SITING AND LAYOUT OF MAJOR HAZARDOUS INSTALLATIONS

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Recent applications of risk contour plotting techniques in the assessment of siting and layout for major hazardous installations are described. The quantitative information obtained has assisted both industry and regulatory authorities to specify appropriate community and inter-plant separation distances and safety zones.

Risk transect analysis has likewise been applied in the case of linear hazards such as cross-country pipelines.

INTRODUCTION

In any new project involving a major hazardous installation, it is essential to confirm at a very early stage that the chosen location is suitable for the type and scale of development proposed. Failure to check this will lead to delay, waste of effort and costly changes in development strategy.

There is therefore a need for a method of assessing the hazard impact in a logical manner which is compatible with the preliminary nature of the available engineering data, and which facilitates judgement of the appropriate separation distances and safety zones between

1) installation and community
2) installation and neighbouring industry
3) plant areas and site office blocks
4) process modules and storage areas.

Once the suitability of the site for the type and scale of the proposed facility has been confirmed, the project can normally be granted outline planning approval and can then proceed with reasonable confidence that safety problems identified in subsequent design audit stages will be capable of solution by minor changes in design or operational procedures, rather than by relocation or major layout modifications. With existing installations, there is often a requirement to quantify safety zones such that compatible development strategies can be

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formulated to use the surrounding land appropriately.

This paper describes examples of hazard impact assessments undertaken using risk contour techniques. The risk contour plots have been found to assist industrialists, local authority planners, regulatory agencies and lay people alike, by providing a visual representation of the rather abstract concept of "risk". Risk contour techniques have been used to examine planning applications for new hazardous developments and to assess the acceptability of locating other developments (industrial, commercial, residential or recreational) in the vicinity of existing hazardous installations.

RISK CONTOUR TECHNIQUES

Risk contours are lines drawn on a map to connect points at which there is equal probability (per unit time) of attaining a defined severity of damage, as a consequence of the range of hazardous events which can occur.

A systematic procedure developed by Cremer and Warner for quantitative analysis of the risks has been described fully elsewhere (Ramsay (1), Comer et al.(2)). This procedure has evolved from a pioneering study prepared on behalf of Highland Regional Council in Scotland in 1978 to enable rational and soundly-based judgements to be made on various options for locating petrochemical plants (3). The main stages of the analysis comprise

1) Preparation of a quantitative description of plant hardware.
2) Identification of failure cases.
3) Assessment of primary failure probability.
4) Quantification of discharge rates for each failure case.
5) Prediction of the dispersion of the discharged hazardous materials in the external environment.
6) Evaluation of the impact of the dispersed material, and determination of hazard distances for particular damage levels relevant to
   i) community impact
   ii) impact on neighbouring industrial facilities and their workforces.
7) Assembly of probability distributions (generally two-dimensional, in the form of risk contour plots) of various intensities of damage in and around the plant or the entire complex.
8) Assessment of the probability of domino effects, and modification of the primary failure probabilities if necessary.
9) Calculation of the total impact on the local community and neighbouring industrial facilities (i.e. risk contour plots modified to take account of domino effects).

10) Formulation of conclusions about the suitability of the layout and chosen site for the hazardous installation.

Computer techniques allow rapid assessment of many hundreds of postulated failure cases, but the calculations for individual cases are based on simple models. Except in assessments of existing installations, where actual inspection and plant records can be employed in defining the failure cases, there will inevitably be uncertainties in the basic engineering data (on layout, process flow schemes, equipment lists, inventories and normal process conditions, number and diameters of pipework connections on vessels, operational procedures, protective systems). These uncertainties generally render it inappropriate to use the more-sophisticated mathematical models which are becoming available for detailed calculation of the consequences of specific failure cases.

The risk contour plots yield information on domino damage and individual risk. If an estimate of societal risk is required, additional techniques of integrating the results of the risk analysis must be employed.

RISK TRANSECTS FOR LINEAR HAZARDS

Certain potentially hazardous activities extend over a very long but narrow stretch of land, such as transport of dangerous goods by rail or cross-country pipeline. For these activities, the degree of hazard is most appropriately expressed in the form of risk values as a function of distance perpendicular to the line (i.e. in the form of "risk transects"). These transects provide information which is directly applicable to the consideration of risk to local populations or vulnerable installations.

The shape of the pipeline risk transects will depend on the local wind direction frequencies and on the orientation of the line, but in general it is found that the variations with position along the pipeline are gradual, so that an essentially one-dimensional representation is adequate. This is only invalidated where major, sharp corners are present.

The risk values depend both on the likelihood of the release cases and on their consequences. For any given place near the line, vapour clouds of a given size can pose risk if they originate in that stretch of the line from which the particular place can be reached, and if the wind is in the necessary direction.

In the case of pipelines conveying flammable fluids such as natural gas, liquefied petroleum gas (LPG) or natural gas liquids (NGL), the risk to local populations is most simply considered in terms of the risk of being enveloped in a vapour cloud above its lower flammable level. Site-specific studies at sensitive locations are necessary to identify potential ignition sources if the probability of igniting the spilled pipeline contents is to be quantified.

