ANNEXE C

Publication de l’industrie
sur le développement de PIPESAFE

THE DEVELOPMENT OF THE PIPESAFE RISK ASSESSMENT PACKAGE FOR GAS TRANSMISSION PIPELINES

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ABSTRACT

PIPESAFE is a knowledge based hazard and risk assessment package for gas transmission pipelines, which has been developed jointly by an international group of gas transmission companies. PIPESAFE has been developed from the BG (formerly British Gas) TRANSPIRE package, to produce an integrated assessment tool for use on PCs, which includes a range of improvements and additional models backed by large scale experimentation. This paper describes the development of the PIPESAFE package, and the formulation and validation of the mathematical models included within it.

1. INTRODUCTION

1.1 Background to Risk Assessment

All activities involve an element of risk, defined as the probability of the occurrence of an undesired event, such as a casualty. However carefully a system is designed, installed and operated there remains the possibility, however small, of failure. Such failures do occasionally occur on gas transmission pipelines around the world, and it is essential to understand the risks involved, and if possible to quantify them, both to support operational decisions, for example by reducing risk in the most cost-effective way, and to develop appropriate standards and design codes.

For a high pressure gas transmission pipeline, a failure may take the form of a puncture or complete rupture of the pipeline, with ignition of the escaping gas giving rise to a large fire which presents a hazard to the surrounding population. The risk to the population can be expressed either as individual risk, that is the probability 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 which may result, and usually expressed in the form of a graph of the frequency of N or more casualties plotted against N (an "FN curve").

1.2 The TRANSPIRE Package

In the United Kingdom, gas transmission pipelines are generally laid in accordance with the IGE/TD/1 design code prepared by the Institution of Gas Engineers (Ref. 1). This has historically been a prescriptive code, however the most recent edition allows for some 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 to increase the operating pressure ("uprating"). To meet this requirement BG plc (formerly British Gas) developed the TRANSPIRE (TRANsmission PIpeline Risk Evaluation) risk assessment package (Ref. 2). TRANSPIRE is a software package for PCs which contains a range of mathematical models, linked in a logical manner, to calculate individual and societal risk. TRANSPIRE was developed by BG Technology, and was based on many years of research into the causes and consequences of transmission pipeline failures. Research included both mathematical modelling and experimental validation at both large and small scale. It contains models to calculate failure frequency (based on third party interference), transient gas outflow, steady-state fire and dispersion behaviour, thermal radiation effects on both people and property, and risk calculation routines which take account of the extended nature of the potential hazard source and the time-dependent nature of the event. TRANSPIRE has been used extensively by BG plc for a number of years, and has also been licensed for use in a number of other gas companies around the world.

1.3 The PIPESAFE Collaboration

In 1994, an international collaboration of a number of gas transmission companies was formed to develop TRANSPIRE into a more sophisticated tool, to extend the models within it to enable it to be applied to a wider range of situations, and to improve its functionality. Phase 1 of the collaboration funded the development of a new package by BG Technology, based on TRANSPIRE, and called PIPESAFE. This included, in addition to the models within TRANSPIRE, new models, for a wider range of failure causes and additional 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. Phase 1 was completed in 1996, culminating in the completion of the first complete version of the PIPESAFE package, operating in a MS Windows environment on a PC.

Phase 2 of the collaboration commenced in 1996, and included a number of activities designed to gain an improved understanding of the risks presented by pipeline failures and the predictions made by PIPESAFE, and to give confidence in the predictions made. For example, 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 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 the risk calculation methodology.

2. ELEMENTS OF A PIPELINE RISK ASSESSMENT

The main elements of a pipeline failure included 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, as illustrated by a simplified logic chart (Figure 1). The elements of a pipeline risk assessment considered in PIPESAFE are described below:

2.1 Failure

Failure of a 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 which 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.

2.2 Gas Outflow

Due to the pressure at which transmission pipelines are operated, a failure of a pipeline leads to a gas release which is a turbulent and complex process. Following a rupture, or large puncture, of a pipeline there will be a rapid depressurisation of the pipeline 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.

2.3 Ignition

Ignition can occur at any time during the release. If it occurs immediately on, or shortly after, rupture, a transient fireball could 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, a quasi-steady fire only will result.

2.4 Thermal Radiation

The levels of thermal radiation, incident on the area surrounding the ignited release, vary with the 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).

2.5 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 thermal radiation doses, and buildings can be ignited by thermal radiation directly from the fire or from secondary fires (e.g. from burning vegetation).

3. INDIVIDUAL MATHEMATICAL MODELS

3.1 Failure Frequency Models

PIPESAFE contains predictive models for the failure mode and failure frequency for third party interference (including the ability to account for the effects of surveillance and protective measures), corrosion and fatigue. The failure mode and associated failure frequency for other causes, such as ground movement and material or construction defects, can be input directly based on any available information, for example historical data. PIPESAFE uses the total of the predicted failure frequencies, for all the failure causes and modes identified for a particular pipeline, in subsequent risk calculations.

Third Party Interference

The availability of historical failure data at a required level of detail, particularly for the more modern, high toughness pipeline steels, is limited. Therefore, the calculation of pipeline failure probability as a result of possible third party interference damage is based on the methods presented in Reference 3, using a predictive model which combines historical damage data with defect failure modelling. The theoretical methods combine statistical data on the frequency and the nature of the damage (i.e. the distribution of defect depth and length), with the likelihood of such damage leading to failure derived from fracture mechanics models. These methods allow the influence of the main pipeline parameters (diameter, wall thickness, design factor, grade and toughness) on failure frequency to be quantified.

PIPESAFE also takes into account the mitigating effect on the likelihood of third party damage of measures such as increased depth of cover (based on historical data for the BG system), and of protective measures such as concrete slabbing and/or marker tapes buried in the ground above the pipeline (Ref. 4). The effectiveness of different protective measures was estimated following a series of studies, in which contractors who were unaware that they were taking part in the study, were instructed to commence excavation work to prepare the foundations for a new building in an area containing a buried pipeline. This exercise was repeated for a number of pipelines, each with different protective measures applied.

A model has also been developed which enables the effects of surveillance to be taken into account, using data for incidents on the BG system arising from activities known and unknown to BG, and the duration of these activities (also described in Ref. 4).

corrosion

A model has been developed and included in PIPESAFE to generate estimates of corrosion incident frequencies for individual pipelines from the average incident frequency of the system. The model has been validated by comparison with on-line inspection results from an actual pipeline. This is achieved by considering a range of factors that are believed to influence the susceptibility of pipelines to external corrosion. For each of these influence factors, numerical weighting factors are derived from the data available from pipelines which have been subjected to on-line inspection. The average corrosion incident frequency for the system is modified by applying the appropriate factors depending on the particular parameters of the individual pipeline. The failure behaviour of external corrosion defects are predicted by representing the irregular profile of a corrosion defect by a general corrosion defect incorporating a pit. Corrosion in a pipeline is modelled by a combination of isolated pits, isolated general corrosion defects, and combined pitting plus general corrosion defects. Rates for pitting and general corrosion can be estimated from the results of on-line inspection of the pipeline, or if not available, by typical corrosion rates for the system as a whole.

Fatigue

A procedure has been developed and included in PIPESAFE to predict the failure frequencies of gas transmission pipelines resulting from the fatigue of seam weld defects, based on a probabilistic crack growth model. The model calculates failure frequencies of a pipeline for a particular cyclic stress regime given a distribution of initial defect sizes (derived from hydrotest failure records).

3.2 Consequence Models

Gas Outflow

Two models for gas outflow are available. The standard model used is a dynamic simulation model which predicts the outflow following the failure of a high pressure pipeline. The outflow calculation takes account of pressure, pipeline internal diameter, friction effects of the pipe wall, position of the failure relative to boundaries such as valves or compressors, and the pressures and flows at the boundaries. The set of algebraic and one dimensional partial differential equations describing the pipeline system are solved numerically to predict the time dependent gas outflow. The second model, developed by Gasunie, is designed to model networks, taking account of valves and valve closures during an event for example, and allowing more complex networks to be modelled.

Dispersion

A mathematical model has been developed and included in PIPESAFE, to predict the dispersion behaviour of an unignited plume of gas released by a high pressure pipeline failure. It is a simple integral-type of model, which predicts the bulk trajectory and dilution of the jet released into a crossflow, and has been extensively validated against a wide range of experimental data including field scale (Ref. 5). Although the model is not generally used for routine assessments, when values for ignition probability are normally taken from historical data (Ref. 6), it can be useful for specific situations to evaluate the likelihood of flammable gas concentrations being produced at a specific location where ignition sources are available.

Initial Fireball

A model has been developed to predict the early stages of an immediately ignited release following a rupture of an underground pipeline. The model predicts the growth of the fire with time and the external thermal radiation field with time during the initial highly transient phase of the gas outflow from the rupture. The model is physically based and includes a source model, to provide representative initial steady-state flow conditions at the crater exit, and fluid flow and combustion models, to predict the geometry and composition of the fire with time. A radiation model uses the predictions of the geometry and temperatures in the fire to determine the external radiation field with time. The interaction of the release with the wind is accounted for by the model, and the model also includes a methodology to account for the effects of soil from the formation of the ground crater, entrained into the fire. The model has been validated against a series of controlled large scale experiments, carried out as part of Phase 1 of the PIPESAFE collaboration, which included experiments to provide information on the effects of varying the initial pressure, soil type, and crater size on the characteristics of the initial fireball (Figure 2).

Eleven large scale experiments were carried out, involving the deliberate rupture of a 6" (150mm) diameter pipeline connected to a large gas reservoir, at initial pressures of 30, 60 and 120 bar. Measurements were taken of gas flow rate and pressure, fire geometry and thermal characteristics. Large fires were produced, up to approximately 100m high during the initial fireball phase, which subsequently decayed in size as the gas flow rate decreased. The influence of soil was also studied, both in terms of the size and shape of the ground crater formed, and the mitigating effect on thermal radiation levels of the presence of soil entrained into the initial gas release. The largest ground craters were produced in sandy soil, which also had the greatest mitigating effect.

A simple model is also included in PIPESAFE to predict the overpressures produced by the initial failure and ignition of the gas plume. The model has been validated against experimental data from large scale experiments. Although the overpressures are generally low, and provide a negligible contribution to the risk associated with a high pressure pipeline failure, the model does provide a convenient means of calculating these overpressures.

Quasi Steady-state Fire

Following the initial fireball phase after a pipeline rupture, the gas outflow gradually decays, and the fire behaviour is quasi steady-state. Two mathematical models for the prediction of the flame size and geometry, and resulting incident thermal radiation levels, from large, wind-blown natural gas fires from high pressure pipeline ruptures have been developed and included in PIPESAFE. The first model uses a source submodel for the flow in the crater to define the source conditions, coupled with an integral model to determine the flame structure (i.e. temperature and species concentration fields), and an associated combustion submodel, which includes soot formation. Conservation equations for total fluxes of mass, momentum and released fluid are solved by stepping along the trajectory from the release point, and the results are used in calculating the radiative heat transfer from the fire. The radiation model is used to predict fluxes external to fires from the data on trajectory, temperature and concentration computed by the fire structure model. There are two aspects to the radiation model; modelling the internal radiative properties and modelling the geometry of the flame/receiver interaction. One-dimensional differential equations are used to calculate the local emissive power in the fire. The surface emissive power is then used to calculate fluxes to external bodies by use of appropriate view factors.

The second is an earlier empirical model which is based on the assumption that a fire may be treated as a surface which emits radiative energy at some mean emissive power, and that the geometry of a wind-blown fire may be approximated by a skewed frustum-cylinder shape. It is based on data from a large number of steady-state field scale experiments, incorporated into the model in terms of empirical correlation equations which express the geometry and radiative properties of a fire as functions of the volume flow rate of gas. The experiments involved ignited steady-state releases of gas from ruptured pipelines up to 6" (150mm) in diameter, at pressures up to 60 bar, into a preformed steel crater.

An empirical model (Ref. 7) is also used to predict the flame geometry and thermal radiation levels generated by ignited releases of high pressure gas from punctures, vertical and inclined, taking into account the effects of a crosswind. The model is based on large scale experimental data for the geometry and overall radiative characteristics of natural gas fires from vertical releases (Ref. 8). The fire, as an emitter of thermal radiation, is represented within the model by a series of point sources, uniformly distributed along the major axis of the flame. The variation of emissive power along the flame locus is represented by weighting the thermal power of each point source according to an expression derived from the experimental data.

Thermal Effects

The release following a pipeline rupture is transient, with the outflow decaying significantly over the time period for which the thermal radiation effects are quantified. In order to take account of this, the fire models are run ten times, at selected times after ignition, and the output data processed to provide the input to a thermal radiation effect model. The model sums the radiation dose received by a target, either at a fixed point such as a building, or for a person attempting to escape. For a time varying fire, and/or a person escaping from the fire, the program interpolates between the successive runs of the fire model and between the distances at which the radiation data is output. For a person attempting to escape from the effects of the fire, the model calculates the position of the moving receiver every 0.3 second during the event and the dose is summed as a probit dose (equal to $t.I^{4/3}$ where t is the exposure time (s) and I is the incident thermal radiation (kW m^{-2})). The dose is summed to one of two criteria for buildings; the piloted ignition of wood; and the spontaneous ignition of wood, using correlations based on data from laboratory experiments. The model output includes a prediction of the distance up to which ignition of buildings could occur (building burning distance).

