

## Pipeline Risk Analysis

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For almost a century, pipelines have been used to transport oil, gas and petroleum products. They have a relatively good safety record but increasing public concerns are leading to European Community proposals that the safety of a pipeline system should be demonstrated in a safety case. Pipeline risk analysis provides an effective means for owners and regulators to judge the safety of existing and proposed pipelines, and to make cost-effective decisions on whether improvements are required.

## Introduction

Oil and Petroleum products have been transported through pipelines since the beginning of the twentieth century. These early pipelines were built in cast iron or steel but the hazardous nature of the products when released into the environment gradually exposed the need for the development of pipeline standards to ensure consistency in safe design and operation. To meet these needs the American Engineering Standards Committee initiated project B31 in 1926 and the first edition was published as an American Tentative Standard Code for Pressure piping in 1935. Over succeeding years the Code has been revised, expanded and divided into various sections of which the ASME B31.4 "Liquid Petroleum Transportation Piping Systems" and the ASME B31.8 "Gas Transmission and Distribution Piping Systems" are applicable to pipelines. These codes probably cover most pipelines throughout the world and are the codes from which the majority of national codes, including IGE TD/1 for methane pipelines and the new BS 8010 for oil and gas pipelines, have been developed.

From a safety point of view pipelines have had a good record in the transport of hazardous materials but several factors are now emerging which are leading to the conclusion that compliance with the best international pipeline standards may be insufficient to satisfy the safety and environmental expectations of the community. The main factors leading to this conclusion are:-

- Pipelines are ageing and records show that the likelihood of incidents in these pipelines is increasing.
- Public tolerance to environmental pollution and accidents is decreasing.

- Pipelines are operating in areas where population density has increased.
- Failures of pipelines carrying some hazardous materials can pose major risks from even small releases.
- Accidents, when they do occur, can have catastrophic effects, for example, more than 300 fatalities occurred following a NGL pipeline failure in the USSR during 1989 and more than 100 fatalities resulted from a gasoline pipeline leak into sewers in Mexico in 1992.
- Potential liabilities for a pipeline owner following a release of oil products are enormous and possible environmental pollution of water resources is now a major problem confronting the pipeline industry.

In recognition of these developments the European Community is developing a Directive on Pipeline Safety which is expected to require the safety and condition of pipeline systems to be demonstrated in a safety case.

#### Risk Analysis

It is possible to install a leak detection system, or to survey the pipeline using an intelligent pig, and hope all the problems will be solved. Both these may ultimately be required but the starting point should be to identify the risks to which the environment and pipeline operators are exposed, establish the base cause(s) of the incidents leading to the risks and identify and systematically evaluate cost effective solutions.

Risk is the chance of an undesired impact on the public or environment as a result of some event occurring. So far as pipelines are concerned it is the chance of fatality or environmental damage occurring following an accidental release of the inventory. Evaluating risk is a systematic process comprising four steps which are:-

- identifying the potential events which could cause a release of inventory from the system (hazard identification);
- predicting the likelihood of such events occurring by comparison with the historical rate at which such incidents have occurred on similar systems (probability analysis);
- assessing the hazard or environmental impact of the release events identified (consequence analysis); and
- presenting risk as a combination of likelihood and consequence of the potential accidents (risk estimation).

Further stages in overall risk management concern the assessment of the acceptability of such events and the analysis of the cost and benefit of proposed risk reduction measures. The process for managing risks is shown in Figure 1.

Risk analysis is most useful in investigating causes of potential accidents, satisfying the needs of regulatory bodies, reducing system downtime, providing inputs for evaluating the extent of liabilities, developing emergency response plans, giving a methodology for selecting alternatives and providing a basis for comparison of pipeline risks with background and other risks.