The distribution of risk as a function of distance from the pipeline is calculated in two ways, to allow consideration of both individual and societal risk.

Individual Risk

The primary calculation is of the risk that a particular point is enveloped by a flammable cloud. A transect of these risks along a line of these points at right angles to the pipeline is then obtained which is useful in assessing the risks to individual people.

Societal Risk

The second calculation is that of the risk to a line of finite length, L, drawn parallel to the pipeline at a distance Z from it. A transect is obtained showing the variation of this risk with distance from the pipeline. The risk considered here is defined as the risk of any part of the target line being enveloped in a flammable cloud; if L is zero, the risk becomes identical to that in the point (individual) risk transect. This calculation yields results which are useful in assessing "societal" risk, i.e. the risk of accidents affecting the communities near the pipeline and thereby causing multiple casualties in the same incident.

Mathematical Model for Risk Transects

The mathematical model employed in the point (individual) risk transect calculations assumes that the pipeline is straight in both directions from the transect for a distance greater than the maximum extent of vapour cloud travel for the failure cases considered, and that the vapour cloud covers an area shaped like the sector of a circle. The radius of the sector is the distance (x) to the lower flammable limit for that particular cloud. The semi angle of that sector, Θ, is defined as:-

$$\tan \Theta = \frac{w}{x}$$

where w in the cloud semi-width at the lower flammable limit.

For a vapour cloud being blown at some orientation to the pipeline by the wind, the risk of encountering such a cloud at any point is given by:-

$$R = FPy \text{ (See Figure 1)}$$

where:

i) F is the frequency (per unit pength of line) of the failure case which produces the cloud under consideration.

ii) P is the probability that the cloud, once formed, will assume the relevant orientation.

iii) y is the interaction distance, equal to the width of the cloud parallel to the pipeline at the distance from the pipeline where the risk is being considered.

The width y is the same as the length of line which could produce a vapour cloud which will encounter the point under consideration at the given orientation.

If the risk is then summed for all possible cloud orientations and all failure cases, a transect of individual risk at a point, i.e. the function R(Z), can be produced. It is then a simple matter to calculate the incremental risk if that point target is replaced by a line target which more truly represents a community.

In a complete analysis where full meteorological records are available, the cloud orientation mentioned above takes into account not only wind direction but also wind speed and atmospheric stability.

Case study examples are described in the remainder of this paper.

COASTAL GAS TERMINAL AND SNG PLANT (ST. FERGUS)

In May 1980, British Gas Corporation (BGC) submitted planning applications for a coastal gas reception terminal and substitute natural gas (SNG) plant at St. Fergus in north east Scotland (4). These plants were required to handle the gas and natural gas liquids which would have been brought ashore in the UK Gas Gathering Scheme (5).

Project Description

The proposed site lies to the north of the existing Total Oil Marine, Shell UK and BGC gas terminals at St. Fergus (Figure 2). The area is relatively sparsely populated, with isolated farm-houses and occasional dwellings nearby, and the villages of St. Fergus and Crimond more than 2 kilometres distant.

Planning permission was sought for the most extensive development which was considered feasible, namely -

i) a 7-stream reception terminal to process gas arriving onshore at a peak rate of 85 million standard cubic metres per day (containing about 40% by weight of NGL, corresponding to 8 million tonnes of NGL per year),

ii) an adjacent SNG plant to convert NGL into substitute natural gas in four stream each designed for 3.8 million standard cubic metres of enriched gas per day. The outline layout is shown in Figure 3.

Quantitative Risk Assessment

Approximately 630 postulated failure cases were taken into account in deriving the risk contour plots for the gas reception terminal, and 270 postulated failure cases for the SNG plant.

Risk contour plots were synthesised for four damage levels:-

i) 0.3 bar explosion overpressure

ii) 0.1 bar explosion overpressure

iii) 0.03 bar explosion overpressure

iv) envelopment in a burning vapour cloud.

The slight toxic hazards associated with the SNG process were considered separately, since calculations indicated that the acute toxic consequences of postulated accidents would be contained within the site boundaries.

Explosion Overpressure of 0.3 bar. This severity of explosion blast would cause the collapse of conventional buildings and rupture of process pipework connections. The risk contour plots for the gas reception terminal and the SNG plant (including the feedstock manifold and pipeline from the gas reception terminal) are shown in Figures 4 and 5, respectively. To the west of the gas terminal process modules, the contours fall off rapidly, and do not impinge on the SNG plant (Figure 4). It is concluded that the risk of domino damage on the SNG plant caused by an explosion on the gas terminal is suitably low. Likewise, the risk to the gas terminal from the SNG plant is low (Figure 5), and the inter-plant spacing is therefore adequate.

The combined risk from the gas terminal and SNG plant is illustrated in Figure 6. The risk to process facilities in the neighbouring Shell terminal to the south is negligible since even the 0.1 in one million years contour does not extend that far. The risk levels at the office buildings of the proposed gas reception terminal and SNG plant indicate a likelihood of building collapse (with about 50% mortality) at a frequency of just over 10 in one million years. This may be considered a suitably low risk as it corresponds to a fatal accident rate (FAR) of about 0.12, or 3% of the FAR for comparable chemical industries.

