A Review of Natural Gas Transmission Pipeline Incidents to Derive Ignition Probabilities for Risk Assessment

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For most fuels transported by pipeline, whether or not ignition of an accidental release occurs is a critical factor in determining the extent of the resulting hazard. The probability of ignition is therefore a key input when undertaking pipeline risk assessments and the value chosen is a direct multiplier of the risk calculated. Typically, the ignition probability assigned is based on an analysis of historical data. In addition, the time of ignition also influences the consequences of gas pipeline rupture releases, due to the time-varying nature of the gas outflow which decreases rapidly following the initial failure.

For high pressure natural gas transmission pipelines it is observed that ruptures of large diameter underground pipelines operating at high pressures often result in ignited releases, even in remote areas with no obvious ignition sources present. Conversely, failures of small diameter pipelines operating at lower pressures rarely result in ignited releases.

The results of previous analyses indicated a trend for the ignition probability for rupture releases to increase linearly with pd^2, with p the pipeline operating pressure and d the pipeline diameter. The relationship forms the basis of the default ignition probabilities recommended for use in the PIPESAFE package for risk assessment of gas transmission pipelines and also presented in standards for pipeline risk assessment such as IGEM/TD/2. The most recent previous study (published in 2008) was carried out using data predominantly from pipeline incidents up to 2004.

The primary objective of this study was to update the statistical treatment to incorporate 10 years of additional data on ruptures of onshore gas transmission pipelines in order to refresh the correlation used to calculate ignition probabilities. A secondary objective was to review the extended dataset to identify cases where the information available on individual incidents included an indication of the time of ignition and to analyse this sub-set to identify any trends.

The detailed analysis of the data resulted in a number of refinements to the dataset used as well as extending it to include the additional pipeline incident data available since 2004. Applying a similar statistical approach to the previous study broadly supported the existing correlation, although possible changes are suggested to the upper bound estimates of ignition probability for very large pd^2 values. The number of incidents where the time of ignition is reported is limited (approximately 10% of the total). However, the available data shows that there is a high probability of early ignition, with the majority reported as igniting immediately or within the first few seconds. The results of the analysis are presented in the paper, together with a discussion of the possible physical causes of ignition that could be consistent with the trends observed.

Introduction

Failures of natural gas transmission pipelines have occasionally occurred around the world. Although these events are rare, their consequences can be severe [1] and well-established methods exist to predict the effects of gas transmission failures [2], [3], [4]. Unignited releases of natural gas from pipeline failures, although disruptive and undesirable commercially, are unlikely to present a significant risk to people nearby as processed natural gas is not toxic. The potential for harm arises from ignition of the gas release, the ensuing fire and resulting thermal effects on people and property (overpressure effects from ignition of natural gas releases in the open are negligible relative to the thermal effects). The probability of ignition is therefore a key input when undertaking pipeline risk assessments and the value chosen is a direct multiplier of the risk calculated. In addition, the time of ignition also influences the consequences of gas pipeline rupture releases, due to the time-varying nature of the gas release rate, which decreases rapidly following the initial failure. Whilst leaks can give rise to risks in the immediate vicinity of the pipeline, it is the full bore ruptures that determine the risks at greater separation distances. As a result, it is usually the possibility that ruptures may occur that dominate societal risk considerations, and therefore the analysis presented in this paper focuses on the probability of ignition of natural gas transmission pipeline rupture releases.

An international group of gas transmission companies established the PIPESAFE Group in 1994, to collaborate in the study of the hazards and risks involved in gas transmission by pipelines. The objective of the collaboration was to develop a risk assessment software package for gas transmission pipelines and included undertaking large and full scale experiments to validate the predictions. An important activity pursued by member companies is the sharing of learning and data associated with pipeline incidents, which supports the development and validation of appropriate risk assessment methods. Group members co-operate in this undertaking with a number of other gas transmission companies, following a similar format to EGIG [5], but not restricted to European gas transmission companies.

For high pressure natural gas transmission pipelines it is observed that ruptures of large diameter underground pipelines operating at high pressures often result in ignited releases, even in remote areas with no obvious ignition sources present. Conversely, failures of small diameter pipelines operating at lower pressures rarely result in ignited releases. PIPESAFE provides default values of ignition probability, related to the pipeline diameter and pressure, derived from historical experience of transmission pipeline operation [3], [6], [7] and independent of the pipeline location. The default values of ignition probability are appropriate for most cases. However, the user also has the option to perform a dispersion calculation, in order to determine whether the flammability limit is reached at specific locations where ignition sources are known to exist.

The results of previous analyses indicated a trend for the ignition probability for rupture releases to increase linearly with pd^2, with p the pipeline operating pressure and d the pipeline diameter. The relationship forms the basis of the default ignition probabilities recommended for use in PIPESAFE. The most recent previous study was published previously by Advantica (now part of DNV GL), following a study undertaken on behalf of the PIPESAFE Group [7]. Data predominantly from pipeline incidents recorded by the group during the period 1970-2004 but supplemented with information available in the public domain on US incidents from the US Office of Pipeline Safety (now the Pipeline and Hazardous Materials Safety Administration - PHMSA), were analysed and a linear function derived to fit the incident data of the form:

$$P_{(ign)} = 0.0555 + \left(0.0137 \times pd^2\right) ;\ 0 \le pd^2 \le 55$$

and

$$P_{(ign)} = 0.81 ;\ pd^2 > 55^1$$

where p is the pipeline operating pressure (bar, gauge pressure) and d is the pipeline diameter (m).

