Part VI

Integrity Management

Chapter 40 Integrity Management of Subsea Systems

40.1 Introduction

40.1.1 General

In recent years risk analysis has become increasingly recognized as an effective tool for the management of safety, environmental pollution and financial risks in the pipeline industry. The purpose of this Chapter is to apply risk-based inspection planning methodologies to pipeline systems, by developing a set of methods and tools for the estimation of risks using structural reliability approach and incidental databases, and to illustrate our risk based inspection and management approach through a few examples.

After outlining the constituent steps of a complete risk analysis methodology, it is intended to give detailed information about each step of the methodology such that a complete risk analysis can be achieved (Sørheim and Bai, 1999). Willcocks and Bai (2000) gave a detailed guidance on evaluation of failure frequency, consequence, risk and risk-based inspection and integrity management of pipeline systems.

40.1.2 Risk Analysis Objectives

The objectives of risk analysis are:

- To identify and assess in terms of likelihood and consequence all reasonably expected hazards to Health, Safety and the Environment in the design, construction and installation of a pipeline;
- To ensure adherence to the appropriate international, national and organizational acceptance criteria.

40.1.3 Risk Analysis Concepts

After completing an investigation of initiating events, cause-analysis should then follow; the final stage would be an analysis of consequences. An outline of the methodology is given in Figure 40.1.

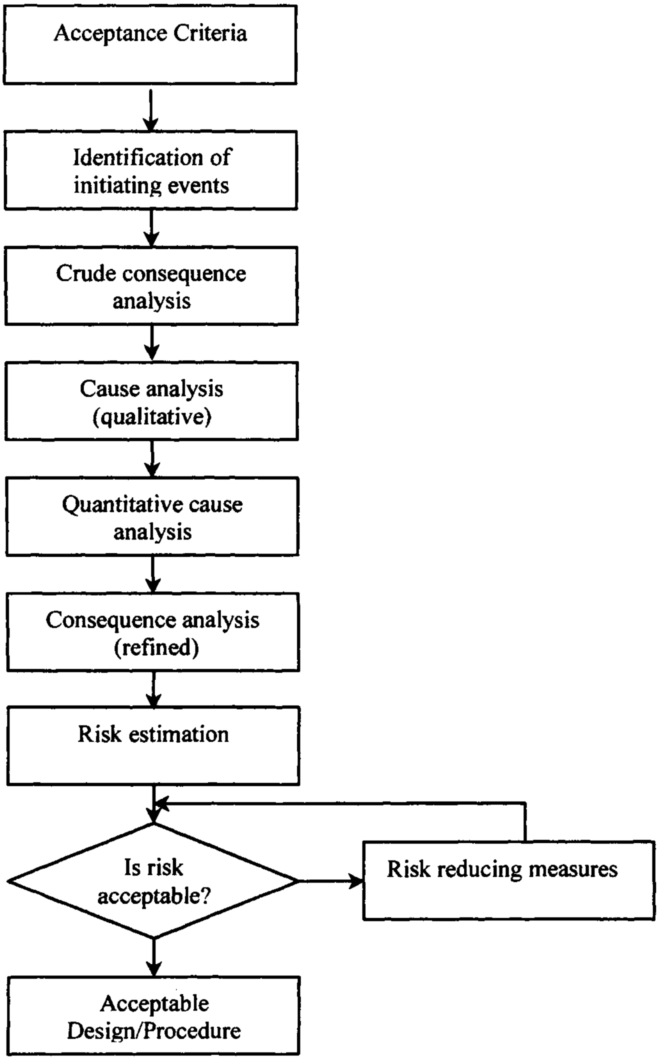

Figure 40.1 Risk analysis methodology.

40.1.4 Risk Based Inspection and Integrity Management (RBIM)

This is a means of focusing and optimizing the use of resources to 'high risk' areas in order to minimize costs, ensure effective and efficient asset management by ensuring the required confidence in the assets integrity and availability. It is employed in pipeline systems due to the high costs for a pipeline modeling, inspection and maintenance, but credible risks of failure.

RBIM is essentially the determination of required Structural Reliability Analysis (SRA), inspections (type, frequency/time and extent), maintenance tasks (e.g. repair to pipeline intervention, coatings, corrosion inhibitor etc.) to maintain the risk of failure via credible/potentially high risk modes below an 'acceptable level'. The establishment of failure patterns and failure rates (FCA) which also identifies failure warnings.

These together define the failure risks. Depending on the level of risk of failure for each mode and pattern of failure the required analysis, inspections, maintenance and repair tasks are selected. For example a review of historical failure databases e.g. PARLOC'00 indicates that the major failure modes are internal corrosion and external impact. Thus the main efforts (in terms of design, structural modeling, inspections etc) should be focused on these failure modes.

40.2 Acceptance Criteria

40.2.1 General

The acceptance criteria are distinctive, normative formulations against which the risk estimation can be compared. Most regulatory bodies give acceptance criteria either qualitatively or quantitatively. The NPD regulation states the following:

- In order to avoid or withstand accidental events, the operator shall define safety objectives to manage the activities.
- The operator shall define acceptance criteria before risk analysis is carried out.
- Risk analysis shall be carried out in order to identify the accidental events that may occur in the activities and the consequences of such accidental events for people, for the environment and for assets and financial interest.
- Probability reducing measures shall, to the extent possible be given priority over consequence reducing measures.
- Subsea pipeline systems shall be to a reasonable extent, be protected to prevent mechanical damage to the pipeline due to other activities along the route, including fishing and shipping activities.