Four criteria are available for predicting casualties: the onset of skin blistering; or '1%, 50% or 99% lethality' (equivalent to 1060, 2370 and 5900 probit dose units). There is a lower threshold flux level (usually taken as $1kWm^{-2}$), which it is assumed a person can be exposed to for an indefinite time without injury. An "escape distance" is calculated assuming that a retreating person is travelling at the assumed escape speed in a direct line away from the fire and that shelter is not available. This represents the distance from which a person can escape from the effects of the fire without becoming a casualty i.e. without receiving the threshold thermal radiation dose for the casualty criterion selected. The building burning distance, the escape distance, and for people outside, the probability of reaching safe shelter between these two, are calculated, enabling the casualty probability at distances from a fire to be determined. The model also accounts for people remaining indoors until the time the building they are in ignites, who then attempt to escape from the effects of the fire. At this time it is likely that the hazard for a person outdoors will have reduced from that which would have existed earlier in the event.

3.3 Risk Calculation Routines

PIPESAFE contains two routines for determining the risk from pipeline failures. The calculation of risk at a particular location from an extended pipeline source is complicated by the fact that the failure position is unknown. 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. The first routine calculates individual risk and generic societal risk due to the thermal radiation following an ignited failure of a pipeline. Individual risk is calculated at specified locations and distances from the pipeline as well as the generic societal risk in terms of the expected number of casualties and the incident likelihood for a pipeline passing through an area with a specified uniform population density.

The second routine calculates the societal risk resulting from an ignited pipeline failure for a specified site near to the pipeline. The site is specified as a series of points using x,y co-ordinate pairs relative to an origin selected as a point on the pipeline. Each point is used to represent a location on the site and the number of occupants and residencies (proportion of time a person is present either indoors or outdoors) are specified for each co-ordinate pair. For steps along the interaction length and for each residency the frequency (f) of an expected number of casualties (N) is calculated. This is presented in the form of an FN curve which shows the cumulative frequency (F) of N or more casualties plotted against N. This routine also calculates the expectation value, the potential casualties per year, from the sum of the fN data.

PIPESAFE also allows the user to consider the benefit of taking risk reduction measures such as increasing the pipeline wall thickness or using protective measures to reduce the failure frequency. This benefit can be seen by the reduction in the potential casualties per year figure, which can be used in cost benefit calculations to determine whether or not such risk reduction measures are justified.

4. PIPESAFE VALIDATION

4.1 Software Testing

In order to give confidence in the predictions of PIPESAFE, once a complete version of the package had been prepared, it was subjected to a comprehensive programme of software testing. This was carried out in three phases; the first phase was the "Quicktest", in which all the parameters and options were systematically checked, and the error message and error handling procedures checked by deliberately entering 'out-of-range' values. The second phase was the "Test of Data Flow Cycle", which followed the life cycle of inputs and model outputs generated in PIPESAFE. This tested that the inputs and model outputs were being used correctly, and where appropriate, being transported through the package correctly to where they are used again. The third phase was the "Module Test", in which all of the individual modules within PIPESAFE were tested, by comparing the inputs and outputs of models in PIPESAFE, with stand-alone versions to check that the same results were obtained.

4.2 Incident Comparison

In order to assess the realism of the methodology employed by PIPESAFE, a study has been performed in which the predictions have been compared against information collected on actual pipeline incidents, involving rupture of a pipeline, and ignition of the gas released. The aim was to compare the predictions with details of actual incidents, to highlight any limitations of the existing approach, and give confidence in the predictions made using PIPESAFE.

The performance of PIPESAFE in modelling the incidents was mainly assessed in terms of the prediction of the burnt area in the vicinity of the failure. The predictions of burnt area were, generally, slightly conservative. Some of the incidents had features not currently modelled within PIPESAFE, such as flame jetting and the formation of two fire plumes. In incidents for which there were sufficiently detailed records, PIPESAFE correctly predicted the observed response of people to thermal radiation.

One of these incidents occurred at Edison, New Jersey, in March 1994.

Edison Incident

This incident was reported in detail by the National Transportation Safety Board (Ref. 9). The pipeline (914mm diameter operating at 67 bar) ruptured as a result of mechanical damage to the exterior of the pipe which caused a reduction in the wall thickness and created a crack which grew to a critical size through fatigue. The released gas ignited within 1 - 2 minutes, and the subsequent fire damaged a number of apartment buildings at distances up to 280m from the failure point. There were no fatalities resulting from the thermal radiation, but there were a number of injuries ranging from minor burns and cuts to more serious burns. The fire occurred during the night, so that the majority of people affected by the incident would be expected to have been indoors. Reports of the incident suggest that it took between 7 and 10 minutes for secondary fires to start on the buildings within the apartment complex, at which time the residents began to try to evacuate their homes and escape to safety.

PIPESAFE was used to model this incident assuming ignition delays of 60 and 120 seconds. By running the thermal effects model for different event times, it was possible to generate information on the predicted time for the onset of wood burning at various distances (downwind) from the fire, according to which the nearest apartment buildings (180m from the failure) were predicted to have begun burning between about 280 and 430 seconds after ignition. This is in reasonable agreement with the reports of building burning at between 7 and 10 minutes after the failure. Results for the probability of escape suggested that, for persons initially inside, escape would be possible from 180m, the distance of the closest apartments to the failure point. Therefore, for this incident PIPESAFE would not predict any fatalities among the residents of the apartments who were initially inside at the time of the incident and then tried to escape when the building they were in began burning. This appears to agree well with what was observed.

4.3 Sensitivity and Uncertainty Analysis

In order to give a greater understanding of the nature of pipeline failures and their consequences, to provide information to enable users of PIPESAFE to identify the most important input parameters, and to guide the future development of the package, a detailed analysis of the sensitivity of PIPESAFE to the different possible inputs has been carried out, and an assessment made of the major sources of uncertainty.

Sensitivity data were generated for each of the failure, consequence and effects models employed by PIPESAFE by systematically varying each of the significant input parameters. The sensitivity study was undertaken for three base case pipe dimensions and operating conditions; 914mm diameter operating at 70 bar; 610 mm diameter operating at 55 bar, and 457mm diameter operating at 40 bar. The model sensitivity for each parameter was measured in terms of the model output data. For a number of parameters sensitivity data were also generated by propagating the sensitivity effects through models run subsequently in PIPESAFE to obtain a measure of the overall sensitivity. For example, when examining sensitivities for an outflow model the flowrates were passed through to the fire model and the predicted external thermal radiation data were passed through to the effects model.

The results of the sensitivity study showed that, in general, the failure frequency models exhibit very high sensitivity to some of their input parameters such as material type, pipeline wall thickness, pipeline age and stress levels, which are generally well known for a specific pipeline. The consequence and effects models generally showed a much lower level of sensitivity to model input. Although varying some parameters did have a significant effect on the model outputs, the dependence was not as highly non-linear as was observed for some of the failure frequency model inputs. The most significant parameters affecting the results of the consequence and effects models were those which influenced the fire source such as gas outflow and the source geometry.

The uncertainty study of PIPESAFE considered a number of potential sources of uncertainty associated with an assessment. The sources of uncertainty considered were natural variability, for example inherent uncertainties such as weather conditions at the time of the failure, and uncertainties associated with the knowledge incorporated in an assessment (including uncertainty associated with the input parameters, uncertainty due to performance of the individual models, and uncertainty arising from incompleteness of the PIPESAFE methodology, such as aspects of a pipeline failure which are not addressed). The conclusions of the study were that inherent uncertainties such as windspeed, wind direction and atmospheric humidity can have significant effects on the result of an assessment which may justify adopting a probabilistic approach to modelling these features. The study also showed that modelling the effects of the orientation of the pipeline ends following a failure, a feature which is not incorporated in PIPESAFE, is a major area of uncertainty. This is also a feature of pipeline ruptures which could be modelled using a probabilistic approach.

5. FUTURE DEVELOPMENTS

Phase 2 of the PIPESAFE collaboration has recently been completed. Phase 2 generated important results, in particular as part of the sensitivity and uncertainty analysis and the incident comparison, which will be used to form the basis of a Phase 3 collaboration. Topics which are likely to form a part of Phase 3 include improvements to PIPESAFE to enable a probabilistic treatment to be given to parameters which have been found to be important, but which cannot be known accurately in advance of a failure. For example wind conditions, atmospheric humidity and source conditions (such as crater geometry and pipeline alignment) can all strongly influence the results of consequence calculations, and although their effects can be accurately predicted by the models in PIPESAFE, this ability is not yet fully utilised because the appropriate values cannot be known in advance. The failure frequency models in particular exhibit high sensitivities to certain parameters, and there have been recent developments in the modelling of failures by BG plc (for example Ref. 10) and others, which could be incorporated in PIPESAFE. Improvements in the ability of PIPESAFE to predict the risks associated with gas transmission pipeline failures may also be possible using a more sophisticated thermal response model, to take account of material moisture content, the effects of convective cooling, and the effects of local fire spread, possibly using a probabilistic approach to predict ranges of the likely extent of damage. Finally, the functionality of PIPESAFE could be extended to allow more flexibility in the risk calculation methodology, to allow a variable casualty approach (see for example Ref. 11) to be used in addition to the existing method.

6. SUMMARY

An integrated hazard and risk assessment package for gas transmission pipelines has been developed by BG Technology, on behalf of an international collaboration of a number of gas transmission companies, and called PIPESAFE. It was developed from the BG plc (formerly British Gas) TRANSPIRE package, to include a range of improvements and models, and produce a software tool for use in MS Windows on PCs. PIPESAFE includes knowledge and models which treat all aspects of a pipeline failure - failure cause, failure mode, failure frequency, gas outflow, dispersion, ignition, thermal radiation, and thermal effects. Models have been extensively validated by large scale experimentation, and by operational experience. In addition to failure frequency and consequence models, PIPESAFE contains routines for calculating the risk from pipeline failures, both individual risk and societal risk, which take into account the extended pipeline source of potential hazard, and the time-dependent nature of the event.

PIPESAFE has been subjected to a comprehensive programme of software testing. A sensitivity and uncertainty analysis, and a comparison with documented pipeline rupture incidents, have also been carried out to give a greater understanding of the nature of pipeline failures and their consequences, and to guide the future development of the package.

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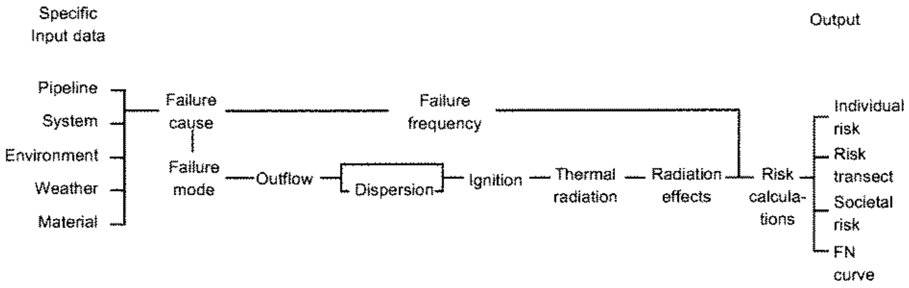

Figure 1: PIPESAFE Simplified Logic Chart

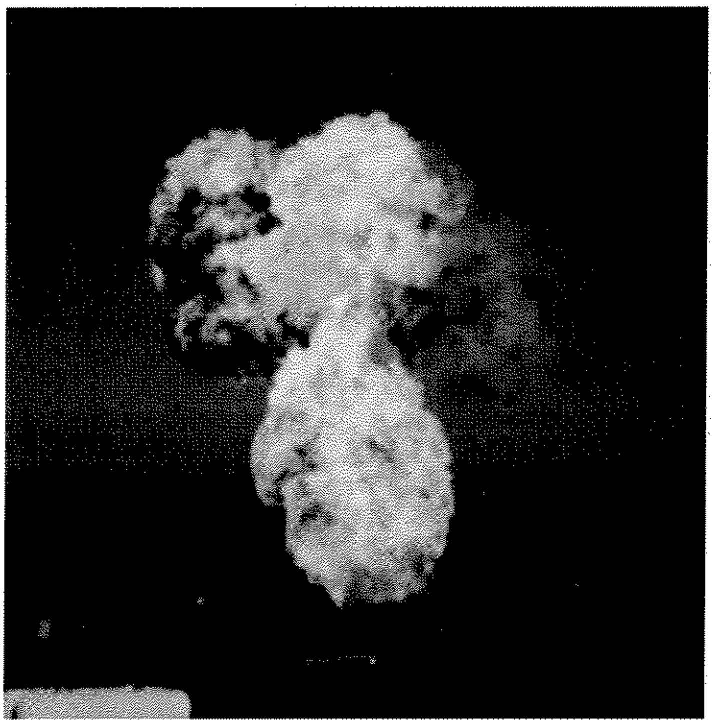

Figure 2: A Large Scale Experiment to Study the Initial Fireball Phase

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ABSTRACT

PIPESAFE is a hazard and risk assessment package for gas transmission pipelines, developed by Advantica for an international group of gas pipeline companies. Although the likelihood of failure of transmission pipelines is very low, the possibility of failure and a subsequent fire cannot be discounted. PIPESAFE provides the means to take consistent and informed decisions on risk issues, including infringements to pipeline design codes, uprating of pipelines (i.e. to operate at higher pressures), pipeline routeing and land use planning. The development of PIPESAFE was first reported at IPC '98. This paper describes recent enhancements to the package, validation of the predictions against full-scale experiments and incidents, and modifications to the risk calculation methods. The paper also describes risk criteria developed in the UK and The Netherlands, the background to their development, and the use of PIPESAFE to generate risk criteria included in the latest edition of the UK pipeline code IGE/TD/1.