The many approximations and the simple models used in deriving the risk contours make the technique unsuitable for assessing spacing between the process modules.

Explosion Overpressure of 0.1 bar. This severity of explosion blast would damage ambient-pressure storage tanks and cause repairable damage to domestic houses. The risk contours are shown in Figure 7, and again indicate satisfactory spacing between the various plants. The condensate storage tanks at the Total Oil Marine terminal lie outside even the 0.1 in one million years risk contour.

The higher contours lie almost wholly within the area of the overall St. Fergus gas complex, and the maximum risk at the nearest dwellings is calculated to be 5 per million years. This is an insignificantly low risk, since even if the unduly pessimistic assumption is made that every person indoors is killed (by flying glass?), the risk is equivalent to about 1% of the total background risk of death from all types of accident.

Explosion Overpressure of 0.03 bar. This severity of explosion blast would cause window breakage with the likelihood of injury due to flying glass. The risk contours in Figure 8 show that the risk of window breakage at the nearest inhabited building outside the terminal complex is less than 50 in one million years, and the risk at St. Fergus village is less even than 1 in one million years.

Envelopment in Burning Vapour Cloud. The risk contours in Figure 9 indicate adequate inter-plant separation distances, with minimal additional risk to workforces on neighbouring plants, and even less to the external population.

Conclusion

The project was granted outline planning permission in Autumn 1980 and the gas reception terminal project then proceeded through a full conceptual design phase (undertaken by Fluor Great Britain Ltd. on behalf of BGC). Cremer and Warner re-worked the risk contour assessment on the basis of the conceptual design, and the results confirmed the conclusions drawn at the planning stage on siting and layout, even though the design had inevitably changed and although the reworked analysis took account of 3000 postulated failure cases. The risk contour plot for the 0.3 bar explosion overpressure is presented in Figure 10, which should be compared with Figure 4.

NGL FRACTIONATION PLANT (NIGG BAY)

In 1980, British Gas Corporation applied for planning permission for a natural gas liquids fractionation, storage and export facility at Nigg Bay on the Cromarty Firth in Scotland. The NGL feedstock was to be conveyed by pipeline from the proposed coastal gas reception terminal at St. Fergus (the subject of the first example given in this paper) and the fractionation plant was to have a capacity of 7.5 million tonnes per year (6).

The risk contour plot for the 0.3 bar explosion overpressure damage level attributable to events on the 3 process modules and the refrigeration facility is shown in Figure 11, to illustrate a situation where certain layout problems were identified, in contrast to the previous example where the siting and layout were satisfactory. While the off-site risks posed no significant problem, the calculated risk of causing serious damage at the proposed on-site LPG storage tanks was high (at a frequency greater than 50 in one million years) and this would have been a dominant potential cause of tank failure unless the tank systems were designed to withstand such explosion overpressures or unless the layout was modified. It was also considered prudent to decrease the level of risk to personnel in the administration building by relocating it further from the process plant.

LPG TERMINAL (SHETLAND ISLANDS)

In March 1980, a planning application was submitted by Tricentrol Oil Corporation for a liquefied petroleum gas (LPG) terminal to be sited on Orka Voe, near to the Sullom Voe oil terminal in the Shetland Islands. Cremer and Warner undertook a hazard and risk analysis of the proposed plant and associated jetty facilities on behalf of Shetland Islands Council, to quantify the risks and assess the implications of the plant in terms of land sterilization (i.e. safety zones) and the implications for extension within the Sullom Voe oil terminal.

Project Description

The feedstock for the LPG terminal was to be propane and butane supplied as pressurised liquids by two above-ground pipelines from the Sullom Voe terminal. The LPG terminal facilities were designed to adjust the temperature of the LPG received, and to store a maximum of 10,000 cubic metres of LPG distributed among 8 storage bullets, prior to shipment by sea or by road tanker. The design throughput was 250,000 tonnes per year.

Quantitative Risk Assessment

From an engineering viewpoint, the proposed facilities were relatively simple, although the storage bullets were unusually large, and consequently only a few failure cases could be postulated. However, the relative simplicity of the site facilities combined with the remoteness of the site made it necessary for the analysis to take account of potential ignition sources in greater detail than is normally required for petrochemical complexes where there is a low likelihood of a vapour cloud developing to cover a large area but not being ignited.

The risk contour plots for the 0.3 and 0.1 bar explosion overpressure levels and for envelopment in a burning vapour cloud are shown in Figures 12, 13 and 14, respectively.