The maximum value of 0.81 represented an upper limit based on the extent of the historical data available. The same approach is used for leak as for rupture releases, except that the hole size is used instead of the pipeline diameter. However the coefficient of the pd^2 value is halved reflecting the difference between the two sources contributing to a gas release following a rupture and the single source from a leak. Since publication, this relationship has been widely used and adopted in standards for pipeline risk assessment such as IGEM/TD/2 [8].

More data has become available in the time since the previous publication. The primary objective of this study was to update the statistical treatment to incorporate 10 years of additional data on ruptures of onshore gas transmission pipelines in order to refresh the correlation used to calculate ignition probabilities. A secondary objective was to review the extended dataset to identify cases where the information available on individual incidents included an indication of the time of ignition and to analyse this sub-set to identify any trends.

Review of Incident Data

Before updating the study, the sources of new data were evaluated. For the purposes of evaluating ignition probabilities, it is essential that the datasets used include all ignited and unignited events that meet the criteria for inclusion. No new data sources were identified that met this requirement with respect to gas transmission pipelines. A significant effort was made to check the data on each incident, particularly those obtained from the PHMSA database, to ensure consistency of interpretation between the two data sources and to avoid the inclusion of incidents that did not meet appropriate criteria for the purpose of deriving ignition probabilities for rupture incidents of gas transmission pipelines. Only incidents classified as ruptures involving onshore, steel, below ground natural gas transmission pipelines were to be included, where ruptures were defined as incidents that satisfied the condition of having a rupture area greater than twice the cross-sectional area of the pipe.

For the data obtained from the PHMSA website [9], [10], the conditions were more numerous, as the data set included many incidents that were beyond the scope of the study. Incidents were therefore only included in the analysis if they fulfilled the following conditions:

1. Natural gas pipelines.
2. On-shore pipelines.
3. Incidents which were defined as ruptures, or unspecified.
4. Systems that were defined as carbon steel, steel or unspecified.
5. Systems that were classified as underground.
6. Incidents before January 2015 (as newer incidents often had ongoing investigations, or could be potentially changed by new information).
7. Incidents involving a pipeline body.
8. Not classed as “Circumferential Separation Ruptures” (which on closer inspection of the data appeared to either demonstrably not fulfil condition 9, or did not have enough information to be certain that they did).
9. Incidents where the rupture area was greater than twice the cross-sectional area of the pipe. (This necessitated that the records contained the rupture length, the rupture width, and the diameter of the pipe.)

In the cases where important information was unspecified, the text of the incident entry was checked for details to identify whether the criteria were met. By applying the above criteria strictly and excluding incidents where the information was not sufficiently complete, the data set that was obtained excluded a number of incidents that had been included previously. This

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[1] The cut-off in the 2008 paper was given in error as $pd^2 = 57$, instead of 55.

resulted in a smaller number of incidents being available for analysis than would otherwise have been the case, but with a greater level of confidence in the validity of the data. All of the Group data relates to pipeline incidents at operating pressures of 16 bar or above (by definition). The data obtained from the PHMSA website and selected for inclusion in the analysis covers a very similar pressure range, with just two incidents included at pressures below 16 bar.

Table 1 summarises the data obtained from these different sets, compared with the data used in the previous study in 2008. The total number of rupture incidents available for analysis has increased by just over 11% and the number of ignited rupture incidents by over 33%.

Table 1: Summary of Pipeline Incident Data Used in Analysis

	Data used in 2008 study [7] **Group data 1970 – 2004 plus PHMSA data 2002 - 2007**	**Group Data 1970 - 2014**	**PHMSA Data 2002 – 2009**	**PHMSA Data 2010 – 2014**	**Total New Data Set**
Total Ruptures	325	266	57	38	361
Ignited Ruptures	65	65	9	13	87

Data Analysis

Impact of additional data on previous correlation

The earlier studies identified a trend of ignition probability linearly increasing with pd^2. For this update, the same methodology was used, whereby the data set was divided into "bins", which were groups of incidents within a certain range of pd^2. The average pd^2 of the bins and the statistical ignition probability for each bin was then used to construct a scatter graph of ignition probability against pd^2, from which a linear relationship could be derived. Initially, the data was sorted into the same pd^2 range bins as in the previous study [7], being 0-5, 5-15, 15-30, 30-45 and 45-80 (bar m²). The trend line derived was weighted, in performing a linear fit to the data, in accordance with the number of data points in each bin. The data set used, broken down into pd^2 ranges, is presented in Table 2 and illustrated as a bar chart in Figure 1. The scatter graph from which the best fit linear trend was derived is shown in Figure 2 with the 80% confidence intervals for each data point, along with the existing correlation for comparison. As can be seen, the best linear fit to the updated dataset has not changed significantly, although the maximum pd^2 value for the highest bin has increased slightly.

Table 2: Variation of Ignition Probability with pd^2 for Rupture Incidents (1970 – 2014)

pd^2 Range (bar m²)	**Mean pd^2 (bar m²)**	**Number of Ruptures**	**Number of Ignited Ruptures**	**Ignition Probability**
0-5	1.524	184	14	0.0761
5-15	9.797	73	21	0.2877
15-30	19.576	55	17	0.3091
30-45	35.672	23	13	0.5652
45-80	57.095	26	22	0.8462

