1. INTRODUCTION

The onshore gas industry worldwide has a good safety record, and accidents are rare. Nevertheless, the possibility of accidental releases can never be discounted, and it is important that operators have an understanding of the causes and potential consequences of such releases in order to help manage the risks involved. The development of techniques to allow quantified risk assessments of natural gas pipelines and associated facilities to be undertaken has accelerated in recent years, supported by mathematical modelling and experimental validation.

These techniques offer operators the opportunity to optimise safety by targeting areas where risk can be reduced most cost-effectively, and to optimise the use of assets by avoiding inappropriate restrictions on operations. Risk assessment techniques have been developed by Advantica for a broad range of gas industry applications, including offshore platforms, reception terminals, high and low pressure pipelines, compressors, gas storage and LNG sites. This paper describes the background to the development of these techniques, the framework that has been established in Great Britain for decision-making based partly on results of quantified risk analysis (QRA) and techniques developed and applied by Advantica for transmission and distribution pipelines, terminals and storage sites.

2. BACKGROUND

All activities involve an element of risk, defined as the frequency of the occurrence of an undesired event. However carefully a system is designed, constructed and operated there remains the possibility, however small, of failure and the consequences of such failures may pose a risk to people or the environment. Such failures occasionally occur on gas pipelines and installations, and it is essential to understand the risks involved, and if possible to quantify them, to support operational decisions, for example by reducing risk in the most cost-effective way or to support pipeline uprating, and to develop appropriate standards and design codes.

The objective of developing risk assessment techniques, and a framework for risk-based decisions, is to enable informed and consistent decisions involving risk to be taken, and to provide the means of maintaining levels of risk that are as low as reasonably practicable. The use of such techniques allows operators to avoid unnecessary safety expenditure, and to demonstrate to safety regulators, the public, and investors, that the risk presented by their operations is managed effectively.

The use of these techniques is now well-established in Great Britain, where the pipeline operator, Transco and its forerunners (including the former British Gas), has over 30 years experience of transmission pipeline operations, and experience of distribution pipeline operations stretching back over 100 years. The British system is extensive, given the relatively small size of the country, with approximately 20,000km of transmission pipeline and 250,000km of distribution
pipelines. Great Britain is a crowded island, and as a result, gas pipelines and installations are inevitably often in close proximity to populated areas. As risk assessment techniques have become better established design codes and legislation have developed to reflect this. For example, Edition 4 of the IGE/TD/1 design code (Ref. 1), and recent changes in legislation in the US, allow greater flexibility in pipeline design and operation, where demonstrated as safe by the use of risk assessment techniques.

3. RISK ASSESSMENT

Risk can be expressed either as individual risk, meaning the frequency of an individual at a specified location being a casualty; or societal risk, defined as the relationship between the frequency of an incident and the number of casualties that may result. This is usually expressed in the form of a graph of the cumulative frequency (F) of N or more casualties plotted against N (an "FN curve"). An expectation value (i.e. the numbers of casualties expected on average per year) may be calculated by integration of an FN curve.

To quantify the level of risk, the range of credible failure causes must be considered, and the failure frequency for each event and the resulting consequences in terms of harm to people need to be evaluated. The risk associated with each event is calculated by combining the results of the failure frequency and consequence calculations, and the results for all events summed to obtain the overall risk level for the pipeline or installation being considered. For pipelines (unlike installations) it is important that the length of pipeline being assessed is consistent with the length of pipeline to which the risk criterion applies, since the frequency of failure, and hence the level of risk, increases directly with pipeline length.

In order to demonstrate that a certain level of risk is acceptable, both individual and societal risks need to be quantified for comparison with established risk criteria. In Great Britain, the safety regulator the Health and Safety Executive (HSE) have published individual risk criteria, with some indication of the levels of societal risk that would be considered acceptable (Ref. 2). However, the key test is generally to demonstrate that the calculated level of risk is ALARP (As Low As Reasonably Practicable). This is achieved by consideration of available practical options for reducing risk. According to HSE, in order for the level of risk to be ALARP, the cost of such risk reduction measures must be shown to be disproportionate to the benefit in terms of risk reduction.

