THE SAFETY EVALUATION OF CROSS COUNTRY PIPELINES

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The Paper outlines an approach to the safety evaluation of cross-country pipeline systems carrying flammable substances and indicates how such evaluations might be used to:

i) identify necessary improvements in safety, and

ii) provide guidance for the routeing of pipelines

INTRODUCTION

In the UK there are several thousand kilometres of pipelines transporting materials outside the boundary of any particular works or site. They range in length from a few metres to several hundred kilometres. The purpose of this paper is to deal with the safety assessment of those pipelines that carry flammable materials, although some aspects could equally apply to pipelines carrying other substances or to on-site pipeline systems.

Pipelines are subject to regulatory control under a number of Acts of Parliament, the most significant of which are outlined in Appendix 1. The principal control with regard to safety lies with the Health and Safety at Work etc Act 1974. It was in this context that the Department of Energy asked the Health and Safety Executive (HSE) for a safety evaluation on the proposed St Fergus to Moss Morran pipeline for which the Secretary of State for Energy has the responsibility for determining whether a Construction Authorisation should be granted. The Report to the Secretary of State by the HSE (1) issued in July '78 was the basis of the advice that the HSE saw no health and safety grounds for objecting to the proposed pipelines. The details of the method used in that report to evaluate the possible effects of the potential hazard were outlined in a paper (Bryce and Turner)(2) presented to the Third International Conference on the Internal and External Protection of Pipes held in September 1979. This paper sets the assessment in a wider context and indicates how such evaluations might be used to identify improvements in safety and to provide guidance for the routeing of pipelines.

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ELEMENTS OF SAFETY ASSESSMENT

The safety assessment of a pipeline system can be divided into three main activities, namely:

i) The identification of important features of the system.

ii) The quantification of the potential hazards.

iii) The quantification of the risk.

While these activities might be considered separately, each depends upon or is affected by the others and the whole process is iterative until a stage is reached where some judgment can be made regarding the safety of the system. Thus typically it would be necessary initially to determine the main design parameters of the system, for example the pipeline length and diameter, the pressure and nature of the material conveyed. From this it should be possible to determine the potential hazards usually in terms of the possible effects from leakages. Then with information concerning the frequency or probability of realisation of the hazards it should be possible to evaluate the potential risk. The first stages of the evaluation are likely to raise more queries leading to more information being required concerning the system, the hazard, or the resulting risk. Taking the three activities in turn, the following sections outline the main elements that might be important in an assessment.

THE PIPELINE SYSTEM

The ultimate safety of a pipeline system depends upon how well it is designed, constructed, operated, inspected and maintained. It is not possible to give an exhaustive list of the aspects that might be of importance, but rather an indication of the type of information that might be required.

For example, it is almost certain that it will be necessary to know:

i) the extent to which recognised codes and standards have been used in the design of the pipeline;

ii) the likely pressure to be encountered in the system: here it will be necessary not only to identify the 'normal' operating condition, but also maximum pressures under both static and dynamic or surge conditions;

iii) the pipeline diameter and wall thickness used throughout the system and how these relate to the system-operating conditions;

iv) the pipeline joint design;

v) the manufacturing inspection procedures, particularly with regard to material quality, weld joint integrity and coatings;

vi) the existence of potential leakage points, eg glands, seals, flanges and fittings;

vii) the corrosion potential of the transported material on the pipeline;

viii) the nature of the pipeline coating;

ix) the cathodic protection system adopted and the protection from sources of interference;

x) the depth of cover and protection against external interference;

xi) the need for special features or design requirements at particular sections of the route: for example, road, rail or river crossings or in areas which might be subject to landslip, washout, subsidence or underground fires;

xii) the provision of block valves and their operation.

