Risk assessment of offshore pipelines and risers*

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1. Introduction

The rapidly growing number of pipelines offshore in the North Sea has caused increasing attention to be given to the risk and reliability aspects of their operation. From an economic point of view, this arises because of the high cost of construction, inspection and repair. From a safety viewpoint, this is because of the large inventories that are contained in some pipelines, which are capable of causing substantial fire and explosion damage if integrity is lost.

In this paper, we propose to concentrate on one particular aspect of pipeline risks — the vulnerable portion where the pipeline leaves the seabed to link up with the process system topsides. Usually this is a separate pipe section, welded or bolted to the pipeline at the seabed, and more commonly known as the riser. By looking at the consequences and likelihood of failure, the risk is put into perspective against other platform risks. In cases where there is a long line transporting gas under pressure, with no means of limiting the inventory, this risk is significant, and various engineering proposals for limiting the hazard are examined.

2. The potential causes of the risks

2.1 Types of hazard

The hazardous conditions which cause failure of the platform risers and the tie-in spool piece between the riser and the main pipeline can be generally classified into two categories, namely:

— natural hazards and disasters caused by environmental conditions;
— inadvertent man-made hazards caused by inadequate design, bad operation or impact from marine activities.

Environmental attack, resulting in extensive corrosion of the riser especially in the splash zone, is normally attributed to a combination of the following: sea states exceeding the design criteria, marine life attack, extreme differential temperatures between the inside and outside of the pipe or disasters resulting from severe storms, earthquakes and conditions generally classed as Acts of God.

Man-made hazards resulting from shipping movements, dragged anchors, trawl board impact, debris discharge, etc., are a serious problem for all platform operators as there is little that designers can do to minimize these problems. Damage from ships and trawl boards should not occur due to safety restriction zones that are imposed by the operators, although many trawlers have been observed operating within safety zones, particularly at night.

Other forms of man-made hazards, all of which ultimately result in riser failure, include operator errors, equipment malfunction, explosions, fire, undetected damage during construction, poor quality control and the use of unsuitable materials.

2.2 Design code requirements

The minimum requirements for the design, fabrication, testing and installation of risers and the associated tie-in spools are normally in accordance with the following codes:

— Det Norske Veritas (DNV) Rules for the design, construction and inspection of submarine pipelines and risers;
— the Institute of Petroleum IP6 Code for submarine pipelines;
— specific oil company standards and specifications developed over a period of years.

In many cases the actual interpretation of the minimum requirements is left up to the consultant or designer and as a result of this many variations occur.

2.3 Impact damage

The main cause of impact damage in the region of a riser is from either:

— collision with work/supply boats whilst they are operating close to the platform;
— large pieces of flotsam, i.e. wooden baulks, discarded packing cases, etc.

The first cause of damage can be largely eliminated by suitable location of the risers inside the jacket frame. The second type of damage is generally unavoidable and thus suitable protection devices must be provided for the risers.

Damage from ships' anchors and trawl boards should not occur in the region of the riser and tie-in spool due to the safety regulations and "no go" area limitations imposed by platform operators, but it does occur. Fortunately due to the shape of the trawl boards and the low trawling speeds, little damage is usually done to the pipeline.

Damage from ships' anchors is an indeterminate quantity as it depends on the weight of the anchor, the

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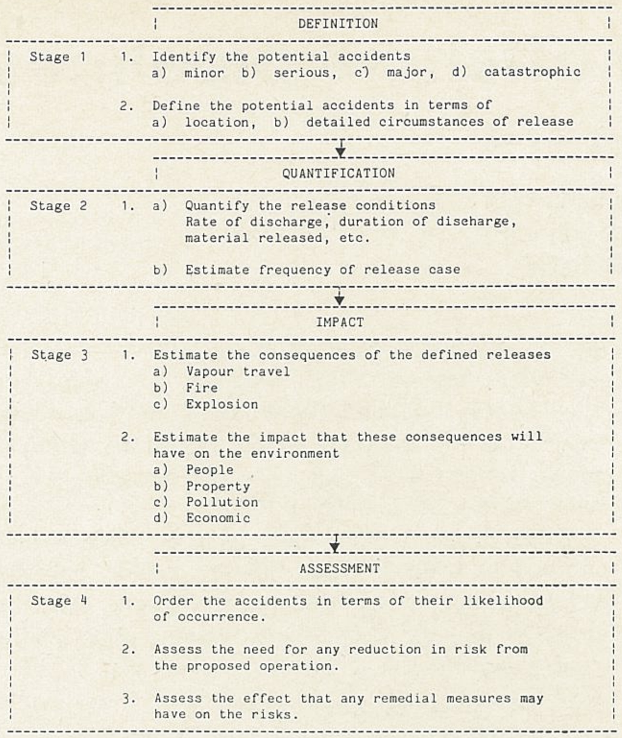

