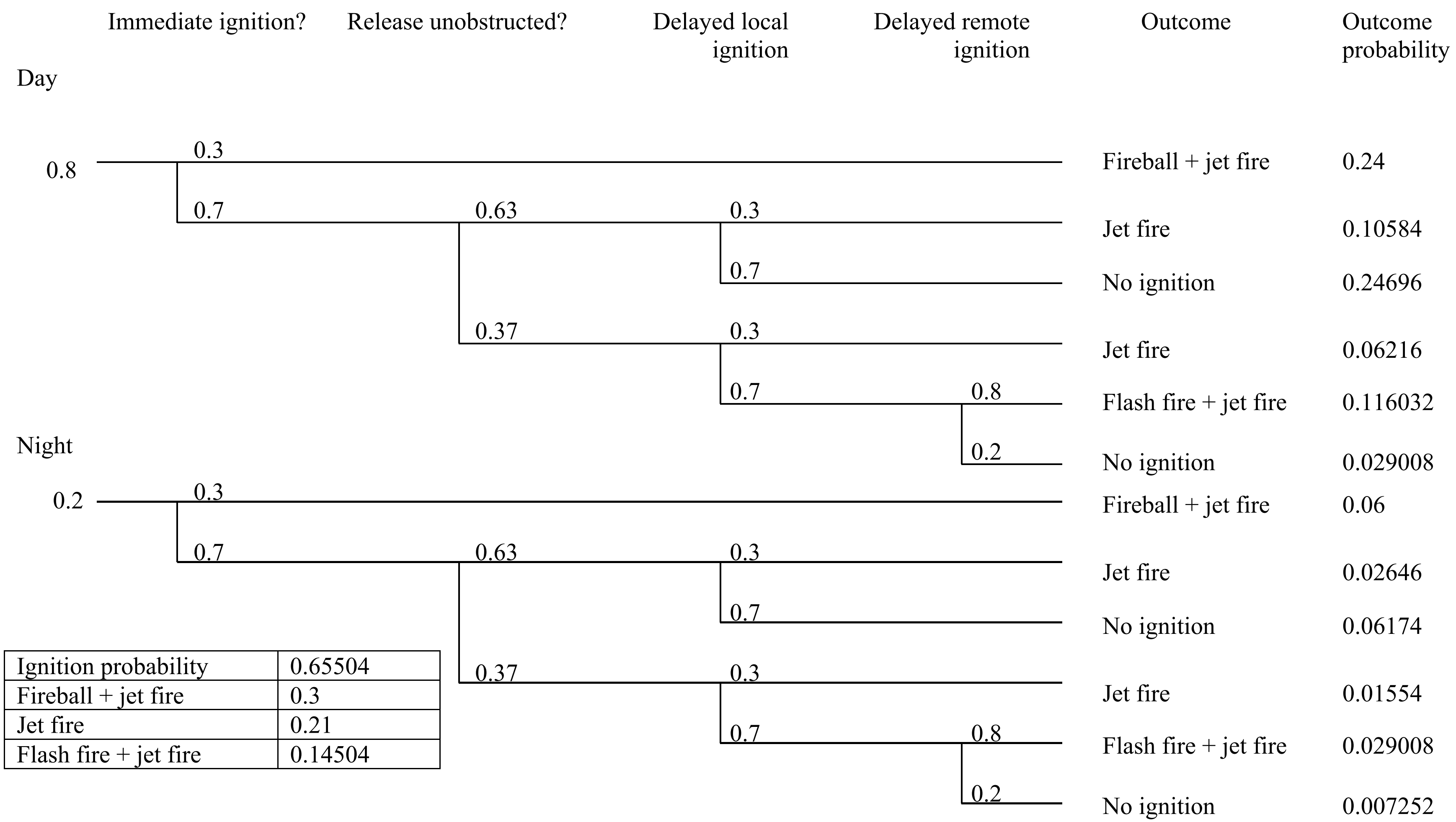
It is suggested that if the delayed ignition energies are changed to appropriate values, the event tree could be used for highly flammable materials with small minimum ignition energies and extremely flammable substances that are low reactive. This way a balance has been achieved between high flammability, low ignition potential and low flammability, high ignition potential. Due to its buoyancy, the delayed remote ignition probability value for natural gas cannot be used here, as substances such as butane are dense gases so a flash fire is a possibility. The value of 0.8 used for event trees 1 and 2 is a suitable choice.

Based on the literature review and suggestions from UKOPA, the event tree in Figure 10 (bracketed values) could be used for modelling highly flammable materials with minimum ignition energies ≥ 0.2 mJ in MISHAP.