These features relate to the pipeline as installed, and to some extent these can be separated from the operational aspects which need to be known and might include:

a) how the system is managed, who is in control, at what time and from where;

b) what control system is provided for the pipeline, including details of how the various data are handled and displayed;

c) how the communications are arranged;

d) what leak detection system is employed and what actions are envisaged for various levels of leak rate and what time-scale is involved;

e) what surveillance of the pipeline is used and at what frequency;

f) what system of testing is employed, particularly for the cathodic protection and stop valves;

g) what corrosion checks are employed;

h) how the coating is monitored;

i) what special arrangements are made or needed for certain pipeline operational conditions such as low or no flow (eg static shutdown of pipeline);

j) what emergency or evacuation procedures are available.

From the information concerning the pipeline installation and its operation it is possible to assess the overall standard of the system, which is a crucial aspect in the judgment of the potential risk. Firstly, however, it is necessary to determine the hazard potential of the system.

THE QUANTIFICATION OF THE HAZARD

Hazard is defined here as the potential to cause harm or damage. To assess this potential threat a number of factors need to be considered, principally including:

i) the inherent properties and nature of the material contained in the pipeline;

ii) the rate and quantity of the material that can escape;

iii) the atmospheric dispersion characteristics of the material released, and

iv) the possible effects of the released material.

Taking these in turn the following comments are appropriate:

The Inherent Properties of the Material

The majority of pipelines contain flammable hydrocarbons and most of the remarks in this paper are directed towards pipelines carrying such materials, although there seems no reason why the approach should not be applied to pipelines carrying other materials.

The principal hazard from flammable materials is clearly that on escaping from the containment of a pipeline they will mix with air and when the vapours are in concentrations between the flammable limits will, if ignited, burn or explode. The material is more likely to burn than to explode if ignition occurs in the open air soon after the initial escape to atmosphere, in which case a fire will persist at the point of emission until the flammable material is exhausted. Here, the main hazard arises from thermal radiation damage to people and property nearby, which may be significant at hundreds of metres from the pipeline. However, if ignition is delayed there is the possibility of an explosion as the flammable vapour may build up in a confined space such as a duct or drain, or form a large vapour cloud containing large amounts of material. It is apparent that if a cloud of flammable material is ignited before the cloud reaches a nearby population, the population is liable to be exposed to thermal radiation or explosion blast effects, depending on the distances involved. A potentially more serious situation will occur if the cloud reaches the population before ignition takes place because this situation will involve more direct exposure to flame, radiation and blast.

The Rate and Quantity of Material that can Escape

This aspect of the hazard evaluation is linked to the physical properties of the pipeline system. It is necessary to postulate certain hole sizes or ranges of hole size, and the statistics of previous pipeline failures may be of help in determining the most appropriate size from which to calculate the possible leakage rates. This in itself can be a complex fluid dynamics problem, particularly with two-phase flow, as would be the case with natural gas liquids. Such factors as the pipeline diameter and lengths, system pressure and flow rates need to be taken into account. The total quantity of material that can escape is generally more straightforward and will depend upon the detection time of the system for particular leakage rates and the distance between stop valves and the time it takes to close these. In this context it should be remembered that for typical petroleum products significant quantities of material (amounting to 100 – 250 tonnes per km for, say, a 300 mm diameter pipeline) can be contained in a pipeline, and for particularly hazardous material the value of remotely actuated stop valves that can readily be closed is an important consideration in assessing the potential consequences of a leakage.

Atmospheric Dispersion of Materials Released from a Pipeline

Materials released to atmosphere may be expected to become non-hazardous only by dispersion in the atmosphere. An initially flammable material will only become non-flammable after it has been diluted to a concentration below the lower flammable limit by the processes of atmospheric dispersion, a potentially toxic material will only become non-toxic after equivalent dilution to below the lower limit of toxicity.

The rate of dispersion will be dependent on the particular atmospheric conditions prevalent at the time, but independent of these the atmospheric concentrations of released material at a fixed point down-wind of the point of emission in general will vary directly as the rate of release to atmosphere. Thus, dangerous concentrations of flammable or toxic materials will reach a given population only from rates of release above a certain threshold level under given weather conditions. The rate of release will depend directly on the size of the hole in the pipeline wall through which the material is escaping.

