Risk Assessment of Natural Gas Transmission Pipelines at Major River Crossings

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Quantitative Risk Assessment (QRA) methodologies for buried onshore natural gas transmission pipelines have become well established and are now codified in standards for pipeline risk assessment such as IGEM/TD/2. The methods take account of the likelihood of failures occurring (either as leaks or full bore ruptures), the probability that ignition occurs, the properties of the resulting gas-fuelled fire and the extent of its effects on people and property in the vicinity. Although such events are rare, their consequences can be severe, and it is important for pipeline operators to understand the risks associated with pipelines in order to manage them effectively. Pipelines are exposed to a wide range of threats, including external interference damage and ground movement which dominate risk for onshore pipelines in the UK.

The QRA methodologies and mathematical models used in pipeline QRA tools, such as the DNV GL PIPESAFE package, have been developed and validated for pipelines on land where the threats to pipeline integrity and the consequences of failure are well understood. However, gas transmission pipelines inevitably encounter situations where the methodologies for onshore pipelines may not be appropriate. In particular, pipelines may need to cross major rivers or estuaries, potentially with shipping traffic passing over the pipeline and an exposed population on the vessels or the shoreline, where the threats to the pipeline and the consequences of failure differ from those for buried onshore pipelines.

The primary objective of this study was to adapt the methodology in place for buried onshore gas transmission pipelines to handle the different threats to pipeline integrity and the potential differences in release behaviour and effects that would be expected for an underwater failure of a high pressure natural gas transmission pipeline crossing a major river used as a shipping route. The methodology was then applied to an operational National Grid pipeline crossing a major navigable river, in order to quantify the level of risk posed to and by the pipeline and support an investment decision on the possible relaying of the pipeline.

A modified version of the PIPESAFE methodology was developed in three stages:

1. Gather information on current approaches to risk assessments of pipelines under water.
2. Identify credible failure causes and failure modes for different types of water crossings and define methods for predicting appropriate failure frequencies.
3. Determine the limitations of PIPESAFE for calculating the consequences of underwater releases, including the dependence on site-specific parameters such as pipeline pressure and diameter and the depth of water above the pipeline.

The application of the modified methodology to a pipeline river crossing on behalf of National Grid, performed in order to calculate risk levels for comparison with relevant risk criteria, is described in the paper, together with a discussion of the assumptions and limitations of the approach.

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]. 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. Quantitative Risk Assessment (QRA) methodologies for buried onshore natural gas transmission pipelines have become well established and are now codified in standards for pipeline risk assessment such as IGEM/TD/2 5. The methods take account of the likelihood of failures occurring (either as leaks or full bore ruptures), the probability that ignition occurs, the properties of the resulting gas-fuelled fire and the extent of its effects on people and property in the vicinity. Although such events are rare, their consequences can be severe, and it is important for pipeline operators to understand the risks associated with pipelines in order to manage them effectively. Pipelines are exposed to a wide range of threats, including external interference damage and ground movement which dominate risk for onshore pipelines in the UK.

The QRA methodologies and mathematical models used in pipeline QRA tools, such as the DNV GL PIPESAFE package, have been developed and validated for pipelines on land where the threats to pipeline integrity and the consequences of failure are well understood. However, gas transmission pipelines inevitably encounter situations where the methodologies for onshore pipelines may not be appropriate. In particular, pipelines may need to cross major rivers or estuaries, potentially with shipping traffic passing over the pipeline and an exposed population on the vessels or the shoreline, where the threats to the pipeline and the consequences of failure differ from those for buried onshore pipelines.

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Methodology

In order to be able to undertake risk assessments of natural gas transmission pipelines crossing under navigable waterways, to an equivalent level of detail to that performed for similar buried pipelines on land, a modified version of the PIPESAFE methodology was developed in three stages:

1. Gather information on current approaches to risk assessments of pipelines under water.
2. Identify credible failure causes and failure modes for different types of water crossings and define methods for predicting appropriate failure frequencies.
3. Determine the limitations of PIPESAFE for calculating the consequences of underwater releases, including the dependence on site-specific parameters such as pipeline pressure and diameter and the depth of water above the pipeline.

Literature Review

A literature review was undertaken to gather information on existing approaches to risk assessments of pipelines at water crossings. No standards or recommended practices were identified that gave detailed guidance in this area, and many approaches were found to be resource-intensive and not suitable for general application, such as Computational Fluid Dynamics (CFD) techniques and Finite Element Analysis (FEA), that can be used to assess specific issues such as gas outflow behaviour and dispersion through the water column and for structural assessment of pipelines exposed to complex external loads.

DNV-RP-F107 6 is DNV GL's recommended practice on Risk Assessment of Pipeline Protection. This document proposes a methodology for assessing the response of pipelines to external impact, based on the impact (kinetic) energy. It accounts for factors such as concrete coating, ground cover, and other pipeline protection. Although it is chiefly intended for assessing the risk from dropped objects and vessel impact to risers, it is also widely used in the industry to assess the damage caused to pipelines by impact from a wide variety of objects, including anchors and grounding or foundering ships, as part of QRAs. This approach was adopted within the methodology, as discussed later in this paper.

