New Developments in the Approach to Assessing the Potential Interaction between Parallel Pipelines

Mike Acton, Senior Principal Consultant, DNV GL, Holywell Park, Ashby Road, Loughborough, LE11 3GR, UK

Kostas Dimitriadis, Senior Engineer, DNV GL, Holywell Park, Ashby Road, Loughborough, LE11 3GR, UK

Clive Robinson, Senior Principal Consultant, DNV GL, Holywell Park, Ashby Road, Loughborough, LE11 3GR, UK

Due to the increasing demand for natural gas in many locations, there is often a need to increase the capacity of gas transmission pipeline networks. In some cases, it may be possible to increase the operating pressure, but in others there may be no alternative but to lay a new pipeline, often along the same route as an existing pipeline. If one pipeline fails in this situation, a second parallel pipeline may also fail. However, because of pressure on the use of land, the minimum separation required for parallel pipelines to be laid and operated safely needs to be considered.

A collaborative project was previously undertaken to provide deterministic guidance on whether a buried high pressure gas pipeline would fail following failure of an adjacent gas pipeline. A framework was developed that identified the sequence of events that could lead to failure of a parallel gas pipeline for initial failures taking the form of either full-bore ruptures or leaks. This methodology has been used both to produce general guidelines for new parallel pipeline installations and to assess the possibility of failure in specific cases taking account of the detailed pipeline properties and local conditions. General guidance, developed using the methodology, is included in the UK recommendations for gas transmission pipelines, IGEM/TD/1.

The framework has been applied successfully for over 10 years. However, it became apparent that improvements could be made in the light of experience and new information. A further phase of the project was therefore agreed with the project partners which has now been concluded.

The further phase of the collaborative project has improved the methodology for parallel pipeline assessments in the following areas:

- The model for the prediction of the crater width resulting from a pipeline rupture has been improved to take account of the pressure in the failing pipeline and the profile of the crater. The predictions have been compared with data from incidents and shown to give better agreement.
- Revised heat fluxes from puncture jet fires have been produced, based upon full scale experimental data, which are less conservative than the previous assumptions. This allows the mass flow rate from the puncture and the position of the second pipeline in the fire to be considered and means that the second pipeline is predicted to be less likely to fail than previously.
- The existing framework is a deterministic approach which indicates whether a pipeline will fail following failure of an adjacent pipeline. The new probabilistic approach enables the calculation of the probability of failure of the second pipeline (given an initial failure has occurred) considering the probability of different failure modes, release directions and ignition.

Introduction

In the transport of natural gas at high pressure through underground pipelines, great care is taken to design and maintain such installations for safe operation. As a result, the gas pipeline industry has an excellent safety record. Nevertheless, it is important that pipeline operators have an understanding of the possible effects of an accidental gas release, including the risk of escalation where pipelines are laid in parallel, in order to inform appropriate pipeline design separation distances and to help manage the risks involved.

Due to the increasing demand for natural gas in many locations, there is often a need to increase the capacity of gas transmission pipeline networks. In some cases, it may be possible to increase the operating pressure, but in others there may be no alternative but to lay a new pipeline, often along the same route as an existing pipeline. If one pipeline fails in this situation, a second parallel pipeline may also fail. However, because of pressure on the use of land, the minimum separation required for parallel pipelines to be laid and operated safely needs to be considered.

Previous Phase of the Collaborative Project

A collaborative project was previously undertaken to provide deterministic guidance on whether a buried high pressure gas pipeline would fail following failure of an adjacent gas pipeline (Acton (2010)). A framework was developed that identified the sequence of events that could lead to failure of a parallel gas pipeline for initial failures taking the form of either full-bore ruptures or leaks. This methodology has been used both to produce general guidelines for new parallel pipeline installations and to assess the possibility of failure in specific cases taking account of the detailed pipeline properties and local conditions. General guidance, developed using the methodology, is included in the UK recommendations for gas transmission pipelines, IGEM/TD/1 (Institution of Gas Engineers and Managers (2008)).

To assist in the identification of the critical processes to be studied, an event tree for parallel pipeline failures was constructed as shown in Figure 1. In this figure, the two parallel pipelines are referred to as pipeline P1 and pipeline P2, with the initiating event being a failure of P1. The outcomes that represent an escalation of the initial failure are indicated in Figure 1 and are discussed below.

Figure 1 Parallel Pipelines Event Tree

Rupture of P1

Failure of P2 due to Pressure Loading

In this event, P2 is damaged by the pressure wave propagating through the ground due to rupture of P1 or the pressure applied to the pipeline by the soil, causing local buckling and collapse of the pipeline body, which may be sufficiently severe to result in a release of gas from P2. In this case, the failure of P2 may be either a rupture or a puncture. If P2 is ruptured and the gas ignited, the resulting hazard would arise from the fires produced by gas flowing from two ruptured pipelines (i.e. P1 and P2). If, on the other hand, the initial rupture of P1 causes only a puncture in P2, then in the event of ignition the hazard would result from a combination of a fire due to the rupture of P1 and a jet fire due to the puncture in P2. This situation may further escalate if the heat loading on P2 is sufficiently high for P2 to weaken and rupture.