The HSE uses a three-band approach in regulating industrial risks. At the top end of the scale there are risks that are so great that they are refused altogether. At the bottom end are situations where the risk is, or has been made, so small that no further precaution is necessary - a 'broadly acceptable' region. In between these two extremes is a region where risks are tolerable only if their level has been reduced to one which is ALARP. For activities in the 'tolerable' region there is an expectation that society desires the benefit of the activity creating the risk and that the nature and level of the risks are assessed and controlled using the best available scientific techniques. Control measures should be introduced to move the residual risk towards the 'broadly acceptable' region until further risk reduction is impractical or the benefit gained in risk reduction is grossly disproportionate to the cost incurred. At this point the risk is ALARP.

The risk framework outlined applies both to individual and societal risks. For individual risks, the HSE quotes risks of fatality that are regarded as broadly acceptable ($1 \times 10^{-6}$ per year) and represent the boundary between tolerable and unacceptable ($1 \times 10^{-3}$ per year for workers and $1 \times 10^{-4}$ per year for members of the public). These benchmark values for individual risk are based on the fact that a level of $1 \times 10^{-6}$ per year is a very low level of risk when compared to the background level of risk for all hazards. For societal risks there are no such detailed criteria, although guidance with respect to gas transmission pipelines is provided in the latest edition (Edition 4) of the IGE/TD/1 design code, which includes an example of an FN type criterion for societal risk (Figure 1). For transmission pipelines and other major hazard installations, which
have the potential to cause multiple fatality events, the consideration of societal risk is usually at least as important as individual risk, which is often well below the broadly acceptable level.

Figure 1: Sample FN criterion (from IGE/TD/1 Edition 4 – Ref. 1)

Advantica has developed quantified risk assessment methodologies that allow individual and societal risks to be calculated across the full range of gas industry installations and plant. Some of these applications are described in the following sections.

4. TRANSMISSION PIPELINES

4.1 Methodology

In Great Britain, gas transmission pipelines are generally laid in accordance with the IGE/TD/1 design code prepared by the Institution of Gas Engineers and Managers (Ref. 1). This has historically been a prescriptive code, however the most recent editions allow for flexibility where justified by a risk assessment. Such a need arises, for example, in the event of an infringement to the code in the vicinity of an existing pipeline, or if the operator wishes to change the operation of the pipeline in a way not foreseen at the time the pipeline was laid, for example by increasing the operating pressure (“uprating”). To address these issues, Transco (formerly British Gas) developed a risk assessment package for transmission pipelines. The package had limited functionality, and was tailored specifically to British requirements. In 1994, an international collaboration of a number of gas transmission companies was formed to develop a more sophisticated tool called PIPESAFE, which could be applied to a wider range of situations, and with improved functionality. PIPESAFE is a software package for PCs that contains a range of mathematical models, linked in a logical manner, to calculate individual and societal risk. It is based on many years of research into the causes and consequences of transmission pipeline failures, including both mathematical modelling and experimental validation at both small and large scale.
Phase 1 of the collaboration funded the development of the new PIPESAFE package by Advantica (Ref. 3). This included new models, for a wide range of failure causes, and new consequence models including a model to predict the initial transient stages of a fire following immediate ignition of a pipeline rupture. The collaboration also developed a pipeline damage database, which allowed members of the collaboration to pool damage data for pipelines to enable failure frequency models to be modified to make appropriate predictions based on operational experience in different countries or companies.

In Phase 2, a detailed analysis of the sensitivity of PIPESAFE predictions to the input parameters and of the levels of uncertainty associated with the model predictions was carried out, and the predictions of PIPESAFE were compared with information available from incidents. Phase 2 also included a comparison of the risk calculation methods used in the different companies participating in the project, and considered ways of extending the risk calculation methods in PIPESAFE to give greater flexibility.

In Phase 3, PIPESAFE has been refined so that a wider range of failure modes can be considered, and provides greater flexibility by implementing a number of the risk calculation methods identified in Phase 2, thus allowing the package to meet the different requirements of gas companies operating in different countries (Ref. 4).