1. INTRODUCTION

The pipeline 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 pipeline 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 (formerly British Gas Research and Technology) 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 and validation of the PIPESAFE risk assessment package for gas transmission pipelines, recent developments to the package as part of an international collaboration and the development of criteria used to make decisions on the acceptability of risk.

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, property or to the environment. Such failures occasionally occur on gas pipelines, 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.

For a high pressure gas transmission pipeline, a failure may take the form of a puncture or complete rupture of the pipeline, with ignition of the escaping gas giving rise to a large fire. There is a range of potential causes of failure, including accidental damage, corrosion or ground movement.

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 pipeline owners and 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. The safety regulator, the Health and Safety Executive (HSE), has developed a legal framework for the acceptability of different levels of risk. In the past, design codes for the construction of gas transmission and distribution pipelines were prescriptive in nature, but as risk assessment techniques have become better established, their importance has been recognised in new editions of design codes, in particular the recent Edition 4 of the IGE/TD/1 design code, to allow greater flexibility in pipeline design and operations, where demonstrated as safe by the use of risk assessment techniques.

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 which may result. Societal risk is usually expressed in the form of a graph of the cumulative frequency (F) of producing 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.

In order to quantify the level of risk, the range of credible failure causes must be considered, and the failure frequencies 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.

3. THE PIPESAFE PACKAGE

3.1 History

In Great Britain, natural gas transmission pipelines are generally laid in accordance with the IGE/TD/1 design code prepared by the Institution of Gas Engineers and Managers [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, Advantica (then part of British Gas) developed a risk assessment package for transmission pipelines. The package had limited functionality, and was tailored specifically to UK 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 natural gas 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, as described at IPC '98 [2]. 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, to enable failure frequency models to be modified to make appropriate predictions based on operational experience in different countries or companies.

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, described in the earlier paper [2].

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.

The results from Phase 2 formed the basis for a further programme of work, recently completed as Phase 3 of the PIPESAFE collaboration. In Phase 3, PIPESAFE has been refined so that a wider range of failure modes can be considered in a probabilistic treatment. It also now 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.

3.2 Phase 3 Developments

Ignition probability analysis

A review of transmission pipeline incident data was performed to provide information on the ignition probability for gas releases resulting from pipeline failures. Data from over 2.5 million kilometre years of pipeline exposure was available for this analysis, obtained from PIPESAFE Group member and other European companies, see, for example, Reference 4. To investigate a possible relationship between the ignition probability and the quantity of gas released, the data were analysed in terms of the product of the pipeline pressure (p) and the square of the pipeline diameter (d^2), which is directly related to the initial gas outflow following a rupture. Ignition probabilities were calculated for groups of pipelines within a particular range of pd^2 values. The proportion of ignited to un-ignited incidents was found to vary with increasing values of pd^2.

The ignition probability (ratio of the number of ignited incidents to the total number of incidents) for each group was plotted against the mean pd^2 value for each of the ranges and was found to increase linearly with pd^2. It was possible to fit an equation of the form

$$P_{ign} = A + Bpd^2$$

to the data (P_{ign} is the ignition probability and A and B are constants) and this is used up to a maximum value of P_{ign} of 0.8.

A similar approach is used to predict the ignition probability due to puncture releases, where $pd^2/2$ is used to reflect the difference between the two sources contributing to the gas release following a rupture and the single source contributing to a puncture release.

Probabilistic treatment of crater source conditions

As part of the Phase 2 development of PIPESAFE a sensitivity and uncertainty study was performed. The study showed that varying certain aspects relating to an ignited accidental release from a pipeline which would be unknown prior to an incident, within observed limits, made a significant contribution to the overall uncertainty associated with a PIPESAFE assessment. The study showed that the prevailing weather conditions and the crater source conditions, in particular, could have a significant influence on the predicted fire characteristics and the resulting risks. The previous PIPESAFE approach used single, best estimate, values for parameters used in an assessment and did not, therefore, take account of the range of possible behaviour. To address this issue, PIPESAFE has been developed to allow probabilistic distributions to be specified for the most influential parameters impacting upon the consequence and risk calculations.

Following a rupture of a pipeline a crater will form. There will be uncertainty about how the pipeline will fail and the nature of the crater produced. These uncertainties result from the random nature of the location of pipeline failure, uncertainty about the exact details of the surrounding environment, and the accuracy of the predictive method. A methodology has been incorporated in PIPESAFE that allows these uncertainties to be taken into account.

The methodology uses pipeline parameters about which there is no significant uncertainty (e.g. the pipeline diameter), and failure parameters about which there will be uncertainty (e.g. the failure length). Given values of the pipeline parameters (diameter, pressure, depth of cover and soil type) and the failure parameters (fracture length and misalignment), mean values of crater parameters (length, width, depth and wall angle) are calculated using simple explicit equations derived from a physically based crater formation model, developed for Gasunie, based on a theoretical analysis and small-scale laboratory experiments.

Once the mean crater parameters are known, non-dimensional probability distributions of the parameters are used to generate probability distributions of the crater parameters for use in PIPESAFE. The non-dimensional probability distributions were derived from comparison of the crater formation model with data from a wide range of transmission pipeline incident data. Incident data were used to obtain probability distributions for pipeline misalignment following pipeline failure.

PIPESAFE can consider up to 81 different crater geometries in a single probabilistic run. However, the default probabilistic case considers only 18. Figure 1 shows a schematic diagram of the range of crater geometries and pipeline alignments considered in the default probabilistic case. Two pipeline failure lengths are considered and for each failure length three crater widths are used. For each crater width, three values of misalignment for the upstream pipeline are used.

Faster and more flexible consequence models

(i) Fire models

An underground pipeline rupture event can be separated into three stages:

i) The initial rupture of the pipeline in which a crater is formed around the rupture due to the excavation of the soil by the release of the decompressing natural gas,

ii) followed by the production of an impulsively started jet in the atmosphere above the crater, which if ignited gives rise to a 'fireball',

iii) and, if ignited, a quasi-steady jet fire stage where the mass flow rate decreases slowly relative to the rapid decrease in flow during the initial pipeline decompression in stage ii).

PIPESAFE includes separate fireball and quasi-steady jet fire (or crater fire) models. Due to the complexity of the models, in particular the crater fire model [3], run times were quite large and therefore not readily suited for use in a probabilistic version of PIPESAFE. To be able to use the model in probabilistic calculations there was a need to reduce model run times. Because of this, and because new experimental data from a series of experiments performed by Advantica was available for validation purposes, a new version of the crater fire model was developed, called CRISTAL.

The crater fire model can be considered as a collection of interconnected sub-models of the physio-chemical processes that occur during a fire from a pipeline rupture:

i) A crater source model, that takes the crater and pipeline specification and calculates crater source conditions consistent with a model for the flame structure,
ii) a flame structure model that takes the crater source conditions and prescription of the atmospheric boundary layer and calculates the location and extent of the hot emitting portions of the flame using sub-models for the processes of turbulent mixing, combustion and soot production, and
iii) a radiation model that takes the outputs from the flame structure model, such as the temperature distribution within the flame, and calculates the received flux to the surrounding people and property.

Computer profiling of the crater fire model in the previous version of PIPESAFE identified that the flame structure model is the most computationally intensive portion of the simulation. The flame structure model consists of a system of ordinary differential equations which are solved numerically. It was possible to reduce run times by adjusting the acceptance tolerances on numerical methods and reducing the number of intervals used in the numerical integrations. In some cases it was possible to avoid these steps altogether by exploiting analytical properties where possible and replacing numerical integrations by the evaluation of polynomials using curve fitting techniques. Improvements in the efficiency of the flame structure and radiation models were also made.

The new crater fire model was implemented such that the typical run-time is of the order of 50 times faster than the previous version of the model making the application of the model to a probabilistic treatment of uncertainty viable. Furthermore, a quantitative comparison of the scatter in the predictions demonstrated that the new model generally gives a slightly better agreement with the experimental data than the crater fire model in the previous version of PIPESAFE. To ensure that the modelling of the overall pipeline fire event was modelled consistently in PIPESAFE, equivalent changes were also made to the modelling of source conditions in the fireball model.

(ii) Thermal Effects Modelling and Risk Calculation Routines

The release following a pipeline rupture is transient, with the outflow decaying significantly over the time period for which the thermal radiation effects are quantified (a PIPESAFE prediction of outflow is shown in Figure 2). In order to take account of this, the fire models are run to generate radiation data for each second of the event during the fireball phase (if immediate ignition occurs) and for selected times during the quasi-steady period of the fire (a PIPESAFE prediction of thermal radiation, for an immediately ignited release, is shown in Figure 3). The output data provide the input to a thermal radiation effects model. The model sums the radiation dose received by a target, either at a fixed point such as a building, or by a person attempting to escape. For a time varying fire, and/or a person escaping from the fire, the program interpolates between the successive runs of the fire models and between the distances at which the radiation data is output. For a person attempting to escape from the effects of the fire, the model calculates the position of the moving receiver every 0.3 second during the event and the dose is summed as a probit dose[1]. An "escape distance" is calculated assuming that a retreating person is travelling at the assumed escape speed in a direct line away from the fire and that shelter is not available. This represents the distance from which a person can escape from the effects of the fire without becoming a casualty (i.e. without receiving the threshold thermal radiation dose for the casualty criterion selected). The building burning distance, the escape distance and, for people outside, the probability of reaching safe shelter between these two, are calculated, enabling the casualty probability at distances from a fire to be determined. The model also accounts for people remaining indoors until the time the building they are in ignites, who then attempt to escape from the effects of the fire. At this time it is likely that the hazard for a person outdoors will have reduced from that which would have existed earlier in the event.

It has been necessary to develop a new version of the thermal effects model in order to be able to carry out calculations using the two-dimensional, time-varying radiation fields which are predicted by the latest versions of the fire consequence models. This is because complex radiation fields can arise due to pipeline misalignment following pipeline failure or unbalanced flows from each of the failed sections of the pipeline during the event. In the new model it is assumed that a person escaping from a fire will run in a straight line away from a fixed point, passing through the two-dimensional radiation field predicted, to calculate the thermal radiation dose.

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[1] equal to $t \cdot I^{4/3}$ where t is the exposure time (s) and I is the incident thermal radiation (kW m^{-2})

Calculations can be carried out for a number of such escape paths; 16 equally spaced radial paths are used by default.

Modifications to the thermal effects model have also been made to allow escape distances or escape probabilities to be calculated for a pre-determined casualty criterion (i.e. at a user-specified probit dose unit value). The previous version of PIPESAFE was only able to do this for a number of fixed casualty criteria. Another feature introduced in the new version of PIPESAFE is to be able to calculate risks using 'fatality' as a casualty criterion (definitions of casualty, fatality and lethality are given below[2]). The basis of this methodology is that an average population has a range of sensitivity to thermal radiation. Consequently, selecting a single fixed casualty criterion, such as 1% lethality, is equivalent to calculating escape distances or escape probabilities for a person who is in the category of being amongst the 1% most vulnerable of the population when placed in order of sensitivity. To obtain a picture of the effect of an event on the population, the entire spectrum of sensitivities is considered. To allow this, escape probability calculations are carried out at each point on each escape path for each 1% band of the population in turn (i.e. 0 to 1%, 1% to 2%, ...98% to 99%). These values are then integrated over the whole population to arrive at an overall casualty rate.

Because of the significant changes that have been made to the fire and thermal effects modelling capability in PIPESAFE it has also been necessary to rewrite the risk calculation routines in the package. In doing this, it was also possible to address a request from one of the sponsoring companies for PIPESAFE to be able to employ a more sophisticated approach to the representation of meteorological conditions. The new version of PIPESAFE can now, in a single run, model up to four wind speeds with two independent wind roses for each wind speed (to represent day time and night time that can have different lengths but must add to 24 hours). Probabilistic calculations can thus be undertaken to address variations in meteorological conditions simultaneously with the probabilistic treatment of crater source conditions described above, although the potential maximum number of calculations becomes very large (just under 15000 individual runs of the fire models).

Software testing

Because of the extensive nature of the changes made to PIPESAFE in moving to the new probabilistic version, a detailed test programme was undertaken that involved three main stages:

i) Comparing results from the probabilistic version of PIPESAFE to those from the previous version for cases where broadly equivalent runs could be made, using the old consequence models,
ii) comparing results of risk assessments using the new fireball and crater fire models with those in the previous version, and
iii) extensive testing of the new features incorporated in the probabilistic version of PIPESAFE.

In stages 1 and 2 of the test programme over 500 complete runs of PIPESAFE were performed. During the testing in stage 3 a wide range of cases were assessed. For example, in total over 150,000 separate runs of the crater fire model were performed. During this testing any problems identified were addressed and re-tested, to give confidence that the probabilistic methodology was operating correctly.

3.1 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, 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 scale experiments to study the behaviour of accidental releases of gas and other fuels, to be conducted safely.

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, presented previously at IPC 2000 [5]. 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

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[2] In this context, a casualty is defined as a person receiving a dose of thermal radiation equal to, or greater than, the threshold dose for the casualty criterion selected and a fatality is a person that dies as a result of thermal radiation received. Lethality is the fatality rate among an 'average' population exposed to a hazard. For example, a thermal radiation dose equivalent to 50% lethality is one that would cause 50% of an average population to become fatalities.

the gas outflow reduced following the initial rupture (a comparison of PIPESAFE predictions, made using the new fire model CRISTAL, against data from one of these experiments is shown in Figure 4).

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:

i) Building ignition times,
ii) burn areas surrounding the failure, and
iii) 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.