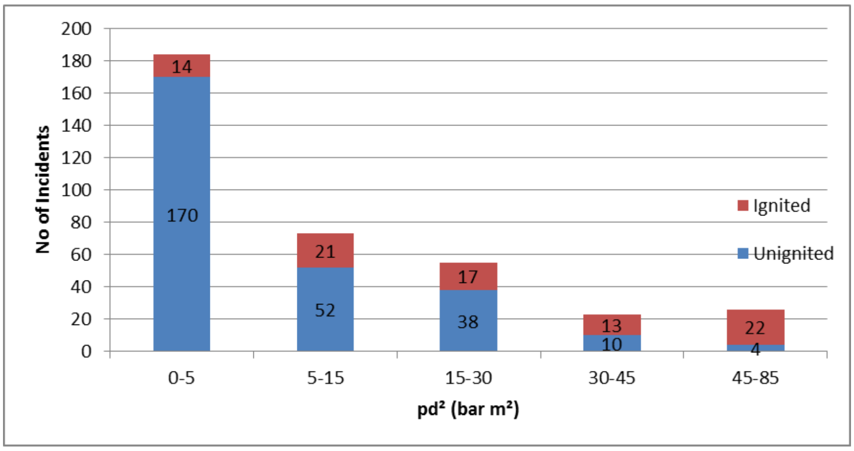

Figure 1: Analysis of Rupture Incident Data as a Function of pd^2 (Existing Ranges)

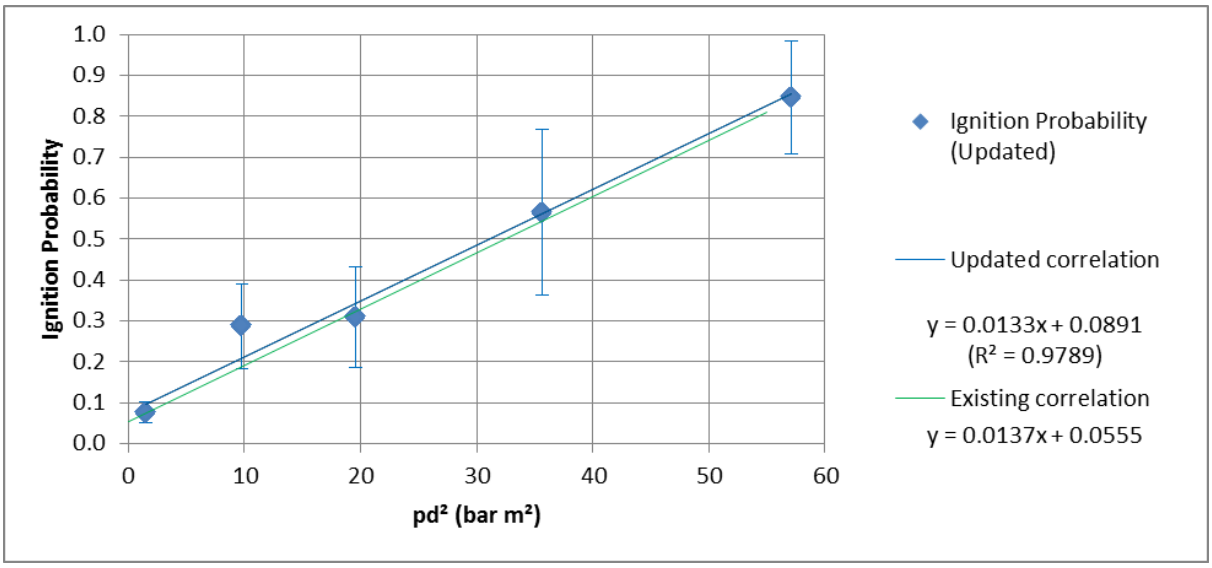

Figure 2: Variation of Ignition Probability with pd^2 (showing 80% Confidence Intervals) with Existing Correlation for Comparison

Refinement of data analysis

With the addition of extra data since the last study, the bin parameters were investigated to see if the bins could be adjusted to distribute the data more uniformly. A number of different bin ranges were tried in order to optimise the linear fit to the data. The result was a different choice of five bins with different ranges in pd^2: 0-0.5, 0.5-1, 1-6, 6-33, and 33-85. The lower value bins were fractional to reflect the very large concentration of data in that region. Table 3 shows the distribution of the data in the revised bin ranges, Figure 3 shows the data in the form of a bar chart and Figure 4 shows the scatter graph and relationship derived using the revised bin ranges, compared with the existing correlation.

Table 3: Variation of Ignition Probability with pd^2 for Rupture Incidents (1970 – 2014) in 5 Bins (Revised Ranges)

pd^2 Range (bar m^2)	Mean pd^2 (bar m^2)	Number of Ruptures	Number of Ignited Ruptures	Ignition Probability
0-0.5	0.261	58	4	0.0690
0.5-1	0.732	34	2	0.0588
1-6	2.898	102	11	0.1078
6-33	15.396	123	37	0.3008
33 -85	48.817	44	33	0.7500

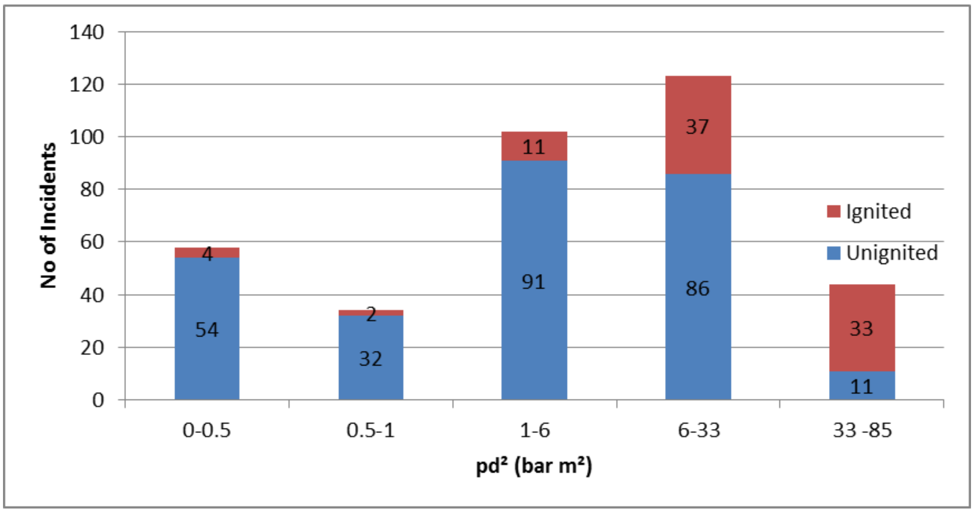

Figure 3: Analysis of Rupture Incident Data as a Function of pd^2 (Revised Ranges)