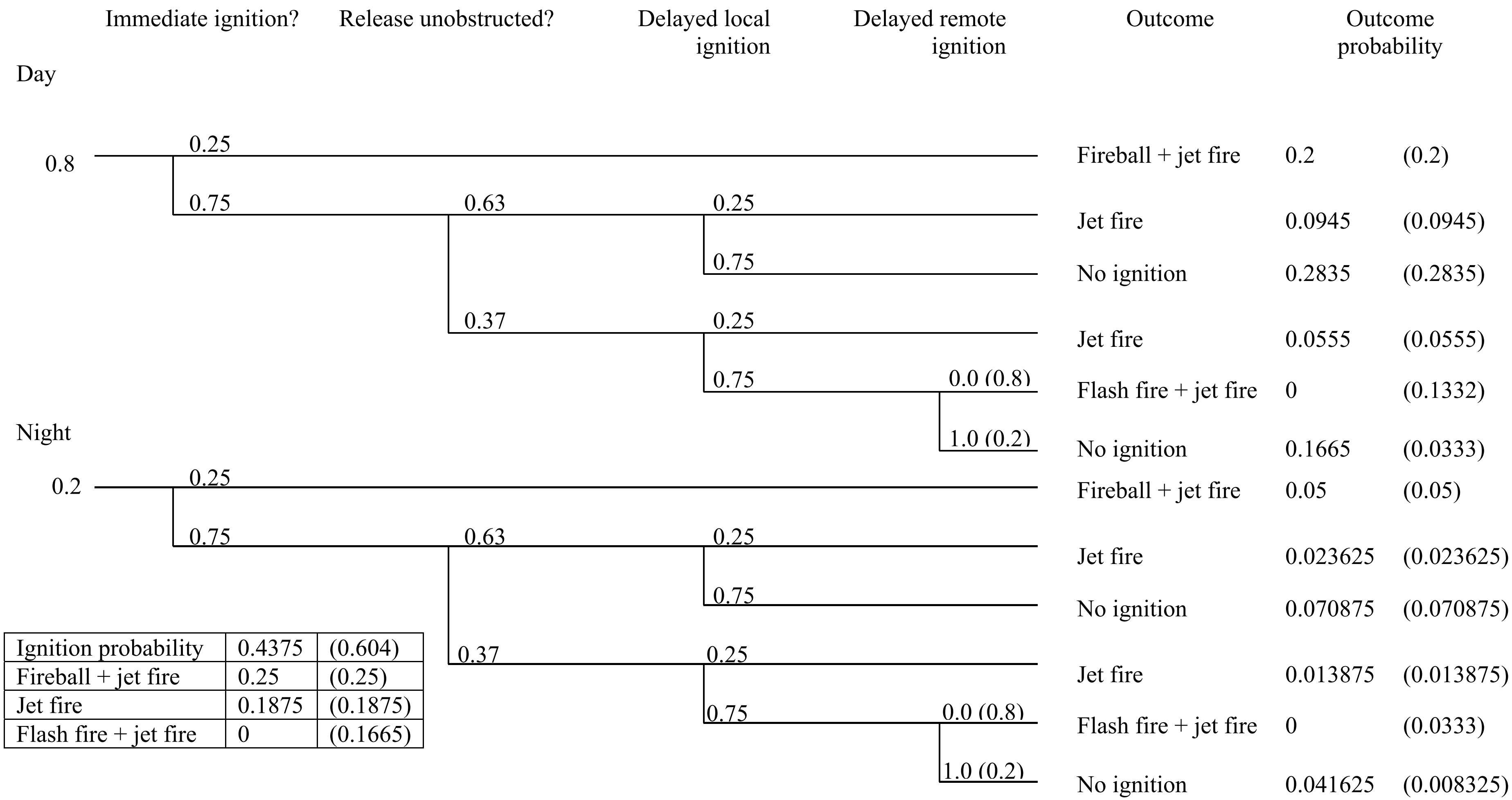
Ignition probability	0.7712
Fireball + jet fire	0.35
Jet fire	0.325
Flash fire + jet fire	0.0962

Figure 8 Event tree 1 – R12 substances with minimum ignition energies < 0.2 mJ



Ignition probability	0.65504
Fireball + jet fire	0.3
Jet fire	0.21
Flash fire + jet fire	0.14504

Figure 9 Event tree 2 – R12 substances with minimum ignition energies ≥ 0.2 mJ



Ignition probability	0.4375	(0.604)
Fireball + jet fire	0.25	(0.25)
Jet fire	0.1875	(0.1875)
Flash fire + jet fire	0	(0.1665)

Figure 10 Event tree 3 – Natural gas event tree. The values in brackets can be used for R11 and low reactive materials

7 CONCLUSIONS AND RECOMMENDATIONS

An extensive literature search was carried out using past HSE panel papers and other relevant HSE documentation to identify the origin of the probability values present in the MISHAP event trees. The search yielded numerous references to the current values used by HSE but they did not fully explain how and why they were chosen.

Another literature search was performed to highlight current probability values that are used elsewhere in industry to see if comparisons could be made with the UKOPA and HSE values to determine which set, if any, is more appropriate.