4. THE DEVELOPMENT OF SOCIETAL RISK CRITERIA FOR TRANSMISSION PIPELINES

4.1 Great Britain

The HSE uses a three-band approach in regulating industrial risks [6]. 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 (As Low As Reasonably Practicable). 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, in terms of the money, time and trouble involved in undertaking the measures necessary to avert the risk. 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 (1×10^{-6} per year) and represent the boundary between tolerable and unacceptable (1×10^{-3} per year for workers and 1×10^{-4} per year for members of the public). These benchmark values for individual risk are based on the fact that a level of $1\ \times10^{-6}$ per year is a very low level of risk when compared to the background level of risk for all hazards. For societal risk, the HSE have not published criteria comparable to those for individual risk. For transmission pipelines, which have the potential to cause multiple fatality events, the consideration of societal risk is usually more important than individual risk, which is generally well below the broadly acceptable level.

In practice, transmission pipelines in Great Britain have been designed and constructed in accordance with IGE/TD/1, issued in a number of editions including Edition 3:1993 and Edition 4:2001 [1]. Edition 3 of IGE/TD/1 was predominantly used in a prescriptive manner, although it did include some provision for risk assessment.

A risk criterion for natural gas transmission pipelines was developed with the objective of representing an acceptable risk consistent with the design, construction and operation of the British National Transmission System (NTS) operated by Transco (formerly part of British Gas). To do this a wide range of scenarios and test cases exploring the envelope of conditions allowed under Edition 3 of IGE/TD/1 was derived. For these cases FN data were generated using the generic societal risk model in PIPESAFE. The data formed a band on an FN plot, through which a line of increasing slope could be drawn. This was adopted as a criterion 'envelope' for pipeline design or land-use planning situations given that fitness-for-purpose considerations had been met. The level of risk was acceptable if it was below this 'envelope'. If the risk level was at, or above, the envelope then it would be necessary to demonstrate that the risk level was ALARP, or modification to development plans made. For an existing pipeline this would mean that risk levels were tolerable above this envelope up to a level at which it became 'reasonably practicable' to carry out modifications to the pipeline. This societal risk criterion, developed using PIPESAFE, was the basis of the example included in IGE/TD/1 Edition 4, shown in Fig 5.

The position of the criterion was checked by carrying out sample cost benefit calculations to examine the costs incurred in reducing the risk from a pipeline by utilising an increased wall thickness. These calculations assumed that the extra cost incurred in moving to a thicker walled pipeline were material and welding costs only. This demonstrated that the criterion envelope represented, as far as possible, a situation where societal risks that were assessed to fall under the envelope were ALARP. It is important to note that the methodology used to assess risk from a pipeline has to be the same as the methodology used to generate any criteria against which the risk assessment is to be compared.

4.2 The Netherlands

The Netherlands has developed two risk criteria for industry. The first deals with the risk of an individual who lives near a potentially hazardous installation, referred to as "location risk" or "point risk". The criterion is that the location risk should be lower than 10^{-6} per year. It is defined as the likelihood of death at a point for a hypothetical individual that is permanently resident and unprotected by either clothes or buildings. The methodology for calculating risk considers the event to last for only 20 seconds and does not consider any attempt by the individual to escape from the effects of the fire.

The second criterion is for societal risk and is defined as an FN curve, indicating the maximum frequency F for N or more people that would be predicted to be fatalities in a single incident. For point sources like compressor stations and chlorine plants the criterion is $F \cdot N^2 < 10^{-3}$ year^{-1}. For transportation type locations like roads, rails, canals and pipelines the criterion is $F \cdot N^2 < 10^{-2}$ km$^{-1}\cdot$year^{-1}. In the societal risk calculation a 20 second exposure and no escape is assumed, but account is taken of the protection afforded by houses and clothing.

Both criteria are described in detail in the 'purple book' [7]. For pipeline fires the dose effect calculation is based on the 'green book' [8].

For transmission pipelines it is not necessary to make risk assessments at all locations. Proximity distances for different diameters and pressures are specified in the pipeline code [9] and in a ministerial circular letter [10]. It is assumed that for developments built outside the proximity distance the location risk is acceptable. Because of the fact that understanding of risk has developed in the last two decades, these distances are now recalculated with PIPESAFE. To account for societal risk, tables have been developed to indicate the maximum number of people per hectare allowed outside the proximity distance. It is expected that these tables will be published by the regulator in 2002. Only in special cases (proximity distance infringements, population concentrations which cannot be assumed to be evenly distributed) do risk assessments have to be carried out.

5. SUMMARY

PIPESAFE is a hazard and risk assessment package for gas transmission pipelines, which has been developed by Advantica (formerly British Gas Research and Technology) for an international group of gas pipeline companies. Although the likelihood of failure of transmission pipelines is very low, the possibility of failure and a subsequent fire cannot be discounted. PIPESAFE provides the means to take consistent and informed decisions on risk issues, including infringements to pipeline design codes, uprating of pipelines to operate at higher pressures, pipeline routeing and land use planning. The development of PIPESAFE was first reported at IPC '98. Since that time, a further phase of the collaboration has been established in order to enhance the functionality of the package.

Previous studies indicated that the uncertainty associated with those elements of a risk assessment that could not be predicted in advance, including the prevailing weather conditions and the pipeline alignment following a rupture, was significant. The ability to account for this uncertainty has been addressed in the recent developments to PIPESAFE that allow a probabilistic approach to be used in the modelling of wind speed and direction, the geometry of the crater formed following pipeline failure and misalignment of the failed pipeline. This paper has described these improvements, further validation of the predictions against full scale experiments and incidents, and modifications to the risk calculation methods to allow risk to be calculated in accordance with the varying requirements of the member companies. In addition, as experience in the application of PIPESAFE has been gained, the criteria used to make decisions on the acceptability of risk have also developed. This paper has described the risk framework used in the UK and The Netherlands, the background to their development, and the use of PIPESAFE to generate risk criteria included in the most recent edition of the UK pipeline code IGE/TD/1.

6. ACKNOWLEDGEMENTS

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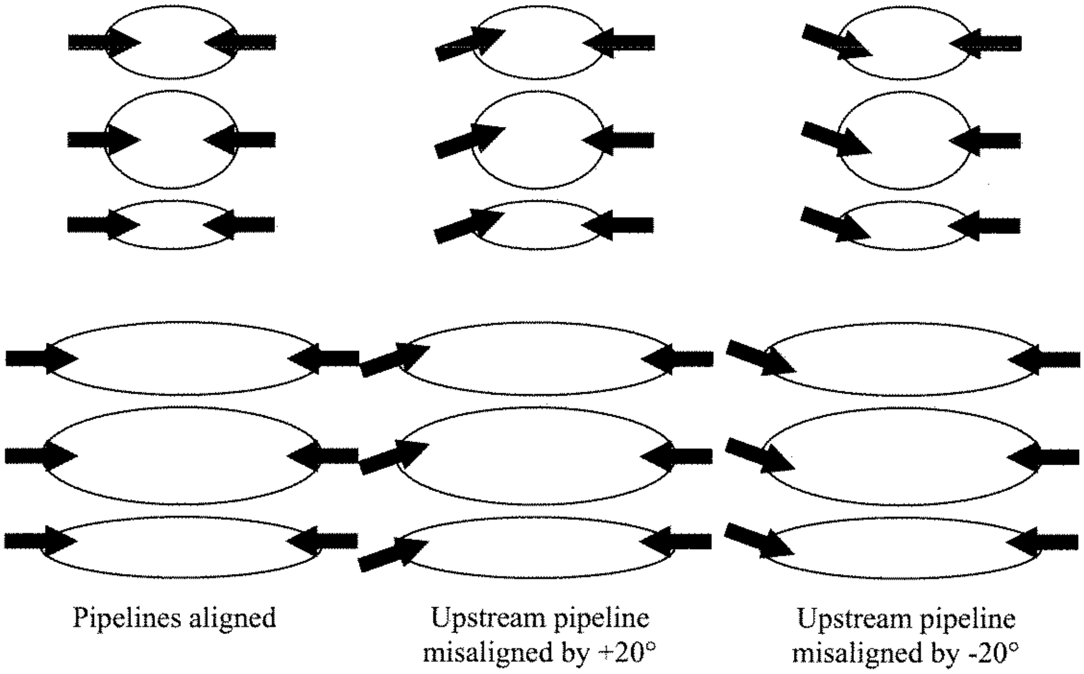

Figure 1: Schematic representation (plan view) of crater geometries and pipeline misalignments used in default probabilistic assessment.

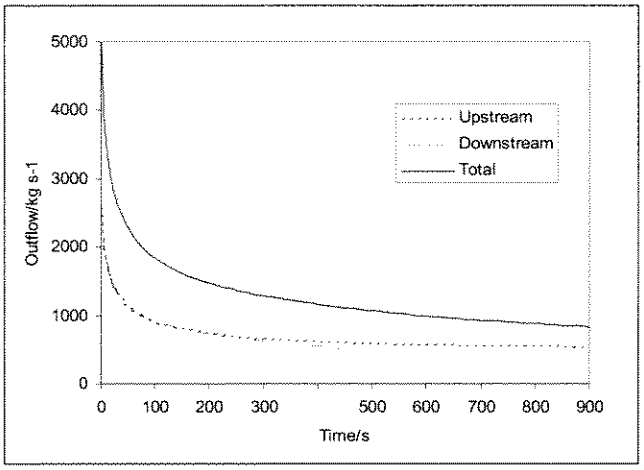

Figure 2: PIPESAFE transient outflow prediction.

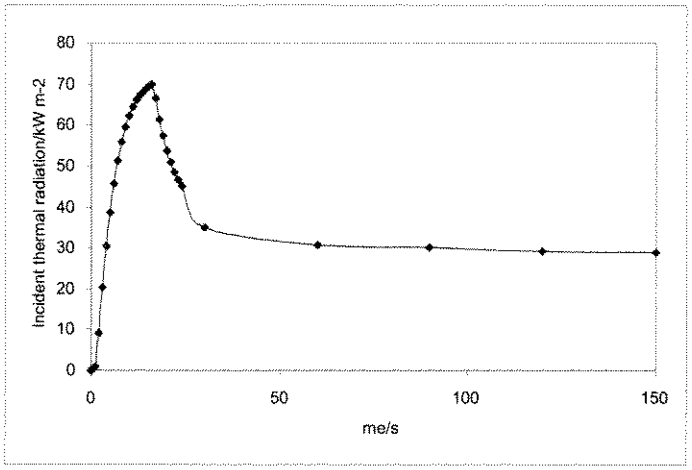

Figure 3: PIPESAFE thermal radiation profile for immediately ignited release.

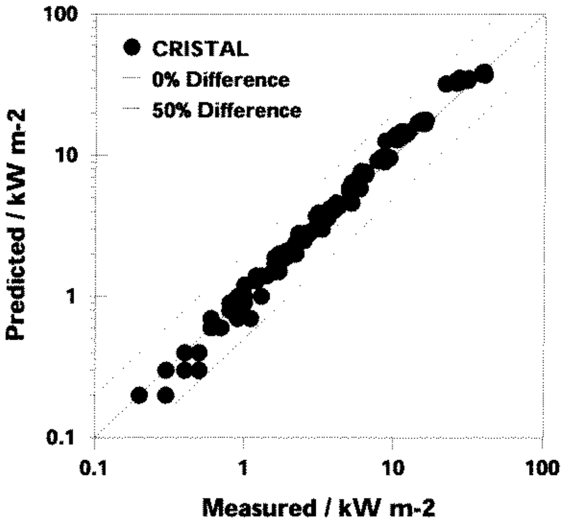

Figure 4: Comparison of PIPESAFE crater fire model (CRISTAL) with full-scale data.

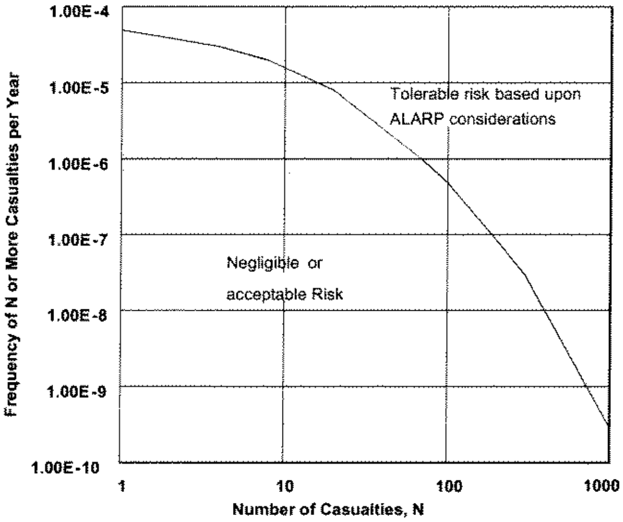

Figure 5: Sample FN criterion (from IGE/TD/1 Edition 4 – [1].

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DEVELOPMENT OF A RISK RANKING TOOL BASED ON QUANTITATIVE METHODS

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ABSTRACT

US pipeline integrity management regulations require operators to rank the risks caused by their operations. Many operators use qualitative methods for this risk ranking process. Such methods have several benefits including simplicity and flexibility. Unfortunately, they rely heavily on engineering judgment and produce results that are very specific to the pipeline system(s) being ranked. This makes it extremely difficult to relate the outputs from different systems or companies within an organization.

This paper describes the development and application of a risk ranking approach that requires less judgment and provides the user with an estimate of the true risk of operating the pipeline. Quantitative methods, based on an understanding of structural mechanics, are applied to seven of the nine threat categories listed in ASME B31.8S in order to determine the pipeline's reliability. An assessment of risk to life is achieved by combining the output from structural mechanics models with a quantitative consequence of failure model. The software operates on a GIS platform, making it easier to demonstrate compliance with the integrity data management requirements that are now part of the relevant federal codes.