Failure of P2 due to Heat Loading

If P1 ruptures, but the pressure loading is insufficient to cause P2 to fail, then in the event of ignition, the hazard shortly after the initial failure is due to the fire from the rupture of P1 only. If, however, the ground cover above P2 is removed due to the rupture of P1, then the heat loading to the exposed P2 pipeline may cause it to weaken and fail. The hazard in this case would result from thermal radiation from a single pipeline rupture fire, subsequently escalating to thermal radiation from two pipeline rupture fires.

Puncture of P1

It is assumed that any pressure loading due to a pipeline puncture is insufficient to cause failure of the parallel pipeline.

However, if the initial failure is a puncture of P1, then the released gas may remove the ground cover above P2, exposing this pipeline to heat loading from a jet fire. If pipeline P2 is weakened sufficiently then P2 may rupture. In the event of ignition of the escaping gas, the hazard will escalate from a jet fire due to a puncture in P1 to a fire from a rupture of P2. (Although not shown in Figure 1, this situation may escalate further if P1 is itself further weakened and ruptures because of the heat loading generated by the fire from the rupture of P2).

As part of the original collaborative project, work was carried out to enable the quantification of the steps in the event tree. This consisted of mathematical modelling (including CFD) and large scale rupture and full scale puncture experiments.

The framework has been applied successfully for over 10 years. However, it became apparent that improvements could be made in the light of experience and new information. A further phase of the project was therefore agreed with the project partners which has now been concluded.

Further Phase of the Collaborative Project

The objectives of the further phase of the collaborative project were to improve and enhance the methodology for parallel pipeline assessments in the following areas:

- Craters resulting from pipeline ruptures
- Heat fluxes from ignited leaks (punctures)
- Estimating the probability of a second pipeline failing following failure of a parallel pipeline

Each of these is described in the following sections.

Crater model

The guidance developed in the previous phase of the collaborative project had concluded that the most appropriate rupture crater model to use was the RUPKRAT model (Schram (1991) and Waterloopkundig Laboratorium (1972)) developed by Gasunie as this had been developed to a greater degree than other models and compared favourably with incident data. This had subsequently been modified with an empirical factor applied to remove possible non-conservatism.

During the development of the guidance, it was observed that the model does not predict any variation in crater width with pipeline pressure, which might be expected, and further work could be carried out to develop the model in this respect. It was also noted that, within the methodology, it is assumed that a second pipeline within the maximum dimensions of the crater at the ground surface will be exposed. Consideration of the likely crater geometry shows that this is conservative, particularly for pipelines at the same burial depth, and could also be refined by further research.

Work by Battelle (Leis (2002)) had developed a model which enabled the pressure in the failing pipeline to be taken into account when predicting the crater width. The basis of the crater formation model is derived from the theory of the gas dynamics of chemical explosions (Henrych (1979)). The width of the crater depends on the strength of the explosion, the depth of cover and the characteristics of the surrounding soil. However, the soil density is not a significant contributor in the equation for the crater width and the critical velocity (the velocity that is just high enough to displace the soil) was determined empirically and set to a single average value from a subset of the examined incidents. Therefore, there is not a significant difference in crater width predictions using the model when comparing mixed, sandy and clay soil results. In practice, significant differences are observed and these effects are included in the RUPKRAT model.

An initial attempt was made to calculate critical velocity values for different soil types using the available incident data. However, it was concluded that the soil types reported in the incident data could be unreliable as this is open to interpretation and classification of soil types is often not straightforward. Therefore, it was suggested that in order to calculate reliable values of critical velocity, only data should be used where the soil type was known. Full scale experiments carried out in Saskatchewan in Canada (Acton (2000)) and at the Spadeadam Test Facility in UK (Johnson 2000) recorded useful data on the size of the craters produced by the rupture of a buried pipeline. Although, this is a very limited data set it was considered that use of this data would give more reliable predictions as the soil types were known. Therefore, critical velocity values were calculated for sandy and clay soil from the experimental data and for the mixed soil from the incident data to give the best fit for the data for each of the soil types.

The crater is defined using an ellipse as shown in Figure 2 and the full set of equations used to determine the crater parameters are given below.