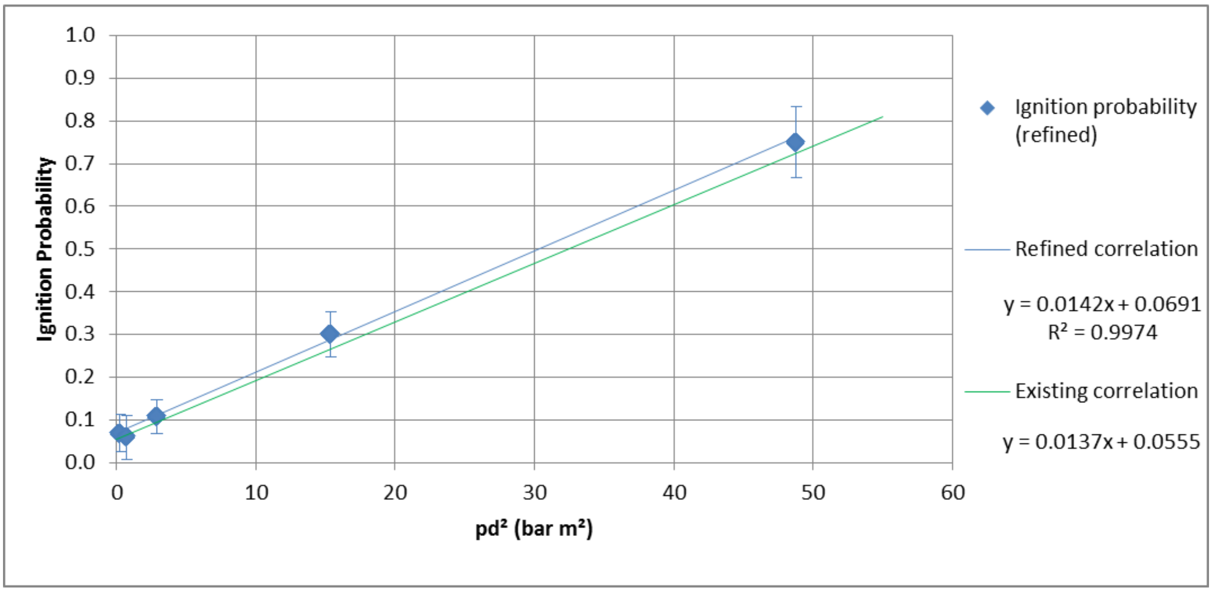

Figure 4: Variation of Ignition Probability with pd² (showing 80% Confidence Intervals) using Revised Ranges with Existing Correlation for Comparison

This bin distribution allows the sample sizes to be distributed more evenly, which reduces the random error for the bins with higher values of pd^2. This was desirable in order to reduce the uncertainty in the higher ranges. Nevertheless, this relationship is very similar to the existing correlation and it is notable that the existing correlation relationship lies within the 80% confidence intervals of the newly derived values. It is therefore suggested that the existing correlation remains appropriate to be used for estimating rupture release ignition probabilities for gas transmission pipeline risk assessments.

Extrapolation to higher pd^2 values

The relationships derived above cover the range of the data points generated by analysis of the expanded dataset, with the addition of new incidents covering a period of approximately 10 years. The results support the linear correlation derived previously, so that the equation for the trend line remains appropriate. However, the existing relationship includes an upper limit for the correlation, set at the upper bound of the range of available data, which has also been reconsidered and different possible approaches to estimating ignition probabilities for high pd^2 values evaluated, where there is no historical data. (N.B. It is recognised that for the purposes of risk assessment, the selection of an upper limit is largely of academic interest, because the effect of increasing the ignition probability from a value of 0.81 to a maximum value of 1 is generally insignificant relative to other uncertainties involved in risk analysis.)

In dealing with pipelines that have a pd^2 outside the range of the available historical data, a number of separate approaches were considered. Firstly, as with the existing relationship, the ignition probability could be considered to be equal to the probability for the largest pd^2 point considered in the analysis. Using this, the updated relationship would then be:

$$P_{(ign)} = \left(0.0137 \times pd^2\right) + 0.0555\ ;\ 0 < pd^2 \leq 57.2$$

and

$$P_{(ign)} = 0.84\ ;\ pd^2 > 57.2$$

In the absence of evidence, an alternative option considered was an exponential asymptote beyond the range of the linear trend, which would tend towards an ignition probability of 1 for increasing values of pd^2. A numerical method was employed to find the equation which extends the linear trend beyond the range of the linear trend based on the historical data without a discontinuity. This method produced the following relationship:

$$P_{(ign)} = \left(0.0137 \times pd^2\right) + 0.0555\ ;\ 0 < pd^2 \leq 57.2$$

and

$$P_{(ign)} = 1 - (21.3 \times e^{-pd^2 \times 0.0856})\ ;\ pd^2 > 57.2$$

The simplest approach considered was to extend the linear relationship outside of the data set until the maximum value for the ignition probability of 1 is reached. This would produce the following relationship:

$$P_{(ign)} = \left(0.0137 \times pd^2\right) + 0.0555\ ;\ 0 < pd^2 \leq 69$$

and

$$P_{(ign)} = 1\ ;\ pd^2 > 69$$

The extrapolations to the linear ignition probability relationship derived using the three alternative methods are compared in Figure 5.