The main elements of a pipeline failure considered in the PIPESAFE methodology are failure cause, failure frequency, failure mode, gas outflow, dispersion, ignition, thermal radiation and thermal effects. Knowledge and models are combined in a logical manner, to calculate casualty probability and risk. These elements are described in more detail below:

**Failure** - Failure of a gas pipeline can occur due to a number of different causes such as external interference, corrosion, fatigue, ground movement, material or construction defects. The failure modes that can occur are leaks (punctures), or breaks (ruptures). The failure mode is determined by the length, depth and type of defect, and is dependent on the pipe diameter, wall thickness, material properties and the operating pressure. Estimates of failure probability can either be made from historical data where appropriate, or by the application of predictive methods. Recently, Advantica has also been at the forefront of developing new predictive methods, sometimes known as Structural Reliability Assessment (SRA), to quantify the significance of the effect on overall failure probability of changes in pipeline parameters (Ref. 5).

Preventive measures to reduce the likelihood of failure offer the main opportunity to reduce risk, and it is these measures that generally form the basis of an ALARP calculation.

**Gas Outflow** - Due to the pressure at which transmission pipelines are operated, a failure of a pipeline leads to a turbulent and complex gas release. Following a rupture, or large puncture, there will be rapid depressurisation in the vicinity of the failure. For buried pipelines, the overlying soil will be ejected with the formation of a crater of a size and shape which influences the behaviour of the released gas. Depending on the alignment of the pipe ends in the case of a rupture, the gas will escape to the atmosphere in the form of a jet, or jets. At the start of the release, a highly turbulent mushroom shaped cap is formed which increases in height above the release point due to the source momentum and buoyancy, and is fed by the gas jet and entrained air from the plume which follows. In addition to entrained air the release can also result in entrainment of ejected soil into the cap and plume. Eventually, the cap will disperse due to progressive entrainment and a quasi-steady plume will remain. Immediately following a rupture the flow from each side of the rupture will be balanced. However, at later stages the flow through each limb will be determined by the behaviour of the pipeline system. This is affected by features such as compressor stations or feeds from, or to, other pipelines which may be at large distances.
from the failure point. These boundary conditions determine whether the flow through the pipeline at the rupture will decrease to zero or to a steady-state flow.

Ignition - Ignition can occur at any time during the release. If it occurs immediately on, or shortly after, rupture, a transient fireball will occur. The fireball, which is the result of combustion of the mushroom-shaped cap lasts, typically, for up to thirty seconds, and then burns out leaving a quasi-steady state fire. If ignition occurs after the initial highly transient phase, the transient involved in establishing a quasi-steady fire is much less pronounced and, for modelling purpose, the consequences of the quasi-steady fire only are considered.

Mathematical models to predict the dispersion behaviour of an unignited plume of gas released by a high pressure pipeline failure can be used for specific situations to evaluate the likelihood of flammable gas concentrations being produced at a specific location where ignition sources are available. Generally, however, routine assessments take values for ignition probability based on historical data (Ref. 6).

Thermal Radiation - The levels of thermal radiation incident on the area surrounding the ignited release vary with time after rupture and with distance from the release point, and are dependent on the shape, nature and extent of the fire (determined by the source and atmospheric conditions), and the atmospheric transmissivity between the fire and the receiver (determined by the humidity). Following the initial fireball phase after a pipeline rupture, the gas outflow gradually decays, and the fire behaviour can be treated as though it is quasi-steady-state.

Thermal Radiation Effects - Both people and property in the vicinity of an ignited pipeline release can be affected by the levels of incident thermal radiation. People can become casualties as a result of receiving large doses of thermal radiation, and buildings can be ignited by thermal radiation directly from the fire or from secondary fires (e.g. from burning vegetation). A number of different criteria can be used for predicting casualties, depending on the definition of a “casualty” being used, taking account of the distance from the pipeline and the availability of shelter.