Individual corporations may choose to implement internal acceptance criteria. These acceptance criteria may be based on the relative cost between implementing a risk reducing measure and the potential loss. Also many projects specify a pipeline availability requirement. Thus total losses must be such to ensure required availability.

If the risk estimation arrived at is not within the acceptable risk, then it is necessary to implement alterations. This new system should then be analyzed and compared with the risk acceptance to ensure adequate risk levels. This is an iterative process, which will eventually lead to a system/ design, which is acceptable.

40.2.2 Risk of Individuals

The FAR (Fatal Accident Rate) associated with post commissioning activities (the installation and retrieval of pigging equipment) has been evaluated. The FAR acceptance criteria are defined to be 10 fatalities per 10^8 working hours. The maximum FAR (Fatal Accident rate, No. of fatal accidents per 10^8 hours worked) for the operational phase should be ≤ 10. The maximum FAR for the installation phase should be ≤ 20.

40.2.3 Societal Risk

The society risk is 3rd Party (Societal) Risks posed to passing fishing vessels and merchant shipping. Acceptance of 3rd party risks posed by pipeline should be on the basis of the F-N curves shown in Figure 40.2 below.

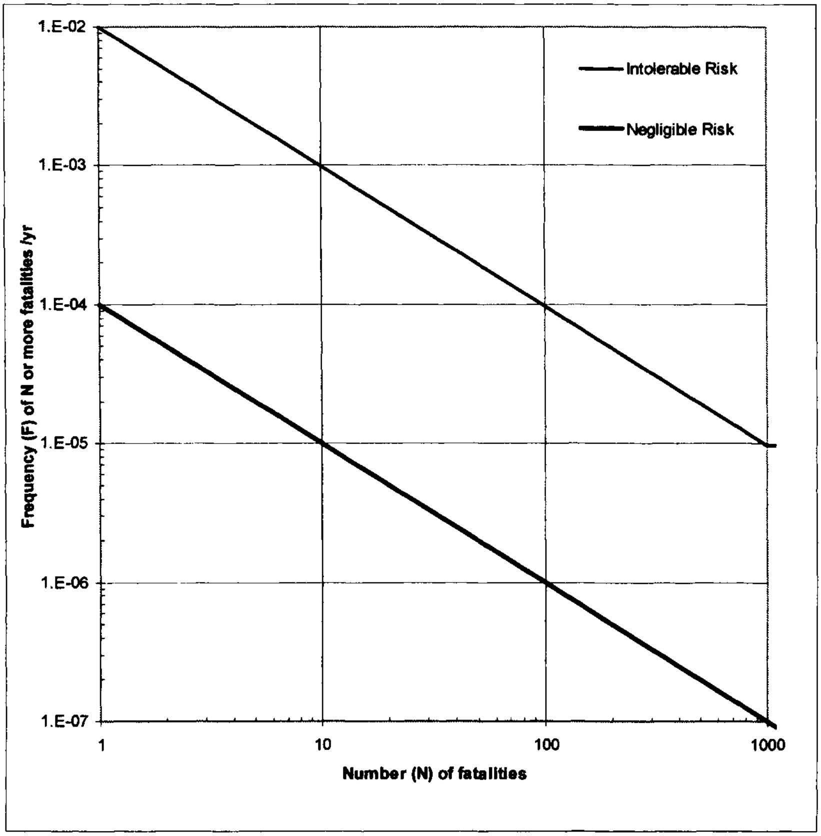

Figure 40.2 Societal risk acceptance criteria.

40.2.4 Environmental Risk

All incidents considered as initiating in the assessment of individual and societal risks during the operational phase are considered to be initiating for the purposes of determining the Environmental Risks. Loss of containment incidents during operation of pipeline will have minor local environmental effects. The environmental consequences of loss of containment incidents are therefore classified as being Category 1 (Table 40.1), i.e. the recovery period will be less than 1 year.

In addition any incidents having the potential to result in the release of corrosion inhibitors during commissioning of the pipeline are considered to be initiating with respect to Environmental Risks. Acceptance of the environmental risks associated with the construction and operation is normally based on the operator's criteria, which is established based on economical and political considerations.

Table 40.1 Acceptance criteria for environmental risk.

Category	Recovery period	Operational phase probability per year	Installation phase probability per operation
1	< 1 year	$< 1 \times 10^{-2}$	$< 1 \times 10^{-3}$
2	< 3 years	$< 2.5 \times 10^{-3}$	$< 2.5 \times 10^{-4}$
3	< 10 years	$< 1 \times 10^{-3}$	$< 1 \times 10^{-4}$
4	> 10 years	$< 5 \times 10^{-4}$	$< 5 \times 10^{-5}$

Causes of Loss of Containment incidents considered during the operational phase are:

- External impact (sinking vessels, dropped objects, trawl impact);
- Corrosion (external and internal);
- Material defect.