#### Hazard Identification Techniques

Hazard identification techniques use two basic reasoning methods - inductive reasoning or deductive reasoning. The inductive technique looks from the specific to the general. Examples are the Failure Modes and Effect Analysis (FMEA) and the What If? technique. FMEA is a hardware orientated method and analyses all components of a system that could fail, identifies potential modes of failure and looks at the consequences of such failures on other components and the whole system. The What If? technique asks a series of questions such as What if? a process upset occurs, What if? a mistake is made or What if? equipment fails. The technique relies heavily on experience and hazards can be missed, but it has the advantage that little training is required. The deductive hazard identification techniques start with the general and finish up with the specific. Such techniques are the Checklist and the Hazard and Operability (HAZOP) study. The Checklist method essentially looks at a system to determine whether it satisfies codes and standards. The check list may be a summary of the previous What If? questions and is a good technique for designs and processes which are proven and well understood. The Checklist in conjunction with a Technical Audit, would enable an assessment for compliance of ageing pipelines with Codes to be ascertained. It does however, require that the Codes and Standards truly address the prevention of hazardous events which have occurred if it is to be used to control risks. In the US for example, the State of New Jersey is currently carrying out a study to assess the relationship between the types of incidents which have occurred in pipelines and the requirements of the Codes which are designed to prevent such incidents.

#### Characteristics of Pipeline Accidents

Most potential pipeline accidents and their causes will have been identified during the hazard identification study. Many of the hazards may be minor and might not have the potential for causing serious loss of life or environmental damage. Some of these minor incidents however, may have a considerable effect on the utilization and economic performance of the pipeline system and their occurrence could lead to a substantial reduction in operability.

Where the hazards are of sufficient size to cause a large potential loss of life or where the releases will be of sufficient duration to cause serious environmental damage it is necessary to consider the likelihood of the incident occurring and to calculate the risk of the potential accident to the community. The calculation of these risks is known as Quantified Risk Analysis.

#### Pipeline Quantified Risk Analysis

Risk may be presented as Individual risk or Societal risk. Individual risk of fatality is the likelihood of a particular person being killed at a particular location per year. Individual risk therefore shows risk for an individual living or working close to a pipeline. Societal

risk of fatality is the likelihood of one or more persons being killed by the pipeline per year. Societal risk therefore presents risk for communities living or working close to the pipeline. Risk levels other than fatality - such as serious injury, onset of injury or environmental damage - can be evaluated, but are not as readily defined.

#### Calculation of Risk

Risk is calculated by combining the likelihood of a hazardous event with its consequence and can therefore be expressed as:-

$$\text{Risk} = f(\text{Probability, Consequence})$$

Probability is estimated by projecting forward the failure rates which have occurred historically in similar pipelines over many years. Release sizes and possible sources of failure will have been identified for the pipeline and its stations and terminals during the hazard identification study.

The effects of possible accidents are calculated by consequence modelling. These models predict the behaviour of the material when released into the atmosphere and enable estimates to be made of the likelihood of fatalities or extent of pollution.

Risk is therefore presented as the likelihood of fatality per year at particular locations and is calculated at various locations along the pipeline route. Risk contours may be plotted as lines drawn on a map connecting points of equal risk. For pipelines, where the risk levels may not change significantly along the entire pipeline route, a cross section of a risk contour may be taken and presented as a Risk Transect.

Societal risk is presented as the frequency at which N or more persons are killed along the route of the pipeline and is presented as an F/N curve.

#### Failure Modes and Durations

The failure modes for liquids pipelines and gas pipelines are significantly different. In liquids pipelines the pressure will fall rapidly following puncture owing to the relative incompressibility of the liquid. The initial high rate of release will therefore reduce rapidly and the drain down of the pipeline will be driven initially by the hydraulic head of the system and finally by the static head, until equilibrium conditions are reached. The release duration will depend on the operating pressure and the time taken to detect the leak or rupture before pump station shutdown and block valve closure have been achieved.

For gas pipelines, the highly compressible nature of gas results in a high level of energy remaining in the vicinity of the puncture for a sufficient period of time to cause small holes to propagate to full bore ruptures in certain circumstances. In either case, gas will continue to be discharged from the pipe and, for high pressure releases, the relatively long duration will be governed by the flow rate limitation caused by gas leaving the pipelines at sonic velocity.

For some liquids pipelines, ie those transporting LPG, NGL or ammonia etc, the substance is conveyed as a liquid but following a leak or rupture it will behave in the atmosphere as

a heavy flammable or toxic gas. Such pipelines will release their contents in a pulsating manner alternately as a flashing liquid and vapour. Initially liquid will be released until the pressure falls sufficiently to cause vaporization within the pipeline. The hydraulic head will drive a further slug of liquid into the rupture and the cycle will repeat itself until the line pressure has fallen sufficiently that all the contents will vaporize before reaching the leak point. The pipeline will finally evacuate as a gas pipeline as the pressure drops. Such liquids pipelines have proven to be particularly hazardous in an accident and US pipeline failure data shows that although these pipelines comprise only 16% of the accidents they contribute 80% of all fatalities. Unstabilised crude oil pipelines will have similar but less severe consequence characteristics as the light ends flash on release.