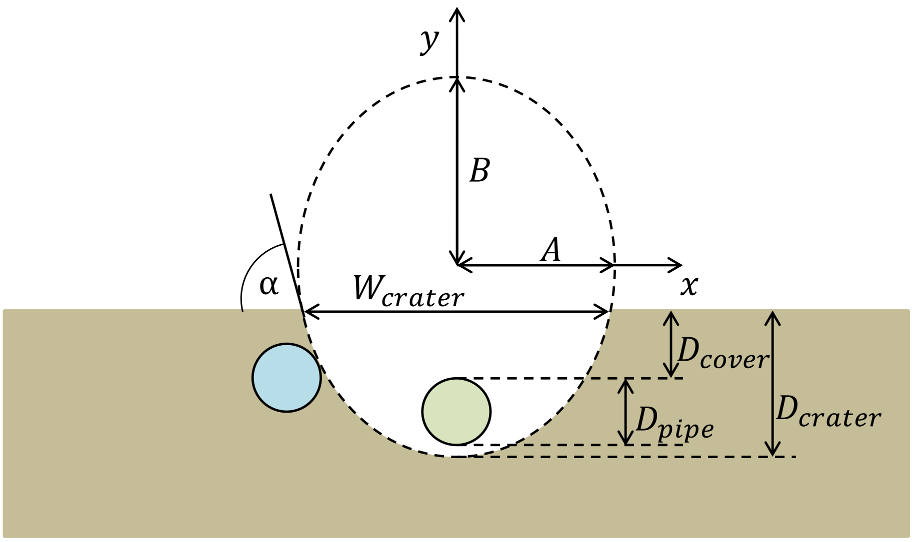

Figure 2 Crater Profile and Parameters

The parameters depending on the type of soil, including g, k and the crater wall angle at the ground level α, are identical to those used in the current model and are shown in Table 1.

Table 1 Ground type and crater calculation parameters

Type of Soil	**g (-)**	***k* (-)**	**α (º)**
Sandy	1.10	3.43	64.54
Mixed	1.75	2.51	70.02
Clay	2.70	2.21	74.88

The soil dependent parameter k and crater wall angle at the ground level α are defined in Equations 1 and 2 in a more general form.

$$k = \begin{cases} 4.3, & \mathrm{g} \le 0.6 \\ 5.43 - 2.07\mathrm{g} + 0.23\mathrm{g}^2, & \le 0.6\mathrm{g} < 2.0 \\ 2.2, & \mathrm{g} \ge 2.0 \end{cases} \tag{1}$$

$$\alpha = \tan^{-1}(\mathrm{g} + 1) \tag{2}$$

The crater depth defined in the model is provided in Equation 3.

$$D_{crater} = 1.20kD_{pipe} + D_{cover} \tag{3}$$

Similarly, the equation for calculating a rupture crater width, as defined in Leis (2002) is defined by Equation 4. Under some circumstances, for example for low pressures, small diameters and clay soil, the model will not predict a crater width. Therefore, a minimum crater width is specified based upon the width of the sub-surface cavity predicted by the model, as defined by Equation 5.

$$W_{crater} = 2\sqrt{\frac{D_{pipe}\left(D_{cover} + \frac{D_{pipe}}{2}\right)}{u_{kr}}\sqrt{\frac{\gamma \cdot p_{pipe}}{3 \cdot \rho_{soil}(\gamma^2 - 1)}} - \left(D_{cover} + \frac{D_{pipe}}{2}\right)^2} \tag{4}$$

$$W_{crater} = D_{pipe}\sqrt{\frac{1}{u_{kr}}\sqrt{\frac{\gamma \cdot p_{pipe}}{3 \cdot \rho_{soil}(\gamma^2 - 1)}}} \tag{5}$$

The critical velocity, u_{kr}, defining the boundary between the gas velocity that can displace soil and the gas velocity that cannot and the density of soil ρ_{soil} are given in Table 2 for the three different soil types. (Note that the value of u_{kr} and the density are not interrelated.) The value of the specific heat ratio, $\gamma = 1.301$, has been use for pipelines carrying natural gas.

Table 2 Critical velocity and density of soil values

Type of Soil	u_{kr} (m/s)	ρ_{soil} (kg m^{-3})
Sandy	0.7	1520
Mixed	1.95	1360
Clay	4.00	1200

In order to calculate the width of the crater at a depth other than the failed pipeline, such as at the location of a pipeline parallel to the failed pipeline, the characteristic parameters of the elliptical profile, A and B, are also defined:

$$A = \sqrt{\frac{B^2 \cdot W_{Crater}}{2 \cdot (\mathrm{g}+1)(B - \mathrm{D}_{crater})}} \tag{6}$$

$$B = \frac{2 \cdot \mathrm{D}_{crater} - W_{crater}(\mathrm{g}+1)}{4 \cdot \mathrm{D}_{crater} - W_{crater}(\mathrm{g}+1)} \cdot \mathrm{D}_{crater} \tag{7}$$

The profile equation for the ellipse defining the crater, as described in Figure 2, is subsequently defined in Equation 8.

$$\frac{x^2}{A^2} + \frac{y^2}{B^2} = 1 \tag{8}$$

The revised model has been compared with data from incidents and gives more accurate predictions compared with the previous version which did not include a pressure dependency.