40.2.5 Financial Risks

All incidents considered as initiating in the assessment of individual and societal risks are considered to be initiating for the purposes of determining the Risks of Material Loss. In addition any incidents occurring during construction and installation and having the potential to result in damage to and/or delay in the construction of the pipeline are considered to be initiating with respect to Risks of Material Loss. The costs of incidents have been considered as being made up from:

- notional cost of fatalities;
- cost of repair;
- cost of deferred production.

The expected (average) number of loss of containment incidents and associated fatalities have been used to derive an expected annual cost incorporating each of the quantities given above. The acceptability of risks of material loss will be determined using cost benefit analysis. Risk reduction measures should be implemented if cost benefit analysis shows a net benefit over the full life cycle.

To summarize, the acceptance criteria shall be based upon a cost benefit evaluation, where the expected benefits must be much greater than the costs of implementing and operating with the risk reducing measure, i.e.:

$$C_{IMPL} + C_{OP} << C_{RED} \tag{40.1}$$

where:

C_{IMPL} : cost of implementing the risk reducing measure.

C_{OP} : net present value of operational cost related to the measure.

C_{RED} : net present value of expected benefits as a result of the risk reducing measure.

40.3 Identification of Initiating Events

Identification of initial events is regularly referred to as hazard identification, in the offshore industry. The main techniques that exist are:

- Check Lists- Review of possible accidents using lists which are developed by experts
- Accident and Failure Statistics- Similar to the checklists but are derived from failure events.
- Hazard and Operability Study- Used to detect sequences of failures and conditions that may exist in order to cause an initiating event.
- Comparison with detailed studies- Use of studies, which broadly match the situation being studied.

After the completion of this investigation it is necessary to examine the hazards and identify the significant hazards, which need to be analyzed further.

40.4 Cause Analysis

40.4.1 General

There are two purposes of cause analysis; firstly, it is necessary for the identification of the combinations of events that may lead to initiating events. Secondly, it is the assessment of the probability of the initiating event occurring. The first one is a qualitative assessment of the system and the latter is quantitative.

The qualitative analyses aim to; detect all causes and conditions that could result in an initiating event and develop the foundation for possible quantitative analysis. The aim of the quantitative analyses is to determine a probability value for the occurrence of an initiating event. The analysis tools that are available are stated below. This chapter will discuss only the first two approaches.

- Fault Tree Analysis;
- Event Tree Analysis;
- Synthesis Models;
- Monte Carlo Simulations;
- Equipment Failure Rate Databases.

40.4.2 Fault Tree Analysis

The fault tree is a graphical diagram of logical connections between events and conditions, which must be present if an initiating event should occur. A fault tree for a system can be regarded as a model showing how the system may fail or a model showing the system in an unwanted situation. The qualitative analysis maps systematically all possible combinations of causes for a defined unwanted event in the system. If available data can be supplied for the frequencies of the different failure causes, quantitative analysis may be performed. The quantitative analysis may give numerical estimates of the time between each time the unwanted event occurs, the probability of the event etc.

The Fault Tree Analysis (FTA) has three major phases:

1. Construction of the Fault Tree: this is the identification of combinations of failures and circumstances that may cause failures or accidents to occur.
2. Evaluation of the Fault Tree: this is the identification of particular sets of causes that separately will cause system failure or accident.
3. Quantification of the Fault Tree: this is overall failure probability assessment from the sets of causes as defined above.

40.4.3 Event Tree Analysis

An event tree is a visual model for description of possible event chains, which may develop from a hazardous situation. Top events are defined and associated probabilities of occurrence are estimated. Possible outcomes from the event are determined by a list of questions where each question is answered yes or no. The questions will often correspond to safety barriers in a system such as “isolation failed?” and the method reflects the designers’ way of thinking. The events are partitioned for each question, and a probability is given for each branching point. The end events (terminal events) can be gathered in groups according to their consequence to give a risk picture.

40.5 Probability of Initiating Events

40.5.1 General

The methods stated above gives a methodology, which can be applied to any scenario such that it is possible to determine the conditions, which will result in an initiating event. However, it is necessary to determine how the probability value is to be assigned, when using the FTA and ETA.

Reliability analysis is used as the main method of determining the probability of failure caused by physical aspects of a pipeline i.e. corrosion, trawling impact, vortex-induced-vibrations etc.

Failure events that are not caused by physical failure of the pipeline may not be compatible with the reliability method of analysis; an example of this is the probability of human error. This type of failure requires deeper analysis using techniques such as historical data analysis or using comparable circumstances from other industries.

40.5.2 HOE Frequency

Human/organization error (HOE) probability is an area of pipeline risk analysis that is rarely quantified with reasonable accuracy, this is primarily due to physical and mental distance placed between individuals designing, constructing and operating the pipeline. A justifiable basis for a risk evaluation can be established by implementing an assessment of HOE. The purpose of a HOE evaluation is not to predict failure events, rather it is to identify the potentially critical flaws. The limitation of this is that one cannot analyze what one cannot predict.

There is little definitive information on the rates and effects of human errors and their interactions with organizations, environments, hardware and software. There is even less definitive information on how contributing factors influence the rates of human errors.

Lack of dependable quantitative data that is currently available on HOE in design and construction of pipeline structures can be compensated for using the following four primary sources of information, presented in work by Bea (1994).