The process of atmospheric dispersion begins to operate immediately this material is released into the atmosphere. The rate at which it disperses depends upon a number of factors and the concentration at any given point depends in most model analogies upon the distance from the source and on the degree of turbulence in the plume. This latter aspect is usually taken to vary according to a classical system of categorising the weather from A to F according to Pasquill, where the tendency towards F is for more stable and therefore less turbulent conditions. Using initial conditions with, if possible, dilution effects due to such effects as jet entrainment, it is possible to estimate, say, the distance to the lower flammable limit for a release rate of a flammable material.

A potentially important aspect in determining the course of atmospheric dispersion is the density of the emitted material relative to the surrounding atmosphere. The established methods for estimating atmospheric dispersion deal with gases with a specific gravity close to that of the surrounding air. The methods for neutrally buoyant gases should not be used without an awareness of other considerations for gases such as methane, which at ambient conditions is less dense than air and will tend to rise in the atmosphere, or for gases such as propane or butane, which are more dense than air and will tend to stay near to the ground. Dense gases released to atmosphere will often form a low-lying pancake-shaped cloud which may on occasions flow against the wind and which will follow surface gradients down available valleys etc to collect on low-lying ground.

Positive density effects may be affected by the nature of the material emitted or by the circumstances of the emission. Pipelines are found which transport liquids held under pressure at temperatures above their boiling points. Damage to such a pipeline would release liquid, which would immediately undergo adiabatic flushing as its temperature fell to its boiling point under atmospheric pressure. A cloud of vapour and suspended droplets would result. The droplets would evaporate and in this evaporation would take up heat from the entrained air. This would cool the air, and as a result a vapour-air mixture might be formed with a net density greater than that of the surrounding air, despite the fact that the material released from the pipeline had a relative density less than that of air under normal conditions of temperature and pressure. Such a mixture would disperse as a dense gas.

Alternatively, it is to be noted that conditions might exist with a dense gas such as propane where the jet characteristics of an emission might be such that sufficient air was entrained to give a resultant cloud with density little different from the surrounding atmosphere which would thus disperse in a neutrally-buoyant fashion.

In summary of this section, therefore, the concentration of airborne material received at a population near a pipeline, in the event of leakage from the pipeline, will:

i) be larger with larger rates of release,

ii) be larger with more stable weather conditions,

iii) be smaller with increasing jet entrainment of air at the point of emission,

iv) be dependent on the wind direction, unless the emitted material forms a cloud which is more dense than air, when surface gradients may be important,

v) be smaller with larger wind speeds in situations where effects caused by the density of the emitted cloud are not important.

The Effects of the Released Material

The appraisal of the potential hazards from a pipeline depends upon consideration of the material properties, the rate and quantity of the release and the dispersion characteristics as discussed above, and the particular location. For a flammable material, realisation of the hazards depends primarily on the material being ignited. Ignition sources are most likely to be found near to and among dwellings. The frequency with which the hazard will be realised depends to a large extent upon the frequency with which vapours above the lower flammable limit will reach the dwellings. This frequency depends in turn upon the relationship between hole sizes that occur in pipelines and their frequency of occurrence.

QUANTIFICATION OF RISK

Risk is defined as the probability of a hazard or certain consequences occurring. Thus statistics on pipeline failures are clearly important in a pipeline hazard assessment. However, it is often difficult to obtain data that are relevant to the particular pipeline under consideration. In References 1 & 2 statistics were reviewed from American, European and UK sources and, while all three were found to be broadly compatible, the latter two were considered particularly relevant and useful in assigning failure rates to the pipelines under consideration. The information from the United States is extensive as pipelines have been used there for more than 60 years. From the data, however, it is not always possible to identify particular categories of pipelines statistics that might be relevant, except in the broadest sense, for a hazard assessment.