Failure Causes, Modes and Failure Frequencies

Credible pipeline failure causes and mechanisms were identified and categorised according to whether or not the associated failure frequency would be significantly different at water crossings than for adjacent underground buried sections. This section outlines the failure causes that have been considered for water crossing risk assessments and how they have been addressed in the methodology.

The following failure causes were not considered to be significantly affected by routing the pipeline under a water crossing and so were not considered to require different treatment in the methodology:

- Fatigue: Fatigue failure due to vortex-induced vibration (or VIV) can be a major concern in subsea pipeline design, particularly if free-spanning is expected to occur as a result of routing or erosion. For water crossings, most pipelines will be buried with a significant depth of cover, preventing the onset of VIV. Therefore it is considered that fatigue failure rates would not generally be higher than for the adjacent land sections, unless the pipeline could be exposed to the water flow.
- Construction/Material Defects: It is assumed that the pipeline is designed appropriately and that measures are taken to ensure that quality of construction is maintained at water crossings. Therefore it is not expected that construction and material defect failure rates would increase significantly at water crossings compared with the adjacent land sections.
- Corrosion: It is assumed that a buried pipeline will be exposed to similar conditions, including maintenance and inspection, at water crossings as for buried land sections. If it is possible that water crossing conditions may be more onerous in terms of corrosion than onshore conditions, it is assumed that appropriate steps will be taken to mitigate and monitor the pipeline for the onset of corrosion issues. Therefore it is considered appropriate to treat corrosion failures at water crossings similarly to neighbouring buried land sections. Furthermore, corrosion incidents are time-dependent and tend to result in small punctures or leaks rather than ruptures, which may be detected and repaired, and are therefore considered to pose less risk than other factors which may be time-independent, and more likely to result in rupture.

If there is reason to believe that the failure frequency due to any of the above causes may be higher at the water crossing than the adjacent land sections (for example, if the pipeline is at risk of exposure at the crossing due to washout, or if the efficiency of a Cathodic Protection system is likely to be affected), then a site-specific study should be undertaken to address the issues in detail.

Ground Movement

Ground movement at water crossings is possible and is known to have occurred. River banks can be unstable and events such as flooding may result in wash-out of part of the river bank or bed. This may lead to a failure directly or increase the pipeline's exposure and hence risk to other factors.

However, information relating to ground movement incidents at pipeline water crossings is limited and it was concluded during the course of the study that further data and investigations would be required to derive generic failure frequencies due to ground movement with the required degree of statistical significance. On this basis, site-specific assessments of the risk from ground movements at water crossings are recommended, based on pipeline properties, geotechnical and hydrological studies, operator experience, and so on.

External Interference

For onshore pipelines, the risk due to external interference generally dominates the overall risk from high pressure gas pipelines, because the threat is at least partly outside the control of the operator and because of the potential for damage to result on a full bore pipeline rupture rather than a smaller leak. The types of external interference likely to occur at water crossings differ significantly to those likely for buried land sections (for example, due to shipping incidents rather than excavating machinery) and therefore specific consideration is given to this failure cause.

The principal identified potential failure causes are summarised in Table 1 and described in further detail below. The main failure modes identified are failure due to denting, caused by impact, and local buckling caused by hooking, lifting, or other loading of the pipeline. The threat associated with gouging is also discussed further.

Table 1: Identified External Interference Failure Causes and Associated Failure Modes

Failure Cause	Sub-Causes	Credible?
Dropped object	Object lost overboard	No
	Drop during lifting operations	No
Dredging	N/A	Negligible in comparison to other causes
Vessel impact	Grounding / stranding	Yes
	Foundering	Yes
Anchor impact (drop/drag)	Anchor drop	Yes
	Anchorings of convenience / emergency anchoring / accidental anchoring / drag from anchorage	Yes

- Dropped objects refer to objects lost overboard or dropped during handling, which land on the pipeline. However, it is assumed that most objects lost overboard from inland waterways vessels will be too light to cause significant damage, and it is assumed to be unlikely that major lifting operations will regularly occur over water crossings. Therefore this failure cause is not considered generally credible. Site-specific studies using appropriate codes and standards should be carried out if this is considered a credible failure cause in specific circumstances.
- Dredging operations take place in many navigable waterways and although there is a high potential for damage due to the nature of the work, it is a controlled and planned activity. The frequency of dredging operations in any given location is typically low in comparison to the vessel traffic and because it would be expected that robust procedures are in place to prevent interaction between a pipeline and dredging operations, it is assumed that in the majority of cases, the frequency of pipeline incidents due to dredging would be negligible in comparison to that from other causes. However, if dredging is considered to pose a particular risk at a specific location, for example where there has been a history of poorly controlled dredging operations, then a site-specific analysis of this aspect may be required.
- Vessel impact refers to direct impact of the vessel on the pipeline. This will involve large energies and therefore failure due to impact/denting is considered credible. It is also possible for the grounding vessel to push the pipeline laterally and therefore local buckling is also considered a credible failure mode.
- Anchor impact refers to interaction between a vessel anchor and the pipeline for any reason. Anchor impact may involve large energies and can cause hooking of the pipeline and therefore both denting and local buckling failure modes are considered credible.