1. Use of judgment based on expert evaluations;
2. Simulations of conditions in a laboratory, office or on sites;
3. Sampling general conditions that exist on site, laboratory and office;
4. Process reviews, accident and near miss databases.

Considering the quantity of conclusive data, which is available, the principle mode by which to quantify assessments is judgment method. As investigations into pipeline failures should eventually lead to comprehensive and reliable databases of HOE, these databases will compliment judgments and allow a more justifiable quantification to be arrived at.

It is necessary that any results that are deemed to be meaningful are qualified and unbiased. Investigations by Bea (1994) gives a number of biases that can distort the actual causes of HOE, these are listed in Table 40.2. It is important for the evaluator to try to minimize these biases, as it is impossible for them to be eliminated entirely.

Table 40.2 Influence on bias (Bea, 1994).

Type of Bias	Influence on Judgment
Availability	Probability of easily recalled events are distorted
Selective perception	Expectations distort observations of variables relevant to strategy
Illusory correlation	Encourages the belief that unrelated variables are correlated
Conservatism	Failure to sufficiently revise forecasts based on new information
Small samples	Over estimation of the degree to which small samples are representative of a population
Wishful thinking	Probability of desired outcomes judged to be inappropriately high
Illusions of Control	Over estimation of the personal control over outcomes
Logical construction	Logical construction of events which cannot be accurately controlled
Hindsight	Over estimation of the predictability of past events

Following research by Williams (1988), Swain and Guttman (1981) and Edmondson (1993), quantified data for HOE has been developed. This is based on experience gained in the nuclear power industry in the U.S.A. Experiments and simulations led to information regarding human task reliability.

Work undertaken by Swain and Guttman (1981) presents general error rates depending on the familiarity of the task being undertaken by the individual, included is a range of limitations or circumstances that the individual may be experiencing, this is shown in Figure 40.3. By assessing the intensity of these limitations or circumstances it is possible to adjust the value assigned to certain tasks. Other investigations (Williams, 1988) appear to correlate with this information. However, a multitude of influences impact upon these values and have potentially dramatic effects on the normal rates of errors (i.e. factors of 1E-3 or more). These influences include organizations, procedures, environments, hardware and interfaces. Information regarding these influences can be found in Bea (1994) and others.

It is important to establish the significance of any error that may occur as this is not established in the information developed. An error can be either major/significant or minor/not significant. Studies performed by Swain and Guttman (1981) and Dougherty and Frangola (1988) indicates that minor or not significant errors are often noticed and rectified, thus reducing their importance in human reliability. Further quantification of human reliability has been corroborated for a number of tasks relating specifically to structural design; the necessary information is investigated by Bea (1994).

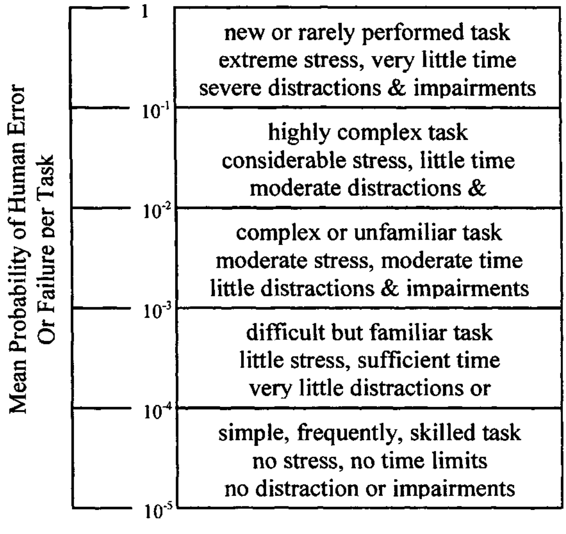

Figure 40.3 Human error rates.

40.6 Causes of Risks

40.6.1 General

This section will outline some common causes for the four different risk scenarios that were outlined in the introduction.

40.6.2 1st Party Individual Risk

The scope of this type of risk is limited to a consideration of the potential for ignited releases as a result of dropped object impact associated with maintenance/workover activities taking place after commissioning or random failure of the pipeline (discussed in next section).

The sources of the potential dropped objects are assumed to be the vessels employed for maintenance/workover. The assumptions made in order to determine the probability of loss of containment is as follows:

- Objects are assumed to fall in a 30° cone centered at a point directly above the pipeline;
- Objects are assumed to fall with equal probability at any point within the circle on the seabed defined by the drop cone. It is assumed that all dropped objects enter the sea, rather than landing on part of the vessel.
- The probability that the hazard zone, resulting from a loss of containment, coincides with the dropping vessel, is assumed to be 0.5.

Details of such operations are unlikely to be known during design, thus judgments are often required (based on previous experience) and the analysis updated later. During design this analysis necessary since decisions about protective requirements need to be considered.

40.6.3 Societal, Environmental and Material Loss Risk

Risks associated with construction, installation and commissioning of the pipeline do not impact on members of the general public. Only incidents that occur during the operation of the pipeline are therefore considered to be initiating with respect to Societal Risk.

The hazards giving rise to societal risks will also contribute to the environmental and material loss risks. These hazards include the following:

1. **Fishing Interaction**

Movement of fishing vessels around the location of subsea pipelines pose a risk. The frequency of such an event can be derived from existing databases (PARLOC).