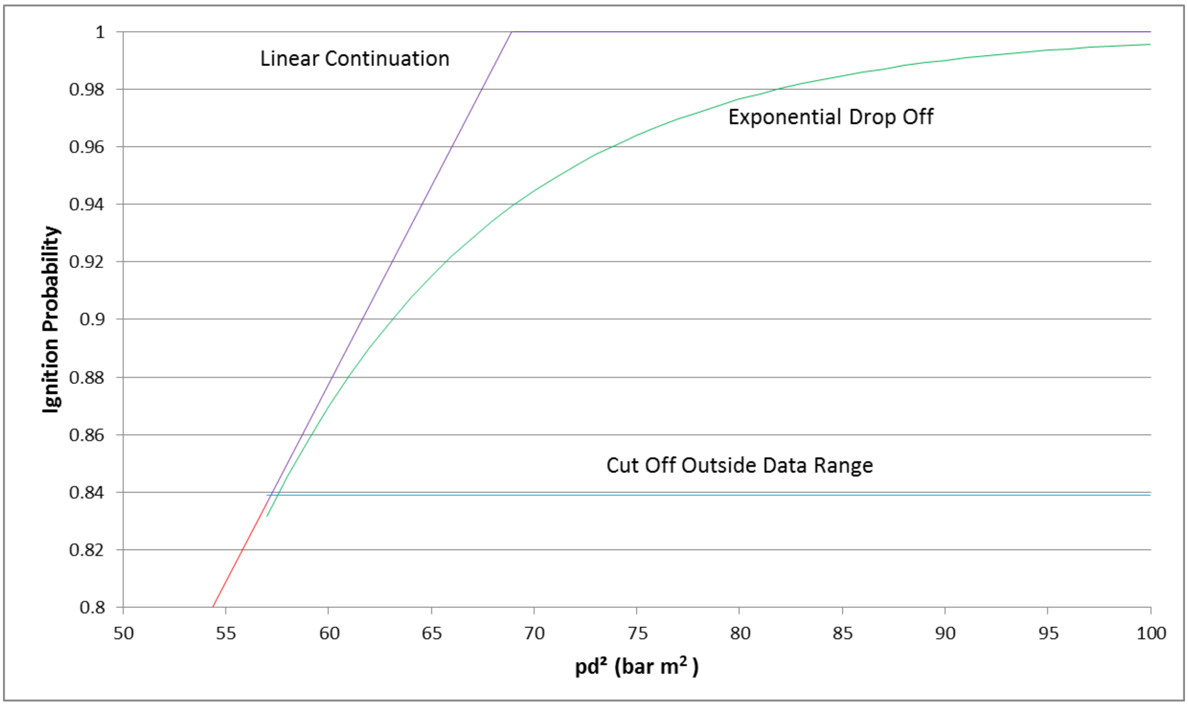

Figure 5: Comparison of different approaches to extrapolating the linear relationship to high pd^2 values

It is recognised that it is unlikely that the linear trend would continue to unity and that there will remain a possibility, however small, that a large gas release will not ignite. However, the linear continuation is considered a pragmatic alternative to the existing relationship and should be a conservative approach for high values of pd^2 where there is no historical data.

Ignition probability for leaks

The above analysis has focussed on rupture releases. For leaks with a release area smaller than that defined for a full bore rupture, the current approach [8] recommends applying a similar correlation as for ruptures, but with d equal to the release diameter and the coefficient of the pd^2 value halved, reflecting the difference between the two sources contributing to the gas release following a rupture and the single source contributing to a puncture release. Very few incidents involving leaks include detailed information on the release hole size and, therefore, it is difficult to undertake meaningful analysis to verify that the relationship is appropriate. However, it is possible to perform a high level check by calculating an average ignition probability for all leaks recorded in the group database (which includes all ignited and unignited gas releases).

This calculation results in an average ignition probability of 0.024 for all leaks smaller than a full bore rupture. This average probability of ignition is lower than the y-axis intercept of the linear relationship derived for rupture releases, which suggests that the use of the rupture correlation for leaks may be overly cautious. However, for high pressure gas transmission pipelines, risks are generally dominated by the rupture failure mode and so, for most cases, this conservatism will not be of concern.

Analysis of ignition probability by cause

The approach presented is purely statistical and takes no account of the physical causes of ignition, which in the case of gas transmission pipeline releases are not well understood. Ignition probability models have been developed that take account of the density of ignition sources present in the area surrounding the release and these are well-established methods of assessing the ignition probability of drifting clouds of heavier-than-air gas. However, in the case of high pressure natural gas releases from below-ground pipelines, which are momentum dominated and lighter-than-air, the extent of flammable gas at ground level is very limited (unlike dense gas releases) and hence ignition sources present at, or close to, ground level associated with human activities are unlikely to play a major part.

The expanded dataset was analyzed in order to calculate an average ignition probability for pipeline ruptures caused by External Interference for comparison with the average ignition probability for all other causes, as presented in Table 4 below. It might be expected that the ignition probability for releases due to External Interference would be higher than for other causes, because in these cases a potential source of ignition (generally excavating machinery) is likely to have been present. However, the average ignition probability calculated for External Interference is significantly lower than for the other causes.