Fig. 1. Formalized procedure for the risk analysis of proposed hazardous operation.

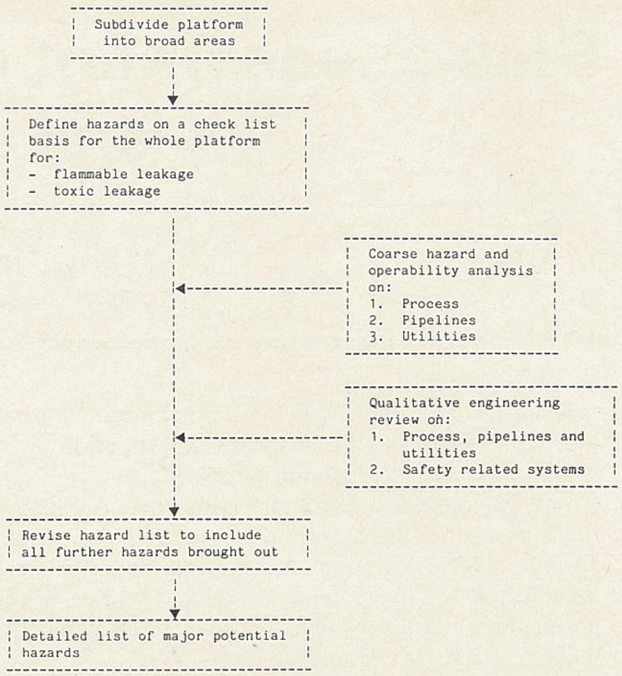

Fig. 2. Procedure for identification of process hazards.

speed at which it is being dragged over the seabed, the fluke and chain holding capacity and the penetration depth into the seabed. Much research has been carried out into the effects of anchor damage on pipelines; it suffices to say that considerable damage will be and has been done should this hazard occur, although newer pipelaying and design techniques are now overcoming this problem.

2.4 Coating damage and failure

Anti-corrosion coating damage, before, during and following installation of the riser, and to a lesser degree, tie-in spool piece, is the main cause of corrosion attack. It is extremely important that strict inspection and testing procedures are adhered to at all times during fabrication and installation operations. Such procedures are one of the major risk reducing measures.

3. Risk analysis of pipelines

In the risk analysis of any hazardous system there are four stages. These are:

(i) the identification of the potential hazards;
(ii) the likely frequency of occurrence of those hazards;
(iii) the consequences of those hazards;
(iv) the assessment of the risk.

These steps are shown schematically in the diagram in Fig. 1.

Each aspect is covered briefly below, and the application to a gas or oil riser is discussed. For discussion purposes, the riser is taken to be part of a steel jacket concept, where there is a significant distance to the pipeline destination and no isolation valve close upstream of the riser.

3.1 Identification of the potential hazards

The identification of the potential hazards may be entirely straightforward, in the case of simple systems where the main hazards are often already known, or it may require a rigorous, systematic analysis of the system in more complicated cases. The full procedure for hazard identification of a particular system usually follows an approach similar to that of Fig. 2. Here the hazards are identified by three separate methods.

First a 'check list', which simply categorizes the process into small readily-identifiable units, and then considers the potential hazards of each unit. In the case of risers, the sections would typically be the spool zone, the splash zone length, and finally the upper section to the topsides, incorporating the insulation flange and topsides flange, where appropriate.