The current crater model is compared to the new model for a variety of pressures (20, to 100 barg) and pipe diameters (12", 18", 24", 36", 48") for a mixed soil type in Figure 3. The crater widths predicted by the current model are similar to the widths calculated by the new model at a pressure of approximately 60 barg. For higher pipeline pressures the new predictions of crater widths are larger and, for lower pressures, the crater widths are smaller. For other soil types the trends are similar.

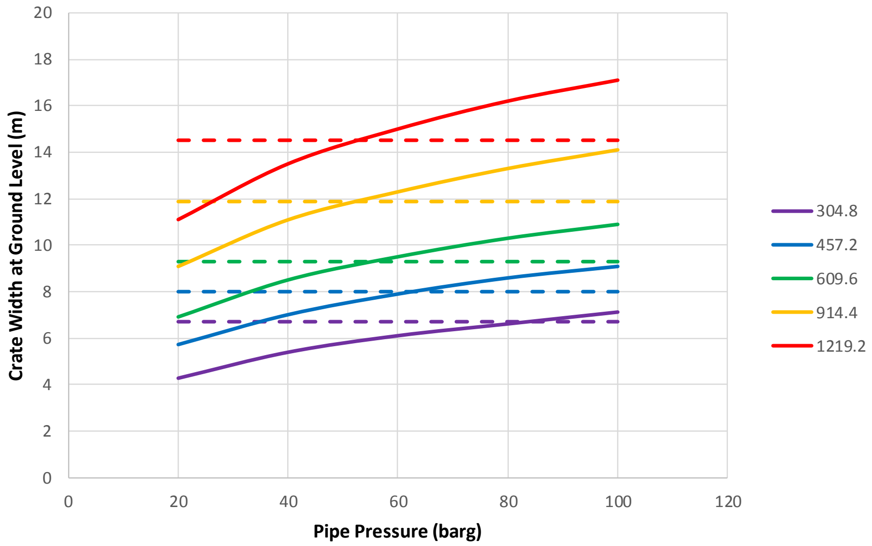

Figure 3 Crater Width Predictions for Different Pipe Diameters (mm) for Previous and New Crater Model

Heat fluxes

Currently, the existing methodology for punctures applies a fixed value for the heat loading from punctures (350 kWm^{-2}), based on the maximum measured heat flux in large scale unconfined jet fire experiments, which is likely to be excessively cautious in the parallel pipeline situation.

Heat flux vs flow rate

There are several sources of guidance information on heat loading from jet fires in the literature. The paper by Lowesmith (2007) gives a comprehensive review of experimental data obtained as part of the Joint Industry Project, Blast and Fire Engineering Project for Topside Structures, Phase 2 (mostly obtained by DNV GL). The paper gives guidance values for gas jet fires which includes heat flux as a function of mass flow rate. Several other publications (Oil and Gas UK (2007), International Association of Oil and Gas Producers (2010) and Fire and Blast Information Group (2014)) provide guidance values for heat fluxes for jet fires but the guidance is the same as contained in Lowesmith (2007). NORSOK (2008) provides guidance for heat fluxes for jet fires. The source of the guidance is not given and is only broken down into two flow rate categories (greater than and less than 2 kg s^{-1}). The values are similar to those given by Lowesmith (2007). API 521 (2007) does not contain any specific guidance on jet fire heat fluxes but quotes a value of 300 kW m^{-2} as an example. No reference is given for the source of the information.

It was concluded that Lowesmith (2007) contains the most comprehensive guidance and shows the experimental data on which this is based. Therefore, this guidance was used. The guidance values for the variation in heat flux with mass flow rate for natural gas jet fires is shown in Figure 4. This information is for free jet fires.

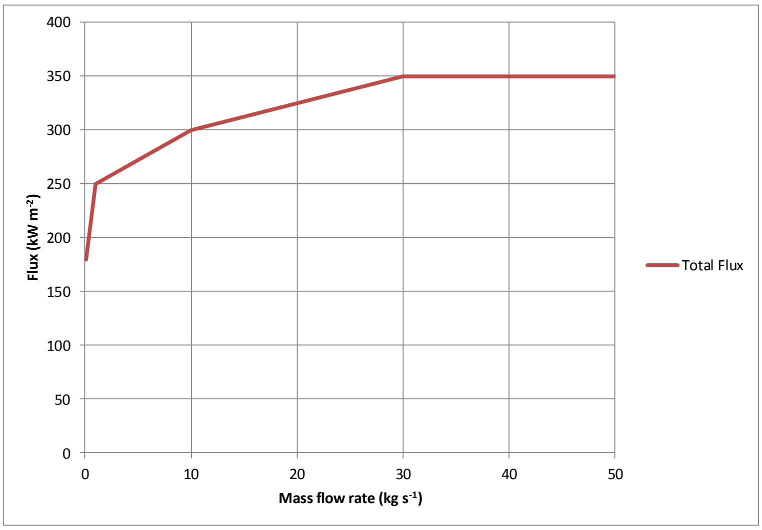

Figure 4 Variation of heat flux with mass flow rate for a natural gas jet fire

Heat flux vs position in the fire

The above discussion does not consider the variation in heat flux with position within the jet fire. The puncture experiments carried out in the previous phase of the collaboration showed that the size of the crater formed by a puncture release is generally much less than the size of the jet fire. This can be seen in the images of two of the experiments in Figure 5 and in the measurements of the crater size and flame length. On average, the crater size to flame length ratio is approximately 0.1. The maximum crater size to flame length ratio is approximately 0.25.