Pipelines may fail in service by a variety of causes. However, the primary causes of failure are external interference by third parties and, to a lesser extent, corrosion. Furthermore, it is becoming apparent from failure statistics that the frequency of corrosion incidents rises with the age of the pipeline.

#### Consequence Analysis

Consequence analysis, as its name implies, assesses the consequences of the possible releases from a pipeline in terms of their potential to cause a fatality. Arthur D. Little have developed hazard models over many years to calculate consequences and these include:-

- Release rates through orifices.
- Generation and dispersion of vapour clouds.
- Thermal radiation hazards from pools, vapour clouds and flame jets.
- Vapour cloud explosions.
- Effects of Craters on releases from buried pipelines

Four types of fire models are generally of interest and these comprise vapour cloud fires, flame jets, pool fires and fireballs. Typical hazard zones to fatality for some pipelines are shown in Figure 2.

The hazard models are mathematical representations of complex phenomena and are based on the observations of the behaviour of materials released in past accidents and experimental data.

The fatality rates assumed in risk analysis are derived directly from observations made following exposure of persons to high levels of thermal radiation during the atomic bombs at Hiroshima and Nagasaki. Analysis of such data would indicate that the level of radiation at which a fatality might occur is an exposure of 10 kW/m<sup>2</sup> for 40 seconds. The rapidity at which fatalities might occur indicates the limited effects of leak detection systems and pipeline isolation in the role of limiting fatalities following a pipeline failure. Even installation of the most sensitive leak detection systems will result in release durations and consequent fires lasting considerably in excess of 40 seconds. However, for toxic release and for releases leading to potential environmental pollution the volume of material escaping and the duration of the release is directly related to the level of risk. In these circumstances a much greater benefit will result from the installation of leak

detection systems with remote and rapid isolation of block valves. In all cases, the benefits of shielding due to clothing or buildings and the potential to leave the hazard area must also be considered.

#### Probability Analysis

Pipeline failure rates are derived by dividing the total number of pipeline incidents involving loss of liquid by the number of kilometre years of exposure. Data on liquids pipeline failures are available from two main sources:-

- Concawe European Oil Pipeline Incidents (1983-91)
- US Department of Transportation

Concawe collects data from the major hazardous liquid pipeline operators in Western Europe comprising some 19,000km of pipeline. Recently Concawe have expanded their reporting to cover the effects of pipeline age and wall thickness on failure rates. The US Department of Transportation also publishes US pipeline failure rates. Both organizations present significant detail relating to the incidents and this assists in confirming the anticipated sources of failure suggested by the hazard identification study.

Overall failure rates predicted by each source are:-

Concawe:	$5.8 \times 10^{-4}/\text{Km}.\text{year}$
US DOT:	$7.4 \times 10^{-4}/\text{Km}.\text{year}$

In reality, these will vary by line size, wall thickness, etc.

In a recent study carried out by Arthur D. Little on pipelines in Eastern Europe built to the standards of the USSR, an analysis of failures indicated similar rates of  $10^{-3}/\text{Km}.\text{year}$ . Whilst these failure represented only some 1000km of pipeline it is interesting to observe that where maintenance standards are similar to those in Western Europe the expected failure rates are not dissimilar.

#### Individual Risk Contours and Risk Transects

Individual risk contours are a combination of the probability and consequence of incidents at various geographic locations. They are presented in terms of annual probability levels, eg:-

$10^{-6}/\text{year}$  or 1 in one million per year

This enables risk to be compared with estimates for alternatives or with mitigation efforts or with everyday risks for an assessment of acceptability. The contours quantitatively express the likelihood that a person could suffer a fatal injury as a result of an accidental release of the pipeline products.

The calculation of risk in a form in which it can be expressed as risk contours has only become practically viable since the introduction of powerful micro computers to process the many thousands of calculations required to compute risk. Risk combines the

probability of release and hole size with the probability of ignition in various locations, and the probability of a fatality over all locations in the vicinity of the release.

Typical risk transects are shown in Figure 3 for a multiproduct pipeline, in Figure 4 for a methane pipeline and in Figure 5 for an LPG pipeline. Note that Figure 3 presents risks of fatality for an average population, while Figures 4 and 5 present the risks of a 'dangerous dose' ie the level which might cause fatality to the most vulnerable part of a population (eg young, old, infirm).