A broad comparison of the three sources can be as follows:

US Data (NTSB(3)).

For 1968
Number of accidents - 421
" " miles - 115,238

giving an overall accident rate per km of 23×10^{-4} km^{-1} yr^{-1}

For 1975
Number of accidents - 169
" " miles - 121,278
giving an overall accident rate per km of 9.4×10^{-4} km^{-1} yr^{-1}

European (1).

For 1972 - 76
Number of accidents - 93
" " kilometres-years - 86.4×10^3
giving an overall accident rate per km yr of 10.8×10^{-4} km^{-1} yr^{-1}

UK (1). For '69 to '77
Number of accidents - 75
" " km-years - 134×10^{-3}
giving an overall accident rate of 5.5×10^{-4} km^{-1} yr^{-1}

Breaking this down to accident causes, we get in percentage terms:

Cause	US	European	UK
Corrosion	45	38	28
External Interference	28	32	28
Defective Pipeline or Weld	12	23	12
Incorrect Operation	2	4	-
Other	13	3	32
	100%	100%	100%

This data, while helpful, is not sufficient for the type of evaluation outlined in References 1 & 2, where it is necessary to know the possible failure rates for varying hole size or leakage rate. The European data appeared on first analysis to provide some indication in this direction, as from a sample of relevant incidents it was found that:

5% of the incidents gave a spillage in excess of 1,000 m^3
25% " " " " " " between 100 & 1,000 m^3
70% " " " " " " of less than 100 m^3.

This data was however treated with caution as, while there was a likelihood of a correlation between hole size and total leakage, it was not possible to confirm this without more details of the actual incidents - information that was not readily available. The UK data was more helpful, and from the 31 relevant incidents used in Reference 1:

3% occurred with a hole size greater than an 80 mm equivalent diameter
10% " " " " " between 20 & 80 mm " "
87% " " " " " less than 20 mm equivalent diameter

Using this or similar data, it is possible to build up an estimate of risk for which one method is outlined in Reference 2.

USE OF SAFETY EVALUATION

The prime purpose of a safety evaluation of pipeline systems will be to provide some guidance as to the safety of the particular system under consideration. Beyond this immediate concern, however, evaluations can be of value in a more general context. For example they will help in identifying improvements in safety that can be made and in providing guidance for the routeing of pipelines.

In the previous section a comparison was made of the various causes of pipeline failures. Clearly corrosion and external interference together are the major factors and demand attention. The combination of improving pipeline coatings, monitoring procedures and reliable cathodic protection are making a valuable contribution to the reduction of corrosion as a problem. The steady reduction of the overall failure rate in the US data from 2.3×10^{-3} in 1968 to 9.4×10^{-4} km^{-1} yr^{-1} in 1975 is largely due to the reduction of failures due to corrosion. External interference is not so readily tackled but the combination of such aspects as deeper cover, increased wall thickness, particularly in populated regions, regular surveillance, good relations with landowners and adequate awareness of the problems by key people along or with interests in the route should make a significant reduction in failure from this cause.

The other area where safety evaluations can be of value is as background to advice concerning what developments or land use is prudent to allow in the vicinity of pipelines carrying hazardous materials. Voluntary arrangements for planning authorities to consult the HSE on developments at, or near to, 'major hazard' sites have been in existence for some time, and while these arrangements did not specifically include pipelines, some Authorities are beginning to ask for advice on the safety and routeing.