Figure 5 Examples of puncture fires in clay (left) and sand (right)

Experimental data exists on the variation of heat loading with distance along the axis of a jet fire (Pritchard (1991)). Although this data is for free jet fires it provides justification for reducing the maximum heat fluxes from those given previously. Figure 6 shows a photograph of one of the experiments in which an instrumented cylinder was placed within a jet fire. The heat fluxes on the cylinder were measured on the surface of the cylinder, which was placed at different distances from the release point.

Figure 6 Example experiment measuring heat loading with a jet fire

The data from these experiments indicates that closer to the source of the release, the fluxes are lower than the maximum values (occurring at approximately 20 m in this example or about 2/3 of the flame length). The closest distance the cylinder was placed to the source was 9 m which is approximately 1/3 of the flame length. The predicted crater size for this release for clay and sand is much closer than the closest location of the cylinder in the experiments. From the trends in the data it would appear that the fluxes would decrease further at the location of the crater width but there are no measurements to support this. Therefore, a multiplication factor has been used to account for the fact that the flux at the location of the crater width (250 kW m^{-2}) is lower than the maximum flux (300 kW m^{-2}). This reduction factor is then applied to all mass flow rates, as shown in Figure 7. The maximum flux varies from 150 kW m^{-2} to ~290 kW m^{-2}.

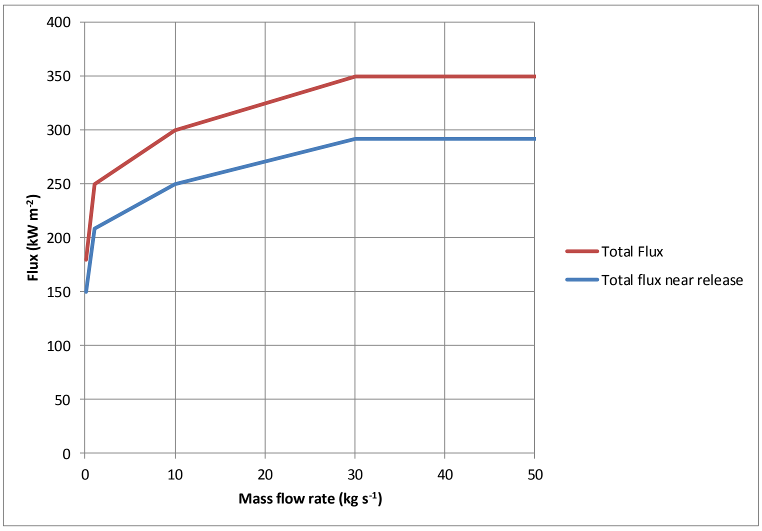

Figure 7 Variation of heat flux vs mass flow rate for a natural gas jet fire. Maximum flux in fire and flux near release point

Influence of revised heat flux estimates

The effect of the revised flux calculations on the critical flow in the parallel pipeline (i.e. the flow which is just high enough to prevent failure) is shown in Figure 8. The example is for a 25 mm diameter puncture. The previous higher flux of 350 kW m^{-2} would have required a critical flow of 6 ms^{-1} for all pressures. No crater is predicted for a clay soil for pressures lower than 80 barg which explains the zero value of critical flow velocity below this pressure.