Secondly, a qualitative review is carried out. This review aims to use experience of other similar systems and practical experience of the operation of such systems to pick out the likely hazards. In the case of risers, the review would conclude that the major area of concern to the riser is likely to be in the splash zone, from collision and corrosion risks, and to a lesser extent at bolted flanges, which may be at the spool piece, the insulation flange and the topsides flange. Depending on the particular installation, there may be other hazardous aspects that would also be pointed out.

Thirdly, a coarse hazard and operability study would be carried out. This type of study is a much smaller version of the full "HAZOP" technique, and is generally carried out by only 1 or 2 people as opposed to a full team. Its purpose is to look at failures in the system, be they leaks, control failures or valve failures and how they might arise, then to look at the response of the system to these failures. In the case of risers, the major features that come out are the inability to limit the

Table 1. Division of initiation causes by relative likelihood.

LIKELIHOOD	INITIATIVE CAUSE
Most Probable	External Corrosion Ship Accident(Collision)
Expected Occurrence	Operator errors Equipment malfunctions Un-noticed damage during installation Internal corrosion
Least Probable	Sea and environmental conditions exceeding design criteria Marine life attack Abrasions and chafing Severe storms Debris discharge Fire and explosion Fishing activities Design deficiencies Material deficiencies Poor quality control erosion

inventory of gas or oil released, if the leak is upstream of the first isolation valve, and the lack of installed fire-fighting measures to contain the fire. It is the first feature which particularly distinguishes the hazards of riser leakages from other platform hazards: elsewhere in the process there is generally at least one upstream isolation valve together with facilities for diverting or blowing down the enclosed inventory.

These three approaches to identifying the hazard serve not only to cover the range of hazards that may occur, but also to pin-point certain of these hazards as being of greater importance than others. In the riser case, the hazard of greatest significance is concluded to be leakage in the splash zone, particularly for a gas riser.

3.2 The likely frequency of occurrence

An important part of a risk analysis is the need to place the hazards from one part of the installation in perspective with the other hazards to which the installation may be subjected. The relative importance is used as a basis for decisions on where best to expend effort in risk reduction. Thus, the risks from collision with a passing vessel on a certain platform may be low in comparison with the risk from blowout, whilst the risk of an aircraft crashing onto the platform is sufficiently small to be ignored completely.

The only way to be able to make such distinctions is on the basis of their expected frequency of occurrence. This in turn must come from the historical accident record, either of directly comparable systems, or by analogy with other systems (or the same system in other parts of the world) that can be considered sufficiently similar.

Inevitably, the more major the hazard, the fewer historical occurrences there have been, and the poorer the confidence in the statistical estimate. In some cases there may have been zero occurrences of the potential hazard. It is thus usually necessary to cross check the direct estimate against at least one other less direct

Table 2. Failure causes for Gulf of Mexico risers.

CAUSE	No. of failures	% of total
Mechanical/operational	4	14
External corrosion	14	48
Internal corrosion	-	-
External forces (natural)	9	31
External forces (manmade)	2	7
Unknown	10	-
TOTAL:	39	100

Table 3. Breakdown of major platform hazards for a typical large PDQ platform (away from major shipping lanes).

Initiating Cause	Risk (/yr)
Blowout	3×10^{-4}
Escalation of topsides fire/explosion	5×10^{-4}
Riser leakage	4×10^{-4}
Topsides fire/explosion leading to major structural damage	1×10^{-4}
Collision, earthquakes, helicopter crashes	0.2×10^{-4}
Total platform risk	13×10^{-4}/yr

source to improve the confidence in the estimate. Alternatively, upper and lower bounds can sometimes be obtained by analogy with other related hazards.

Thus, for risers in the North Sea, although a best estimate can be obtained from direct data on North Sea riser leaks and cracks (and this is the figure used in any risk analysis applied to the North Sea), it is a useful exercise to examine the record from the Gulf of Mexico. A brief discussion of the relevant data is given in Appendix I.

3.2.1 Relative frequency of occurrence

A picture of the relative contributions from each contributory cause can be obtained quantatively from a breakdown of the historical accident data by cause from the qualitative review. Examples are shown in Tables 1 and 2.