It was concluded therefore, that the main failure causes dominating the overall external interference failure frequency in the general case are vessel impact and anchor impact. The approach for calculating these is outlined in the following section.

Calculation of External Interference Failure Frequency

The external interference failure frequencies for vessel impact and anchor impact are calculated as the sum of the product of the collision frequency (or hit frequency) and the conditional probability of failure for each failure sub-cause. Because both the hit frequency and conditional probability of failure depend on the vessel size and the types of vessel and anchor impact, the summation is refined to include several vessel size classes and impact types.

The failure frequency due to external interference is heavily dependent on the amount of vessel traffic passing the pipeline and therefore the annual vessel traffic passing the pipeline should be established. The assessment of both hit frequency and failure probability are dependent on vessel-specific parameters and, therefore, assumptions are made regarding relevant vessel properties such as vessel displacement (total mass of the vessel and all contents), length and anchor size. It is noted that these properties may vary greatly between vessels of different sizes and it would be overly cautious to apply worst case properties to all vessels. Therefore, in the methodology, the estimated vessel traffic is divided into a number of size classes and representative properties are applied to all of the vessels in each size class.

Hit Frequency due to Vessel Impact

Direct vessel impact on a pipeline is considered possible due to two causes: grounding/stranding and foundering. Grounding is generally caused by navigational error or failure of the hull or machinery (for example, the engine or rudder). As such, grounding incidents may be broadly categorised as powered grounding (e.g. navigational errors) and drifting grounding (e.g. engine and rudder failures), based on the vessel speed at the time of the incident.

Foundering refers to the sinking of a vessel for any reason. This may occur due to grounding, collision, hull or machinery failure, weather, for example, but is generally reported as a separate cause in incident data.

The methodology utilises historical data for estimating vessel grounding and foundering frequencies, although the frequencies could be refined using site-specific methods if better data is available. The frequency of grounding and foundering impact events are calculated for each vessel size class and the total predicted failure frequency calculated as the sums of the contributions of each.

Hit Frequency due to Anchor Impact

Vessel anchoring, which may occur for a number of reasons including convenience, emergency scenarios, and by accident, can pose a threat to pipelines at water crossings from both anchor drop and anchor drag. However, the length over which anchor drop impact is likely (one pipeline diameter) will generally be negligible compared to the length over which anchor drag is likely (the total anchor drag length) and additionally, an anchor drag scenario is likely to involve higher impact energies as the kinetic energy of the vessel will contribute. The overall risk from anchor drop is assumed to be negligible compared to that from anchor drag.

The methodology estimates hit frequencies due to anchor drag as a function of the frequency of each type of anchor drag event and the area over which the event could occur (anchor drag length), which accounts for likely vessel velocity, vessel size and anchor type and size. As for vessel impact, the analysis is undertaken in the methodology for each vessel size class and the contributions of all classes are summed to give the overall frequencies.

The penetration depth of anchors depends on the size of the vessel and anchor and the anchor type; the threat of anchor impact may be discounted if the pipeline depth of cover exceeds the anchor penetration depth. This is taken into account in the methodology by developing a relationship between vessel size and anchor penetration depth. Note that it may be possible to neglect anchor impact from some vessels, but not all. Riverbed erosion may reduce the depth of cover to levels less than anticipated, which may be difficult to detect due to infrequent inspection. A site-specific analysis could account for an additional risk factor depending on the properties of the river bed and the inspection interval.

Probability of Pipeline Failure

DNV-RP-F107 6 provides a method for assessing the failure frequency due to denting caused by impact to pipelines. The approach is widely used in the industry for assessment of impact due to dropped objects, anchor drag, and vessel impact in QRAs and similar assessments. This approach has been adopted within the methodology to evaluate the conditional probability of failure for each threat to the pipeline. The document is freely available for download from the DNV GL website (www.dnvgl.com) and so the approach is not reproduced in detail here. Suffice it to say that depending on the energy of impact and the energy absorption capacity of the pipeline and any protecting measure (e.g. concrete jacket), three probabilities are calculated; namely those for rupture, puncture and hit on the pipeline with no gas release.

Consequence Modelling

Release Behaviour

The presence of water means that pipeline releases at water crossings may behave significantly differently to an equivalent release from a buried pipeline on land, depending on the water depth. PIPESAFE is specifically designed to model high-momentum releases from below ground pipelines on land and in order to use it as a simplified approach for modelling releases at water crossings, limits on the release conditions were defined, within which it is expected that an underwater release will behave in a broadly similar way to an equivalent buried release on land, so that PIPESAFE can be used without modification in such cases.