It was concluded that the proposed location of the LPG terminal was eminently satisfactory (from a hazard viewpoint) with regard to its distance from the existing Sullom Voe terminal. The risk to local inhabitants was negligible since the existing community is several kilometres distant. In terms of the constraints on future developments in the vicinity of the terminal the following conclusions were drawn by Cremer and Warner:-

1) At distances greater than 1000 metres from the LPG storage area, there need be no constraints on land use or population density. This distance corresponds to both the maximum vapour cloud travel distance, and to the 1 per million years contour in Figure 13.
2) At distances between 500 metres and 1000 metres from the LPG storage area, industrial development may be permitted, but neither residential accommodation nor industries requiring a high population density should be allowed. The 500m distance corresponds to the likely limit of major explosion damage (Figure 12) and to the 5 kW/m^2 radiation level from fireballs.
3) At distances between the boundary fence and 500 metres from the LPG storage area, development should be severely restricted. Only developments requiring a very low density of staff should be countenanced, and ideally all developments should be located beyond this zone of highest risk.

With reference to possible expansion of the Sullom Voe oil terminal, it was considered that there need to be no restrictions on such expansion up to the 1000m line from the storage vessels at the proposed Orka Voe LPG terminal. This would appear to leave ample scope for such future expansion. Expansion closer to the Orka Voe terminal would need to be examined in the light of the potential to cause damage or injury within the Orka Voe terminal.

Although planning permission was granted, the project has not gone ahead. This is attributed to the current LPG market situation.

DANISH CRUDE OIL/NGL PIPELINE (JUTLAND)

In Autumn 1981, Cremer and Warner were commisioned by Dansk Olierør A/S to undertake an initial safety analysis for the land section of the pipeline which will convey crude oil and NGL from the offshore fields in the Danish North Sea across Jutland to the refinery at Fredericia. Risk transects were produced as part of the quantitative assessment of vapour cloud/aerosol behaviour following pipeline fracture.

A transect for individual risk is illustrated in Figure 15. This shows that the individual risk varies up to about 2 per million years. If the risk values are taken as a true reflection of the risk of death (rather than the risk of envelopment in a flammable vapour cloud), it could be concluded that the risk from the pipeline is low in relation to other risks faced in everyday life, and thus an individual may live as close as he likes to the pipeline, provided that his presence does not threaten the integrity of the pipeline. This proviso is crucially important, and since the presence of third parties does usually threaten the integrity of the pipeline, it is necessary to have protection zones on either side of the pipeline where dwellings (or other facilities) are not permitted.

The societal risks were evaluated for hypothetical small communities (towns or villages) such as may occur relatively close to the pipeline route. It was assumed that the length of the community parallel to the pipeline is 500 metres. The results are presented in Table 1.

TABLE 1 - Societal Risks from Crude Oil/NGL Pipeline

Distance from Pipeline	Societal Interaction Frequency (per million years)
50m	4.2
100m	1.8
200m	0.5

For the purpose of gaining a meaning from these numbers, a somewhat arbitrary assumption can be made that between 10 and 100 people would be killed at those frequencies of up to 4 times per million years (making assumptions about the ignition probability and resulting damage severity). The predicted risks can then be judged against any criteria of societal risk which are considered appropriate.

ACKNOWLEDGEMENTS

The authors are indebted to the Partners of Cremer and Warner for permission to present this paper. Grateful acknowledgement is also made to British Gas Corporation, Shetland Islands Council and Dansk Olierør A/S, at whose request Cremer and Warner undertook the studies from which the examples are extracted. The authors wish to record that the conclusions and opinions expressed in this paper are theirs alone, and do not necessarily reflect the policy of any clients of Cremer and Warner.

SYMBOLS USED

F = frequency
P = orientation probability
R = risk
w = vapour cloud semi-width (m)
x = distance to lower flammable limit (m)
y = interaction distance (m)
Z = perpendicular distance from linear hazard (m)
θ = semi-angle of vapour cloud

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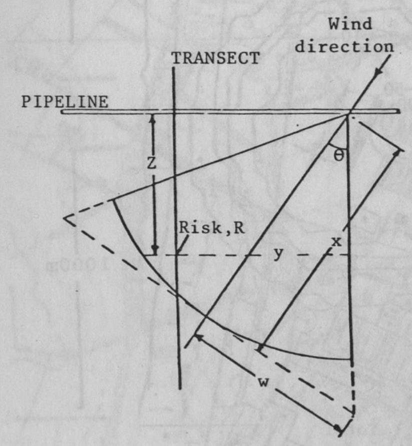