2. **Merchant Vessels**

Incidents caused by passing merchant ships include emergency anchoring, dropped containers and sinking ships. Databases can again be used to determine the density of merchant vessels and the probability of the above incidents occurring.

3. **Construction Vessels**

Loss of containment incident frequencies as a result of construction vessel activities may be estimated based on databases. However, while it is accepted that construction activities contribute to the overall loss of containment frequency for pipelines, it is not considered to be appropriate to treat such incidents as initiating for Societal Risk calculations. This is because the presence of construction vessels will in itself exclude the presence of merchant shipping.

4. Random Failures

This may be due to any material failure of the pipeline and can usually be determined using reliability analysis.

40.7 Failure Probability Estimation Based on Qualitative Review and Databases

A risk review 'largely at a qualitative level' of the pipeline segments to generic failure and degradation modes is performed to establish the failure modes that may pose a threat at various locations along the pipeline. The risk review is based on:

- Generic/historical failure rates from relevant pipeline databases;
- Pipeline design and history of operating conditions;
- Known condition and incidents affecting pipeline and basic/high level structural damage and probability predictions.

The review is incorporated within a spreadsheet, in which as much design and operational data as possible regarding the pipeline is first input. Where relevant the pipeline is divided into suitable segments e.g. where other components in the line exist such as Tees, Risers, Riser bases, spools etc., crossing of shipping lanes, trawling areas and inshore areas. In this way the specific failure modes relevant to a particular location or item/component can be established.

A high level (basic) structural reliability assessment considering the specific failure mode is made, mainly considering the normal/accepted uncertainties. Failure predictions based on generic/historical failure data are also made. These represent the accidental cases where the pipeline will have been subject to conditions outside its design conditions or required design conditions were not achieved. The occurrence of accidental events are generally random, often result in immediate failure or within a very short time period such that inspecting the pipeline for accidental conditions/damage generally provides no benefit. The main means in dealing with accidental/unplanned conditions is to eliminate or reduce their likelihood to acceptable levels. Thus the identification of potential accidental events and their elimination is critical to the effective risk management of pipeline systems.

Generic Hazard/Pipeline damage list

Extreme Environmental Loads

- Earthquakes
- Severe wave and current loading
- Seabed movement & instability

Process Deviations

- Over-pressure
- Under-pressure

- Over & Under temperature
- Process upset – Offspec product into line

Excessive Internal Corrosion

Excessive Internal Erosion

Excessive External Corrosion

External Interference

Commercial Marine Traffic

- Dropped anchors
- Dragged anchors
- Sinking vessels
- Grounding vessels

Fishing/Trawling

- Impact loading
- Pull over loads
- Hooking
- Trawl pull-over combined with thermal buckling

Munitions

Falling/Rolling Boulders

Example of Risk Review - Considering Internal Corrosion

A sample of such a review is presented here considering internal corrosion of a new pipeline transporting normally dry gas but containing CO_2. The gas is dried to a high quality prior to export by a glycol drier. Thus the potential for internal corrosion (and hence failure) from CO_2 in wet service exists, it cannot be readily discounted and further assessment is required.

The general issues are; what are the required reliabilities of the gas drier, gas monitoring and process upset detection requirements, drying of the line after an upset, extent of corrosion allowance, if any and how often the line should be cleaned and inspected.

Part of the input data to the workbook is the product mass balance; the user is to ensure that all potential corrosive products are entered. For the case in question the cause of internal corrosion is CO_2 in wet service as a result of a) minute water content during normal production, b) process upset c) accidental operation (e.g. accidental water ingress into line during subsea pigging operations).

In this case the corrosion rates for each condition are calculated based on de Waard et.al. '93 (which is included in the workbook) and expected duration of wet service. For the process upset and accidental cases, estimates of the duration of wet service need to be established. These are based on:

- Probability/frequency of process upsets (based on driers reliability);
- Probability of detection (are there alarms, process trips on drier, monitoring of gas quality etc.);
- Probability of drying line within certain period after incident;
- Probability of accidental ingress (based on historical failure probability of gas pipelines from internal corrosion (PARLOC '96).

The uncertainties (potential variation) in these estimates are also input, high estimates are generally used. A basic conservative estimate of the pipelines structural reliability over time is then made based on the predicted safe operating pressure (accounting for corrosion damage) according to Bai et al '97 (– *Strength/Resistance model*), design pressure and uncertainties in the above estimates.

With respect to the estimates of accidental corrosive/wet service, the frequency of such an occurrence is based on the historical corrosion failure rate from PARLOC'96. Accidental internal corrosion conditions can result in very significant corrosion rates, but should rarely occur. Thus accidental corrosive service is not included in the 'normal/accepted' estimate of yearly corrosion rate over the life of the pipeline.

The causes of potential accidental events and resulting extreme conditions to the line are to be identified and estimated as far as reasonably practical e.g. undetected water ingress during subsea pigging or other activities in which water or other/increased corrosive products may be introduced (undetected). Eliminating or reducing the likelihood of these events is the main means of managing this risk. The potential time to failure in the event of such accidental operation is also predicted. For the case in question it was considered that water ingress from subsea pigging was the only potential accidental condition. If it occurred the service limit state acceptance criteria would be exceeded relatively quickly (within the year), though actual pipeline failure would be expected to take a few years. Thus normal cleaning pigging on a yearly base should protect against failure from such an accidental event, though if it occurs significant corrosion damage is inevitable.