Results produced from the quantitative approach have been compared to those generated by qualitative methods, in a case study. This illustrates some important differences between the two and show that a more rigorous, quantitative approach can provide the operator with significant benefits including the ability to generate meaningful results with less data. In particular, quantitative methods have the potential to allow operators to move towards a more performance-based approach to their ongoing integrity management processes.

INTRODUCTION

US pipeline integrity management regulations require operators to rank the risks caused by their operations, in order to develop a schedule for carrying out integrity assessments. Qualitative or 'Relative Assessment' methods are frequently used for this purpose. Unfortunately, Relative Assessments suffer from a number of drawbacks and produce results that are very specific to the pipeline system(s) being ranked, making it extremely difficult to relate the outputs from different systems or companies within an organization.

Advantica has developed a risk ranking methodology and software application that specifically addresses the compliance requirements of recently published US pipeline regulations. This provides the user with an estimate of the true risk of operating the pipeline. Quantitative or 'Probabilistic Assessment' methods, based on an understanding of structural mechanics, are applied to in order to determine the pipeline's reliability. An assessment of risk to life is achieved by combining the output from structural mechanics models with a quantitative consequence of failure model. The term 'risk' relates to the definition provided in Section 5.2 of ASME B31.8S [1] *"Risk is typically described as the product of two primary factors; the likelihood (or probability) that some adverse event will occur and the resulting consequences of that event"*.

The paper outlines the reasons for selecting a quantitative approach to Risk Ranking, which is a component of Advantica's Uptime integrity management services, before presenting the methodology adopted.

A case study compares the results obtained using a Relative Assessment technique and the Probabilistic Assessment technique, in order to highlight some important differences between the approaches.

While the primary focus of the paper is on the approach taken to rank the risks associated with the various integrity threats affecting gas transmission pipelines, a further objective is to describe a fully integrated software application that enables a pipeline operator to demonstrate compliance with many elements of the relevant US integrity management regulations. This is achieved using a GIS platform so that locations where different integrity threats exist can be accurately located and visualized againt the mapping data and high consequence areas (HCA's).

RISK ANALYSIS

There are four approaches to risk analysis described in ASME B31.8S [1]:

- Subject Matter Experts
- Relative Assessments
- Scenario Assessments
- Probabilistic Assessments

The first two calculate the relative risk for one segment compared to another. Scenario-based models are more sophisticated and allow risk values to be determined for each segment. Probabilistic assessments use a fully quantitative methodology that produce outputs for each segment that can be compared to risks that are acceptable.

The reasons for adopting a probabilistic approach to Risk Ranking are briefly summarized below.

Relative Assessments

- While such schemes have considerable flexibility, they are heavily reliant on engineering judgment and failure statistics. The algorithms are often based on intuition and some observation.
- One pipeline or pipeline segment is ranked relative to another. The results produced are very specific to the system being assessed, making it difficult to relate the outputs from different systems or companies within an organization.
- Lack of engineering rigor makes it difficult to determine the benefit of various inspection and mitigative actions the operator may wish to implement.

Probabilistic Assessments

The approach to Risk Ranking that will be described in the remainder of this paper relies primarily on Structural Reliability Analysis (SRA). Features of the approach include:

- The models are based on an understanding of structural mechanics, and knowledge of damage that has affected the pipeline.
- It produces a quantitative (absolute) measure of pipeline reliability
- It produces a quantitative (absolute) measure of risk and hence impact to the public and environment
- It allows benefits of inspection and mitigative activities to be quantified.
- It is less demanding than relative risk schemes in terms of the data required to produce results.

The last of these features is discussed further in the section on the Case Study.

BACKGROUND TO APPROACH

Before describing the approach used in Risk Ranking, this section considers some of the factors that influenced the design of the software.

Identifying Integrity Threats

To meet code requirements an operator must consider each of the 21 threats listed in ASME B31.8S that might affect a pipeline segment. However, it is highly unlikely that every one of these threats, which fall into 9 threat categories, will apply to a given pipeline and it is usually possible to eliminate threats by responding to a series of questions. 'Threat Assessment' has been adopted as the first stage of Risk Ranking in order to meet several objectives.

- To guide the operator towards the most important integrity threats affecting the pipeline.
- To provide documentary evidence that the code requirements have been addressed.
- To avoid running quantitative models for some threats, where this would not add value to the output.
- To minimize data gathering.

Probability of Failure

Having chosen to use the probabilistic approach, Advantica's existing Structural Reliability models were evaluated to determine how they could be incorporated in a system to address the risk ranking requirements of relevant federal and state codes. (Note that the federal code 49CFR192 incorporates ASME B31.8S by reference so the risk assessment requirements specified in B31.8S were assumed).

Of the 21 integrity threats listed in B31.8S, it was found that existing models addressed the following root causes and could determine the probability of a failure occurring:

- External corrosion
- Internal corrosion
- Defective pipe seam
- Defective pipe
- Defective pipe girth weld
- Defective fabrication weld
- Third party damage (instantaneous / immediate failure)

Published statistics in the US on gas pipeline transmission and gathering systems incidents [2] confirm that the above list contains many of the most frequently occurring threats to pipeline integrity. For instance, the three most common causes leading to incidents are: third party damage (27.6%), internal corrosion (12.8%) and external corrosion (9.9%).

It was determined that quantitative models for the following threats would also be required:

- Stress corrosion cracking
- Earth movement

As these models were being developed, the threats could be addressed in a Risk Ranking system using a combination of threat screening, industry statistics, and visualization of hazards along the pipeline route.

Finally, it was determined that the remaining threats to integrity, including equipment failure, weather related threats, and some of the less common stable threats, may be readily addressed using widely available industry statistics.

Consequences of Failure

Advantica has developed models for determining the consequences of a gas release from a pipeline. A series of papers submitted to successive International Pipeline Conferences describe the development and validation of the PIPESAFE package, which provides detailed modeling of the risks associated with the consequences of releases from high pressure gas systems [3-5]. The same principles can also be applied to pipelines carrying other fluids, and Advantica has recently developed methods for pipelines carrying sour gas, sweet crude and sour crude oil.

Based on the knowledge and experience gained from previous work, it was concluded that the prescriptive requirements of the ASME B31.8S code could be met using a more straightforward approach. Accordingly, the approach adopted by Risk Ranking uses the simple Potential Impact Area calculation specified in section 3.2 of ASME B31.8S for buried pipelines. In this case, a simplified correlation based approach is used to allow 'interaction' of the pipeline with the neighboring population to be identified. In particularly sensitive areas or high risk situations, more sophisticated consequence modeling may be required, particularly to support decision making on risk reduction options. This type of analysis is beyond the scope of this paper.

There is also a need to consider the consequences of failure at above ground installations associated with transmission pipelines, such as compressor stations, possibly with associated gas treatment equipment, pressure reduction stations and single block valve installations. There is a possibility that releases could occur from above ground pipe work or inside enclosures at such installations. Methods have been developed to perform fully quantified risk assessments at such facilities and are described in another paper being presented at this conference [6]; these involve detailed consideration of the dispersion, fires and, if applicable, explosions that might arise. However, in the current paper we note that it also possible to provide a simpler correlation based approach to define a representative exposure radius, as for the buried pipelines.

The quantified approach accurately determines the impact on the surrounding environment and population and potential impact to the business (loss of gas and associated penalties). This allows operators to demonstrate to regulatory authorities and management that the pipeline system is being operated to a quantified, consistent and acceptable level of risk (safety).

Data Management and Integration

Many activities and processes concerned with integrity management are closely linked to the effective management of engineering information and records. ASME B31.8S provides guidelines for the types of data required and acknowledges the importance of comprehensive pipeline and facility knowledge to implementing a performance based integrity management program.

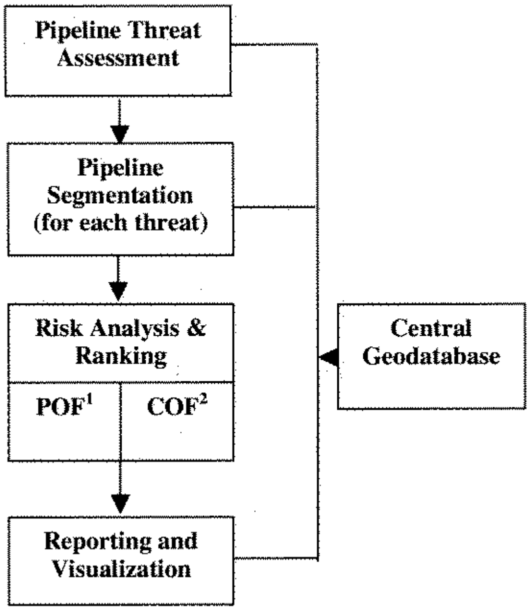
The framework described in ASME B31.8 addresses both the establishment of a formal management plan and its ongoing maintenance. Though the framework and integrity management plan elements are beyond the scope of the current paper, it is worth noting the information requirements which fall into several broad groups of activities:

- Collation of 'attribute' data (design and construction records, operating parameters)
- Establishment of prevention, detection, assessment and repair procedures for any threats that cannot be eliminated
- Evaluation and review of failure trends and frequencies, and revision of procedures as appropriate

In designing the Risk Ranking software, the authors recognized the need to collate much of the same data in order to meet both functional and code requirements. It was therefore appropriate to develop the Risk Ranking around a core data repository, capable of storing the relevant information for both prescriptive and performance based integrity management plans, as well as data necessary to run the risk assessments.The system should also be capable of integration with a client's existing information systems.

OVERVIEW OF METHODOLOGY

An overview of the process used by the Risk Ranking module is shown in Figure 1. A description of each step is given in the next section. Figure 1 shows that all data used in the analysis is accessed and stored via the central geodatabase.



[1] – Probability Of Failure, [2] – Consequence Of Failure

Figure 1 – Overview of Risk Ranking Process

DESCRIPTION OF METHODOLOGY

Step 1 – Pipeline Threat Assessment
This module enables the user to determine which of the nine possible threats to integrity (the categories defined in ASME B31.8S) are credible for the specified pipeline based on the information available.

The user is guided through a series of questions via on-screen forms. For each threat there are algorithms that relate the inputs to the Threat Assessment, to determine whether or not the threat is credible. An example is shown below for the threat of manufacturing related defects. The algorithms used in this process were developed from various sources including published literature and Advantica's own reports and publications.

As an example, the threat from manufacturing defects associated with low frequency ERW pipe is assessed using the following algorithm, adapted from [7]. The numbers (1,2,3 etc) correspond to 'Ref' in Table 1.

```
IF [3<=1970 AND 5=(ERW-Low Freq OR Flash Welded)
AND (6=Y OR Unknown)] OR
IF [3<=1970 AND 5=(ERW-Low Freq OR Flash Welded)
AND 6=N AND 12<1.25 x HP OR
IF [3<=1970 AND 5=(ERW-Low Freq OR Flash Welded)
AND 6=N AND 12>=1.25 x HP AND (13=Y OR Unknown)
OR
IF [6 to 10 =Y OR Unknown] OR
IF [10=N AND (11=Y OR Unknown)] THEN Manufacturing
threat exists ELSE Manufacturing threat is not credible
```

Ref	**Data**	**Value**
1	Pipe Material	Steel / Other
2	Steel Grade	e.g. X42, X46
3	Year of Installation	
4	Manufacturing Process	e.g. Seamless
5	Seam Type	e.g. ERW
6	History of Seam Failures	Y/N/Unknown
7	History of Pipe Failures	Y/N/Unknown
8	Joint Factor < 1.0?	Y/N/Unknown
9	Any Proposed Operating Pressure Changes?	Y/N/Unknown
10	Pressure Cycling History?	Y/N/Unknown
11	Proposed Changes to Pressure Cycling Regime?	Y/N/Unknown
12	Hydrotest Pressure	
13	Seam related test breaks	Y/N/Unknown

Table 1 – Data Required for Manufacturing Threat Assessment

The output from Threat Assessment is a list of credible and non-credible threats to integrity for each pipeline. This avoids unnecessary time and effort being spent on those threats already dismissed. Threat Assessment has been developed in such as way as to find a threat credible unless there is sufficient and reliable data to deem otherwise. In addition, the software recommends appropriate integrity assessment(s), mitigation action(s) and monitoring programs, in accordance with those stipulated in ASME B31.8S, to deal with each of the credible threats to that pipeline so that they may be incorporated into the operators' integrity management plan.

Note that Threat Assessment is carried out at the pipeline, rather than the segment level. Subsequent risk analysis is carried out for each segment where the segmentation process is dictated by the key parameters for each threat, as described below.

The software allows any assumptions about data used in each threat assessment to be recorded by the user and recovered later for audit and other purposes.

Step 2 – Pipeline Segmentation
Once the Threat Assessment has been completed, it is necessary to segment the pipeline into portions having similar attributes. This must be done against the relevant parameters for each credible threat. This is achieved using predefined auto-segmentation routines. For example, the design and construction parameters used to segment for the external corrosion threat include:

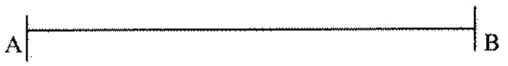
- Operating pressure
- Diameter
- Wall thickness
- Material grade
- Age of pipeline
- Coating type

The user has the option to further segment according to pipe environment parameters, for example based on:

- Soil conditions
- Location class (population density), HCA
- Other areas of sensitive developments, e.g. schools, hospitals.