3.2.2 The risk in perspective — the absolute frequency

The estimated mean failure rate for significant leakage from a typical riser in the North Sea is 8×10^{-4} per riser-year (see Appendix I). In order to conclude whether or not this is a significant risk, it needs to be compared to other risks to offshore installations. A typcial comparison is shown in Table 3, based on other available data.

This comparison suggests that riser hazards do indeed require considering seriously, thus reinforcing the conclusions reached in the qualitative review and the coarse *hazop* above.

3.3 The consequences of leakage

With a high-pressure gas line, cracks of even small dimensions will result in sizeable releases of gas, either as a jet (for releases above sea level) or as a diffuse cloud at sea level (from subsea releases).

The estimated size of gas release from a variety of crack sizes is shown in Table 4.

In the event of ignition of a riser leak, there is likely to be flame impingement on the structure. Flames from all discharge sizes given in Table 4, except 'serious', would be able to impinge on at least one leg, and some

Table 4. Release from consequences of gas riser (based on 150 bar gas pressure).

a) In or above splash zone

Parameter	Equivalent crack diameter		
	20mm	70mm	140mm
Discharge rate (kg/sec)	4	70	280
Jet length (to LFL) (m)	19	63	130
Jet width (to LFL) (m)	1	4	8
Flammable mass (kg)	2	100	800

b) Below splash zone (buoyant cloud release)

Parameter	Equivalent hole diameter		
	20mm	100mm	200mm
Discharge Rate (kg/sec)	4	100	400
Release diameter at sea surface (m)	2	10	20
Distance of cloud to LFL			
2m/sec windspeed	40	220	500
10m/sec windspeed	20	80	200
Flammable mass (kg)			
2m/sec windspeed	50	8500	80000
10m/sec windspeed	3	500	5000

LFL = Lower flammable limit

of the horizontal or diagonal bracing on typical steel platforms. Flames from a serious leakage are likely to affect the nearest leg and associated bracing only. All ignited leakage cases could affect any nearby risers.

In the case of direct impingement of flames on the riser or others adjacent, total failure can be expected in a fairly short time, calculated to be less than 30 minutes. There is thus a high probability in these cases that a fire in the splash zone from either an oil or a gas riser will escalate into an incident that may envelop a significant part of the platform in fire in a timescale of approximately half an hour after ignition.

In the case of flame impingement on the structure, the consequences depend on the type of structure. It is calculated theoretically that exposed members of a steel jacket may lose their strength within 15 to 30 minutes if subjected to direct flame impingement (i.e. a leg or brace). With a concrete structure the resistance time is calculated to be considerably longer, generally of the order of a few hours.

If the release takes place some distance below the splash zone, the momentum of the initial jet is effectively neutralized, and the resulting gas emerges at the water surface at a relatively-low velocity. This means that in the case of smaller rates for smaller failures, only a limited fire will result. However, there is a possibility, although slight, that such a fire would surround a structural member or riser. Failure of either of these would occur with effects as described above. With all but the smallest leak size, a relatively-large fire would occur with consequent effects on the platform support structure although the fire is not expected to be large enough to impinge on the platform topsides.

3.4 *Assessment of the risk*

Having examined the type and origin of the hazards, the expected frequency compared against other hazards and the consequences of the hazard, the final steps are

Table 5. Summary of severity and likelihood of potential hazards.

	Potential hazard	Damage Potential: Extensive	Damage Potential: Moderate	Damage Potential: Minor	Probability of Occurrence: Most probable	Probability of Occurrence: Expected occurrence	Probability of Occurrence: Least probable
Natural hazards	External Corrosion	X			X		
	Sea State Exceeding Design Criteria		X				X
	Marine Fouling (Crustations)			X			X
	Thermal Effects		X			X	
	Abrasion and Chafing			X			X
	Severe Storms	X					X
	Erosion			X		X	
Manmade hazards	Ship Accidents	X				X	
	Anchor Dragging	X					X
	Fishing Operations		X				X
	Debris Discharge		X				X
	Operator Errors		X			X	
	Equipment Inadequacies	X				X	
	Equipment Malfunction	X				X	
	Internal Corrosion	X				X	
	Fire and Explosion	X					X
	Undetected Damage During Construction		X			X	
	Material Deficiencies		X				X
	Poor Quality Control		X				X
	Design Deficiencies			X			X

to summarize the risk picture and to assess the significance of the results. If the risks seem high, then it is necessary to widen the scope for risk-reducing measures.