#### Societal Risk

Sometimes pipeline risk is presented in terms of Societal risk along the length of the pipeline. For societal risk the frequency at which accidents could occur for one or more fatalities are calculated and presented as an F/N curve (See Figure 6). The F/N curve is calculated for different sections of the pipeline eg, in rural areas or densely populated areas. This methodology enables zones of higher or lower risk along the pipeline to be identified. The advantage of societal risk is that it demonstrates the relative likelihood of both large and small accidents, and shows the size of the various events.

#### RIPS Analysis

In 1990, the Dow Chemical Company<sup>(1)</sup> suggested a judgmental pipeline risk methodology which can be applied to existing pipelines. The aim of the analysis is to give an objective assessment of the levels of risk along the pipeline route. The categorization is given in terms of a Relative Index of Pipeline Safety (RIPS) and combines the consequences of an accident with an assessment of the likelihood in terms of third party interference, corrosion, design flaws and incorrect operation. In the paper, consequences are presented judgmentally and take account of population density and product characteristics (toxicity, reactivity, flammability and volatility). Using a scoring system the likelihood of an incident is assessed in terms of:-

- Third party interference (taking account of depth of cover, external protection, amount of construction activity in vicinity, patrol frequency, ROW condition, public awareness, etc).
- Corrosion (taking account of internal/external corrosion, product, inhibitor, coatings, cathodic protection, age, soil corrosivity, monitoring, etc).
- Design (taking account of pipe wall thickness, design factor, fatigue loading, surge loading, SCADA system, block valve spacing, intelligent pigging, etc).
- Operation (taking account of ease of overstressing pipe, operations procedures, ESD systems, operator training).

The RIPS index is determined for sections of the pipeline by combining and weighting the scores and consequences to enable areas of high risk to be identified. The lower the RIPS figure the higher the risk along the route (see Figure 7).

The method promises to be effective in giving pipeline operators an on-line view of priorities for reducing risk and is well suited to computer database storage and forward planning of maintenance activity.

The main disadvantage of the methodology is that it is entirely judgmental. However, Arthur D. Little consider that the application of historic probability criteria and consequence calculations as previously described could make this a very effective methodology for identifying high risk areas for existing pipelines when combined with a safety audit.

#### Risk Acceptability

Clearly almost all human endeavours entail some level of risk, so the acceptability of that risk must be balanced against the benefit derived. The most important factors which influence decisions on risk acceptability are:

- **Economic benefit.** Individuals or communities which receive direct economic benefit from a development through increased employment or income will be more tolerant of associated risk. Those who see no economic benefit are generally less tolerant of the development.
- **Amenities.** Individuals and communities are generally intolerant of developments that will be visually intrusive, noisy, smelly or pollution threats.
- **Voluntary or involuntary risk.** Individuals who move into an area have generally made a decision to accept the existing risk, providing they can identify that the risk exists. Additional risk associated with new developments are usually considered involuntary risks that can only be avoided at great cost, such as by moving away from the area. Involuntary risk is much less acceptable than voluntary risk.
- **"Visible risk".** Where risk is concentrated in a local area, for example in a coal mining community, the impact of an accident will be very visible and deeply felt. This can be contrasted with road accidents, or disease, where isolated individuals are affected and there is little concentration of risk on communities. Generally society will expend greater efforts to reduce the visible risks despite the fact that more lives are lost by other causes.

In the document "Risk Criteria for Land Use Planning in the Vicinity of Major Industrial Hazards"<sup>[2]</sup>, the UK Health and Safety Executive have adopted the concept of dangerous dose levels for risk acceptability criteria. A dangerous dose is defined as "a level of hazard which has the potential to cause a death but will not necessarily do so". This concept recognises the possibility of directly attributable deaths from a particular incident on the specified site and normally broad assumptions for the average person affected are made.

Individual risk is the probability of receipt of a dangerous dose or greater, ie. providing conditions in which fatalities are likely to occur, for certain individuals. In order to assess whether the risk is reasonable, it is necessary to assess other individual risks in the areas

affected by a pipeline. One approach is to compare the risk with other causes of death. Deaths by road accident in Europe total some  $1 \times 10^4$ /year or a one in 10,000 chance of dying each year. Deaths from lightning strikes total  $1 \times 10^7$ /year or a one in 10,000,000 chance of dying each year.