Gas outflow rates can be calculated with the PBREAK model in PIPESAFE, which takes account of the ambient pressure at the location of the pipeline failure. In conjunction with the development of this methodology, a modification was made to PBREAK to allow a water depth to be specified, thereby taking account of the correct external pressure, which consists of the atmospheric pressure plus the pressure head of the water above the pipeline.

The movement of gas through the water column will result in the gas plume spreading out and losing momentum. Criteria were developed to classify whether or not, when it reaches the water surface, an underwater release would behave as a high-momentum, jet-like release, for which the predictions of the fire models within PIPESAFE would remain valid. The method used to predict the momentum of the release is derived from a simple Cone Model, discussed in 7 and illustrated in Figure 1, where D represents the maximum water depth of the crossing. In accordance with 7, a cone half-angle (θ) of 10° is recommended. In essence, the criterion compares the estimated average gas velocity at the water surface V_S with a minimum value V_{MIN} dictated by the requirements of the fire models. If $V_S > V_{MIN}$, the release is classed as high momentum and the PIPESAFE models can be used without modification. The same principle applies to both rupture and puncture releases.

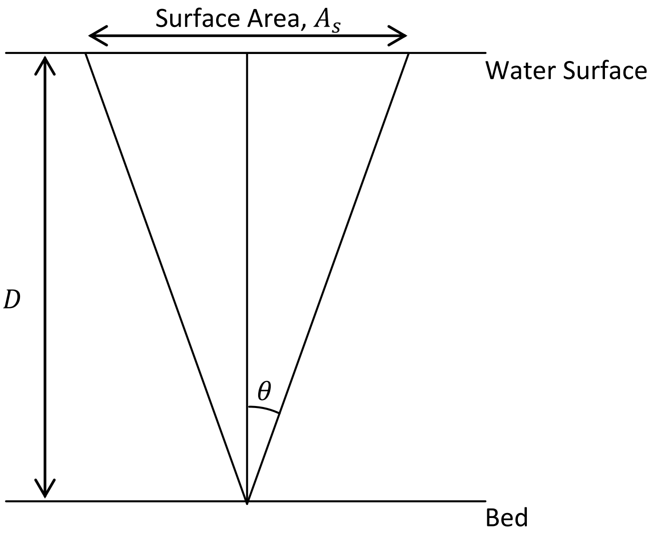

Figure 1: Simplified underwater release profile ("Cone Model")

The mechanisms causing gas releases to ignite, both onshore and offshore, are not yet fully understood and it is difficult to assess whether the probability of ignition will be more or less likely for underwater releases, compared to releases from buried pipelines on land. Therefore, the approach taken is that the ignition probability used for calculating the risks from underwater releases should not be less than that for an equivalent buried pipeline on land. A correlation based on historical data is been used 5.

Effect on Populations

Vessels may be classed as "incident-causing" or "other". An incident-causing vessel will be present where the rupture was caused by external interference, but not otherwise, and the methodology assumes that an incident-causing vessel will always be located close to the rupture location. When modelling consequences for populations on board vessels, the methodology takes into account that the population has no access to shelter and no means of escape (i.e. 0 m/s escape speed). This differs from the assessment of populations on land, where it is assumed that populations will attempt to escape and find shelter and the calculated accumulated thermal dose received takes this into account.

Application

The water-crossing methodology has been applied to a pipeline crossing a major river estuary, in the context of a QRA carried out on behalf of National Grid, in order to calculate risk levels for comparison with relevant risk criteria.

Description of Pipeline and Underwater Section

The pipeline studied originates at an Above-Ground Installation (AGI), which is located less than 1 km from the river bank. Several other pipelines are also interconnected at the same AGI, shown in Figure 2. In the other direction, the pipeline reaches a compressor station, which is approximately 63 km away from the river estuary.