Risk Calculations - The calculation of risk at a particular location from an extended pipeline source is complicated by the fact that the failure position is unknown in advance. It is necessary to consider the effects from the predicted pipeline fire along the interaction length, which is the length of pipeline that could pose a hazard to the development or point of interest. Individual risk is calculated at specified locations and distances from the pipeline, and societal risk can either be calculated generically, based on estimates of population density, or in a site-specific manner, taking account of the precise locations of buildings and people.

4.2 Validation

In order to have confidence in the predictions of a package such as PIPESAFE, it is essential to demonstrate that the results are realistic. The approach adopted for the consequence models in PIPESAFE has generally been to develop the models on the basis of theoretical understanding, guided by the results from small scale experiments. However, because many of the processes involved are strongly dependent on the scale of the event, especially fires, it is also necessary to conduct experiments at as large a scale as practical, to validate the models and to provide an essential input to further development. All of the consequence models in PIPESAFE have been validated by comparison with results from comprehensive programmes of experiments carried out at very large scale, mainly conducted at the Advantica Spadeadam Test Site (see Figure 2), in the north of England. Spadeadam is a unique facility, consisting of a large area of open ground within an area controlled by the Ministry of Defence, equipped with gas storage and delivery systems and the necessary infrastructure to allow large and full scale experiments to study the behaviour of accidental releases of gas and other fuels at high and low pressure, to be conducted safely.
Figure 2. Aerial view of Advantica Spadeadam Test Site, where many of the experiments were performed to provide data for model development or validation

In addition to experiments undertaken at Spadeadam, a very important source of data for validation of the models and methodology in PIPESAFE is the results of two full scale experiments conducted in Canada as a collaborative project, managed by Advantica (Ref. 7). The experiments involved the deliberate rupture of a 76km length of 914mm diameter natural gas pipeline operating at a pressure of 60 bar, with the released gas ignited immediately following the failure. Over 200 instruments were successfully deployed in each experiment to take detailed measurements, which included the weather conditions, the gas outflow, the size and shape of the resulting fire, and the thermal radiation levels. Large fires were produced in both experiments, with maximum flame heights of over 500m in the initial stages, which decayed rapidly in size as the gas outflow reduced following the initial rupture.

As a further check, the predictions of PIPESAFE have also been compared against information collected from actual pipeline incidents, involving rupture and ignition of the gas released. Three types of comparisons between PIPESAFE predictions and incidents were made:

- Building ignition times,
- Burn areas surrounding the failure, and
- Injuries to people.

If the ignition time of any buildings adjacent to the pipeline fire is known this can be compared directly with results from PIPESAFE. PIPESAFE can generate ignition times for structures based on either piloted or spontaneous ignition of wood.

Information relating to the burnt area around the pipeline fire is generally available from pipeline incident reports. However, comparisons with modelling predictions can be complicated by a number of factors, for example, the subjective nature of determining the burnt area. Materials that have been scorched may appear to be similar to materials that have actually ignited and been partially burnt, but the levels of radiation required for these two scenarios could be substantially different.

In addition to uncertainties in quantifying the consequences of an incident, there may also be difficulties in making direct comparisons, because the information available from incident reports is often not sufficient to provide all of the necessary inputs to PIPESAFE. For example, it may be that the features of the pipeline system governing the boundary conditions following failure (as required by the outflow model) are not well defined. This means that incident data are
not suitable for detailed model validation. They can, however, be used to give an indication of a
general level of consistency of the predictions from PIPESAFE.

An exercise to compare the predictions of PIPESAFE with details of 18 incidents and the
two full-scale experiments indicated that PIPESAFE gives a reasonable but generally
conservative prediction of burn area. However, because of the subjective nature of determining
the burnt area, and uncertainty due to fire spread and moisture content of the surrounding
combustible materials, a wide spread in the predicted and reported burn areas was found.

A more rigorous test of the PIPESAFE consequence models was possible where ignition
times and thermal radiation effects on people were reported. Where comparisons were possible,
the PIPESAFE predictions gave good agreement with the ignition time of adjacent properties.
The level of burn injuries seen in the population near to the pipeline fire was also consistent with
the predictions of PIPESAFE. The PIPESAFE package has also been subjected to a
comprehensive programme of software testing, and independent checking.