The safety of people living near a pipeline is achieved firstly by measures, outlined in Section 3, that are aimed at ensuring the integrity of the pipeline system, then as an additional precaution by the provision of a separation distance. These two aspects should not be considered in isolation and any consideration of a separation distance must be based upon some assumed standard of integrity of the pipeline system. In the first instances, in order to obtain maximum separation, it might be reasonable to take, say, the presumption that any person who is in control of a pipeline system fulfils his duty under the HSW Act to take all reasonably practicable means of ensuring the health and safety of persons who might be affected by his activity. This implies that the engineering and operational considerations that have a bearing on safety are to some minimum overall requirement taking one feature with another. A separation distance could then be set so as to make it most unlikely, although not entirely eliminating the risk, that people would be affected by the pipeline, taking into account the probability of a leakage occurring, the possible dispersion characteristics, the chance of ignition and the possibility of moving away from the danger. With separation set in this way, it would be possible, if it could be clearly demonstrated that there are features of a pipeline system that result in a material improvement in safety above the minimum as defined above, for a reduced separation to be adopted. These additional features might include increased wall thickness, depth of cover, effective leakage detection, remotely-operated valves and special surveillance systems.

In order to obtain a reasonable framework in which to set separation distances, it is necessary to identify on one hand various groups of pipeline and on the other various categories of development or land use. Clearly a wide range of pipeline systems could be identified to take account of the various flammable material that could be transported and combination of design that might be possible. However, for workable and practicable guidance it might be possible to define, say, three groups of pipeline system which would relate to the possible consequences following loss of containment and which would depend upon the nature of the material conveyed and the pipeline system. *For example:*

A hazard group 1 might contain pipeline systems conveying substances that would be unlikely to cause large vapour clouds if a leakage should occur. Thus this group would contain flammable materials of low vapour pressure, eg kerosene, that would be unlikely to present a hazard beyond a short distance from the pipeline. It might also include pipelines containing materials of higher vapour pressure where the effect of an escape was limited due to small diameter piping or a low-operating pressure.

A hazard group 2 might contain pipeline systems conveying substances where, while there could be the possibility of a large vapour cloud, there are significant mitigating factors. For example, the escaping vapours may be lighter than air, allowing rapid dispersion, or the vapour cloud may be unlikely to explode with significant overpressures. As for the Group 1 pipeline, the effect of the escape might also be limited by factors such as the pipeline diameter or the operating pressure.

A hazard group 3 might contain pipeline systems containing materials that on escape to the atmosphere could give rise to large vapour clouds that could travel large distances before dispersing safely and give rise to the possibility of an explosion.

Similarly development or land use might be separated into categories and when combined with the pipeline groupings a matrix would be formed to give basic separation distance. With regard to separation distances, HSE's present advice would be that it would be prudent to allow 400 metres between the highest hazard category of pipeline and the category of development that involves large numbers of people who lie in the vicinity for a large proportion of the time, for example hospitals or residential developments. This distance would be general guidance, without taking into account any high standard that might be associated with any particular pipeline system. Such separation distances would only be recommended for new pipelines and for new developments in the vicinity of existing pipelines. It should be recognised that separation recommendations are a new concept and will only be achieved over a period of time. Existing populations that are closer than would be recommended in any particular circumstance are not necessarily substantially at risk. In these cases HSE would recommend that they should be examined and, as required by the Health and Safety at Work Act, improvements should be made where these are called for.

DISCUSSION

The purpose of bringing together the information outlined above is to provide some guidance as to the safety of the particular pipeline system under consideration. In making any decision, judgments will be required on a number of aspects of the assessment. For example, how good are the standards of design and operation in relation to the normal requirements or the statistical estimates; how valid are the statistics themselves and how realistic is the hazard evaluation? The answers to such questions are crucial as they indicate how realistic and confident one can be in the evaluation. *Areas of uncertainty should be exposed and important assumptions* in the analysis highlighted. This in turn can lead to requirements for further study or more information on certain aspects. For example, there is clearly a need to investigate further the modelling for heavy dense gas dispersion in relation to the more usually adopted neutrally-buoyant models. This is an area in which the HSE has taken a particular interest. Also there is a need for improving the recording and reporting of pipeline statistics. It would be helpful if there were more data regarding leakages and the hole sizes - information that should not be difficult to record. Also it should be relatively easy to record statistics relating to depth of cover. Is a pipeline with half a metre cover significantly more at risk than one at one and a half metres.