Figure 1 Risk transect geometry

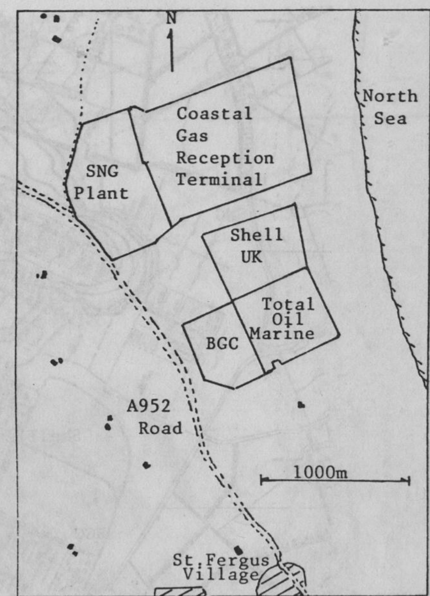

Figure 2 Sketch map of St.Fergus

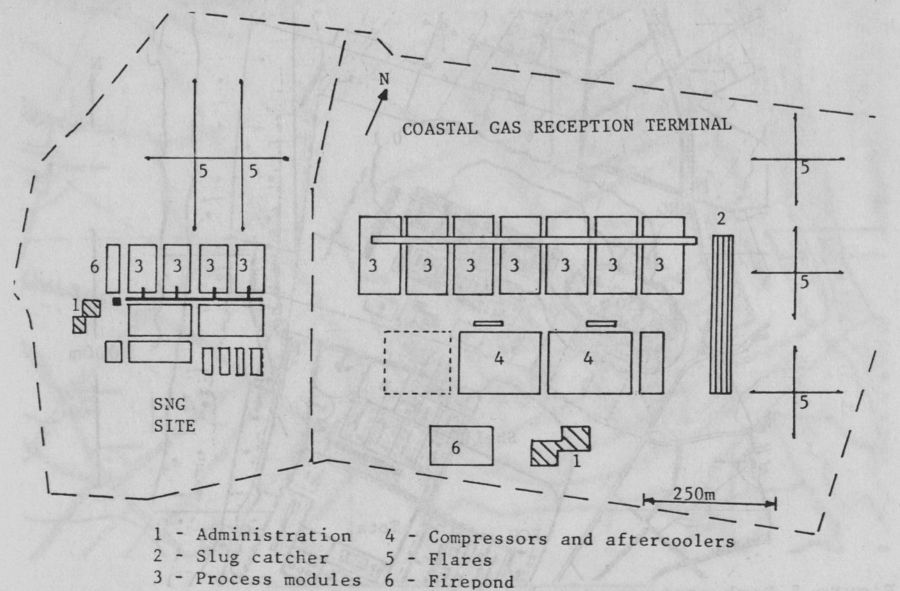

Figure 3 Layout of proposed coastal gas reception terminal and SNG plant at St.Fergus

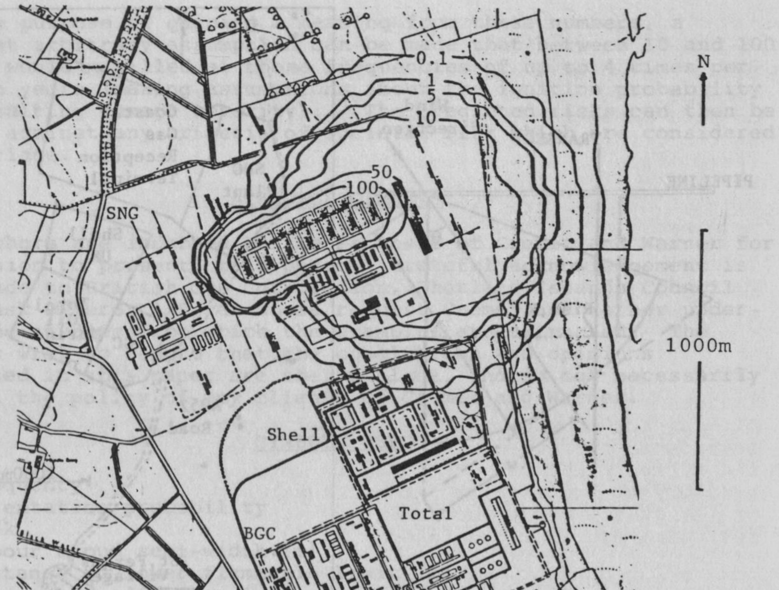

Figure 4 Risk contour plot for 0.3 bar explosion overpressure risk (per million years) for St. Fergus coastal gas reception terminal.

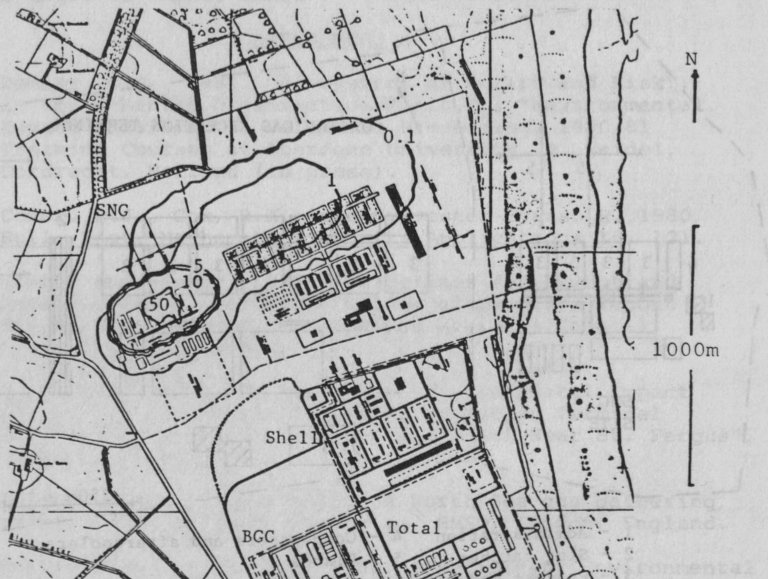

Figure 5 Risk contour plot for 0.3 bar explosion overpressure risk (per million years) for St. Fergus substitute natural gas plant.