In the land use planning document the UK Health and Safety Executive suggest limits for exposure to a dangerous dose for the public. A more stringent acceptable risk criteria is suggested for more vulnerable populations, such as schools, homes for the elderly, caring institutions and long-stay hospitals. Some of these criteria are summarised as:

Upper limit: $10^{-5}$ /year	Housing developments providing for more than about 25 people
Upper limit: $10^{-6}$ /year	Housing developments providing for more than about 75 people
Lower limit: $10^{-6}$ /year	Trivial for average populations if lower
Lower limit: $3 \times 10^{-7}$ /year	Trivial for vulnerable populations if lower

These criteria are for those members of the public who are involuntarily subject to the risk. The HSE<sup>[3]</sup> has also suggested that the maximum tolerable level of risk to any member of the public from any large-scale industrial hazard should be  $1 \times 10^{-4}$ /year (one in 10,000 per annum).

Some other countries, notably Italy, the Netherlands and Australia have accepted a lower limit of risk of  $10^{-6}$ /year below which risk is regarded as acceptable.

These criteria are summarised in Figure 8.

#### Conclusions

The main conclusions of this paper are:-

- Risk analysis techniques have been developed which combine the probability of an incident with its consequence to quantify risk against acceptability criteria.
- The risks from crude oil pipelines are primarily those relating to environmental pollution. Risks from products pipelines affect both public safety and the environment. Risks from flammable and toxic volatile liquids pipelines primarily concern public safety.
- Pipelines are ageing assets and the likelihood of incidents increases with age unless defects can be identified and repaired before a leak occurs.

## References

1. "RIPS - A pipeline evaluation system", Dow Chemical Company, ASME Energy Sources Technology Conference, New Orleans, January 1990.
2. "Risk criteria for land-use planning in the vicinity of major industrial hazards", UK HSE, 1989.
3. "The tolerability of risk from nuclear power stations", UK HSE, 1988.

Figure 1: Process for Managing Risk

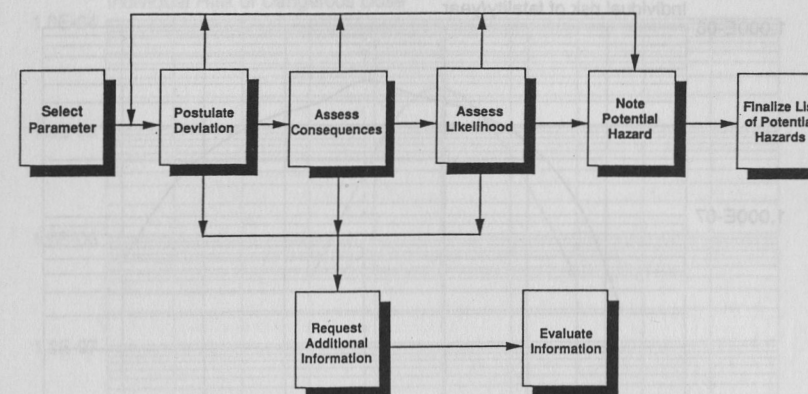


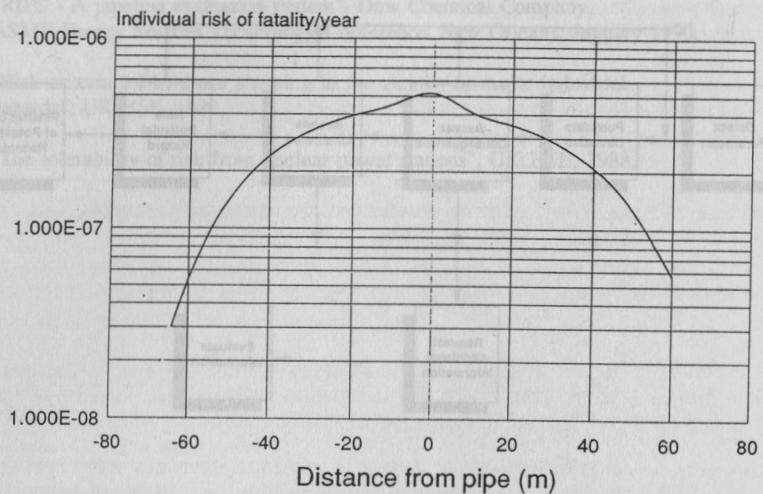
Figure 2: Typical Hazard Zones from Liquid Pipelines