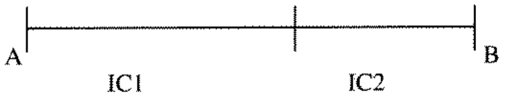
It is possible to specifying start and end points on the pipeline to be segmented, using a variety of parameters including stationing. The output from the segmentation routine is a series of segments in a form suitable for analysis using the relevant threat elements of the Risk Analysis and Ranking models.

Note the way in which the segmentation process deals with multiple credible threats. A risk value will eventually be required for each segment and threat category, so separate segments are required wherever there is a change in the parameters affecting a credible threat. An example is shown below.

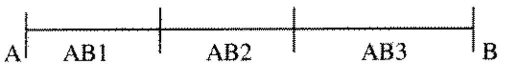


Pipeline A B is segmented for external corrosion assessment, into Segments EC1 and EC2.

Pipeline AB is also segmented for internal corrosion assessment, into segments IC1 and IC2 (note that the segmentation parameters to run Risk Analysis and Ranking models are naturally different).



Then, Pipeline AB has two probability of failure (POF) values POF(EC1) and POF(EC2) for external corrosion and two POF values POF(IC1) and POF(IC2) for internal corrosion. If these were the only two credible threats for Pipeline AB the total probability of failure would be calculated for 3 segments:



Segment AB1 where, POF(Total) = POF(EC1) + POF(IC1)
Segment AB2 where, POF(Total) = POF(EC2) + POF(IC1)
Segment AB3 where, POF(Total) = POF(EC2) + POF(IC2)

Segmentation for other credible threats are treated in the same way. Given the probabilities will be small, the total POF for each individual segment is the summation of the threats, expressed as the probability of failure per year.

Pipe sections where there is no significant change in a set of specified parameters are treated as a single segment for the purposes of analysis. In practice the number of segments will be dictated by the requirements for each credible threat.

Step 3 - Risk Analysis and Ranking

Calculating POF:
Once the pipeline has been divided into segments, the Risk Analysis module is used to calculate the probability of a segment failing due to credible integrity threats. The approach is based on Structural Reliability Analysis (SRA), in which a thorough understanding of structural mechanics is combined with probability theory to calculate a probability of failure.

SRA comprises six elements:

- Establishment of Limit States
- Identification of Failure Modes
- Formulation of Limit State Functions
- Uncertainty Analysis
- Evaluation of Failure Probability
- Assessment of Results

A brief description of each of these elements and the role they play in the overall analysis is given below.

Establishment of Limit States

A limit state is defined as the state of a structure when it no longer satisfies a particular design requirement. The limit states thus determine the conditions that are to be avoided. For example, a leak is a limit state.

Identification of Failure Modes

A failure mode is the mechanism that causes the pipeline to reach a limit state. A failure mode is thus always associated with a particular limit state but a failure mode is not a limit state. Corrosion growth is a failure mode that can cause a pipeline to leak.

Formulation of Limit State Functions

A limit state function is a mathematical relationship between the parameters that characterize a particular failure mode that exists when the pipeline has reached a limit state. It is generally expressed in the form:

$$G(x_1, x_2, \ldots x_n) = 0$$

where $x_1, x_2, \ldots x_n$ denote the n parameters which characterize the failure mode under consideration. Some of the parameters may be dependent on time. In this case the limit state function determines the relationship that exists between the parameters at the current time ($t = 0$, say) that will result in a failure at a later time, t_{future}.

Uncertainty Analysis

In any practical engineering circumstance, each of the input values to a limit state function is subject to uncertainty.

Uncertainties are accounted for in a structural reliability analysis by describing variables in statistical terms.

For each limit state function, the variability in the sensitive parameters must be quantified by data analysis and ultimately the construction of probability density functions (p.d.f.'s). This is achieved by performing appropriate statistical analyses of the data available from various sources including construction records, test certificates and inspection records. The outputs of these calculations are mathematical functions describing the likelihood of occurrence of specified values of particular parameters.

Parameters typically belong to one of four groups: pipeline geometry, material properties, defect dimensions and loads.

Evaluation of Failure Probability

The probability density functions for each sensitive parameter are used in conjunction with the limit state functions to determine the probability of failure. For a given limit state and failure mode, the failure probability is the sum of the likelihoods of occurrence of all combinations of the relevant parameters which cannot coexist in an un-failed state.

The objective of a structural reliability analysis is to determine the likelihood that the structure can resist the loads applied to it. Failure occurs if the resistance, R, is lower than the load, S, where R is derived from material and geometric properties, and S is derived from operational loads, fault loads, damage and deterioration. The probability of failure is therefore the probability that R is less than or equal to S, given by:

$$P_f = P[R - S \leq 0]$$

where P[ ] denotes the probability of the event described within the brackets occurring. The equation $R - S = 0$ defines the limit state function. Denoting the combined p.d.f. of load and resistance by $p(R,S,t)$ the probability of failing within the time interval $(0,t)$ is given by

$$p_f(t) = \iint\limits_{R-S\leq 0} p(R,S,t)dRdS$$

To avoid duplication, no further details are provided here of SRA or the limit state functions used by Risk Ranking. The subject is covered in a series of publications, including others at this conference see for example [8-11].

Priority has been given to the accurate determination of failure probability for the most serious threats to integrity. The following threats (failure mechanisms) are modeled using SRA within Risk Ranking:

External Corrosion: Time-dependant failure mechanism generally resulting from the loss of protection from the coating, the level of cathodic protection and corrosivity of the external environment. Causes localized defects, or pits, which reduce structural integrity.

Internal Corrosion: This often results from corrosive components in the product being transported, such as water, oxygen and carbon dioxide. Internal corrosion is often characterized by long, general metal loss and the consequential reduction in structural integrity.

Third Party Damage: Published data show this is the most common cause of pipeline failure, causing leakage or in some cases ruptures. Such damage can often result from workings close to the pipe (e.g. mechanical diggers and earth moving equipment).

Manufacturing and Construction: It is usual to identify and remove construction defects through a high pressure hydrostatic test which is some factor above the operating pressure of the pipeline. However, the pre-service hydrostatic test does not remove all construction and manufacturing defects from the pipeline and if the pressure in the pipeline is either raised above normal or if the pipeline is subsequently pressure cycled then defects that remain can grow to a critical size and result in failure of the pipe.

At the time of writing, probabilistic models for a further two threats were being developed, with the intention of including them in Risk Ranking in the near future.

Stress Corrosion Cracking : This form of environmental attack usually occurs when high stress and environmental corrosion occur simultaneously. The damage forms closely spaced cracks with a shallow aspect which usually occurs at seam welds and sometimes at the girth weld.

Ground Movement : The ground supporting a pipeline can often be subject to movement due to subsidence, landslides, seismic effects, flooding or frost heave amongst others.

The failure probability for all the remaining threats are treated using historical failure data. Threats that are dealt with this way include:

Equipment Failure
Incorrect Operations
Vandalism

Calculating Failure Consequences:

In order to determine the overall risk associated with a pipeline segment it is necessary to combine the likelihood of the pipeline failing, with the consequences of a release.

The failure modes that can occur are leaks (punctures) or ruptures (breaks). 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 stresses on the pipeline. Usually it is the probability of rupture, not leak, that is the most important consideration because the hazard associated with an ignited rupture release from a natural gas transmission pipeline far exceeds that from an ignited leak and generally dominates the risk.

As stated earlier, the approach adopted for buried pipeline segments uses the Potential Impact Area calculation specified in section 3.2 of ASME B31.8S.

The approach taken for above ground facilities is to use published information on the dispersion of jetted releases of natural gas to provide an estimate of the distance to a safe concentration for a rupture on an above ground pipe. This distance has been compared with a series of more detailed calculations using Advantica's specialist risk assessment methodologies to investigate the hazards from ignited releases. The approach has been shown to provide a slightly cautious, yet still plausible, estimate of the hazard range. Explosions could also occur at these installations, if flammable mixtures accumulate within a confined volume or a gas cloud overlaps a congested region. Experimental and theoretical work have both shown that it is possible that significant overpressures may be generated by combustion of a flammable mixture within such regions. A simplified correlation has been produced to define a hazard radius for such cases, based on published methods for gas explosions. This requires the user to provide details of the extent of the congested or confined region and also to provide information on the nature of the confinement or congestion. As with buried transmission pipelines, use of such correlations is appropriate to determine interaction with the surrounding areas.

Step 4 – Reporting and Visualization

The outputs from the Risk Analysis are as follows for each threat:

- Probability of failure (no. of failures / mile-yr)
- Consequence of failure (no. of casualties if the pipeline were to fail)
- Quantified risk (Expected no. of casualties per mile-yr)

The results are written to the database and can be viewed both in tabular and graphical form. The use of the GIS data management platform also allows for the results to be visualized against the pipeline profile. The analyzed pipelines are ranked according to probability, consequence and total risk for each and all threat categories.

Providing quantitative results allows the operator to evaluate whether the risks associated with pipeline operation are acceptable with the company's integrity management policies and regulatory expectations. Other benefits are that it becomes easier to prioritize integrity assessments and determine the value of various integrity assessment activities.

CASE STUDY

This section illustrates some of the differences between a typical relative assessment method and the probabilistic approach using SRA, which has just been described.

The relative assessment method used in this study has been adapted from work conducted in the mid- 1990's, and originally described in [12]. The approach is similar to other methodologies developed by Advantica around that time, for example to prioritize integrity assessments on gas transmission networks. The method shares many features with other risk ranking models currently being used by pipeline operators.

The relative assessment method used for this illustration adopts the following scheme:

$$\text{Relative Risk}_i = P_i \text{ X } C_i \quad \text{for a single threat}$$

$$\text{Relative Risk} = 1/6\Sigma\ (P_i) \text{ X } 1/5\Sigma\ (C_i)$$

where P represents the failure likelihood (for i=6 threats) and C represents the failure consequence (for i=5 consequences). In this case study only the consequence in terms of risk to life is considered. An earlier version of the scheme is described in detail elsewhere [12]. As an example, the external corrosion threat scheme includes Susceptibility, Severity and Consequence Factors to calculate risk of the form:

ECSSF = XCP + YIPS + ZCCon + ...

Where:

ECSSF = External Corrosion Susceptibility Factor
CP = Cathodic Protection Factor
IPS = Instrumental Pig Survey Data Factor
Ccon = Coating Condition Factor

And X,Y and Z are relative weights applied to each parameter.

Pipeline Information

Both relative and probabilistic methods were applied to three pipeline segments with the characteristics shown in Table 2.

	Segment 1	**Segment 2**	**Segment 3**
Length (miles)	43	179	170
Diameter (inches)	30	30	30
Wall Thickness (inches)	0.375	0.375	0.5
Material Grade	X52	X65	X52
Location Class	3	1	1
MAOP (psi)	759	807	807
Installation Date	1952	1992	1965

Table 2 – Case Study Pipeline Segment Details

Information for Relative Assessment

The input parameters for each Segment are given in Table 3 below. Values used in the relative risk assessment (other than basic pipeline parameters) vary from 0 to 1 representing low to high risk accordingly.

Input Variable	**Value**		
	Segment 1	**Segment 2**	**Segment 3**
Diameter (inches)	30	30	30
Wall Thickness (inches)	0.375	0.375	0.5
SMYS (Mpa)	358	448	358

Operating Pressure (psi)	759	807	807
Date of Commissioning	1952	1992	1965
Segment Length (miles)	43	179	170
Gas Type (Sweet or Sour)	0	0	0
Coating Type	0.2	0.1	0.2
Coating Condition	0.7	0	0.7
Type of Soil	0	0	0
Cathodic Protection Quality	0.7	0	0.7
Gas Discharge Temperature	0	0	0
Population Density	1	0	0
Duplication of Supply	0	0	0.5
Number of Small Crossings	0	0	0
Number of Large Crossings	0.25	0.25	0.25
Access for Repair	0	0	0
Surveillance Level	0	0	0
Internal Corrosion Rate	0	0	0
Number of SCC Indications	0	0	0
In-line Pig Survey Data	0.5	0.5	0.5
Soil Aggression	0	0	0
History of Internal Corrosion	0	0	0
History of External Corrosion	0.5	0.2	0.5
Average Metal Loss for External Corrosion	0.5	0.2	0.5
Cyclic Loading Stress	0.5	0.1	0.1
History of Fatigue	0.1	0.1	0.1
Evidence of SCC	0	0	0
History of SCC	0	0	0
Land Use	1	0	0
History of Damage Incidents	0.5	0	0.5
Protection Levels	0	0	0
History of Mechanical Damage	0.5	0.1	0.5
Mining Activity	0	0	0
Soil Stability	0	0	0
Washout or Scour	0	0	0
History of Girth Weld Problems	0	0	0
History of Pipe Modifications	0	0	0
History of Loss of Ground Support	0	0	0
Criticality of Supply	0	0	0
Environmentally Sensitive Areas	0	0	0
Hydrotest Result	0	0	0
Protection at Large Rivers or Estuary Crossings	0	0	0
Minimum Charpy Level	0	0	0

Table 3 – Input Parameters Required for Relative Assessment

Information for Probabilistic Assessment

The input parameters for each Segment are given in Table 4 below.