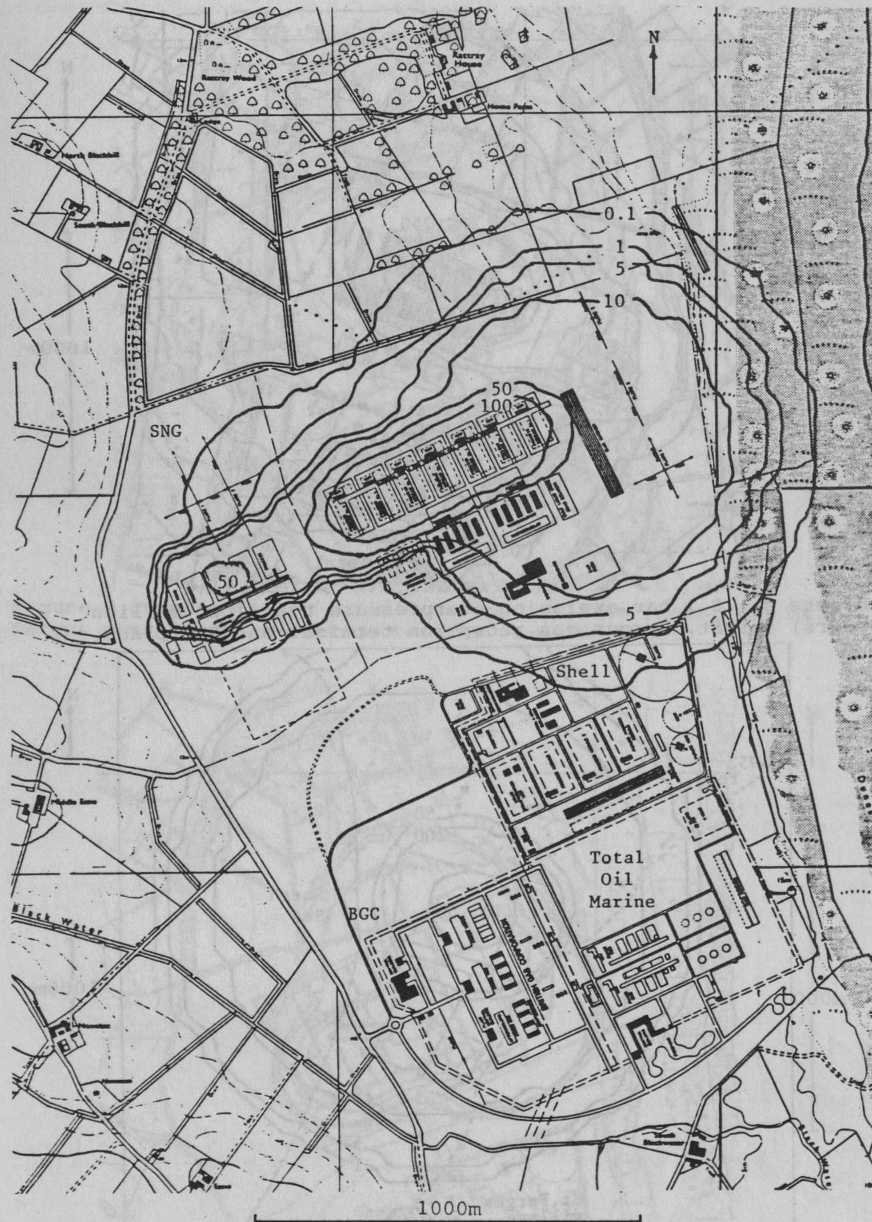

Figure 6 Risk contour plot for 0.3 bar explosion overpressure risk (per million years) for St. Fergus gas terminal and SNG plant.

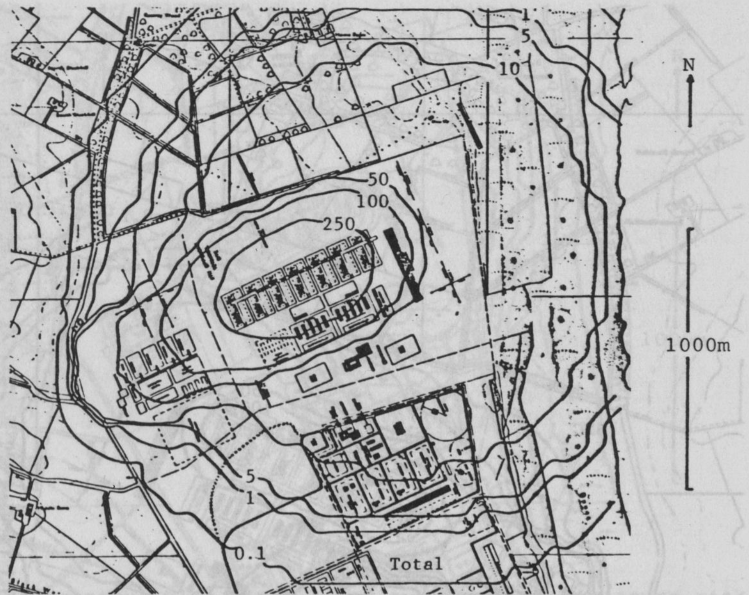

Figure 7 0.1 bar explosion overpressure risk (per million years) for St. Fergus gas reception terminal and SNG plant.