Material	Release Hole Size (mm)	Flammable Vapour Hazard Zone (meters)	
		D Stability 5m/s	F Stability 2m/s
Propane	250	850	3,500
	50	270	900
Gasoline	300*	50	190
	50	40	170

Material	Release Hole Size (mm)	Pool Fire Radiation (meters)	
		Fatality (10kw/m <sup>2</sup> )	Injury (5kw/m <sup>2</sup> )
Gasoline	300*	45	70
	50	30	50

\* modelled as an instantaneous release.

Figure 3: Risk Transect of Multiproducts Pipeline



Note: -ve N, +ve S

Figure 4: Risk Transect for a Methane Pipeline (36" Pipeline at 90 Bar)

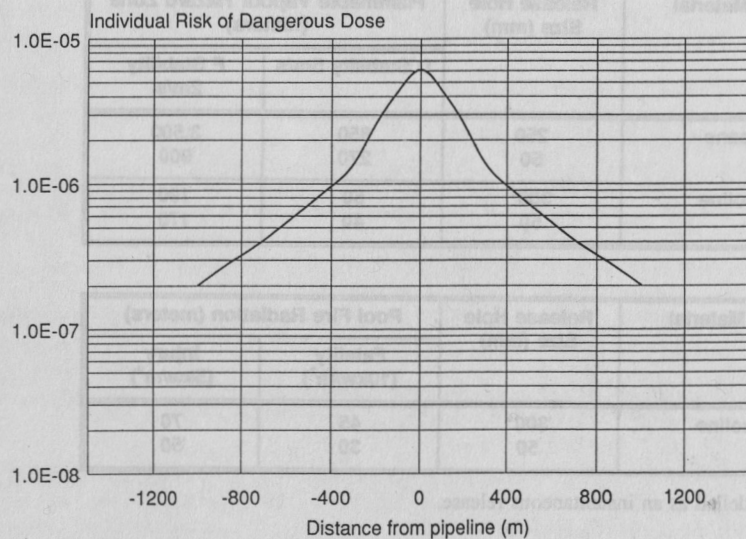


Figure 5: Risk Transect for LPG Pipeline (6.625" Pipeline at 30 Bar)