A qualitative summary of the risks from risers is shown in Table 5. Such a table serves to condense all the "frequency" and "consequence" analyses into a single page that can be readily assimilated.

There are many different ways of presenting and assessing the risk. These include:

— ranking;
— criteria for risk to individual employees (e.g. FAR);
— criteria for societal risk (i.e., groups of employees) (e.g. F-N curves);
— criteria for total platform risk (e.g. the Norwegian NPD requirements for concept safety evaluation);
— criteria for preventive safety measures against each hazard (e.g. API & RP 14C).

The merits of the different criteria and the situations where they are most appropriate are not discussed in this paper. In the case of riser hazards, it suffices to say that any of these criteria would indicated that the hazards are significant.

3.5 *Risk reducing measures*

At this stage, the pure risk analysis side of the study is complete: the potential hazards have been identified, their likelihood and consequences examined, and the conclusion reached that certain of the hazards require looking at in more detail, with a view to identifying risk reducing measures.

4. Ways of minimizing the probability of leakage

Minimizing the probability of damage to risers and the associated tie-in spools can be achieved in three main ways. These are:

— corrosion protection;

— protection from falling objects;
— protection from ship operations.

4.1 *Corrosion protection*

An effective corrosion-control programme is essential if the operator is to avoid the high cost of leak repair, riser/pipe replacement, clean-up, production shutdown, damaged equipment, etc., and the attendant risk of continuing operation in a partially corroded situation beyond the safe limits. Two methods of controlling external corrosion are generally used, namely protective coatings and/or cathodic protection.

Various types of protective coating have been suggested, or have been applied in the past. These include:

— thicker steel, which provides an additional corrosion allowance;
— steel cladding, which is slightly better than increasing the steel thickness as new cladding can be installed without production shutdown. However, this is not a good method on its own as corrosion can and will take place between the outside of the riser and the inside of the cladding;
— proprietary anti-corrosion coatings. These are perfectly acceptable but are prone to damage, especially in the splash zone if left on their own. These coatings are excellent as anti-corrosion devices but are invariably rather thin and therefore weak with regard to mechanical strength;
— concrete, which is the normal method of giving subsea pipelines the desired negative buoyancy, but is impractical for risers and to a lesser degree tie-in spools, due to the increase in weight;
— *Monel* sheathing, which is the most popular choice of cladding and has been used successfully on many risers for several years. Unfortunately, it is very expensive and this results in its being used sparingly. Under normal circumstances it is only applied in the splash zone. Its one main disadvantage because it is relatively thin, is that it is prone to impact damage.

Many combinations of the above have been tried with varying degrees of success in the past, and are considered later in this paper.

Corrosion control is of particular importance to the portion of the riser located in the splash zone — an area of severe corrosion potential. Many combinations of coatings have been tried but all have inherent weaknesses. Ideally, the design should afford the riser protection against corrosion, impact and chafing. In Fig. 3 we illustrate what we feel to be the ideal combination.

Many proprietary coating methods are available on the commercial market, all of which have their respective merits and weaknesses. These factors have to be taken into account when determining the system most appropriate for the particular riser or tie-in spool. These points are illustrated in Table 6.

Other than for field joints, hand-applied tapes (C) are very seldom used on their own as protection for offshore risers and pipelines. There is little to choose between the remaining systems, all of which have their good points and their weaknesses. Table 6 illustrates the problem facing the designers when developing an operation and safety philosophy. For corrosion protection, coating categories (D) and (E) seem to be favoured for the riser and tie-in spools but it is apparent that combination coatings are necessary in the splash zone. Protection of the riser within the splash zone must comprise of three elements, namely:

— anti-corrosion coat;
— buffer coat — to prevent impact;
— armouring coat — to prevent abrasion.