A variety of different probability values were suggested by the literature search, so no values are corroborated completely by more than one author. Most of the event tree values have been based on expert judgment plus, in some cases, historical data for similar substances or events. However, it is likely that some of the probability values used are case specific so will not be suitable for general use. There was difficulty obtaining appropriate literature for ethylene pipelines as only two papers were found that were suitable, so it would not be prudent to perform a complete overhaul of the non-natural gas event tree based solely on these sources. Natural gas/methane pipeline probability values were also troublesome to find; however, offshore hydrocarbon releases were found and included in the literature review for use as a cautious comparison. Most sources gave overall ignition probabilities and did not specify if they were obstructed or not, nor if they were remote or local.

Table 30 lists the overall ignition probabilities for current HSE and UKOPA event trees for natural gas/methane and non-natural gases, and Table 31 contains the proposals for a series of new event trees based on substance properties.

Table 30 Current ignition probabilities

	HSE current natural gas	HSE current non-natural gas	UKOPA proposed ethylene	UKOPA proposed propane
Fireball and jet fire	0.25	0.2	0.2	0.2
Jet fire	0.19	0.51	0.4	0.2
Flash fire and jet fire	0	0.13	0.06	0.098
Ignition probability	0.44	0.84	0.66	0.502

Table 31 Proposed ignition probabilities

	Event tree 1	Event tree 2	Event tree 3
Fireball and jet fire	0.35	0.30	0.25 (0.25)
Jet fire	0.33	0.21	0.19 (0.19)
Flash fire and jet fire	0.096	0.15	0 (0.17)
Ignition probability	0.78	0.66	0.44 (0.61)

Event tree 1 corresponds to R12 materials with a minimum ignition energy < 0.22 mJ; Event tree 2 corresponds to R12 materials with a minimum ignition energy ≥ 0.22 mJ and Event tree 3 corresponds to methane/natural gas (non bracketed values) as well as R11 materials and other low reactives (provided the delayed remote ignition energy is amended which affects the scenario probabilities as shown by the bracketed values in Table 31).

For ethylene (represented by Event tree 1) an overall ignition probability of 0.77 was identified from the literature for urban releases and 0.43 for rural releases. The value for urban releases comes midway between the current non-natural gas value (0.84) and UKOPA's proposed value (0.66) and is the same as the value proposed by Event tree 1 (0.78).

The literature identified overall ignition probabilities between 0.2 and 0.5 for larger releases of natural gas, depending on the degree of confinement. This is not too far removed from the value currently used (0.44) and the value proposed (0.44) for the natural gas option in Event tree 3. Evidence was not found to support the overall ignition probability of 0.60 for Event tree 3 (R11 material and other low reactives), though based on judgement, it stands to reason that it should be lower than Event tree 2.

The literature review mainly focussed on materials currently modelled by MISHAP, e.g., natural gas, ethylene and propane, so a further review may be required to substantiate the proposed values for substances other than MISHAP substances.

Despite the many variables that can affect the ignition probability, it is better to have a set of event trees that are based on the best judgement that is available at the time, in the same way that MISHAP was based on the best available knowledge at the time of inception; however, as shown, these values are not absolute and can be changed if the evidence discussed in this report is considered suitable. It may be necessary to conduct further investigation, such as historical analysis of non-natural gas releases, to see how often delayed ignition occurs. Experimental work is also a possibility if a suitable release site can be found. This further work could validate the agreed probability values.

Sharing the event trees with industry will allow the proposals to be examined, improved upon and then adopted if all parties are in agreement. Using widespread knowledge and experience in this way will identify any shortfalls in the outlined proposals and any improvements will be based on more solid foundations.

7.1 SUMMARY OF CONCLUSIONS

Overall, this report concludes that:

- The MISHAP event tree structure appears to be well founded, as all suitable event sequences and most final scenarios have been included. The inclusion of Vapour Cloud Explosions (VCEs) may be required at a later date due to the implication from the events at Buncefield;

- The probability values used in the MISHAP event tree were based on the best judgment available at the time but there is limited documented supporting evidence from HSE;

- UKOPA has put forward a number of reasonable arguments for changing HSE's non-natural gas event tree, but no detailed written supporting evidence has been provided;

- Using properties such as the minimum ignition energy to construct event trees was considered suitable, though users should bear in mind that the minimum ignition energy can vary from site to site;

- It is accepted that the probability of an obstructed (or unobstructed) release is not substance dependent, so the probability values should be the same for natural and non-natural gas. A value of 0.63 was identified from literature, rather than UKOPA's proposed value of 0.8. Note that changing this value does not affect the overall ignition probability or the totals for each scenario for the current natural gas event tree, though it does have an impact on the non-natural gas event tree by increasing the overall ignition probability;

- There was no evidence to suggest why the value for delayed local ignition of obstructed non-natural gas releases was set to 0, though using this setting converts the MISHAP event tree to the earlier PRAM event tree, which has been used to model ethylene in the past. It could be a precautionary decision made by HSE for conservatism, but there is no corroborating evidence;