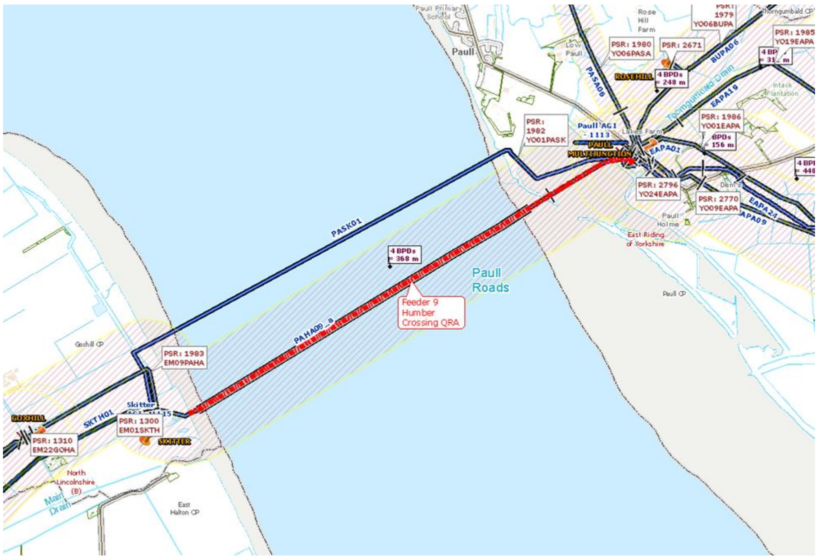

Figure 2: Pipeline river crossing assessed

The river is a major waterway with high volume of vessel traffic. The underwater section of the pipeline is approximately 3 km, but the vast majority of the vessel movements are within the navigation channel, which is approximately 400 m wide. The pipeline was originally laid along a shallow trench at the river bed, which was subsequently filled by natural processes, thus covering the pipeline. The depth of cover varies greatly along the pipeline route and has also varied to some extent over time. The navigation channel is contained within the deepest section of the river, approximately 800 m wide, where the depth of cover is greatly reduced. In most of the remaining underwater section the depth of cover is large enough to preclude damage to the pipeline from passing vessels and appears to have varied very little over time. In the deepest section of the river, the water depth varies between 10 and 12 m.

The pipeline is protected by a concrete jacket 150 mm thick and two sets of gravel filled bags laid either side of the pipeline. In addition, the trench containing the pipeline has been overlaid by Frond mattresses to a width of about 34 m. The function of the Frond mattress is to facilitate sedimentation and the filling of the trench, as well as to impede the removal of sediment in adverse conditions. Therefore, its main function is to increase the depth of cover of the pipeline rather than to offer direct protection from impact.

Vessel Traffic

Detailed information on vessel traffic was available in the form of a list of all recorded vessel passages over the past 12 months. The vast majority of the vessel movements is in the navigation channel. Classification of the data by vessel type is shown in Table 2. It is noted that the three most common types (i.e. cargo, tanker and passenger ships), represent about 74% of all vessels. These types also include the largest vessels, which are more likely to cause a pipeline incident.

Table 2: Classification of Vessel Traffic by Vessel Type

Vessel Type	Number of Passages
Cargo	5290
Tanker	1139
Passenger	1091
Tug	922
Dredging/Underwater Ops	757
High Speed Craft	102
Fishing	46
Other/Unspecified	803
Total	**10150**

In addition to the vessel type, for each vessel in the provided list the length, draught and DWT (Dead Weight Tonnage) were also given. Subsequently, the data was processed and split into groups of increasing average size, as required by the methodology.

Calculation of External Interference Hit and Failure Frequencies

Due to the high volume of vessel traffic, external interference by passing vessels was considered to be the most likely cause of damage to the pipeline. Other failure causes were considered not to contribute significantly to the results of the assessment. Of particular concern was the possibility that a free-spanning section could develop due to scouring and reach a critical length that would result in a high probability of pipeline failure. However, a parallel study that was conducted to address this issue concluded that this possibility was unlikely. Therefore, following the methodology outlined in earlier sections, two failure causes were accounted for; namely vessel and anchor impact.

The methodology considers the energy that is absorbed by the pipeline wall and any additional protection, which in the present case is a concrete jacket. The related data used in the analysis are summarised in Table 3.

Table 3: Pipeline and Concrete Jacket Characteristics

Parameter	Value
Pipeline diameter	1066.8 mm
Pipeline wall thickness	19.05 mm
Pipe material grade	X65
Pipe material SMYS	450 MPa
Concrete coating thickness	150 mm
Concrete coating crashing strength	105 MPa

No credit has been taken for the Frond mattresses, because their function is not to protect against impact. However, the presence of gravel-filled bags, mentioned earlier, has been accounted for by selecting the type of covering soil as ‘gravel’ for the vessel impact model and ‘hard soil’ for the anchor impact model, which offer greater protection than the alternatives available in the methodology.

Three different scenarios that can result in direct vessel impact are considered in the methodology:

- Grounding under power, i.e. when the vessel is moving at normal cruising speed. This is most likely a result of navigational error.
- Grounding due to drifting. This is most likely a result of mechanical failure (e.g. engine or rudder failure).
- Foundering.

The methodology uses generic base frequencies for the above scenarios derived from historical data that include both seagoing and non-seagoing ships. The derivation of the recommended base frequencies is conservative in a general sense, because the average frequencies for seagoing vessels tend to be higher than those for inland vessels in most cases. At the time the present study was conducted, no specific information for the river crossing in question was available to allow a more refined estimation of the base frequencies. However, the frequencies used for the grounding scenarios were substantially reduced based on site-specific factors; namely that over the greatest part of the river span either the depth of cover is too high or the water is too deep for grounding to be credible.

Regarding anchor impact, the methodology considers three contributing scenarios:

- Anchoring of convenience. The probability of this is greatly reduced in a ‘No anchoring’ zone.
- Accidental anchoring
- Emergency anchoring

The appropriate vessel speed to be used in the analysis would be different for each of the above scenarios. The values assumed in the assessment, as well as the depth of cover used, are listed in Table 4. It is noted that, based on detailed available information, two values of the depth of cover have been used with equal probability, pertaining to the deepest, 800m section of the river span.