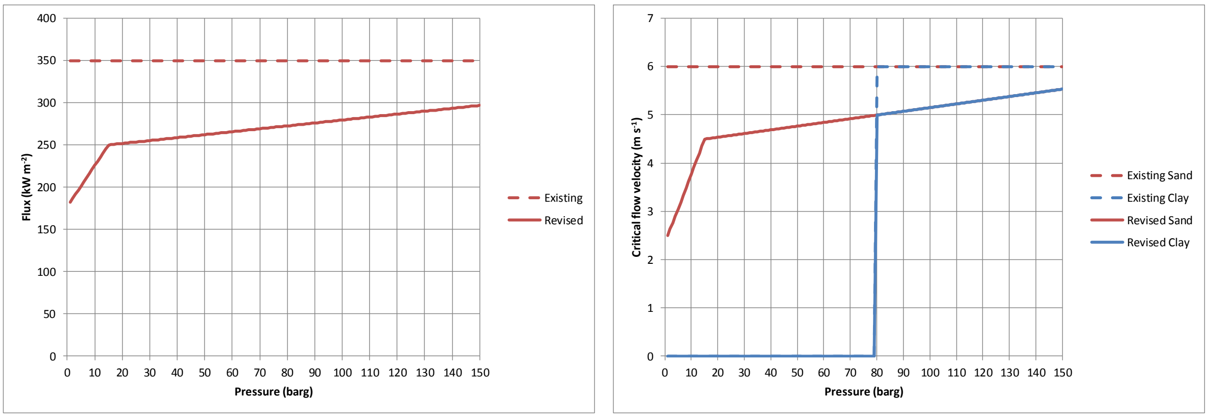

Figure 8 Variation of flux and critical flow velocity with puncture release pressure (25 mm diameter), second pipe 60 barg operating pressure

Probabilistic approach

The existing framework is a deterministic approach which indicates whether a pipeline will fail following failure of an adjacent pipeline. The new probabilistic approach enables the calculation of the probability of failure of the second pipeline (given an initial failure has occurred), considering the probability of different failure modes, release directions and ignition.

The methodology considers all failure modes, i.e. ruptures and punctures, and applies the same consequence methodology used for the deterministic assessment to all paths through the event tree. A diagram of the event tree is shown in Figure 9. For each failure mode, a probability of failure is calculated.

In the context of the present methodology the pipeline failure frequencies for P1 are required for different modes of failure, namely ruptures and punctures of various ranges of hole sizes. The failure frequencies are primarily specified by the user and are used in two different ways.

1. Given that pipeline P1 fails, to calculate the probability that the failure is a rupture or a puncture.
2. Given that a puncture has occurred, to calculate the probability that its size is large enough to cause failure of P2.

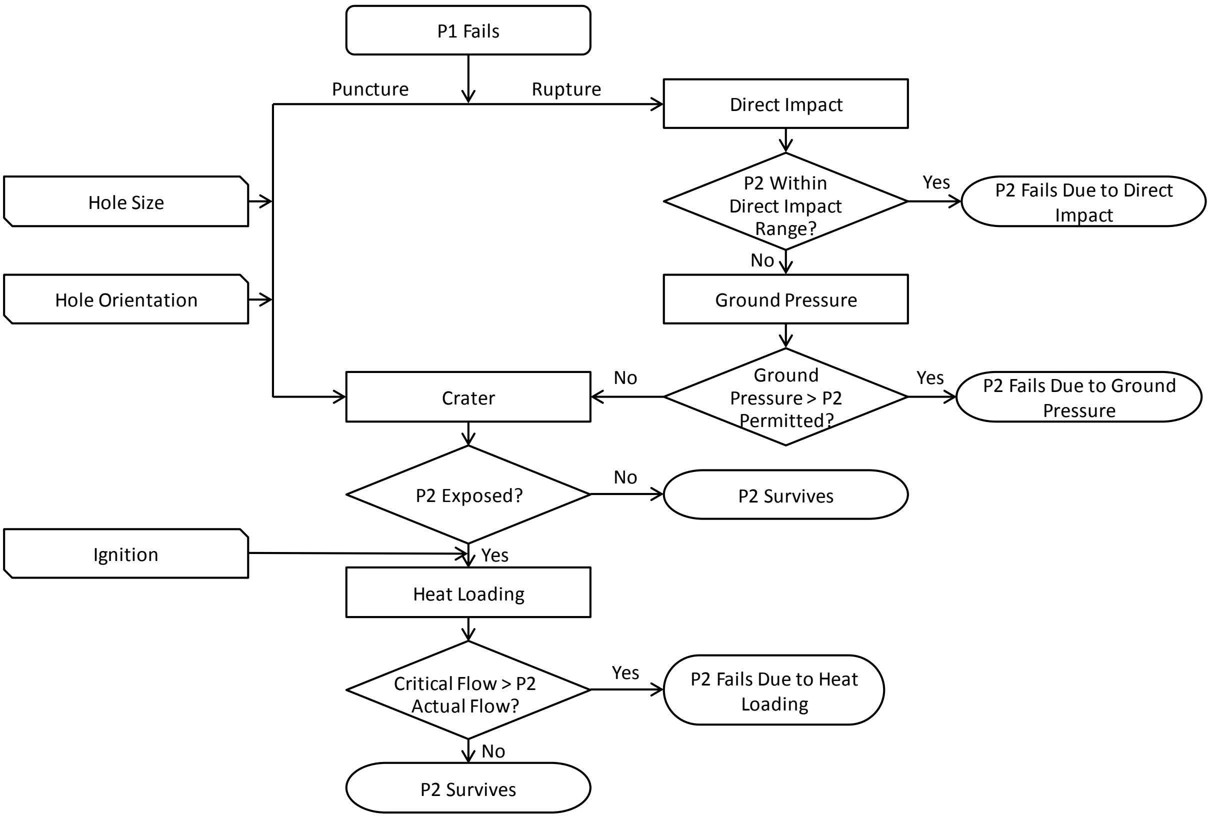

Figure 9 Event tree for parallel pipeline probabilistic assessment

The failure frequencies are not prescribed in the methodology but can be obtained from a number of sources. The recommended source of failure frequencies due to external interference is the FFREQ model, which is available in the DNV GL PIPESAFE package (Acton, 1998, Acton, 2002 and Acton, 2007). The failure frequencies due to external corrosion and material and construction defects can be obtained from Institution of Gas Engineers and Managers (2013). Other sources are also available, e.g. EGIG (2013), UKOPA (2016)