Input variable	**Value**		
	Segment 1	**Segment 2**	**Segment 3**
Operating Pressure (psi)	759	807	807
Diameter (inches)	30	30	30
Wall Thickness (inches)	0.375	0.375	0.5
Material Grade	X52	X65	X52
Installation Date	1952	1992	1965
Length (miles)	43	179	170
Asme Location Class	3	1	1
Dent Depth	Weibull Distribution		
Gouge Depth	Weibull Distrubution		
Gouge Length	Weibull Distribution		
External Corrosion Defect Depth	Weibull Distribution		
External Corrosion Defect Length	Weibull Distribution		
Girth Weld Defect Depth	Weibull Distribution		
Seam Weld Defect Depth	Weibull Distribution		
Pressure Cycling Data			
Frequency of Occurence of Defects			

Table 4 – Input Parameters Required for Risk Ranking

Results

The relative and probabilistic assessment methods were applied to three of the threat categories, namely:

- External Corrosion
- Third Party Damage
- Fatigue of Manufacturing / Construction Defects

Results were obtained for Probability of Failure and Consequence of Failure. For the purposes of this illustration, only risk to life has been considered.

The results are shown in Tables 5 and 6 respectively for Relative and Probabilistic assessments.

		Segment 1	**Segment 2**	**Segment 3**
Probability Of Failure (Relative)	**External Corrosion**	3355	828	3245
	3rd Party Damage	1938	155	765
	Fatigue	1720	232	232
	Total *	1169	202	707
Consequence Of Failure (Relative)		71	12	12
Risk (Relative)		82,999	2424	8484
Ranking		1	3	2

Table 5 – Results of Relative Assessment

* - normalised for 6 threat categories

		Segment 1	Segment 2	Segment 3
Probability Of Failure (no. of failures per mile-yr)	**External Corrosion**	2.4E-04	1.5E-07	3.8E-05
	3rd Party Damage	1.9E-04	2.6E-04	8.1E-05
	Fatigue	8.7E-04	0	0
Risk Band (No. of casualties per mile-yr)		~1E-02	~1E-04	~1E-05
Ranking		1	2	3

Table 6 – Results of Risk Ranking

Discussion of Results

As expected, the results obtained using the two methods bear many similarities. For example, both methods have Segment 1 as having the highest value for each of the threats analyzed, and the highest risk ranking. Note however that the rankings based on total risk differ for segments 2 and 3 according to the method applied. This could impact the priority of an integrity assessment program developed from the risk assessments.

Whereas the results of the Relative Assessment provide the relative importance of each threat, they cannot be readily compared with an assessment obtained on another pipeline or pipeline system, unless exactly the same attributes and weightings have been applied.

The information generated by the Probabilistic Assessment quantifies the probability of failure for each threat. Results may be compared with other pipelines or pipeline segments analyzed using a Probabilistic Assessment. Note also that this analysis predicts the number of casualties that might be expected if a release should occur.

Finally, the data requirements for the two approaches are seen to be significantly different. ASME B31.8S describes the probabilistic approach as "*the most complex and demanding with respect to data requirements*". While the authors accept that the models themselves may be more complex than those used by most relative assessments, it is incorrect to assume that all probabilistic models require more data to run. In fact the approach described in this paper requires the user to provide less data in order to generate meaningful results. This is illustrated by the case study.

INTEGRATED SOFTWARE

Earlier sections of this paper have described the approach taken to rank the risks associated with the various integrity threats. This section briefly describes how the Risk Ranking software has been developed into an integrated software application intended to help gas pipeline operators meet the integrity management requirements of recent pipeline safety regulations.

The basic philosophy incorporated in the design is the integration of a robust GIS platform, built using an industry standard data model, with the rigorous analysis capabilities offered by Probabilistic Assessment using SRA. This allows the user to view integrity and risk information against the background mapping. This is a key part of the design which helps the user to locate pipeline segments at increased risk of failure in the context of High Consequence Areas.

The data model is based on the ArcGIS Pipeline Data Model (APDM), extended where necessary to accommodate attributes required by Risk Ranking. The model provides a description of risk information and the relationships between these and other fundamental integrity management parameters such as pipeline centerline and in-line inspection data.

An accompanying data management application is integrated with Risk Ranking. This provides a wide range of facilities for querying, viewing and analyzing integrity data.

All stages of Risk Ranking interact directly with pipeline and risk data stored in the geodatabase. The software provides a full audit trail of the data, analysis and results for each run.

CONCLUSIONS

Many pipeline operators are seeking to respond to the increased public and regulatory expectations concerning pipeline safety and reliability, by implementing improved methods of managing pipeline integrity. This paper has concentrated on meeting the compliance requirements of regulations recently introduced in the US, and in particular gas pipelines covered by the provisions of ASME B31.8S.

Probabilistic assessments can help operators achieve this objective. The Risk Ranking software described in this paper should enable the operator to make more robust assessments of the credibility and importance of various integrity threats and the risks of pipeline operation. The case study demonstrated that meaningful results can be obtained using less data, which is likely to benefit companies limited by time or resources to gather new information.

The results obtained using Risk Ranking should lead to integrity management plans that address the operator's most significant concerns.

ACKNOWLEDGMENTS

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METHODS FOR ASSESSING RISKS AT ABOVE GROUND INSTALLATIONS

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ABSTRACT

This paper describes a package of computer models that has been developed to assess the risks from gas releases at above ground installations associated with natural gas transmission pipelines. The package can be applied to compressor stations (containing compressor enclosures and associated gas treatment equipment) and pressure reduction stations, through to single block valve installations. It has been designed for use by safety engineers in performing quantified risk and hazard analysis, as required to meet regulatory requirements, such as the COMAH Regulations or the DSEAR Regulations in the UK. It can also be used in the design stage of projects to support decisions related to site layout for example. The package contains a range of mathematical models to assess the consequences of accidental releases of gas (including outflow, dispersion, gas accumulation, fire, explosion and thermal and overpressure response), validated by data from large and full scale experiments. The individual models are linked in a logical manner constructed around a series of "knowledge bases" that provide a defined structure to allow a wide range of different scenarios to be assessed. The predictions of the consequences arising from various scenarios can be combined with estimates of the frequency of initiating events (based on industry statistics where available, or using predictive models), in risk calculation routines which sum the outcomes for the different scenarios to calculate individual and/or societal risk.

To illustrate the use of the techniques, examples of their application are given. In particular, it is shown how the risks arising from releases from high pressure vessels or in confined volumes, such as compressor enclosures, can be evaluated.

INTRODUCTION

In previous papers, the development of methods for assessing the risks associated with ruptures or punctures of natural gas transmission pipelines have been described (specifically the PIPESAFE package [1,2]). These methods are used regularly to assess the implications of infringements to codes of practice for existing pipelines and in design studies for new pipeline routes. However, in order to obtain a complete view of the potential hazards and associated risks, there is also a need to assess any above ground installations associated with the pipeline. These include reception terminals, compressor stations (containing compressor enclosures and associated gas treatment equipment) and pressure reduction stations, through to single block valve installations. Such assessments may be required to meet regulatory requirements, such as the Control of Major Accident Hazards (COMAH) Regulations that apply in the UK to sites storing more than certain threshold quantities of dangerous substances, for example. Further, assessments of different levels of complexity are often carried out during the various stages of the design of new facilities. Incorporating this in the design process can result in significant cost savings, as well as ensuring that safety becomes an integral consideration. From a safety perspective the ultimate aim is to produce the most cost effective, safe design.

Mathematical models have been developed to perform assessments for such facilities, validated by data from large and full scale experiments. The predictions of the consequences arising from various scenarios can be combined with estimates of the frequency of initiating events (based on industry statistics where available, or using predictive models) in order to define a numerical measure of the risk to people posed by the facility. This is usually in the form of a predicted individual risk, either at a fixed location or to a particular representative worker group for example, or as a societal risk, such as the expected loss of life per year arising as a result of possible major accidents at a facility.

In the following sections of this paper, an outline is provided of these models, together with examples of their application. In particular, it is shown how the risks arising from releases from high pressure vessels or in confined volumes, such as compressor enclosures, can be evaluated.

MODELLING APPROACH

A package (known as ORDER) has been produced to provide users with access to a range of consequence and risk models for major hazard safety assessments. Individual (stand-alone) models for predicting the characteristics of dispersion, fire, explosion and response to fire and blast effects are available in the package. Details of the formulation of many of these models have been published previously (see [3,4] for example), along with supporting information comparing the predictions of the model with experimental data, often obtained at large or full scale. However, in addition to the individual models, there are also a group of 'knowledge bases' that comprise sets of linked models in which data transfer and the procedures for running the models are managed to allow specific scenarios to be assessed. The knowledge base approach is intended to ensure that different users of the package will employ a consistent approach for assessing similar scenarios.

Assessment of the consequences of releases from above ground installations associated with gas transmission systems will mainly require scenarios involving natural gas releases to be modelled. The knowledge bases have been set up so that a fully quantified risk assessment of a particular release scenario can be performed. This includes methodologies for determining the consequences of continuous ignited or unignited natural gas releases from vessels or pipework, instantaneous releases from vessels, releases in a compartment or room, including a methodology for assessing the consequences of small leaks to allow assessments that investigate compliance with the UK HSE Guidelines for gas fired turbines in enclosures [5], and a methodology which has been assembled to allow assessments following the Chemical Industries Association [6] guidelines for the assessment of occupied buildings.

The calculations are performed for a range of possible parameter values, such as those that relate to the weather conditions and process information. The frequency with which each combination of the parameters occurs is defined and the vulnerability of people to each combination is evaluated. A probabilistic picture of the range of possible outcomes for each scenario is constructed in this way.

The methodology distinguishes between people who are indoors and those who are outdoors. An occupancy level is defined for all locations that could be affected by the scenario and this is taken to vary according to the time of day. Office buildings, for example, are likely to have a higher population during the day than at night. The opposite is likely to be true for domestic buildings.

The vulnerability of people at a location for each 'realisation' of the scenario (i.e. combination of release, weather and population distribution parameters) is combined with the probability with which each realisation occurs to produce a 'location specific risk'. Individual risks can be calculated from the location specific risk, provided that the occupancy at each location, including the fraction of time spent outdoors, is specified.

The number of fatalities that are likely to result for each 'realisation' of the scenario (i.e. combination of release, weather and population distribution parameters) is then combined with the probability with which each realisation occurs to produce a curve showing the cumulative frequency with which a number of fatalities occur (commonly referred to as an F-N curve). The resulting F-N curve may then be compared against acceptability criteria, such as those recently discussed by the HSE in the UK [7]. The maximum number of fatalities and the potential loss of life, or expected number of fatalities per year, can also be calculated.

The flow chart for a typical QRA knowledge base, consisting of one or more consequence models, followed by a risk model, is shown in Figure 1. The results from such assessments can be added to a database. In general, the consequence models take longer to run than the risk model. The structure of the QRA knowledge bases allows the time-consuming consequence calculations to be run, and the results saved, before the risk calculations are performed. This allows the user to reassess the effects of different inputs to the risk model without re-running the consequence models. This can be used to investigate sensitivity to different failure frequencies or population distributions, for example.

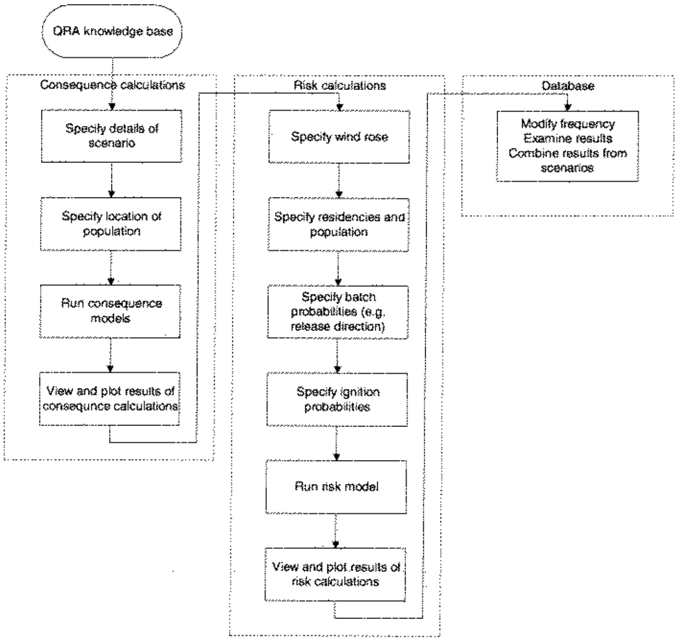

Figure 1 Flow chart for QRA knowledge bases

In this process, the program menu functions allow the user to display area maps of a site being assessed and, optionally, to superimpose model predictions and user-specified text on them. The user can identify the locations at which the vulnerability and location specific risks are to be calculated by clicking on appropriate positions on the site map. Buildings can be represented either by a single point or by a linked group of points, depending on the resolution required in the calculations. (Buildings should be represented by more than one point if the radiation on the part of the building that is closest to the fire is significantly larger than the radiation on the part of the building that is furthest from the fire.) The occupants of a building that is impaired by a fire are assigned a probability of evacuation. This determines the number of people who are assumed to become trapped fatalities in the event of secondary fires. The remaining people are assumed to escape at the calculated evacuation time, when they are then subject to the thermal radiation from the fire and their vulnerability is calculated as they attempt escape.

Each of the QRA knowledge bases uses appropriate models to predict one or more of the following consequences:

- Thermal radiation
- Overpressure
- Gas concentration
- Missiles

The response of people to these hazards is calculated in the same way for each of the QRA knowledge bases. The blast vulnerability of people inside buildings is based on information given in the CIA guidelines [6] and the blast vulnerability of people outside is based on lethality correlations given in Baker et al. [8] The vulnerability of people to thermal radiation from a fire is calculated from the thermal radiation predicted by the appropriate fire model. The criteria and approach used for jet or pool fire hazards, for example, is summarised in Table 1 to Table 3.