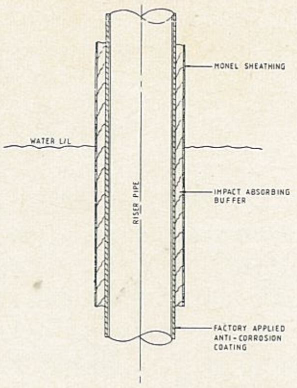

Fig. 3. Riser protection in splash zone.

We contend that splash zone protection for the riser must always contain these major elements and submit that many of the riser problems will be minimized if a combination system were adopted as standard.

4.2 *Protection from ship operations*

Excluding falling objects and the fact that supply boats, etc., are not allowed to drop or drag anchors in the vicinity of the platform due to operation regulation and the depth of water, the only damage that can be caused to risers is from collision.

Several platform operators insist that suitable fendering devices, attached to the main structure, are provided within the splash zone area. We feel that "fendering" in this particular area should be mandatory on all structures where the risers are secured to the "outside" of a platform.

Table 6. Relative merits of different riser protection methods.

Coating Types:

A Coal tar enamels
B Butyl rubbers and neoprenes
C Hand/machine applied tapes over primers
D Factory applied extruded plastics
E Factory applied thin film epoxy
F Corrosion resistant sheeting (monel)

PROBLEM	RATING					
	A	B	C	D	E	F
Corrosion Protection	1	1	1	1	1	2
Electrical Resistance	1	1	1	1	1	1
Resistance to water	2	1	2	1	2	1
Durability	2	2	3	2	2	1
Ease of application	1	2	2	2	2	2
Resistance to environmental attack	2	2	3	2	2	1
Bond strength	2	1	2	1	1	3
Weather resistance	3	2	3	2	2	1
Long life	2	2	3	2	2	2
Total:	16	14	20	14	15	14

1 = Good
2 = Moderate
3 - Poor

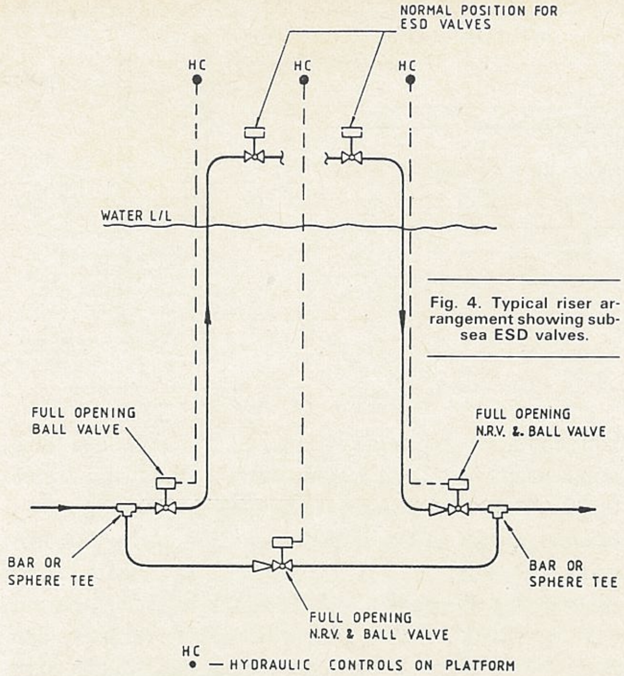

Fig. 4. Typical riser arrangement showing subsea ESD valves.

5. Ways of minimizing the consequences of leakage

5.1 Emergency shutdown operations (ESD) above the water level

In order to minimize the consequences resulting from riser failure the majority of platforms incorporate an emergency shutdown (ESD) system.

These systems usually have one major limitation in that they are installed on the platform side of the most vulnerable point on the riser system, i.e. the splash zone. Failure of a riser, particularly below the water line, means that the entire contents of the pipeline will be uncontained and this will lead to fire hazards or to contamination of the product. In the case of gas lines particularly, an extremely hazardous situation will arise.

Conventional "topside" ESD systems minimize the consequences of failure in relation to platform processes but do not overcome the pipeline system consequences.

5.2 ESD systems subsea

In order to minimize the consequences resulting from riser failure, it is worth considering a subsea ESD system similar to that illustrated as Fig. 4.

The system comprises of a full-bore isolating valve on incoming risers, with full-bore isolating and non-return valves on export lines. These valves should be located in the horizontal mode as close as possible to the base of the platform where controls for the valves can be run direct from the platform topside, thus eliminating diver operations.