4.3 Applications

Risk assessment may be applied to transmission pipelines for a variety of reasons,
including:

- Infringements to pipeline design codes
- Pipeline uprating
- Pipeline design and routing
- Land use planning
- Emergency planning

The most frequent use of PIPESAFE is to make decisions on the appropriate course of
action when developments encroach upon the pipeline. When pipelines are laid in Great Britain,
they are routed to IGE/TD/1 such that no buildings would be located within 1 BPD (Building
Proximity Distance) of the pipeline. Encroachments can cause code infringements of two main
types:

a) Proximity infringements

b) Population density infringements

Encroachments to the pipeline are identified when the pipeline is surveyed according to
the methods and frequencies recommended in the IGE/TD/1 code. The survey will identify if any
buildings have been built within 1 BPD of the pipeline or if the population density has increased
within the survey zone, defined as 4 BPD either side of the pipeline, due to further development
between 1 and 4 BPD from the pipeline, such that the population density now exceeds that for the
pipeline designation. This can occur, for example, when the population density surrounding a
pipeline increases sufficiently to be classed as ‘suburban’, although the pipeline itself is
designated as being laid and run to standards appropriate for a ‘rural’ area.

A pipeline risk assessment may be carried out to determine the risk levels at any
infringement and the results used to decide on the appropriate course of action. Having
calculated the risk levels at the infringement, the key determining factor is usually the level of
societal risk. This is because the high design integrity of most pipelines means that individual risk
levels are rarely a problem, although there is still the potential for high numbers of casualties.
The determining factor as to whether a risk is acceptable or unacceptable, is whether the risk
from the pipeline is ALARP (As Low As Reasonably Practicable). This will be assessed by
evaluating the risk reduction arising from a number of possible measures, and carrying out cost
benefit calculations on each option before a decision is made.
Another major application of the use of pipeline risk assessment techniques is pipeline uprating, where the pipeline operator needs to increase capacity, usually because of a forecast or actual rise in demand, without the high cost associated with construction of an additional pipeline. In this situation, the key determining factor is the effect of the increased pressure on the integrity of the pipeline, and Structural Reliability Assessment (SRA) techniques are applied to determine whether or not the predicted failure frequency will be significantly increased by the proposed change in operating pressure. The predicted change in failure frequency is then used to assess the increase in risk to the population in the vicinity of the pipeline, in order to determine the acceptability or otherwise of the risk levels.

The SRA approach has been applied in examining the potential for pipelines with a design factor of up to 0.72 (the current limit in IGE/TD/1) to operate at a higher design factor (up to 0.8). This approach, which is recognised in the latest edition of IGE/TD/1 (Ref. 1), involves:

- Identification of all credible failure mechanisms, based on consideration of all the loads the pipeline is likely to see and the ability of the pipeline to resist those loads
- Assessment of the proportionate increase in failure probability when operating at the Higher Design Factor rather than 0.72, for each failure mechanism
- Assessment of whether the absolute value of failure probability from a particular failure mechanism at the Higher Design Factor is a significant contributor to the overall pipeline failure probability. This applies for each failure mechanism for which the proportionate increase in failure probability is significant.

These techniques have been successfully used to demonstrate the potential for pipeline uprating in order to meet forecast growth in demand for gas in Great Britain as an alternative to new pipeline construction.

5. DISTRIBUTION PIPELINES

5.1 Methodology

Although the gas distribution industry has a good safety record, a small number of incidents involving failures of distribution pipes occur each year, and an understanding of the hazards and risks associated with distribution pipeline operations is important in order to manage the risks effectively. To quantify the risk posed by distribution pipes the causes of failure and the failure modes of the pipe together with the possible consequences of the failure need to be established. The main hazards posed by releases of natural gas are from an explosion or a fire.