- Due to the difference in minimum ignition energies, it is accepted that as ethylene is twice as likely as methane to ignite, the unobstructed, delayed local ignition event probability should be twice that of methane. This assumption cannot be applied to immediate ignition as during this period, the release rate is higher and there are other factors (e.g. stoichiometry of the fuel/air mixture, temperature etc) present which can greatly influence the ignition probability. A value of 0.35 for immediate ignition probability was applied for substances with a similar flammability to ethylene. For substances not grouped with ethylene it is assumed that the immediate ignition probability is the same as the delayed local ignition probability until better evidence can be found;

- Literature relating directly to pipelines was not available in some cases so other relevant literature was used as support. This is particularly the case for natural gas where appropriate offshore data were used. On the whole, the review identified overall ignition probabilities which are comparable to the values proposed, though further evidence would be preferable;

- Rather than representing all non-natural gas materials with the same event tree, as is current practice, the idea of using physical properties was expanded upon to include the flammability (by way of risk phrases), as this is also a measure of the ease of ignitability;

- Based on the literature, physical properties such as minimum ignition energy and flammability as well as some judgement, three new event trees have been constructed:

    - Event tree 1 – R12 materials with a minimum ignition energy < 0.22 mJ;

    - Event tree 2 – R12 materials with a minimum ignition energy ≥ 0.22 mJ;

    - Event tree 3 – natural gas and other buoyant materials. R11 and low reactivity materials are also appropriate provided the delayed remote ignition probability is amended to suit.

7.2 RECOMMENDATIONS

The recommendations are:

- The unobstructed release probability should be independent of the material released. A value of 0.63 has been derived in this report based on recent work by HSL;

- To use a set of event trees based on physical properties such as minimum ignition energy and flammability;

- Further work is required to determine if VCE should be included as an event, and what the implications would be;

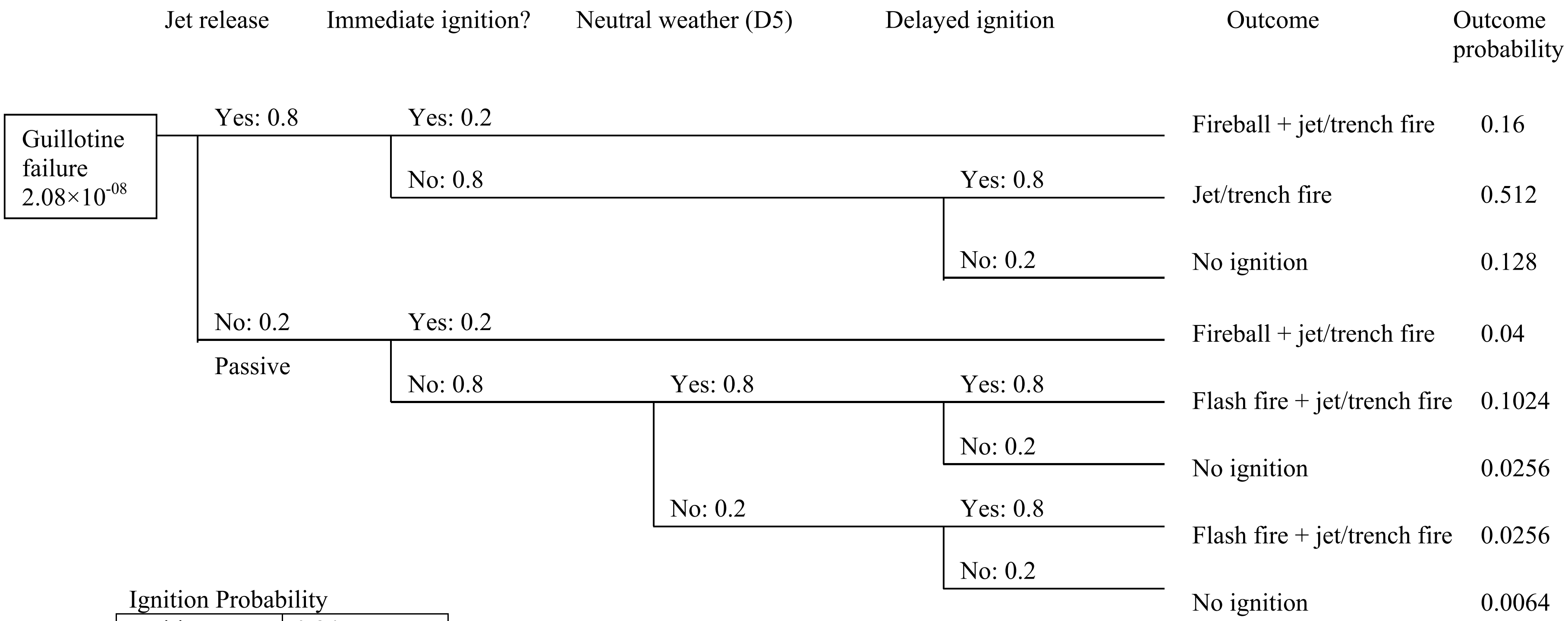
- Sensitivity studies should be carried out to identify the implications, in terms of hazard footprints and risk, from moving from two event trees to three;

- Further validation by experiment or analysis of historical data would be useful for completeness. This could include small scale experiments using common MISHAP materials, e.g. natural gas and ethylene, and performing immediate, delayed local and delayed remote ignition trials as well as obstructed releases, to compare the theoretical values proposed here with practical results. However, it is appreciated that any experimental set up would be complicated and costly to run; and

- The event trees should be made available to industry for comment.