It was found that the corrosion was very dependent on the upset frequency and incidental duration such that reliable means of detection and limitation of incidental duration is required. With such means in place the assessment predicts negligible corrosion such that no corrosion allowance is recommended nor intelligent pigging operations. However it is considered that an inspection should be made on a medium term basis (e.g. every 3-5 years), particularly in the early phase of operation to verify the corrosion prediction models and ensure no damage during RFO. Only if it is 100% certain that no significant upsets and accidental operations has occurred should such an inspection be omitted. With such means in place the assessment predicts negligible corrosion such that no corrosion allowance is recommended nor intelligent pigging operations.

40.8 Failure Probability Estimation Based on Structural Reliability Methods

40.8.1 General

Where the failure mode is identified as being significant and/or more specific details of the structural damage (defect data) to the pipeline are known (i.e. for pipelines that have been in operation for a number of years) then a more detailed SRA is possible and justified. Such analyses is performed using simple SRA spreadsheet based tools, based on simplistic 'boot strap' probabilistic methods (API 2A-LRFD), that do not require propriety software. For such analysis the following base data is required:

(1) Measured defect data from survey

If such data is available, then it needs to be correlated into useful input data e.g. the nature of the defects (type of corrosion – pitting, grove, girth welds), mean defect depth, length and area, along with the variance/standard deviation of such parameters. Else nominal defects are assumed based (where possible) on experience from similar lines.

(2) Pipeline Material/Strength Properties

The pipeline SMYS, SMTS and flow Stress are required. The variance in these mean values need to be established and is generally obtainable from published and manufactures data.

(3) Pipeline geometric properties

The following geometric properties in terms of mean value and variance need to be developed for each relevant section of the pipeline:

- Nominal diameter, it is not expected that this will vary along pipeline
- Wall thickness, the design/mean wall thickness and variation along the pipeline length
- Ovality, again such factor may vary along the pipeline length – though a design limit will be specified.

(4) Pipeline Loading Characteristics

Pressure loading at relevant segments along the pipeline is to be defined in terms of mean operating pressure, standard deviation and variance. Extreme high pressures should be accounted for, based on the reliabilities of pressure regulating and protection systems.

Temperature profile, this is not a strict loading, but affects the corrosion rates and axial force in pipeline. Over operating life the temperature profile may vary and may need to be accounted for.

40.8.2 Simplified Calculations of Reliability Index and Failure Probability

The probability of failure is dependent on the likelihood of the loading exceeding the pipelines strength/resistance as illustrated in Figure 40.4.

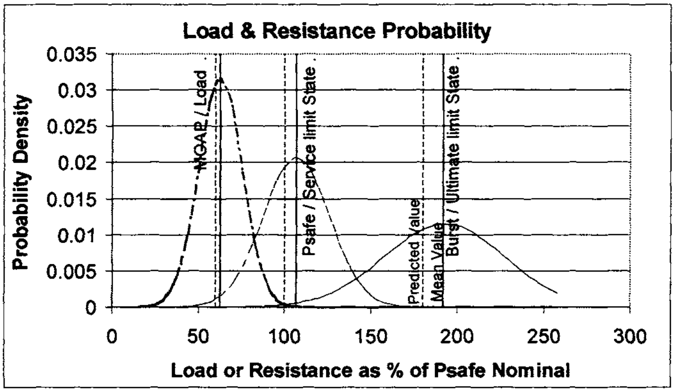

Figure 40.4. Load and resistance probability densities.

The Safety Index (β) is defined as (API 2A-LRFD):

$$\beta = \frac{\text{MeanSafetyMargin}}{\text{Uncertainty}} \equiv \frac{R_m - S_m}{\sigma_{RS}} = \frac{P_{safe.mean} - P_{op.mean}}{\sigma_{Psafe.meanPop.mean}} \tag{40.2}$$

and the probability of failure P_f is calculated from:

$$Pf = 1 - \Phi(\beta)$$

By establishing and accounting for the main uncertainties in the:

- Pipelines nominal strength (load resistance against specific loading) dependent on the type of damage/degradation to the pipeline
- Pipelines nominal operating loads

The Reliability (Safety) Index (β) and probability of failure is calculated for a single defect as presented in the following text and illustration. These probabilities for all defects are then combined to give the safety index and failure probability of a pipeline segment and pipeline as a whole.

40.8.3 Strength/Resistance Models

An example model for the pipeline mean resistance (strength) against structural damage is presented here for damage from internal corrosion. The model was developed by Bai et al 1997, though many other models are available e.g. Shell '92 (D.Ritchie et al).

40.8.4 Evaluation of Strength Uncertainties

The uncertainty of pipeline strength is dependent on:

- Material strength uncertainty
- Defect measurement, detection and prediction uncertainty
- Pipeline parameter/geometry uncertainty.