Table 4: Parameters used in Vessel and Anchor Impact Analysis

Parameter	**Value**
Reduction factor for grounding frequency	0.05
Vessel speed for grounding under power	15 kts
Vessel speed for grounding under drifting conditions	8 kts
Vessel speed for foundering	4 kts
Vessel speed for accidental anchoring	15 kts
Vessel speed for emergency anchoring	8 kts
Vessel speed for anchoring of convenience	0.5 kts
Depth of cover (two values used with equal probability)	1.4 & 0.4 m

The results of the analysis are summarised in Table 5. The ‘Hit - No release’ values correspond to hits that do not result in a pipe break. The ‘Vessel + Anchor’ frequencies are the sum of the corresponding ‘Vessel’ and ‘Anchor’ frequencies.

It is noted that all predicted failures are rupture, i.e. punctures do not contribute in this case; therefore, only ruptures will be considered in the consequence and risk analyses that follow, using the rupture frequency for ‘Vessel + Anchor’ from the table. In onshore pipeline QRAs it is usually the case that punctures are not included in the assessment, even if their frequency is high, because the resulting risks tend to be much lower than those from ruptures.

Table 5: Calculated Frequencies for Vessel and Anchor Impact

Mode	**Frequency (per year)**	**Once every**
Rupture (Vessel)	3.12×10^{-5}	32,000 yrs
Hit - No release (Vessel)	3.35×10^{-5}	29,800 yrs
Total hit frequency (Vessel)	6.47×10^{-5}	15,400 yrs
Rupture (Anchor)	9.08×10^{-5}	11,000 yrs
Hit - No release (Anchor)	1.59×10^{-4}	6,300 yrs
Total hit frequency (Anchor)	2.50×10^{-4}	4,000 yrs
Rupture (Vessel + Anchor)	**1.22×10^{-4}**	**8,200 yrs**
Hit - No release (Vessel + Anchor)	1.93×10^{-4}	5,200 yrs
Total hit frequency (Vessel + Anchor)	3.15×10^{-4}	3,200 yrs

Consequence Assessment

The consequence assessment consists of the outflow calculation and the fire and thermal response calculations. Before proceeding with the assessment, however, it is necessary to confirm that the water depth and the release conditions are such that the predictions of the PIPESAFE models will be valid. Following the criteria discussed earlier and using a maximum water depth of 15 m[1], the estimated gas velocity at the water surface V_S is 296 m/s and the lower limit V_{MIN} is 162 m/s. Therefore, the criterion $V_S > V_{MIN}$ is comfortably met.

For the purpose of the outflow calculation the release was simulated as a two-ended pipeline rupture, with the upstream section extending up to the AGI, about 1.5 to 2 km from the navigation channel, and the downstream section extending to the compressor station 63 km away. Since several other pipelines are interconnected at the AGI, a maintained-pressure boundary condition was assumed there, which is cautious considering the proximity to the rupture point[2]. On the downstream side, a no flow boundary condition has been assumed. The PBREAK outflow model in PIPESAFE predicts the mass-flow rates from each pipe end as functions of time, which are used as inputs to the fire calculations.

The fire and thermal response calculations have been carried out in accordance with the standard methodology specified for use in onshore assessments for National Grid. The fire models in PIPESAFE predict a time-varying radiation field from the transient ignited release, which in turn is used to calculate building burning distances, escape distances and casualty rates. These calculations have been repeated for three wind speeds (2, 5 and 10 m/s), twelve wind directions and two ignition

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[1] The average water depth in the navigation channel varies between 10 and 12 m but a cautious value of 15 m was used in the assessment.

[2] The potential effect of the upstream length on the predicted risks was investigated by conducting a second calculation with the upstream length set to 63km (i.e. the same as the downstream length). The predicted risks were only reduced by 2.6%; therefore, any approximation in terms of the upstream length will have an insignificant effect on the risk assessment.

delays (0 and 30 s). In the subsequent risk assessment, the different wind speeds, wind directions, as well as ignition delays, are assumed to occur with equal probabilities.

The escape distances and casualty rates have been predicted with the SLOD (Significant Likelihood Of Death) casualty criterion, which corresponds to a radiation dose of 1800 thermal units and is frequently used in assessments in the UK. Another important parameter is the escape speed (i.e. the speed at which a person moves away from the fire trying to escape). In standard assessments, which are appropriate for onshore populations, the usual value is 2.5 m/s. For vessel populations, the recommendation in the current methodology is to use a value of 0, on the grounds that vessels may be slow or unable to react in the emergency situation that will arise after the onset of the fire. Moreover, some vessels may be moving towards the fire and others in the opposite direction at the time of the incident. Therefore, a value of zero seems appropriate, albeit conservative as it ignores other possibilities (e.g. people jumping into the water).