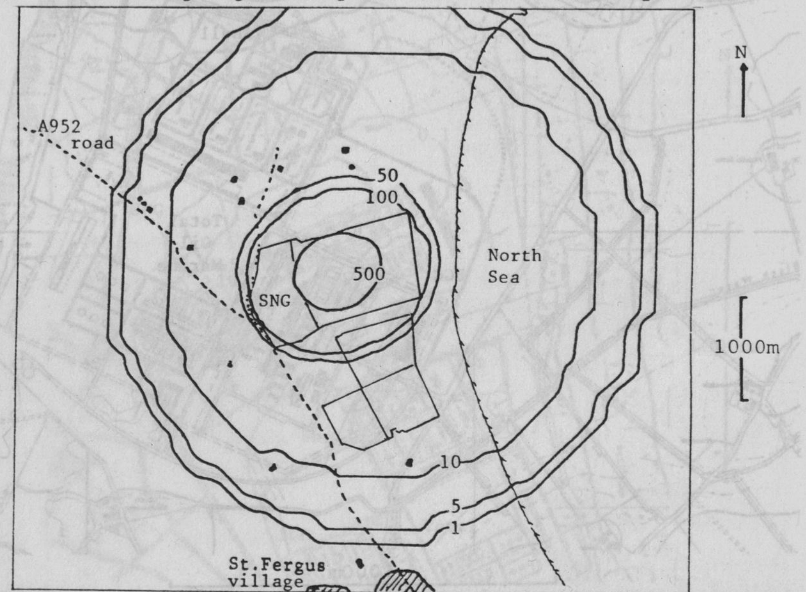

Figure 8 0.03 bar explosion overpressure risk (per million years) for St. Fergus gas reception terminal and SNG plant.

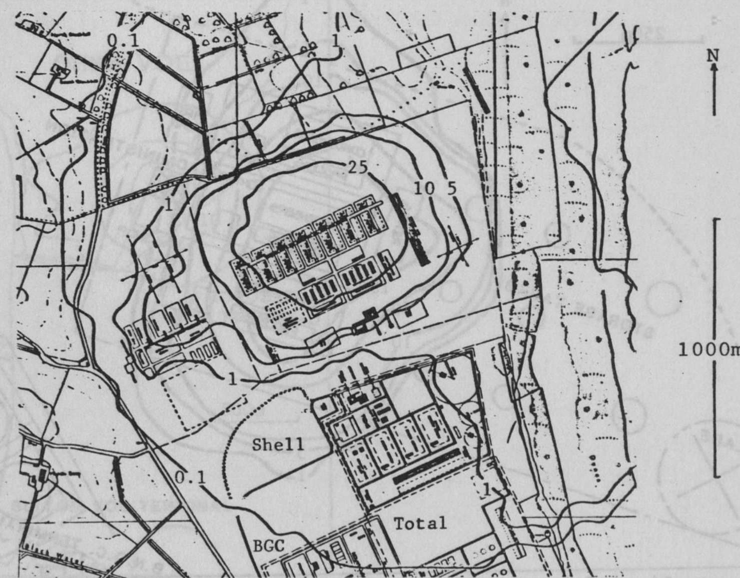

Figure 9 Burning vapour cloud risk (per million years) for St. Fergus coastal gas reception terminal and SNG plant.

Figure 10 0.3 bar explosion overpressure risk (per million years) for St. Fergus gas terminal after full conceptual design stage.

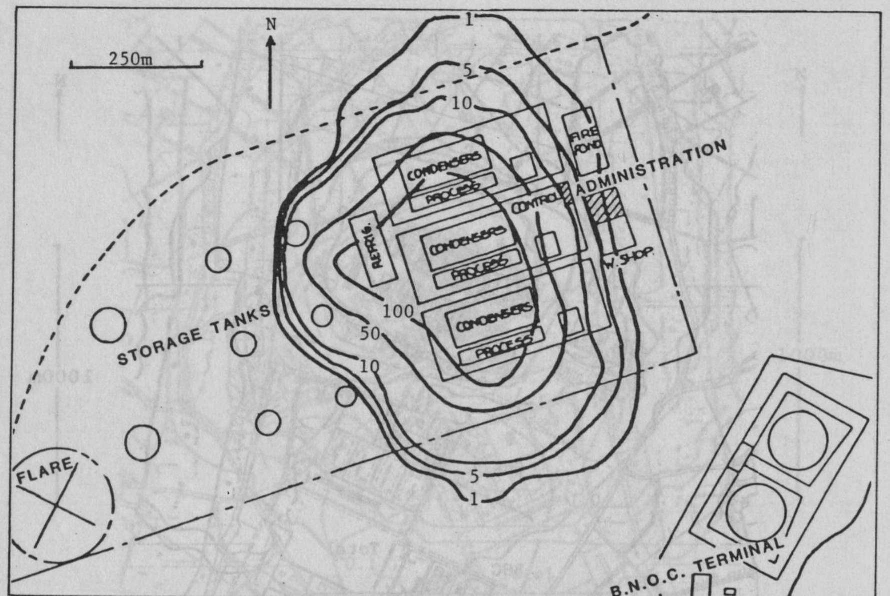

Figure 11 0.3 bar explosion overpressure risk (per million years) for NGL plant process and refrigeration facilities at Nigg Bay.