Explosions may occur following in-ground failures of distribution pipelines, which for low pressure pipelines (typically < 2 bar) usually result in gas being released into the ground around the failure. The presence of soil around the failure normally reduces the amount of gas released compared to a release directly to atmosphere. The gas is released into the soil and will travel in the direction of least resistance to flow. When the surface above the failure is “open” (e.g. grass) the gas is likely to vent through the upper surface. However, when the surface above the failure is “sealed” (e.g. by a tarmac or concrete covering) the gas may travel large distances in the soil. This is especially likely to happen if there are tracking routes in the ground along which the gas can travel easily. Examples of these are disused drainage pipes, a sandy or gravel pipe bed or the routes of other pipes. In some cases gas can reach and enter an adjacent property in sufficient quantities to form a flammable gas/air mixture, which could be ignited by ignition sources such as domestic appliances.

Fires following gas releases directly to atmosphere can occur as a result of interference damage to the pipe by excavation work or as a result of an in-ground failure of a higher pressure pipeline (typically greater than 2 bar) which removes the ground cover above the pipe. This can
lead to releases of significant quantities of gas. In such situations, the historical record suggests that relatively few releases are ignited. However, the sources of ignition for those that are ignited are very varied, including adjacent damaged electricity cables, vehicles or equipment in the vicinity. In the event of ignition, the size of the fire is affected by parameters including the pressure of the pipeline, the size of the failure, the release geometry and the weather conditions. Figure 3 shows an experiment performed at Spadeadam to study an ignited release from a distribution main into a trench.

Figure 3. Example of experimental simulation of a fire produced following a release from a distribution main.

Advantica has developed two risk assessment methodologies to quantify the risk associated with the explosion and fire hazards (Ref. 8).

5.2 Explosion Methodology

The risk assessment methodology developed to predict the frequency of an explosion occurring for distribution pipelines uses a combination of predictive mathematical models and historical statistics on pipeline failures. The risk assessment methodology predicts the likelihood and consequences of an explosion incident occurring per km of distribution pipeline per year. It uses a site-specific approach to calculate the risks and therefore a survey of the area surrounding the pipeline needs to be conducted before the pipeline can be assessed. The methodology considers the likelihood of each of the different stages occurring in turn.

The first step is to calculate the likelihood of an in-ground failure of the pipe, using historical data on failures of pipes. The model calculates the quantity of gas released from the pipe, requiring the range of possible failure sizes, established from historical data, and the pipeline pressure to be known.

The behaviour of the gas as it travels through the ground is calculated using mathematical models. Three mathematical models have been developed by Advantica and validated against full scale experiments at the Spadeadam test site. One is used in cases where the surface above the pipe is sealed (e.g. by tarmac or concrete) and this assumes the gas spreads radially away from the failure but cannot vent through the sealed upper surface. Another is used where the surface is open (e.g. grass) where the gas can vent through the upper surface. The final model is for situations where there is a tracking route in the ground along which gas will travel preferentially.

The next stage is to calculate the likelihood and quantity of gas that could enter any adjacent properties. The probabilities of gas entering properties given the failure of an adjacent
buried distribution pipeline are calculated using historical data on the failures of pipelines. Given that gas enters the property the quantity of gas entering is calculated using mathematical models. Following gas ingress, the build-up of gas within the property is calculated, for a range of likely room sizes, ventilation rates and gas entry points. The build-up of gas within the room is calculated assuming perfect mixing of the gas and air from the point of entry of the gas to the top of the room. The calculations for the build-up of gas within the property are also combined with calculations to assess the likelihood and consequences of the release of gas being detected and action taken subsequently to disperse the gas release, such as opening windows and doors to increase the ventilation rate.

The final stage is to assess the likelihood of any flammable gas/air mixtures being ignited and the consequences of any explosions. Ignition probability is estimated from experience of dealing with gas escapes and explosion incidents. Advantica’s model to calculate the consequences of confined explosions has been developed and validated against full scale explosion experiments.