The probability of ignition is calculated from a correlation that is already implemented in PIPESAFE and is based on an assessment of information gathered on pipeline incidents worldwide (Acton (2016)). For a rupture, the ignition probability is a function of the pipeline diameter and pressure. A similar correlation is used for puncture releases but in this case the pipe diameter is replaced by the hole diameter and the ignition probability is reduced to reflect the fact that the release is from a single hole, rather than a double-ended release from a pipeline rupture.

The treatment of punctures is complicated by the fact that the hole size can vary and only sizes above a certain threshold can lead to escalation. The methodology is used iteratively to determine the minimum hole size that causes escalation. The probability of escalation is then determined from the probability of this hole size and a corresponding ignition probability. The event tree shown in Figure 9 shows that a puncture release can only cause escalation through heat loading; there are four requirements for this event to occur, namely that the failure is a puncture, the size of the hole is large enough to cause escalation, the direction of the release is such that P2 will be hit and the release is ignited. The default value that the probability that the orientation of the puncture is such that it will hit pipeline P2 is 0.25, corresponding to one quadrant under the assumption that the release is perpendicular to the pipeline axis. However, this parameter can be specified by the user.

Figure 9 shows that a rupture can cause escalation in three different ways, namely direct impact, ground pressure and heat loading. Failure by direct impact or ground pressure is determined by the fixed parameters of the configuration, while failure by heat loading has the additional requirement that the release is ignited.

Application example

The probabilistic methodology has been applied to the following fictitious example, which illustrates how it can be used in comparison to the deterministic approach:

- Failing pipeline P1: 70 barg, 508 mm diameter, 7.9 mm wall thickness, 0.9 m depth of cover.
- Adjacent pipeline P2: 70 barg, 914.4 mm diameter, 11.8 mm wall thickness, 1.2 m depth of cover.
- The horizontal separation distance of the pipelines (centre to centre) is 1.5 m, giving about 0.8 m edge to edge separation. The soil type is mixed and the bulk gas velocity in P2 is 0.4 m/s.

With the previous, deterministic, approach the analysis would be carried out separately for a full bore rupture and for a puncture of a specific size (taken to be 25 mm in this example). The results in both cases are that pipeline P2 fails due to thermal loading. Additional calculations can be performed for different flow velocities and/or hole sizes.

In the probabilistic approach, failure frequencies for ruptures and punctures must be specified first, so that the relative probabilities of failure of each mode can be determined. In this example, three contributors to the failure frequencies have been accounted for, namely 3rd party interference, external corrosion and material and construction defects. The failure frequencies have been obtained from the FFREQ model for 3rd party interference and from Institution of Gas Engineers and Managers 2013 for the other two causes. Regarding the orientation of the puncture, it has been assumed that any circumferential direction has equal probability; hence a factor of 0.25 has been taken to represent the proportion of punctures that can affect pipeline P2.

The probabilistic analysis predicts that both ruptures and punctures can cause escalation (i.e. P2 fails), due to heat loading. Given that a loss of containment failure of P1 has occurred, the most important results include:

Probability that the failure is a puncture	0.87
Probability that the failure is a rupture	0.13
Puncture ignition probability	0.06
Rupture ignition probability	0.30
Minimum puncture hole size for escalation	9 mm
Total probability of escalation given that a failure of P1 has occurred	0.045

The example illustrates that the existing deterministic approach provides only a fail/no fail answer, which is appropriate in many applications, particularly for determining suitably cautious design guidance for new pipelines systems where a minimum separation distance is required. However, it is less useful in the assessment of risk for existing installations, where the minimum separation distances specified in the guidance are not met, or where space limitations (particularly where there are multiple pipelines in a single corridor) mean that it is impractical to do so without incurring excessive additional costs.

In this example, the probabilistic analysis shows that less than 5% of failures of pipeline P1 will result in escalation. The results from the new probabilistic model can be applied in a risk-based approach, such as that set out in IGEM/TD/2, to consider the risk from escalation in the context of the risks from other threats to the pipelines and to weigh up the costs and benefits of possible mitigation measures in order to demonstrate that risk is managed effectively and to a level that is as low as reasonably practicable (ALARP).