Table 4: Variation of Ignition Probability with Cause of Failure for Pipeline Rupture Incidents

Cause of Failure	Number of incidents	Number of ignited incidents	Ignition Probability
External Interference	155	20	0.129
Other Causes	206	67	0.325

On the other hand, External Interference is more likely to occur in built-up areas, where the diameters of the pipelines tend to be smaller, and pressures lower, than in more remote areas, giving a lower ignition probability according to the pd^2 relationship. In order to investigate the influence of failure cause further, the pd^2 relationship was also taken into account, by analysing the External Interference data subset in the same way as the full dataset, but with fewer bins to reflect the smaller sample size, as presented in Table 5 and Figure 6. Also, since the data is skewed towards the lower end of the total pd^2 range for this cause, the scatter plot was done on a reduced scale so that meaningful comparisons with the total dataset could be made within the range of data available. This was again compared to the relationship derived in the previous report, as presented in Figure 7.

Table 5: Variation of Ignition Probability with pd^2 for Rupture Incidents attributed to External Interference

pd^2 Range (bar m^2)	Mean pd^2 (bar m^2)	Number of Ruptures	Number of Ignited Ruptures	Ignition Probability
0-0.5	0.253	49	4	0.082
0.5-1	0.739	23	2	0.087
1-10	3.115	62	8	0.129
10-85	19.012	21	6	0.286

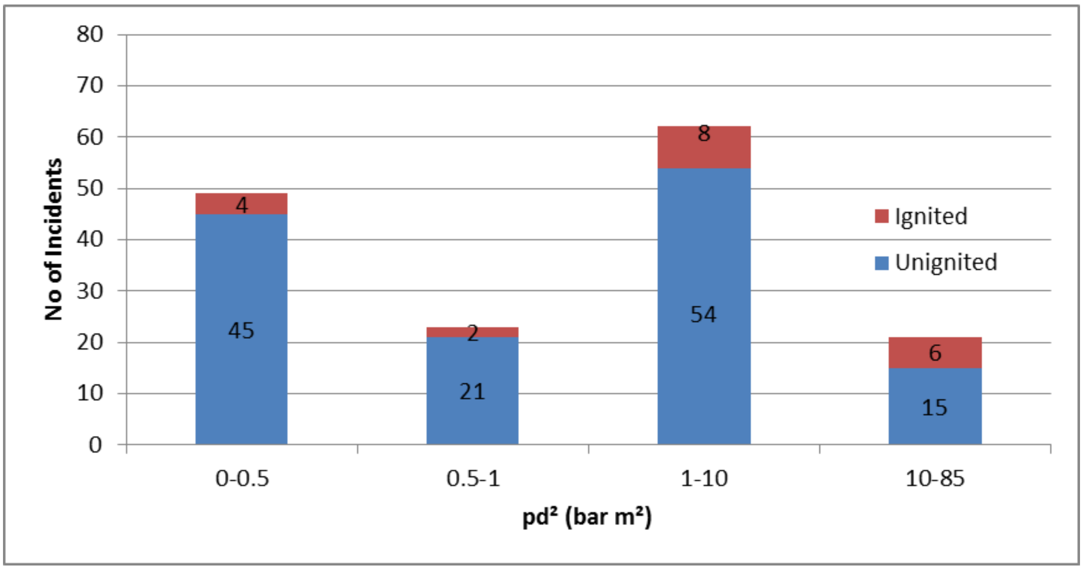

Figure 6: Analysis of External Interference Data as a function of pd^2 in 4 bins

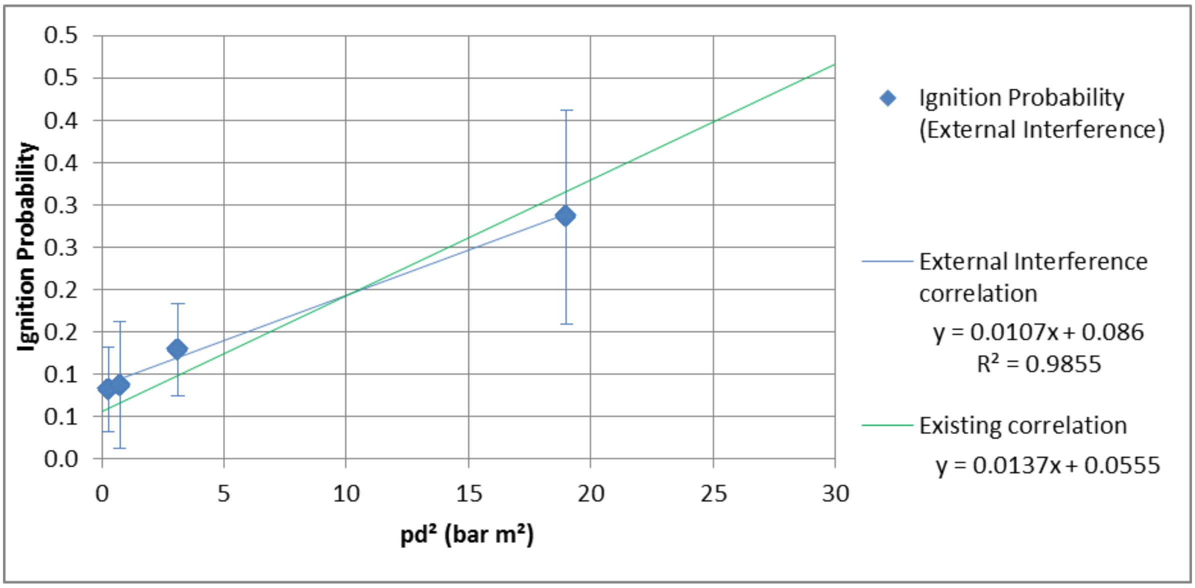

Figure 7: Variation of Ignition Probability with pd² (with 80% Confidence Intervals) for External Interference with Existing Correlation for Comparison