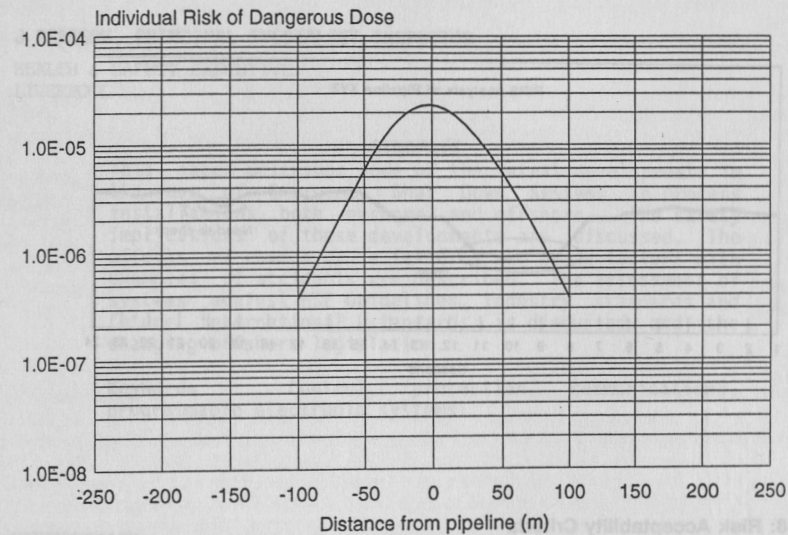


Figure 6: Societal Risk Profile

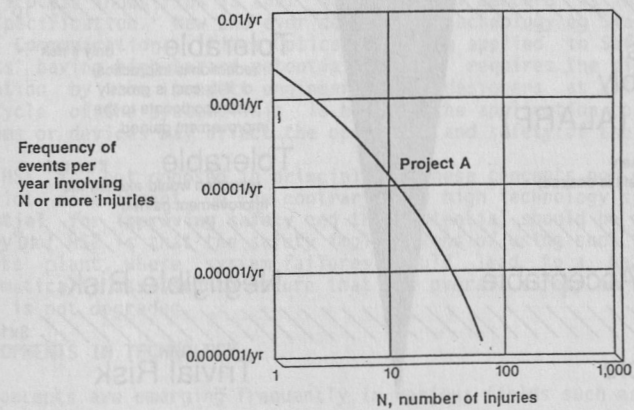


Figure 7: Risk Profile by RIPS Analysis

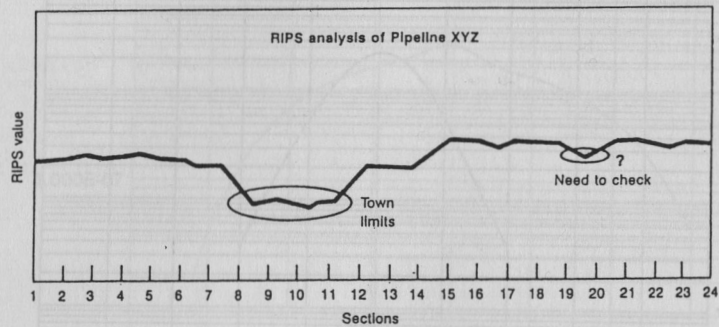
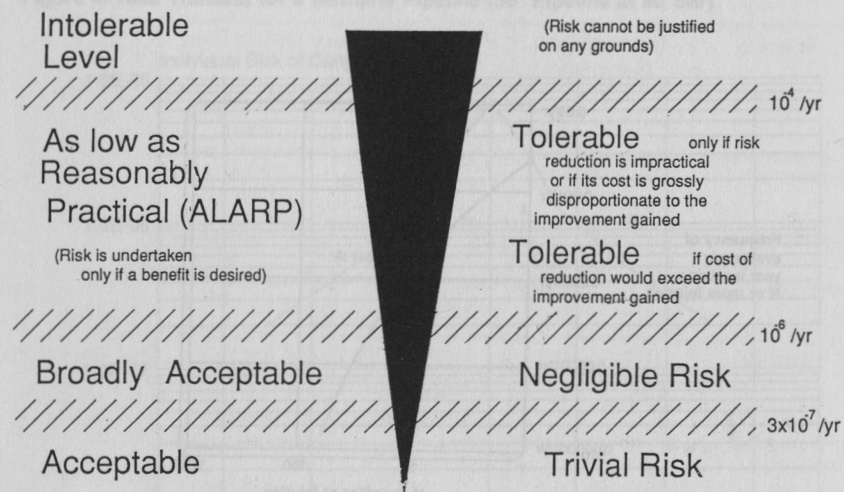


Figure 8: Risk Acceptability Criteria



EMERGENCY SHUT DOWN SYSTEMS IN ONSHORE AND OFFSHORE PROCESS OPERATIONS

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SYNOPSIS

This paper describes some of the latest developments in the use of Emergency Shut Down Systems in process installations both onshore and offshore. The safety implications of these developments are discussed. The effects of common cause failures and human factors with examples of accidents are described. The assessment of systems against HSE Guidelines, industry standards and future international standards is discussed and the changing offshore legislation.

**Keywords :** Control, protection, communications, programmable electronic systems.

INTRODUCTION

HSE Inspectors are called upon to inspect and assess safety systems, in a wide range of industries having major hazard potential. Safety systems include Emergency Shut Down (ESD) systems, Fire and Gas (F&G) Detection Systems, Alarms and Control & Communications systems. The experience of Inspectors when assessing computer based control and protection systems in the process industries is that one cause for concern is inadequate design and specification. New and ever developing technology eg Smart transmitters Data Communications, Fibre Optics is being applied to Safety Systems on plants having high hazard potential. This requires the highest level of attention by the project engineers and designers at all phases in the lifecycle of the system. This is because the application of new concepts, systems or devices may affect the operation and safety of the plant.

The HSE is not opposed in principle to these concepts nor does it wish to restrict development. On the contrary many high technology systems have the **potential for improving safety** and this potential should be exploited. The policy of HSE is that the safety implications of using such technology on a process plant where system failures could lead to a hazard should be systematically assessed to ensure that the overall safety performance of the plant is not degraded.

DEVELOPMENTS IN TECHNOLOGY

New concepts are emerging frequently in various fields such as:

- microprocessor sensors,
- communications links, including fibre optics and radio, microwave, satellite,