The maximum hazard distances predicted over all relevant scenarios considered (i.e. all wind speeds and ignition delay times) are listed in Table 6. The building burning distance, as calculated with the standard PIPESAFE methodology used for onshore assessments, may be too conservative when applied to large ships with a metallic shell. This issue is discussed later, where some modification of the methodology is considered.

Table 6: Maximum Predicted Hazard Distances

Hazard Distance	**Value**
Building burning distance	322 m
Escape distance for onshore populations	515 m
Safe[3] distance for vessel populations	1175 m

Societal Risk Assessment

The predicted hazard distances are such that no onshore populations are within hazard range. Therefore, only vessel populations need be included in the assessment. After careful analysis of the vessel traffic data, the vessel movements were divided into four categories; namely, Passenger ship (P), Large ship (L), Medium ship (M) and Small vessel (S).

Given that no other failure causes except External Interference have been included in the analysis, the assumption is made that if an incident occurs, a vessel will always be near the pipeline (i.e. the vessel that caused the incident). The probability that the initiating vessel belongs to a particular category can be approximately calculated from the category sizes[4], taking into account that the failure frequency calculations suggest that vessels in the Small category are extremely unlikely to cause a rupture. The results are summarised in Table 7.

Table 7: Vessel Categories for Risk Analysis

	Vessel Categories				**Total**
	P	**L**	**M**	**S**	
Number of vessels	1091	1967	5696	1396	10150
Probability of causing incident	0.1246	0.2247	0.6507	0	1
Number of people in vessel	1500	20	10	5	-

The passenger ship traffic consists of regular services operated by three large ferries, which can carry up to 1500 passengers and crew. The analysis has been further refined by allowing the possibility that a second ship may be present within the hazard area and be affected. The probabilities of such events are calculated in terms of hazard distance, number of vessel movements and average vessel speed. However, the probability of two passenger ships being present at the same time is excluded on the grounds that their movements follow a regular timetable and their transits are too far apart in time.

In the standard PIPESAFE methodology, as applied to onshore assessments, the building burning distance is calculated on the basis of piloted ignition of wood, where ignition is facilitated by the presence of materials that ignite at lower levels of thermal radiation than wood (such as plastic, fabric and vegetation), which then act as a pilot flame. Buildings which are beyond the burning distance can offer permanent protection to people indoors, while buildings within the burning distance (BD) can only do so until they ignite. After that people indoors have the chance to run away and escape.

In the case of vessel populations, it is assumed that the vessels and the people on board are stationary (i.e. their escape speed is 0). This is a conservative assumption because it ignores the possibility of small vessels turning around quickly and moving away from the fire or people jumping into the water. Moreover, the building burning criterion used for onshore

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[3] With current assumptions, vessel populations cannot escape, hence this is referred to as 'Safe' rather than 'Escape' distance.

[4] It can be argued that larger ships are more likely to cause an incident. It would be possible to calculate the category probabilities more accurately, taking into account vessel sizes, but this would have made little difference in the results, given that the smallest sizes are excluded, while the analysis would have become significantly more cumbersome and time demanding.

housing is probably not uniformly appropriate for all vessel types. Consequently, the methodology has been modified in accordance with the following assumptions, with two different scenarios, 'Base Case' and 'Worst Case' being considered:

- Vessels in the S category (Small vessel) do not offer any protection from thermal radiation.
- Vessels in the M category (Medium vessel) will ignite, if within BD, but they will offer protection to people inside if beyond BD and within the escape distance (ED). A parameter used in the methodology is the proportion of people who are assumed to be outdoors. This parameter is set to 0.1, in accordance to the value used for standard onshore assessments. Therefore, if a category M vessel is within BD all people on board become casualties but if it is beyond BD and within ED only 10% do so.
- Worst Case - Vessels in the L (Large ship) and P (Passenger ship) categories are treated as M vessels.
- Base Case – Vessels in the L and P categories are treated differently. Such ships have a metallic shell, relatively small area of fenestration and windows made of very thick glass which absorbs thermal radiation more than ordinary glass used in housing. Consequently, it is reasonable to assume that either they will not ignite at all or only parts will ignite allowing people to find shelter in other parts or they will ignite after a sufficiently long time for the crew to react and extinguish any fires or for the gas flow to the pipeline to be cut off. In this scenario, if the ship is anywhere within ED only 10% of people on board (i.e. those initially assumed to be outdoors, will become casualties). This scenario ignores some other possibilities, e.g. petrol tanks of cars or flammable cargo being exposed to radiation and causing explosions or large fires that cannot be controlled. However, on balance it is considered more realistic than the 'Worst Case'.

Societal Risk results have been obtained with both scenarios. The predicted Potential Casualties Per Year (PCPY) and maximum numbers of casualties are summarised in Table 8.