Table 1 Vulnerability of people outside to thermal radiation

Dose received attempting to escape	Effect
> 5906 [$(kW/m^2)^{4/3}s$] dose units	Fatality
1060 to 5905 [$(kW/m^2)^{4/3}s$] dose units	Percentage vulnerability calculated from correlation, based on received dose received.
< 1060 [$(kW/m^2)^{4/3}s$] dose units	<1% chance of fatality

Table 2 Vulnerabilities of people inside to thermal radiation

Location	Effect
Inside secondary fires distance	Some residents are assumed to be trapped and to become fatalities- the remaining residents seek to escape at time of piloted ignition and vulnerability is calculated as for people outdoors. The fraction of people who are trapped fatalities is a user input, with a default value of 10%.
Outside secondary fires distance	People are assumed to remain in buildings and to be safe

Table 3 Vulnerability to flash fires

Location	Outside	Inside
Within LFL contour	Assumed fatalities	Protected by building
Between LFL contour and 0.5 LFL contour	Vulnerability reduces from 100% at edge of LFL contour to zero at edge of ½ LFL contour	
Outside 0.5 LFL contour	None	

The probability of a person surviving the event is assumed to be the probability of them surviving each hazard, and the hazards are assumed to act independently

WORKED EXAMPLES

Two specific examples are discussed below to illustrate how this approach is used in practice. These refer to the failure of a high pressure vessel (or pig trap) and a gas release inside an enclosure.

High Pressure Vessel Failure

A knowledge base has been developed to allow the risks from failures of high pressure natural gas storage bullets or of pig traps to be evaluated. Both spontaneous failures and failure due to flame impingement can be modelled. Spontaneous failures may occur due to fatigue, overpressurisation or impact. After a spontaneous failure, the releases may ignite immediately, ignite after a delay (when the cloud has dispersed) or be unignited. Failures due to flame impingement are assumed to ignite immediately. The hazards due to immediate and delayed ignition and due to unignited releases are listed in Table 4. The knowledge base accounts for all of these hazards.

Table 4 Hazards for different ignition times

Hazard	Type of ignition		
	Immediate	Delayed	Unignited
Thermal radiation from fireball	Yes	Yes	No
Thermal radiation from flash fire	No	Yes	No
Overpressure	Yes	Yes	Yes
Missiles	Yes	Yes	Yes

A high pressure storage bullet can fail in a range of ways, for example a fracture may propagate around the circumference of the vessel, causing the end of the vessel to fail. This is likely to lead to a release with significant horizontal momentum directed along the vessel. Alternatively, a failure could propagate along the vessel, leading to a release with vertical momentum. If the failure occurred very rapidly, or if the release was directed towards the ground or towards another large obstruction, then the release could disperse as though it were from a low momentum source. The most likely mode of failure for a pig trap is a failure of the door, resulting in a release with significant horizontal momentum directed outwards through the door. The knowledge base accounts for the appropriate failure modes, and supplies a suggested probability for each mode for both bullets and pig traps.

The overpressure due to the blast wave cause by a bullet or pig trap failure is predicted using a model from the literature adapted for natural gas releases [9]. The hazards due to missiles are predicted from correlations taken from the literature, see Lees [10], which uses data from over 100 vessel failures, mainly BLEVEs of vessels containing liquefied gas, to produce correlations for spherical and cylindrical vessels. In particular, account is taken of the end caps of cylindrical vessels, because of 'their tendency to form rocketing vessel sections'. For high pressure bullets, 80% of releases are assumed to produce four missiles, and the remainder do not produce any missiles. These missiles land predominantly in two regions of radius 200m and width 60 degrees, at each end of the vessel. Correlations also predict the lower probabilities of missiles to greater distances, and to the sides of the vessel. For pig traps, all failures are assumed to produce two missiles. These missiles land predominantly in a region of radius 200m and width 60 degrees, directed towards the pigtrap door. Correlations also predict the lower probabilities of missiles to greater distances, in a region of width 180 degrees.

The thermal radiation from the fireball is predicted with the model BULLET (described below). For low momentum releases, the predictions are identical to those for the fireball model [11]. The dispersion of the release is also predicted with this model.

The gas cloud is modelled as a sphere of gas. For high momentum releases, the initial velocity is calculated from the vessel pressure and the properties of the gas using the approach of Birch et al [12]. The initial momentum may be set at any angle between horizontal and vertically upwards, and may be in any horizontal direction relative to the wind direction. There is also an option to specify the initial velocity, for example to consider low momentum releases.

The model solves 11 linked ordinary differential equations in time for the following independent variables:

- 3 components of momentum
- 3 components of position
- Centreline distance
- Mass of air, gas and combustion products
- Energy

The form of these equations is very similar to those in Cleaver and Edwards [13], but with entrainment occuring over the surface of the spherical gas cloud, rather than over the circumference of the jet. The formulation of Turner [14] is used for the virtual mass of the gas cloud.

For immediately ignited releases, the entire mass of fuel is burned in the fireball. For clouds that undergo delayed ignition at concentrations exceeding the stoichiometric concentration, some of the fuel is assumed to be burned with the air in the cloud, as a flash fire, and the remainder is burned in the fireball. An example of the predictions for an immediately ignited release are shown in Figure 2, for a release into zero wind, for a low momentum release and a horizontally directed high momentum release.

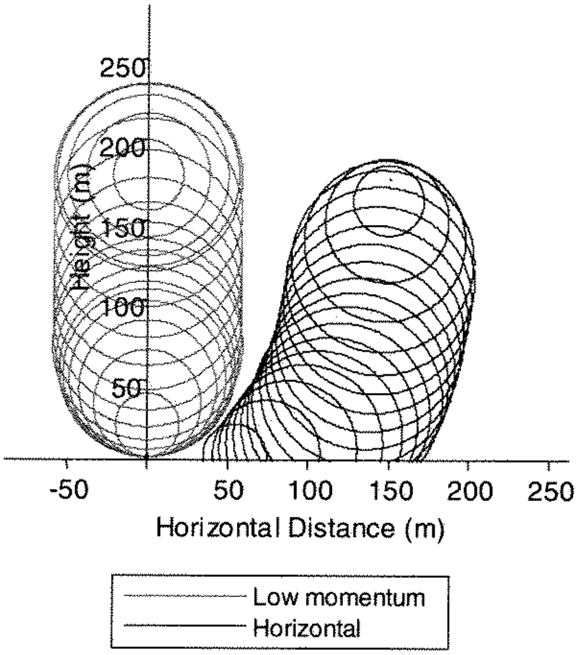

Figure 2 Predicted cloud position for immediate ignition

An example of the predictions for delayed ignition are shown in Figure 3, for the same high momentum, horizontal release into a 5 m/s wind. The gas cloud is ignited when the bulk concentration reaches the upper flammable limit. The figure shows that because of the release momentum, the cloud remains at ground level until it ignites, when combustion causes the cloud to become very buoyant. The cloud is smaller than that shown for immediate ignition, since approximately 55% of the fuel is burned in the ground level flash fire, and only the remaining 45% is burned in the fireball.

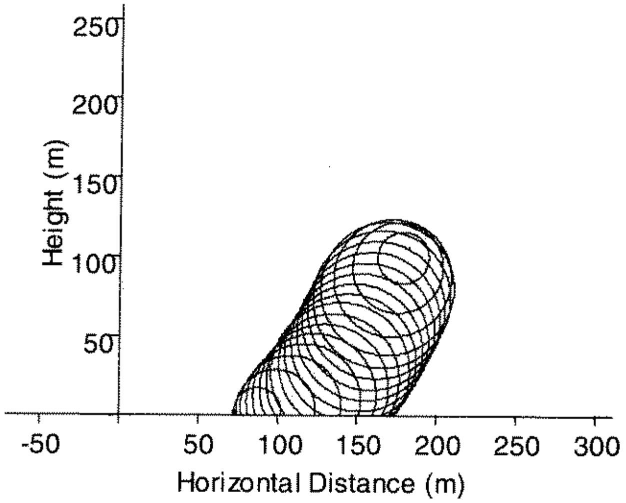

Figure 3 Predicted cloud position for delayed ignition

Immediately after the consequence models have been run, the following hazard distances are predicted for each distinct realisation:

- 40 mbar overpressure
- Lower flammable limit
- 1% lethality
- Piloted ignition

It is possible to assess the risks from a spontaneous failure and a failure due to flame impingement separately in order to assess their relative contribution to the combined risk. For HP bullets, the vessels may not operate at their maximum pressure for the whole year. In this case, the consequences of failures at a range of inventories, for example 25%, 50% and 75% full, may be assessed, in addition to the maximum inventory.

By considering the likely causes of flame impingement, and modelling the response of the vessel or pig trap with a suitable response model, it may be possible to discount the possibility of the vessel failing due to flame impingement when the inventory is low. Alternatively, the calculations with the response model may be used to assess an appropriate frequency for failure due to flame impingement.

Releases in Confined Volumes

The enclosure QRA knowledge base is designed for buildings containing natural gas pipework, in particular compressor enclosures. The knowledge base models the hazards to personnel due to ignition of a gas release. The vulnerability of personnel within the enclosure is based on their exposure to any flash fire following ignition, any overpressure generated as a result of ignition and the residual jet fire. The vulnerability of personnel outside the enclosure, on the rest of the site, is based on their exposure, if any, to the explosion overpressure. A separate calculation is included to allow the hazards to personnel within the enclosure due to missiles generated by turbine blade failure to be calculated.

The outflow from the user-defined release is used to calculate the accumulation of gas within the building for 12 different scenarios, representing combinations of safety systems working or failing [15]. The modelling takes into account the release size, the release location, the system pressure, the isolatable volume, the time delay on each safety system and the number of gas detectors. The modelling allows for two levels of gas detection and by default, the lower level is assumed to trigger an increase in forced ventilation, whilst the higher level initiating shut down and blow down. The user-defined safety system availabilities, the number of gas detectors and the release location are used to calculate the probability associated with each of the gas build-up scenarios.

The ignition probability for each gas build-up scenario is based on a delayed ignition sub-model; this sub-model allows the increase in ignition probability due to the existence of hot surfaces within the building to be included, for example. The explosion model is run for a fixed number of flammable cloud sizes and gas concentrations. The result of each of the gas build-up scenarios is combined with the ignition probability and matched with the most appropriate explosion case. These results are used to calculate the explosion exceedance curve for the building and at a nominal location 30m from the building.

The vulnerability profile of personnel inside and outside at all site points are carried forward to the F-N curve calculation section, which allows this vulnerability data to be combined with residency values at each of these points to give the overall PLL figures (Potential Loss of Life) and societal risk curve (FN curve).

Figure 4 shows the type of results that can be obtained for one particular example. It shows the predicted value of the gas concentration in the bulk atmosphere as a result of a release from natural gas pipe work within an enclosure that has a forced ventilation system. The three different curves show the outcome in the event that no remedial action is taken, gas is detected and an emergency shut-down (ESD) takes place, and finally, as a result of ESD with blow down of the trapped inventory through a separate vent system. The model has been used to take into account a delay in initiating ESD following detection at a preset gas concentration and the release size was chosen to illustrate a case in which a flammable mixture is produced if no remedial action is taken. In this particular case, operation of the ESD system with or without blow down, is insufficient to prevent the accumulation of a flammable atmosphere. However, the time during which the flammable atmosphere is present, and hence the time during which the cloud could be ignited, is greatly reduced. In addition to performing quantified risk assessments for current or proposed plant, the model can be used to investigate the sensitivity to different detection or blow down systems or philosophies. This can be used to identify those measures that have the greatest impact on reducing the risk.

By tracking the flammable volume produced by different sized releases within the enclsoure it is possible to produce information to help in asssessing compliance with guidelines for operating gas turbines in enclosures [5]. When combined with calculations for the ignition probability and for explosions, the results can also be used to derive an excedance curve showing the predicted frequency with which a given overpressure would be produced as as result of ignition of a mixture within the enclosure. Such explosion overpresure excedance curves are familiar in offshore applications [3] and have been used onshore in assessing the suitability of control rooms to blast loading, as studied in carrying out occupied building assessments.

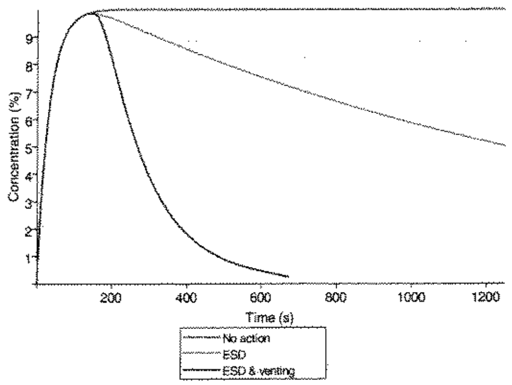

Figure 4 Predicted concentration within a ventilated enclosure as a result of a gas release (for three different cases)

DISCUSSION

The paper describes a software package developed to assess the hazards and associated risks arising from releases on above ground installations. Two specific examples of scenarios that can be addressed by the package are given to demonstrate the approach taken and the results that can be obtained. Other scenarios can be assessed in a similar way. The approach complements the use of simpler methods, such as correlation based methods to determine a single hazard range for screening purposes. The more detailed models can be applied cost effectively, to a smaller number of cases identified by the screening process. In practice, to date, this has ranged from helping to demonstrate regulatory compliance to helping decide on the appropriate design or strategy to be followed for new installations. In all cases, however, when used as part of an integrated approach, they can help to ensure that safety issues are addressed in an appropriate and responsible manner and to demonstrate effective risk management to authorities and the public, if required.

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