The alternative of placing the valve a few hundred metres away should also be discussed, thus eliminating the main need for dropped object protection, even if it is ultimately rejected in favour of a closer locations and the use of cages.

The requirement that will need to be satisfied before this risk-reducing measure can be seen to be feasible is that the valves are seen to be reliable. Some experience is already available to judge this for large-diameter subsea valves for liquids. It is important to note, however, that from a safety point of view, the reliability does not need to be high. Even a very poor reliability figure of, say, 0.1 failures to close on demand, will reduce the risk from riser failures to an extent where it is no longer a major contributor to the risk. Although failures that may interfere with production, particularly undesired closure and problems requiring maintenance, are clearly of concern from an operating viewpoint, the major gains in safety would make detailed considerations of such valves well worth while.

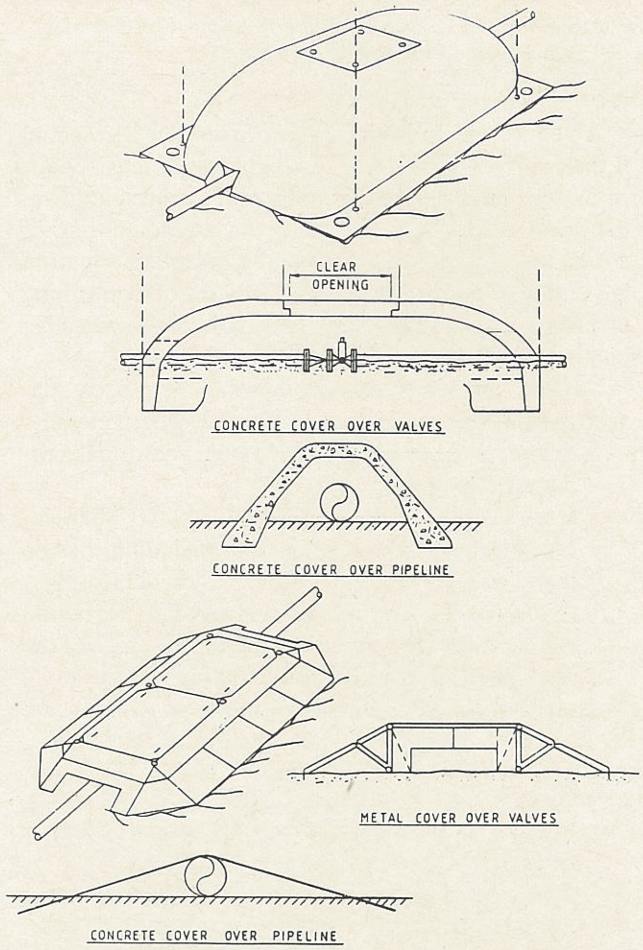

Fig. 5. Protection from falling objects.

5.2.1 Protection of valves from falling objects

Subsea valve protection devices of various types can be installed, close to the platform, to protect valve installations and pipelines from falling objects. In Fig. 5 we show a typical selection which fall basically into two categories, namely concrete covers and prefabricated steel cages.

Covers made from reinforced concrete, are very difficult to install due to their shape and size. Additionally, due to their construction they have to be installed in one piece which makes them very expensive.

Prefabricated steel covers, in accordance with the basic design shown and comprising of a steel space frame covered by hinged side plates, have been installed in the North Sea to protect lateral connections. We see no reason why a modified version of this cover should not be installed to protect subsea ESD valves. The relative costs of these devices, although high, is a small price to pay when offset against the costs resulting from a platform shutdown due to riser failure and no subsea bypass system.

5.3 Limiting riser structural damage

In order to limit possible damage to risers it is prudent to examine, at the platform design stage, the alternative positions available for the attachment of these important items.

The alternatives are:

(a) externally on a leg;
(b) externally on a face;
(c) internally within the structure.

In cases (a) and (b) the risers are prone to environmental and impact loads but are relatively easy to replace. In case (c), the possibility of impact loads (from work boats, etc.) is removed but replacement if necessary, is far more difficult. The consequences of 'minor' failure will also be more severe. Thus the safety philosophy related to this part of the design must be established at the design concept stage of the project.