5.3 Fire Methodology

The approach adopted to assess risks associated with releases to atmosphere from damaged distribution pipelines, and the resulting fire if ignition occurs, closely follows the methodology for gas transmission pipelines described previously. The approach addresses all the main elements required to undertake a quantified risk assessment of the fire hazard, namely failure cause and frequency, failure mode, gas outflow, ignition, thermal radiation and thermal radiation effects. Knowledge and mathematical models are combined in a logical manner to calculate risk, in an integrated software package similar to PIPESAFE.

For PE pipelines, the main cause of failure is third party interference damage. Historical data from Great Britain is used to estimate the likelihood of an impact on a PE pipeline, and the likely damage that could be produced. Generally, interference damage leads to a release of gas directly to atmosphere, although it is possible for activities such as moling techniques for laying cables, for example, to lead to an in-ground failure. In such cases, a release directly to atmosphere may still occur, with the potential to present a significant fire hazard, because gas released from failures of pipelines operating at pressures in the region of 2 bar and above will generally lead to the removal of the ground cover above the pipeline. Larger PE pipelines, particularly those constructed from materials such as High Density Polyethylene (HDPE), offer significant resistance to impact damage, and only a proportion of impacts will be of sufficient force to cause rupture.

5.4 Applications

In Great Britain both metallic and PE pipes are used to transport natural gas within the distribution system at pressures of less than 7 bar. If not addressed, ageing distribution pipelines constructed from iron can fail, possibly leading to an explosion hazard as described in this paper. In order to minimize the likelihood of such events, a programme has been undertaken to replace selected cast or ductile iron pipelines with new PE pipelines. Since the commencement of the replacement programme in Great Britain, the number of incidents associated with failures of distribution pipelines has been significantly reduced.

One application of the risk assessment methodologies is in identifying metallic distribution pipelines for replacement. The process by which pipelines are selected for replacement has recently become more formalised with the introduction of risk-based techniques. The methodology for assessing explosion risk described in this paper has been implemented to optimise the effectiveness of the replacement programme, by selecting pipes for replacement on the basis of risk.
The risk assessment methodologies can also be used to help develop industry standards and are being used to support design guidelines for the installation of new PE pipelines. The models can be used to determine hazard-based proximity distances for new pipeline projects or to assess the impact on the risk of changes in the way distribution systems are operated, such as the effect on risk of increasing or reducing the operating pressures of distribution pipelines.

6. TERMINALS AND STORAGE SITES

Under British legislation, all industrial sites that store above a certain quantity of a flammable or toxic substance, are required to produce and maintain a 'Safety Report'. The report has to be submitted at regular intervals to the HSE and the relevant Environment Agency, who ensure that health, safety and environmental issues are being addressed in a responsible manner. The Safety Reports should describe measures to prevent accidents and limit their consequences and provide a systematic analysis that determines the safety measures on the site. Unlike the previous Regulations, the emphasis in the reports is now on demonstration. Therefore, sufficient details are required to enable the inspectors to understand the purpose of the establishment and the nature of the surrounding environment and to verify that appropriate management arrangements, including the safety management system, are in place. Information should be provided on the possible releases that could occur, identifying and analysing in detail those incidents that might give rise to major accidents to people or the environment.

By their very nature, major accidents at terminals or storage sites have a low frequency, albeit with potentially high consequences. Assigning quantitative measures to the risks of such accidents is difficult, as there are few observations on which to base a judgement of how the scenarios may evolve. In such cases, the consequences are often sensitive to the assumptions that have to be made in representing the scenario within the analysis. Using a worst-case analysis or considering only a single, representative case may distort the assessment compared with a full evaluation, taking into account the range of ways in which an accident may develop. This is similar to the situation that has arisen in evaluating the explosion risks on offshore platforms, particularly those situated in the North Sea. Here a worst-case analysis, involving ignition of a uniform stoichiometric mixture throughout a module, may lead to very severe blast loading criteria being adopted in the design process. The results of a recent joint industry project, carried out by Advantica, Shell Global Solutions and Gexcon, has demonstrated that releases are likely to lead to a range of flammable cloud sizes and hence, if these are ignited, overpressures (Ref. 9). Studies by Advantica have shown that taking into account the likely range of explosion pressures, through the construction of overpressure exceedance curves, for example, allows more realistic design criteria to be adopted (Ref. 10).