From the graph in Figure 7, it can be seen that the confidence intervals for the External Interference subset are relatively large, so there is a significant amount of uncertainty in the linear relationship derived. However, it can still be observed that the External Interference data broadly agrees with the existing correlation, within the limits of the data, suggesting that gas releases caused by External Interference would be no more likely to ignite, on average, than for any other cause of a pipeline rupture, confirming the view discussed previously that ignitions of the gas released by high pressure pipeline ruptures are generally generated by the rupture events themselves.

Time to ignition

The time of ignition is important for risk analysis of high pressure gas pipelines, because of the rapid depressurisation that follows a pipeline rupture and the highly transient nature of the initial gas release rate. Figure 8 shows a typical example of a prediction made using PIPESAFE of the gas outflow following a pipeline rupture event, with a pressure maintained boundary on one side (upstream) and a no-reverse flow boundary on the other (downstream). The total gas flow rate from both rupture pipe ends is shown in blue and can be seen to fall very rapidly; to less than half of the initial value within 1 minute of the rupture occurring. As a result, the corresponding fire is much larger at earlier times and, hence, the consequences are more severe for people and property in the vicinity of the incident if early ignition occurs.

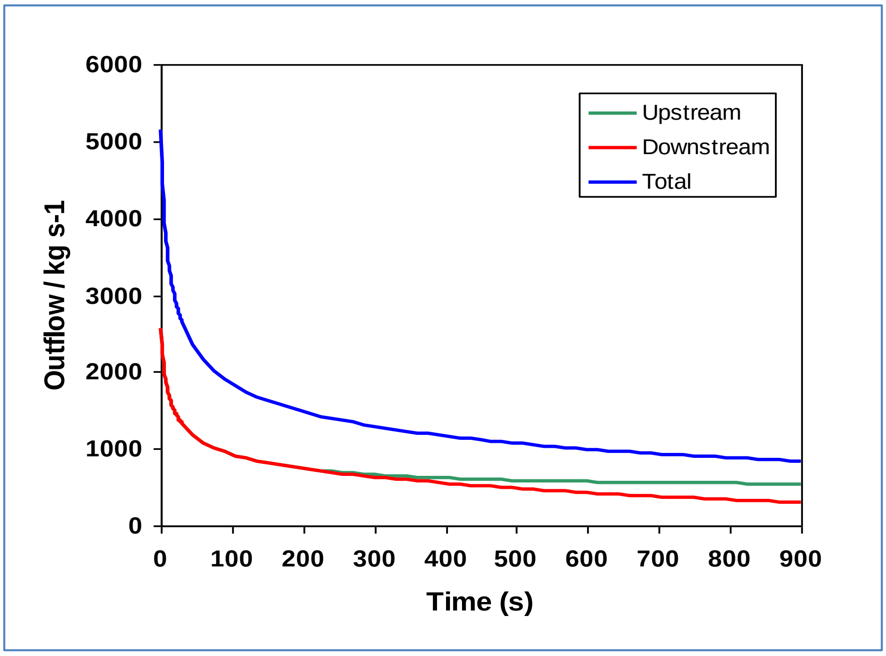

Figure 8: Example Prediction of Gas Outflow Rate with Time following Pipeline Rupture

To provide information on the time of ignition observed in actual incidents, a simple analysis was performed of the time to ignition for those incidents where information on the ignition time was recorded. For most of the incidents considered in the ignition probability analysis, there was no information recorded on the time to ignition. However, for the purpose of this particular analysis it was possible to include other incidents on public record, where information on the time of ignition was recorded, in addition to the incidents analysed in deriving ignition probability correlations. Inevitably, because of the variable nature of the information recorded on incidents, the time of ignition is subject to a significant degree of uncertainty. Nevertheless, by analysing the detailed descriptions of incidents where information was available, it was possible to assign an estimated time of ignition within certain time bands and the results are presented in Table 6 together with the probability of ignition occurring with each band.

Table 6: Time to Ignition Analysis for Rupture Incidents

Time from failure to ignition, t (s)	Number of rupture incidents	Probability of ignition within timeframe	Cumulative probability of ignition
$0 \leqslant t \leqslant 30$	27	0.64	0.64
$30 < t \leqslant 60$	2	0.05	0.69
$60 < t \leqslant 120$	2	0.05	0.74
$t > 120$	11	0.26	1.00
Total	42	-	-

As shown in Table 6, 64% of the incidents were estimated to have ignited within the first 30 seconds. Uncertainty in the time of ignition has generally been represented in PIPESAFE by selecting two possible ignition times for the risk calculations – either immediate ignition or ignition after a delay of 30 seconds, each with an equal likelihood, which appears to be an appropriate representation in the light of the above data and suitably cautious, bearing in mind that ignition at later times results in lower consequences according to the risk calculations, due to the rapid reduction in the gas flow rate.