Notwithstanding these queries, it is clear that in a relative sense safety evaluations can be important in highlighting features that have special safety significance. As the previous section pointed out, corrosion and third party damage are rightly aspects that warrant the attention being paid to them.

With regard to safety evaluations being used in an absolute sense, that is, relying solely upon the results to determine a particular course of action, more caution is required. The safety evaluation should only be used as guidance to making judgments as there are usually many unquantifiable factors involved which need to be taken into account in any particular case. This would apply to the considerations relating to routeing as given in the previous section. The safety evaluations can only give a framework within which particular judgment can be made and provide some consistency across a wide range of situations. The determination of certain criteria must be open to discussion in a wider context in order to arrive at a consensus view as to what is realistic, practicable and acceptable over a large range of interests.

REFERENCES

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APPENDIX 1

CONTROLS ON PIPELINES

The Health and Safety at Work etc Act 1974 is the principal Act which statutorily controls the health and safety aspects of pipelines. This Act provides a general requirement that persons conducting an undertaking should take all reasonably practicable means of ensuring the health and safety of persons who are affected by his work activity, which includes not only other people at work, but also members of the public.

Other regulatory controls for pipelines are derived from a number of Acts, the principal of which, as far as this paper is concerned, are:

Pipelines Act 1962
Gas Act 1972
Land Power (Defence) Act 1958

Aspects of particular relevance are as follows:

The Pipelines Act 1962

This Act applies to pipelines laid across land, including any portion of the pipeline that crosses a river, lake or estuary and any portion of a submarine pipeline that is above the low water mark. Under the Act, pipelines are classified as "cross-country" (defined as greater than 10 miles in length) or "local", (less than 10 miles). There are over 3,500 kilometres of pipelines covered by this Act, the vast majority of which are defined as cross-country. They carry a range of substances, the principal of which are petroleum products ranging from crude oil to refined petroleum spirits (white oils).

The prime purpose of the Pipelines Act is to ensure the orderly provision of cross-country pipelines to meet the requirements of pipeline users, while at the same time protecting the rights and obligations of those who might be affected by the pipeline, in particular farmers, landowners and Local Authorities. The Secretary of State for Energy is responsible for these functions, which are administered by the Pipelines Inspectorate, which is part of the Department of Energy. The sections of the Pipelines Act concerned with safety were made relevant statutory provisions of the Health and Safety at Work etc Act 1974. They are therefore the responsibility of the Health and Safety Executive, who have made the Pipelines Inspectorate their agents for these and certain other aspects of the Health and Safety at Work etc Act.

The Gas Act 1972

The extensive natural gas (principally methane) transmission system of over 14,000 km of pipeline operated by the British Gas Corporation is controlled by the Gas Act. In laying a pipeline the Corporation consult relevant Planning Authorities and other local and national bodies and obtain rights to control a strip of land, usually about 25 m in width, along the length of the pipeline. This control does not affect normal agricultural operations, but prevents any activity which might affect the integrity of the pipeline, as, for example, the erection of buildings. In addition, Planning Authorities are invited to notify the British Gas Corporation of any development within a wider corridor of about 400 m either side of the pipeline at the earliest possible moment, to identify any conflict of interest and to allow discussions to be held between the Planning Authority, the Corporation and the developer.

Land Powers (Defence) Act 1958

This Act allows pipelines to be laid for purposes of defence and is usually, if not wholly, related to refined petroleum products. The Act allows the Government to acquire land and rights over land for the pipelines. Part of the control is to prevent, without the consent of the appropriate Minister, activities within 10 ft of the surface of the land immediately above the pipeline which might affect the pipeline integrity. No consent is required for normal agricultural operations. The pipeline system is operated for the various Government departments by a single body known as the British Pipelines Agency.