Just as for the offshore assessments, Advantica has developed a similar risk assessment methodology for onshore plant. This allows the different realisations of scenarios to be analysed, taking into account relevant parameters such as release and wind directions. Details of this method have been summarised in recent papers (Refs. 11 and 12). The methods allow the location specific risk to individuals, either on or off the site, to be evaluated. Further, by accounting for the residency of different groups of people in different locations, the risk to average and the most exposed groups of people can be evaluated. This is useful in that the values can be compared with the published acceptability criteria (Ref. 2), as noted previously. The method also allows an assessment of the risk to workers in occupied buildings to be evaluated, in accordance with methodology incorporated within the Guidelines issued by the Chemical Industries Association (Ref 13) and in associated publications (Ref. 14).

The societal impact of the major accidents can also be addressed as a result of these calculations. Curves showing the frequency F with which N or more casualties are predicted to occur can be constructed from the frequency and number of casualties for each individual
realisation. Such curves can then be compared with acceptability criteria for societal impact, as for transmission pipelines, although as noted earlier at present there is rather less guidance published as to the exact location of the bounding curves for individual installations. Nevertheless, the method allows the contributions from the different realisations to be analysed. The cases that contribute the most to the risk can be identified and, hence, guidance can be given on those situations for which risk reduction should be considered. The FN curve can also be analysed to determine the expectation value of the number of casualties any scenario could produce. When this value is multiplied by the event frequency, a single measure of the risk is obtained. In an offshore context, this is sometimes referred to as the expected loss of life for a given accident scenario. This number can be used to rank the different scenarios and provides a useful way of comparing a low frequency - high consequence scenario with a more likely, but less severe scenario. This approach has been adopted by Advantica in a number of Safety Reports.

It is noted that using this method may reveal that some preconceived ideas about what is the ‘worst case’ are not always correct. Figure 4 shows one specific example of this type of analysis, in which a measure of the maximum harm from a specific release of liquefied natural gas (LNG) is plotted against the time of ignition.

![Figure 4](image.png)

**Figure 4.** Example of analysis comparing maximum harm arising for different ignition delay times following a large gas release

It would have been difficult to have guessed before hand what would have been the sensitivity to the time of ignition for this situation, as shown in Figure 4.

As well as being of use when carrying out qualitative risk assessments for Safety Reports for example, these methods are of great help in cost benefit analysis. As noted in (Ref. 11), using worst-case assumptions can often mask the benefits of protective measures, as they may have little effect on the worst-case realisation. However, using the methodology allows a correct identification of suitable measures to be taken to reduce risks, as the impact of the measure on all the different realisations is assessed. Again, the HSE have given guidance as to how such cost benefit analyses should be performed as a part of an ALARP demonstration, if required, for a specific site.
7. DISCUSSION

The above sections have demonstrated how methodology has been developed to enable assessments to be made of the risks posed by onshore gas installations and transmission and distribution pipelines. This methodology can be used to assess the impact of changes at the design stage and to optimise expenditure to achieve the maximum benefit in terms of risk reduction. The methodology can be used within the context of a wider cost benefit analysis to support arguments that demonstrate to a wider audience that risks have been reduced to as low as is reasonably practicable – the so-called ALARP criteria for risk reduction adopted within Great Britain by the HSE. However, the basic approach of developing a linked series of consequence and frequency models that can address the many different possible realisations of a single accident scenario is equally applicable to other applications within the onshore gas supply system. For example, Advantica has produced packages to assess the risks arising from gas services, connecting the distribution mains to individual domestic, industrial or commercial properties. The packages have been extended to consider both metallic and PE pipes, combining knowledge of incident history to determine appropriate failure frequencies with consequence models for fires or gas movement and explosion. An important aspect of these models is modelling the response of people to gas detection and the possibility of successful intervention to prevent fires or explosions. Work such as this allows the most safety critical areas on the whole of the gas supply chain to be identified and, hence, expenditure to be targeted to achieve cost effective risk management.

8. REFERENCES