8 APPENDIX 1 – SAFETY EVALUATION OF THE TRANS-PENNINE ETHYLENE PIPELINE (TPEP) AND BOOSTER STATION: MHAU EVENT TREE (RUPTURE)

This event tree was developed by MHAU (now HID CI5) for guillotine failure of ethylene pipelines. It was presented during 1988.

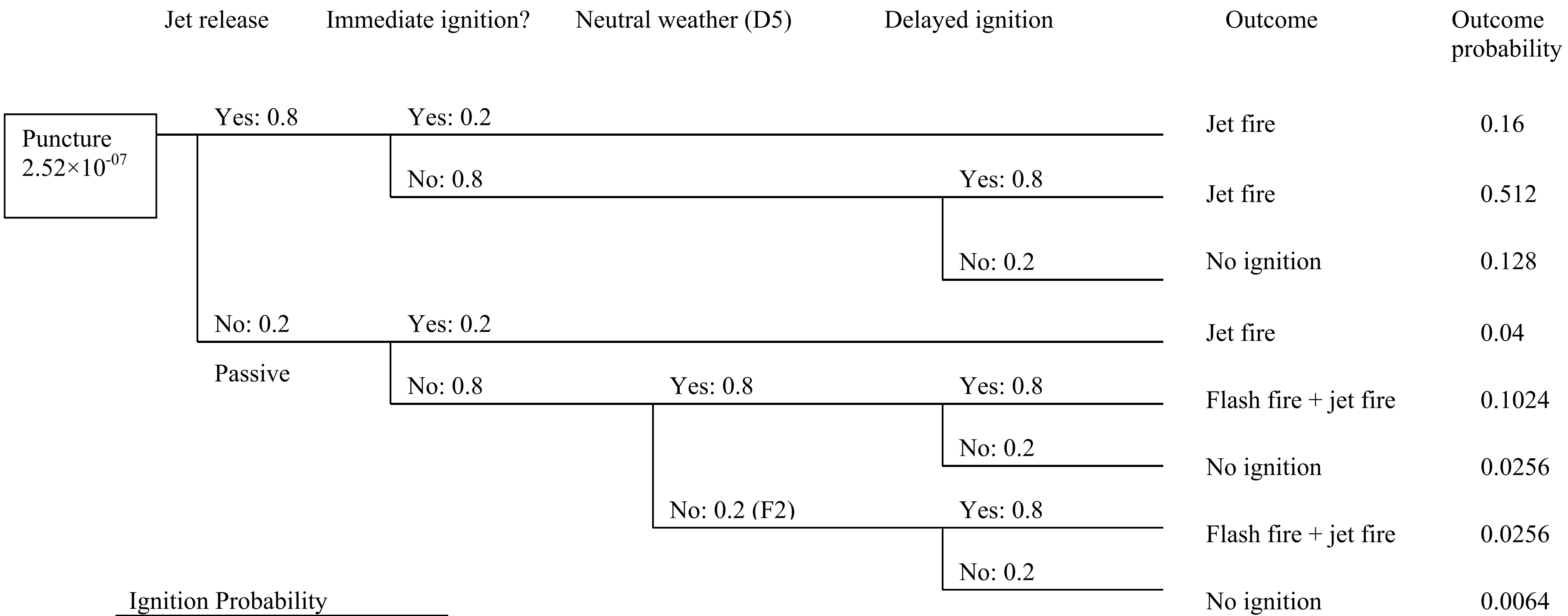


Ignition Probability

Ignition	0.84
No ignition	0.16

9 APPENDIX 2 – SAFETY EVALUATION OF THE TRANS-PENNINE ETHYLENE PIPELINE (TPEP) AND BOOSTER STATION: MHAU EVENT TREE (PUNCTURE)

This event tree was developed by MHAU (now HID CI5) for punctures in ethylene pipelines. Note that the conditional probabilities and thus overall ignition probability are the same, the difference in holes sizes are accounted for by the event failure frequency.