- Strength model uncertainty

The uncertainties are measured in terms of standard deviation and variance from mean values and combine to give an uncertainty in the predicted pipeline safe operating pressure. The mean bias (B) and COV of the burst prediction model is (Bai et al 1997):

Model Bias, $B_M = \dfrac{P_{burst.actual}}{P_{burst.predicted}} \equiv 1.07$ with COV of 0.18.

and mean bias and variances of the equation parameters are:

$$B_{XA} = \frac{X_{A.actua}}{X_{A.predicted}} \equiv 0.8 \text{ with a COV of } 0.08;$$

$$B_{Xf} = \frac{\sigma_{f.actual}}{\sigma_{f.predicted}} \equiv 1.14 \text{ with a COV of } 0.06;$$

$$B_{Xf} = \frac{X_{L.actual}}{X_{L.predicted}} \equiv 0.9 \text{ with a COV of } 0.05.$$

Multiplying the mean bias by the 'predicted value' gives the mean 'actual value': $B_{mean} \cdot X_{predicted} = X_{mean.actual}$

Thus the nominal/design $P_{safe.design}$ value is calculated using the predicted values. The mean P_{safe} value is calculated by substituting the measured or assumed $X_{mean.actual}$ values into the above equation and multiplying by the model bias B_M giving $P_{safe.mean}$.

$$P_{mean\ busrt\ value} = P_{mean\ safe\ value} \cdot \gamma$$

In the Bai et al '97 criterion P_{safe} is determined by applying a safety factor to the predicted burst pressure (Ultimate limit State), this is about 1.8 to give the desired/required reliability. P_{safe} is the Service Limit State.

P_{safe} is thus a factored value of P_{burst} to account for the P_{burst} bias and variance. The mean value and variance of P_{safe} is thus only dependent on the corrosion parameter predictions (length and depth) and not the model bias and variance, as the latter is accounted for by the safety factor.

40.9 Consequence Analysis

40.9.1 Consequence Modeling

The consequence model attempts to model the sequence of events that occur after a failure event. The sequence for consequence Modeling is shown in Figure 40.5. It should be noted that this method of consequence Modeling is only suitable for failures relating to the pipeline releasing some type of fluid or gas. The following steps for the Modeling of a release event gives only a general outline of the sequence of events that ultimately leads to a calculation of the various losses. Many different models exist for modeling these release characteristics (from simple to sophisticated/complex). However, there has not been extensive research/experimentation into Modeling of subsea releases so generally there is a high degree of uncertainty in this Modeling and conservatism is often used. One specific suite of computer Modeling programs available is the HGSystem written by Thornton Research Center.

Discharge

In order to determine dispersion, information is required for the discharge, this includes; hole size, duration, rate and quantity.

Dispersion of Gas

Leakage of a gas pipeline under water will result in a plume, which rises and exits from the surface of the water in the shape of a circle.

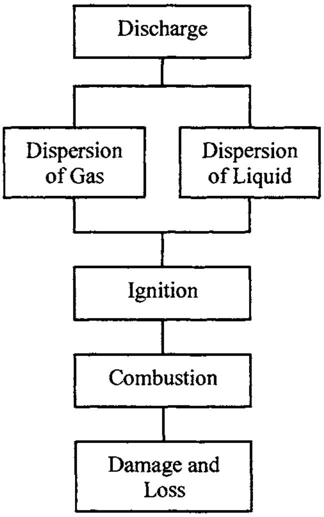

Figure 40.5 Modeling of consequence.

Dispersion of Liquid

The dispersion is dependent on the fluid released. Unstable condensate tends to be modeled as gas release (though a sound qualitative discussion about hydrate formation in water is required). Stable condensates will eventually rise to the surface to form a liquid pool at the surface. However, much of the dispersion is very complex and difficult to model.

Ignition

A leakage which does not ignite (i.e. not toxic, H_2S) will not present a risk to humans. A risk of ignition is developed using the following equation:

$$f_{fire}=f_{leakage} \times p_{ignition} \text{ (per year)} \qquad (40.3)$$

$p_{ignition}$ is probability of ignition occurring, given a leak of a flammable substance. This can be determined using an ignition model, which considers all possible methods by which ignition could take place.

Subsea releases can usually be considered to be delayed hence, ignition will result in an explosion or flash fire (few unconfined flammable gas clouds will develop into an explosion) for gas leakage. Fire pool could arise from an oil leak. However, in the case of a shallow water release a low momentum jet fire may develop if ignition occurs before a significant cloud can develop. Such an ignition will result in a jet flame.

Combustion

Jet fire-There are a number models establishing jetfire characteristics e.g. Shell Thornton. A jetfire is characterized by flame length and radiated heat flux.

Pool fire- the height of the flame is highly dependent on the depth of the slick, the rate of combustion of the liquid and the wind speed.

Explosion-clouds of flammable gas can explode when ignited this is termed an unconfined vapour cloud explosion. (UVCE). This type of explosion is relatively mild, and has two effects; heat and force. The force effects can be modeled using the multi-energy method. For humans exposed to an explosion heat is the critical factor in determining bodily harm. Force can also act indirectly on persons exposed to the explosion, injury or death can result from flying debris or glass splinters. For structures it is the effect of force, which is critical.