Conclusions

The further phase of the collaborative project has improved the methodology for parallel pipeline assessments in the following areas:

- The model for the prediction of the crater width resulting from a pipeline rupture has been improved to take account of the pressure in the failing pipeline and the profile of the crater. The predictions have been compared with data from incidents and shown to give better agreement.
- Revised heat fluxes from puncture jet fires have been produced, based upon full scale experimental data, which are less conservative than the previous assumptions. This allows the mass flow rate from the puncture and the position of the second pipeline in the fire to be considered and means that the second pipeline is predicted to be less likely to fail than previously.
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References

Acton, M.R., Baldwin, P.J., Baldwin, T.R., and Jager, E.E.R., 1998, The Development of the PIPESAFE Risk Assessment Package for Gas Transmission Pipelines, Proc. 2nd International Pipeline Conference (IPC98) Calgary, ASME International

Acton, M.R., Hankinson, G., Ashworth, B.P., Sanai, M., and Colton, J.D., 2000, A Full Scale Experimental Study of Fires following the Rupture of Natural Gas Transmission Pipelines, Proc. 3rd International Pipeline Conference (IPC'00) Calgary, ASME International

Acton, M.R., Baldwin, T.R. and Jager, E.E.R., 2002, Recent Developments in the Design and Application of the PIPESAFE Risk Assessment Package for Gas Transmission Pipelines, Proc. 4th International Pipeline Conference (IPC '02) Calgary, ASME International

Acton, M.R., Baldwin, P.J. and Dimitriadis, K., 2007, The Application of Risk Assessment to Routing Issues for Gas Transmission Pipelines, Proc. 12th International Symposium on Loss Prevention and Safety Promotion in the Process Industries, Edinburgh

Acton, M.R., Jackson, N.W. and Jager, E.R., 2010, Development of Guidelines for Parallel Pipelines, Proceedings of IPC 2010, IPC2010-31287

Acton, M.R., Acton, O.J. and Robinson. C., 2016, A Review of Natural Gas Transmission Pipeline Incidents to Derive Ignition Probabilities for Risk Assessment, Hazards 26 (Edinburgh), Symposium Series No. 161, IChemE, May 2016

ANSI/API, 2007, Guide for Pressure-relieving and Depressuring Systems: Petroleum petrochemical and natural gas industries, ANSI/API Standard 521, Fifth Edition, January 2007

EGIG, 2013, 9th Report of the European Gas Pipeline Incident Data Group (period 1970 – 2013); www.egig.eu

Fire and Blast Information Group, 2014, Design Guidance for Hydrocarbon Fires, Technical Note 13, September 2014

Henrych, J., 1979, The Dynamics of Explosion and Its Use, Elsevier Scientific Publishing Company

International Association of Oil and Gas Producers, 2010, Vulnerability of plant/structure, OGP Risk Assessment Data Directory, Report No. 434-15, March 2010

Institution of Gas Engineers and Managers, 2008, Steel pipelines and associated installations for high pressure gas transmission, IGEM/TD/1 (Edition 5)

Institution of Gas Engineers and Managers, 2013, Assessing the Risks from High Pressure Natural Gas Pipelines, IGEM/TD/2 (Edition 2)

Johnson, D.M., Cumber, P.S., Horner, N., Carlson, L. and Eiber, R., 2000, Full-scale Fracture Propagation Experiments: A Recent Application and Future Use for the Pipeline Industry, Proc. 3rd International Pipeline Conference (IPC'00) Calgary, ASME International

Leis B.N., Pimputkar S.M. and Ghadiali N.D. Line Rupture and the Spacing Parallel Lines. Battelle Memorial Institute, Contract PR-3-9604, April 2002

Lowesmith, B.J., Hankinson, G., Acton, M.R and Chamberlain, G., 2007, An Overview of the Nature of Hydrocarbon Jet Fire Hazards in the Oil and Gas Industry and a Simplified Approach to Assessing the Hazards, Process Safety and Environmental Protection, Trans IChemE, Part B, May 2007

NORSOK, 2008, Technical Safety, NORSOK Standard, S-001, Edition 4, February 2008

Oil & Gas UK, 2007, Fire and Explosion Guidance, Issue 1, May 2007

Pritchard, M.J. and Cowley, L.T., 1991, Thermal Impact on Structures from Large Scale Jet Fires", Safety Developments in the Offshore Oil and Gas Industry, IMechE, Glasgow, 23-24 April 1991

Schram, W., 1991, Prediction of the Crater Caused by an Underground Pipeline Rupture, N.V. Nederlandse Gasunie Report TP/T 91.R.2043

UKOPA Pipeline Product Loss Incidents and Faults Report (1962-2015), United Kingdom Onshore Pipeline Operators' Association UKOPA/16/006, December 2016; www.ukopa.co.uk

Waterloopkundig Laboratorium, 1972, Soil Erosion due to Gas Pipeline Fracture – Report on Model Tests, Waterloopkundig Laboratorium Report M1136-R743