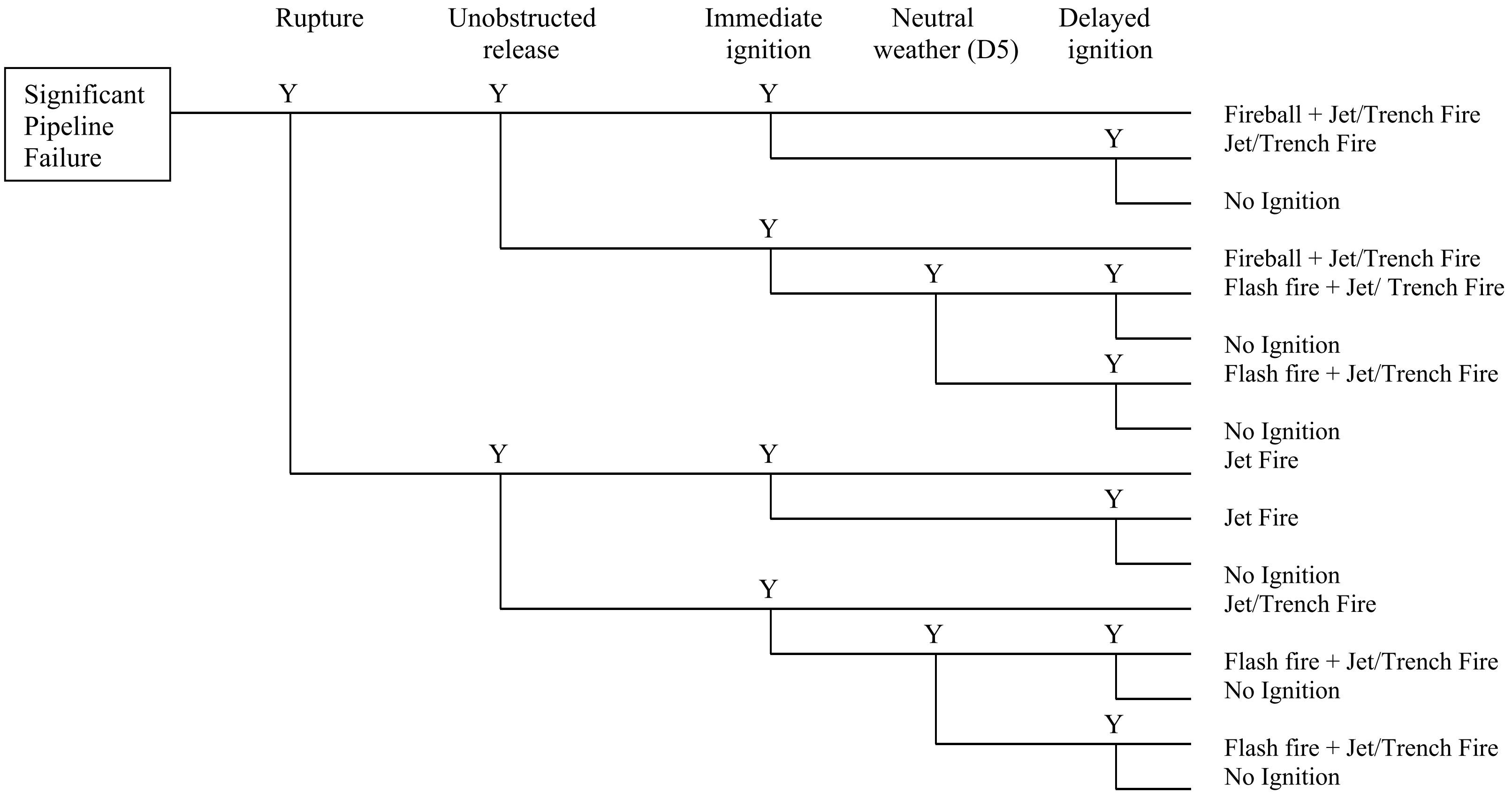


Ignition Probability

Ignition	0.84
No ignition	0.16

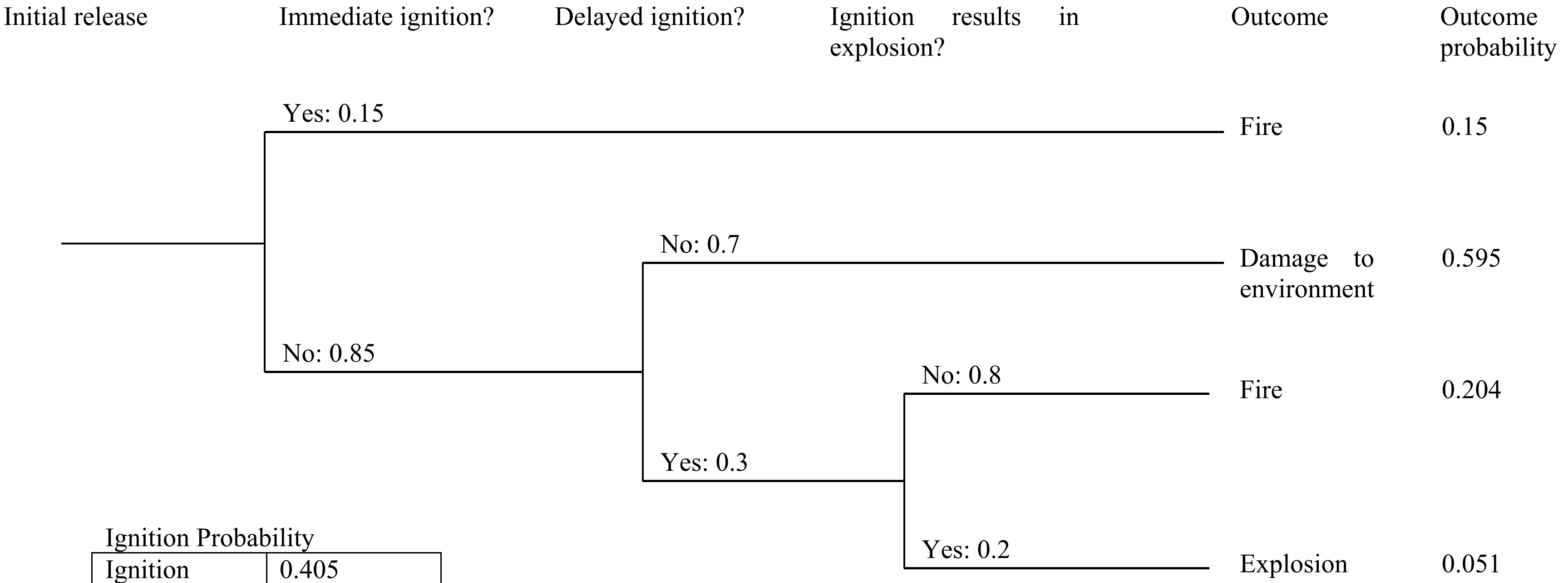
10 APPENDIX 3 – PRAM EVENT TREE

This event tree is a modified version of the event tree in Appendices 1 and **Error! Reference source not found.** and the earliest documented appearance from the literature review was 1991 [6]. Note that this event tree includes obstructed releases for the first time.



11 APPENDIX 4 – EVENT TREE BY MOOSEMILLER

This appendix illustrates the default event tree and conditional probabilities proposed by Moosemiller [20] which is based on oil and chemical process operations as well as input from nuclear and offshore oil/gas production.



Ignition Probability

Ignition	0.405
No ignition	0.595

12 APPENDIX 5 – IGNITION STRENGTH MULTIPLIERS

This appendix should be used in parallel with section 4.8, of the literature review of the ‘Development of Algorithms for Predicting Ignition Probabilities and Explosion Frequencies’ paper [20]. Table 32 was taken from this paper and lists pre-calculated source strengths which should be used for calculating the probability of delayed ignition.

The values in this table were calculated on the assumption that the cloud either continuously covers the ignition source or for some cases a stated fraction of the ignition source.

Table 32 Values for ‘S’ used in the modified duration equation

Source Type	Source	Probability of ignition in one minute (Strength ‘S’)
	If the flammable cloud size is known, use the following relationships for process plants:	
Specific (point) sources	Fired heater	0.9
	Boiler	0.3
	Flare	1
	Motor vehicle	0.3
	Train engine	0.5
Line sources	High power electrical line	$0.001 \times L$
	Roadway	$1 - 0.7^V$
Area sources	Process unit	F
	Residential population	$1 - 0.99^N$
	If the flammable cloud size is not known, use the following relationships for process plants:	
	High equipment density	0.5
	Medium equipment density	0.25
	Low equipment density	0.1
	Confined space with ~ no equipment	0.02