Table 8: Predicted Societal Risk Results

Scenario	Potential Casualties per Year	Max. Number of Casualties
Base Case	2.21×10^{-3}	155
Worst Case	1.55×10^{-2}	1506

The corresponding F-N curves are plotted in Figure 3, where the IGEM/TD/1 Societal Risk criterion 8 used in National Grid pipeline risk assessments is also shown. Both scenarios give F-N curves above the criterion envelope, in a region where the risks are only tolerable if it can be demonstrated that they are ALARP (As Low As Reasonably Practicable).

Some additional calculations were also carried out in the context of a sensitivity analysis (see next section), to investigate the potential effect on the societal risks of increasing the depth of cover or reducing the loading factor of passenger ships. Both these variations reduced the predicted risks, as expected, but not sufficiently for the risks to become broadly acceptable.

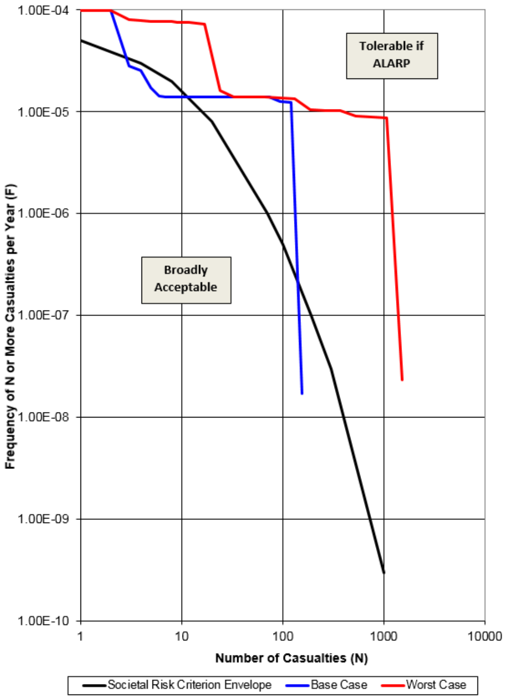

Figure 3: Predicted F-N Curves

Results of Application of the Methodology

The main findings of the QRA application of the water crossing methodology are summarised below:

- The hit rate of the pipeline from vessel and anchor impact is predicted to be once every 3,200 years, while the resulting rate of pipeline failures due to rupture is once every 8,200 years. No pipeline punctures are predicted. These rates reflect the high volume of vessel traffic in the estuary with a significant proportion of large ships.
- The most likely location of a pipeline failure is within an 800 m long section at the deepest part of the estuary, where the depth of cover is at its minimum.
- The predicted maximum hazard distances for onshore and vessel populations are 515 m and 1175 m, respectively; the difference arising from different assumptions applied to each population type. There are no onshore populations within this range; therefore, only vessel populations need to be considered in the societal risk calculation.
- The Societal Risk has been calculated for two different scenarios, namely, an intentionally cautious 'Worst Case' and a 'Base Case' based on more realistic assumptions. The corresponding F-N curves have been compared to the IGEM/TD/1 societal risk criterion used in National Grid pipeline risk assessments and are both found to exceed it, suggesting that the risks are only tolerable if demonstrably ALARP (As Low As Reasonably Practicable). The relatively high level of risk is a reflection of the numbers of large ships crossing the pipeline, a significant proportion of which are passenger ships carrying up to 1500 people.
- A sensitivity analysis that has been carried out to investigate the effect of increasing the pipeline depth of cover (DoC) suggests that when the minimum DoC increases from 0.4 m to 1 m the risks are almost halved. However, even if the minimum DoC is increased further[5] to 3 m, the results still enter the "Tolerable if ALARP" region of the IGEM/TD/1 criterion.
- An additional sensitivity analysis has been carried out to investigate the effect of the passenger ships load factor, which in the 'Base Case' is assumed to be 100% (full capacity). In the sensitivity study, the passenger ships have been assumed to operate at 75% capacity in half of the year and at 25% capacity in the remaining half. Compared with the 'Base Case' the Potential Casualties Per Year (PCPY) are reduced by about 40% and the part of the F-N corresponding to the higher numbers of casualties is substantially lower; however, the F-N curve still enters the "Tolerable if ALARP" region of the IGEM/TD/1 criterion.

Conclusions

The above methodology was developed to address situations that occur rarely. In the example above, it was practical to develop a detailed site specific analysis to support a QRA to inform investment decisions. This allowed what can be emotive safety issues to be quantified and assessed objectively. Although the methodology described above has limitations because of the necessity to make simplifying assumptions (resulting in a generally conservative approach), it does illustrate that the risks associated with rare situations such as vessel impact and anchor drag can contribute to the overall risk profile.

The results of this analysis, along with other engineering studies, provided an important input into a major investment decision for National Grid to replace the existing pipeline crossing with a tunnel under the river which eliminates the risks identified in this paper, thus illustrating the value in this approach.

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[5] A value of DoC of 3 m is hypothetical, since it might interfere with passing traffic. However, the calculation has been carried out to illustrate that it is not possible to bring the risks below the ALARP region by increasing the DoC.

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