Risk analysis approaches to this type of problem, where the advantages and disadvantages are being compared, use one of several available ranking techniques, such as Kepner-Tregoe decision analysis, to try to structure the problem into one where all the key features can be put in perspective and ranked in order of importance.

5.4 Other methods

Various other schemes have been proposed to limit the consequences of an uncontrolled riser fire. These include protecting the structure itself, providing extra redundancy to the jacket legs, and large separation of the risers (where there are more than one). Other schemes have been proposed where a different concept is embraced: for example, a structure more resistant to fire at sea level, such as concrete structures, or the concept of a separate unmanned riser platform.

All of these alternative schemes have merits from the safety viewpoint, although their overall desirability depends also of course on other factors besides that of safety.

6. Conclusions

This paper has set out to demonstrate the application of risk analysis to offshore pipeline system, and particularly to the case of oil and gas risers from which there is expected to be a significant risk of major damage to a platform. Some of the areas in which the hazards can be reduced have been discussed. The choices for optimum protection against external corrosion to reduce leakage probability and the use of ESD valves upstream of the riser are highlighted as the main risk-reducing measures.

The main advantage of approaching the analysis of hazards in this way is that it provides a quantitative basis on which to determine needs and priorities for action in an area which is not as simple as it seems at first sight..

APPENDIX I

The likelihood of leakage

The riser system can generally be expected to have a greater risk of failure than an undersea line. It is liable to collision damage, impact by falling objects from the platform, corrosion/erosion by wave action in the splash zone, and temperature changes over the riser length. Fortunately some data exist specifically for riser failures although not all of this is in published literature. Because so much of the risk is associated with that part of the riser in the splash zone it is more appropriate to quote failure rates per riser rather than per metre length of riser.

I.1 Data sources and basic failure rates

For North Sea experience, data sources record at least one major riser failure incident, leading to a fire and explosion. For an estimated 1,230 riser-years this gives a failure rate per riser of 8×10^{-4} per year, albeit based on very poor statistics, with upper and lower 90% confidence limits of 24×10^{-4}/yr and 4×10^{-5}/yr respectively. Other sources indicate a number of other riser cracks and leakages, but these are not yet available in sufficient detail for analysis.

Some figures are also available for serious riser failures leading to fires and/or explosions in the Gulf of Mexico. Five large failures and a much larger number of small or medium leaks are believed to have occurred. With a relevant estimated number of riser-years total of about 22,000 in the period concerned, this gives failure rates for:

— large failure: 2.3×10^{-4} per riser-year;
— smaller failures: 1.9×10^{-3} per riser-year.

US Geological Survey also publish data for riser incidents in the Gulf of Mexico. For all sizes of riser and leak rate, 39 incidents are listed. We estimate that for the time period covered (1967-76) the relevant number of platform years would be about 8,500, leading to a failure rate of 4.6×10^{-3}. Note, however, that this is a lower number of leaks than would be expected from the data above, and may represent poor reporting prior to 1970.

Because the North Sea data is the most directly applicable for North Sea platforms, the basic failure rate for major riser failures leading to fire/explosion is taken as 8×10^{-4}/riser-year. The Gulf of Mexico data is taken into consideration when this figure is subdivided by leak size.

I.2 Sub-division of Data by Cause

For risers it is essential to form a view of the causes of failure so that the relevance of possible protective measures can be assessed. Fortunately, although the North Sea data are too sparse for analysis, the Gulf of

Mexico data provide some information, although of limited relevance, according to the cause of failure. Of the total of 39 incidents, 10 of unknown cause (or unrecorded cause) are excluded. The breakdown is shown in Table 2.

Other data, more recently examined, gives a somewhat different picture, however. In an examination of incidents recorded by the USGS, using a breakdown of failures by both incident size *and* failure cause, it was found that whilst external corrosion was the dominant failure mode for all small and medium-sized failure external forces, ship-related external causes were responsible for all the larger ones. These larger failures were mostly at seabed level immediately adjacent to the platform, due to anchor problems, and are thus not directly appropriate to the North Sea operations.

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