L = length of the line covered by the cloud, in feet

V = average number of vehicles covered by the cloud in the flammable range

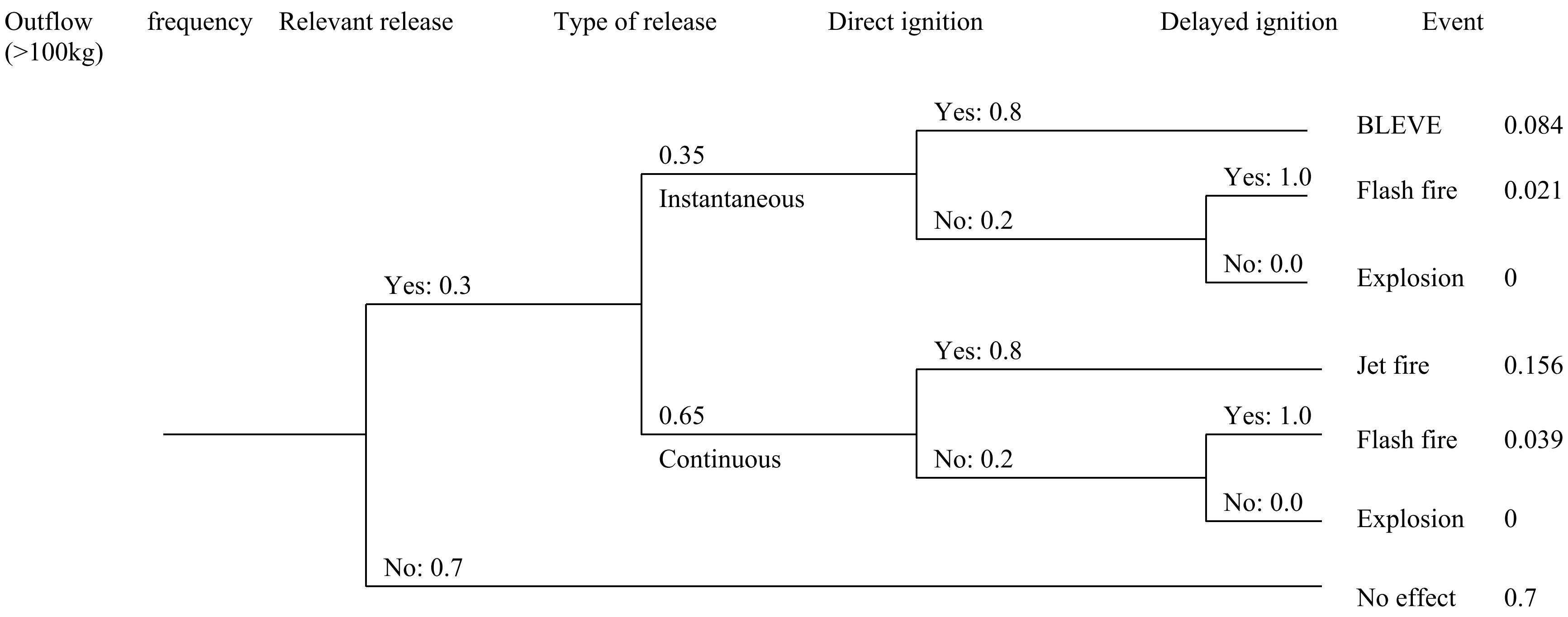
F = fraction of process unit covered by the cloud in the flammable range

N = number of people covered by the cloud in the flammable range. This includes people who are in buildings not in the flammable range inside, but having a flammable atmosphere outside.

A similar table to this for calculating the probability of ignition in one minute is presented in the Dutch Purple Book [23]. The Dutch propose a value of 0.9 for an outdoor furnace which is equivalent to the value of 0.9 given above for a fired heater.

13 APPENDIX 6 - DUTCH ROAD TRANSPORT EVENT TREE

This event tree comes from the Dutch purple book [24] and is used in the risk assessment process for pressurised flammable releases associated with road transport (e.g. drums and cylinders etc.).



Ignition Probability

Ignition	0.3
No ignition	0.7

14 APPENDIX 7 - SUBSTANCE REACTIVITY

This table comes from the Dutch purple book [23] and illustrates the reactivity of a number of substances. The asterix (*) indicates that little or no information is available about the substance in question so it has been labelled as highly reactive.

Table 33 Substance reactivity

Low	Average	High
1-chloro-2,3-epoxypropane	1-butene	1-butanethiol*
1,3-dichloropropene	1,2-diaminoethane	Acetylene
3-chloro-1-propene	1,3-butadiene	Benzene*
Ammonia	Acetaldehyde	Carbon disulphide*
Bromomethane	Acetonitrile	Ethanethiol*
Carbon monoxide	Acrylonitrile	Ethylene oxide
Chloroethane	Butane	Ethylformate*
Chloromethane	Chloroethene	Formaldehyde*
Methane	Dimethylamine	Hydrogen sulphide*
Tetraethyl lead	Ethane	Methylmethacrylate*
	Ethylene	Methylformate*
	Ethylethanamine	Methyloxirane*
	Formic acid	Naptha, solvent*
	Propane	Tetrahydrothiophene*
	Propylene	Vinylacetate*

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HSE

Health and Safety Executive

Review of the event tree structure and ignition probabilities used in HSE's pipeline risk assessment code MISHAP

The Health and Safety Executive (HSE) uses the MISHAP01 (Model for the estimation of Individual and Societal risk from HAzards of Pipelines) model to calculate the risks associated with Major Accident Hazard (MAH) pipelines in Great Britain. The risks calculated are used to determine the distances to land-use planning (LUP) zones around the MAH pipeline. The UK Onshore Pipeline Operators Association (UKOPA) has queried some of the assumptions and methods currently used within the tool and has compiled a briefing note outlying areas of concern. In response to the briefing note, HSE asked the Health and Safety Laboratory to review the MISHAP tool. The review examined the natural gas and non-natural gas event tree structures used by the tool as well as the probability values used to populate them. The review proposes replacing the generic natural gas and non-natural event trees with three event trees that take into account the minimum ignition energy of the substance and the substance reactivity. The derived event trees will feature in future versions of the MISHAP tool.

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