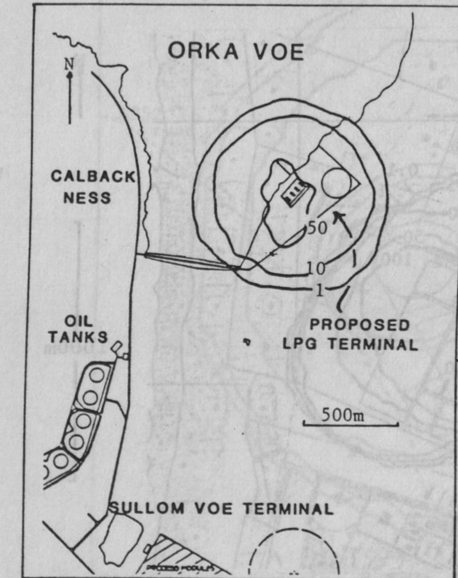

Figure 12 Shetland LPG terminal; 0.3 bar risk (per million years)

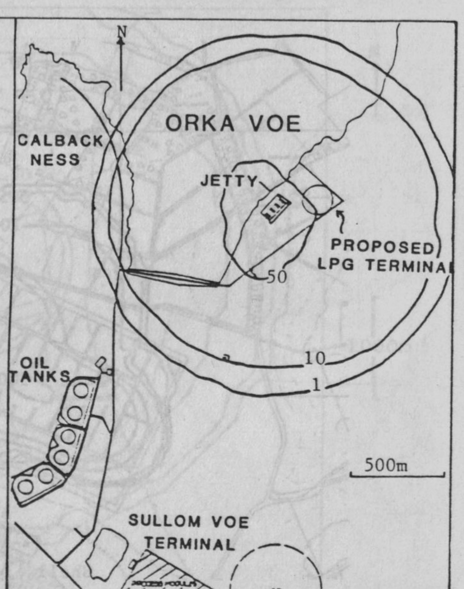

Figure 13 Shetland LPG terminal; 0.1 bar risk (per million years)

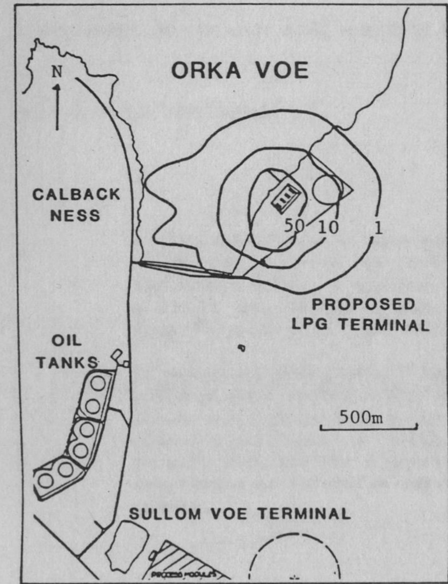

Figure 14 Shetland LPG terminal; burning vapour risk (per 10^6 years)

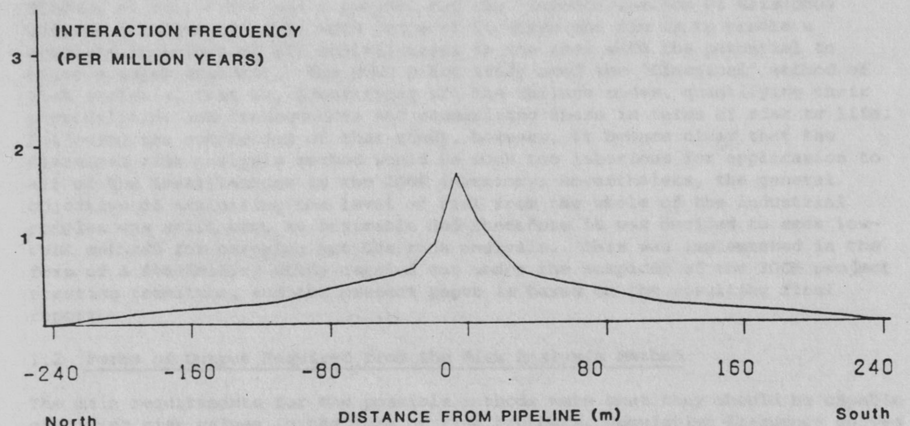

Figure 15 Transect for individual risk (of interaction with vapour cloud); Danish crude oil/NGL pipeline project.