Discussion

Possible causes of ignition

The physical causes of ignition of gas releases from high pressure pipelines are not yet well understood. A separate study was initiated to investigate possible explanations of the high probability of ignition for releases from large diameter, high pressure, pipelines and the observed correlation with pd^2 (a measure of both the initial gas outflow and the energy released). The project commenced with an extensive review of possible ignition sources, divided into three categories:

- “External natural” causes (e.g. lightning)
- “External human” causes (e.g. machinery, electrical sources, domestic appliances)
- “Release-generated” causes (e.g. impacts between debris traveling at high velocities following a rupture)

Ignition due to natural causes is expected to be rare (albeit possible) because of the low probability that a lightning strike, for example, will coincide with a pipeline rupture release. Similarly, as observed above, there is little evidence that human causes make an important contribution to the overall ignition probability for high pressure natural gas pipeline ruptures. Nevertheless, this mechanism must also be considered possible in specific circumstances. The most likely explanation appears to be that the dominant mechanism of ignition is related to the pipeline rupture event itself, involving a large and sudden release of stored energy, the magnitude of which is related to the pressure and diameter of the pipeline (pd^2).

A wide range of possible mechanisms were considered, that could be generated by the pipeline rupture event itself. The credible mechanisms that were considered most likely be consistent with the observed pd^2 relationship were impact generated sparks and/or electrostatic discharge (either as a spark from an electrically isolated conductor or as a discharge from a grounded object or protrusion) and both of these were therefore investigated further. For impact sparks, a large number of experiments were carried out under controlled conditions to launch a variety of different rock types at different targets to observe the conditions when visible sparks were produced and also when visible sparks resulted in ignition of a gas-air mixture. The experiments found that ignition by impact sparks was difficult to generate, with only one ignition occurring (with a flint rock projectile launched at a steel target) despite visible sparks being produced under a number of different configurations. The results were sufficient to conclude that it is possible for impact sparks to generate ignitions; however, this may not be the only explanation to account for the number of ignited incidents observed. Theoretical work was also carried out, which identified that ignition due to electrostatic discharge (either spark or brush discharges) may also be possible under the conditions following a pipeline rupture event. In the case of spark discharges, an ungrounded conductive object or surface which has gained an electric charge can discharge to ground. This spark can be a source for ignition and this process has been identified as the cause of many industrial fires and explosions. It is possible that, in the specific case of a natural gas pipeline rupture, the isolated conductor could be a fragment of metal pipe, clump of soil or some other conductive material, thrown up through the gas cloud caused by the release. The cloud could theoretically have a large electric field and the conductor could accumulate some of this charge, which then discharges again when it approaches the ground, causing a spark. However, experimental investigation of the possibility of electrostatic discharges causing ignition of gas pipeline rupture releases would be difficult and costly and this has not yet been pursued.

Comparison with other methods

Consideration has been given to how the relationships derived in this report can be compared to methods of estimating ignition probabilities for similar scenarios. As commented above, ignition probability models that take account of the density of ignition sources present in the area surrounding the release are not generally appropriate for rupture releases of high pressure natural gas pipelines located below-ground, because the gas releases are typically vertical, momentum dominated and lighter-than-air.

The approach which was identified as most appropriate for comparison is guidance on ignition probabilities published by The International Association of Oil and Gas Producers (OGP) [11], which includes the scenario (numbered 4) of a “Pipe Gas LPG Rural (Gas or LPG release from onshore pipeline in a rural area)”. In the OGP report, ignition probability is given as a function of the release rate (in kg s^{-1}), instead of pd^2, with a linear relationship for releases greater than 10 kg s^{-1}, similar to that presented in this paper. Because of the highly transient nature of the gas release rate following a transmission pipeline rupture, illustrated in Figure 8, it is necessary to select a representative release rate for a given value of pd^2 in order to make a direct comparison.

In order to make the comparison, reference was made to the results of two full scale pipeline rupture experiments, conducted in Canada [12] and involving the deliberate rupture of a 36” (914mm) diameter below-ground gas transmission pipeline at an initial pressure of 60 bar. It was found that in order to achieve good agreement between the ignition probabilities estimated by the two methods for this case, the maximum initial gas outflow measured in the experiments needed to be taken as the release rate to estimate the ignition probability using the OGP method, consistent with the observation from incidents that the majority of ignitions occurs in the early stages.

Conclusions

The detailed analysis of the data resulted in a number of refinements to the dataset used as well as extending it to include the additional pipeline incident data available since 2004. Applying a similar statistical approach to the previous study broadly supported the existing correlation, although possible changes are suggested to the upper bound estimates of ignition probability for very large pd^2 values where there is no historical incident data. The simplest approach considered, which should be cautious for risk assessment purposes, was to extend the linear relationship outside of the data set until the maximum value for the ignition probability of 1 is reached. This would produce the following relationship for ignition probability:

$$P_{(ign)} = \left(0.0137 \times pd^2\right) + 0.0555\ ;\ 0 < pd^2 \leq 69$$

and

$$P_{(ign)} = 1\ ;\ pd^2 > 69$$

where p is the pipeline operating pressure (bar, gauge pressure) and d is the pipeline diameter (m).

For leaks with a release area smaller than that defined for a full bore rupture, the current approach recommends applying a similar correlation as for ruptures, but with d equal to the release diameter and the coefficient of the pd^2 value halved to reflect that leaks are from a single hole only rather than double-ended rupture. Consideration of the average ignition probability for all leaks recorded in the group database (which includes all ignited and unignited gas releases) suggests that the use of the rupture correlation for leaks may be overly cautious. However, for high pressure gas transmission pipelines, risks are generally dominated by the rupture failure mode and so, for most cases, this conservatism will not have an appreciable influence on the overall results.

The number of incidents where the time of ignition is reported is limited (approximately 10% of the total). However, the available data shows that there is a high probability of early ignition, with the majority reported as igniting immediately or within the first few seconds, consistent with the default modelling approach in PIPESAFE.

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