Damage and Loss

It is also necessary to model the potential damage and loss that can occur to the following (Olshausen, 1998):

1. Humans
   - Heat from explosions or fires
     - The injury is dependent on the dose, which is $D = \text{time} \times (\text{kW/m}^2)^{4/3}$
     - 50% death rate is likely when exposed to $D_{50} = 2000 \text{ sec} \times (\text{kW/m}^2)$
   - Force/missiles from explosions
     - There is a 50% chance of lung injury at 1.4 barg
     - There is a 50% chance of perforated eardrum at 0.5 barg
   - Toxic effects
     - For a majority of substances the D_{50} dose is known, that is a product of the time exposed and the $(\text{concentration})^n$ which results in a 50% likelihood of death.
2. Material loss
   - Repair of pipeline
   - Loss of Production
     - This is cost of lost income due to incapacity to provide a product to sell, this is a function of the time it takes to restore the pipeline to a functioning state.
3. Environmental damage

Uncertainty

All of the models in the sequence of analysis contain a significant degree of uncertainty. If taking a pessimistic approach and use factors of safety in the magnitude of 1.5 for each stage of calculation this will result in a total factor of safety of (1.5^4=) 5. This might be an unrealistic overestimate of the total value so it is necessary to adjust this figure to suit the situation.

Another difficulty with the consequence Modeling technique is that it is necessary to assume an initial discharge condition (i.e. the size of hole). This has a large influence over the models used, for a more comprehensive analysis a sample of likely release conditions could be evaluated. However, generalizations can be made regarding hole size based on failure rate data and type of failure, e.g. corrosion is likely to lead to small/pin pricks, where as third party interference tends to cause large diameter holes.

40.9.2 Estimation of Failure Consequence

The consequences of failure are:

- Consequential production losses
- Contract penalties (these can be extremely severe)
- Cost of repairing the pipeline
- Cost of repairing any damage to adjacent installations and environment
- Potential fatalities
- Cost of negative publicity

The potential consequences are very dependent on the operating pressure, pipeline length, diameter and content and size of the failure/release. The latter has been based on historical failure rates, for Subsea North Sea pipelines presented in PARLOC'96.

Potential fatalities, damage to adjacent installations and environment are assessed using standard consequence assessment methods incorporated within a spreadsheet suite of tools based on numerous published methods. The potential development of loss of containment is illustrated in the event tree, Figure 40.6. Consequence analysis techniques are generally well established within the Oil and Gas industry, though in certain areas better models are still required. The specific consequence models used for a subsea gas release are; pipeline time dependent gas release primarily based on Fannelop *et. al* '81, though other models are also used for comparison and Subsea plume modeling primarily based the methods for dispersion of Subsea Release reviewed by Rew, P.J. *et. al* '95 and hydrodynamics of underwater blowouts (Fanneløp, T.K. *et.al* '80). The potential surface gas cloud size and dispersion extent is modeled based on the methods reviewed by Rew, P.J. *et al* '95 and using HGSYSTEM suite. The potential explosion, flash fire extent and effects at the sea surface are calculated based on methods presented by AIChemE.

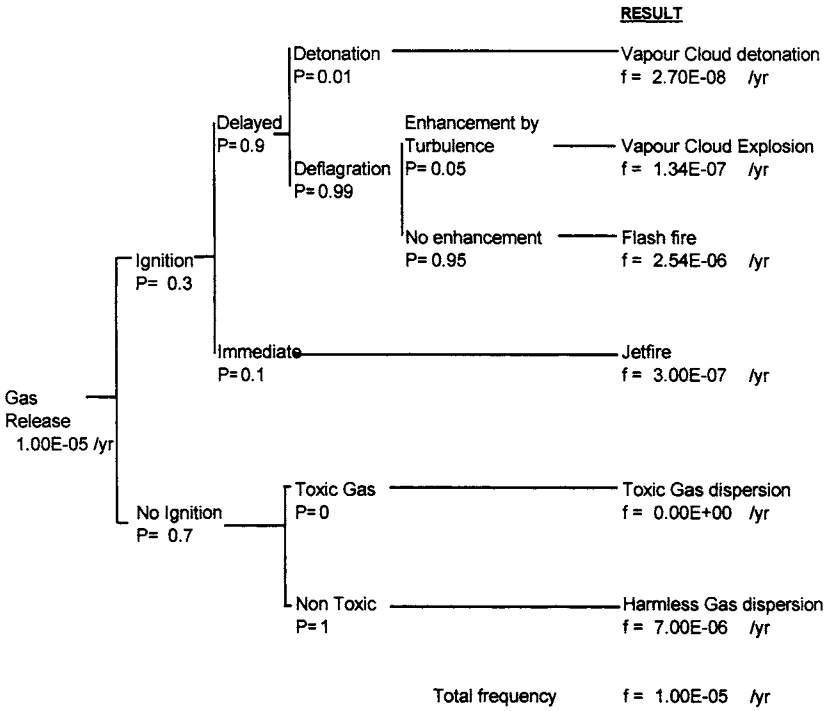

Figure 40.6. Event tree for gas release.

The calculated risks are compared against acceptance criteria, where these are not met further design or operational measures must be introduced to reduce the risks to within acceptable limits. The risk cost can calculated by adding all of the above consequence cost elements and multiplying it by the predicted frequency of pipeline failure and accident probabilities as presented by Bai et al '99 and Goldsmith et al. As the probability of failure increases with time (i.e. due time dependent structural degradation) the risk cost from last inspection can be plotted against the inspection and maintenance costs for increasing intervals, as illustrated in Figure 40.7 below. In this way the optimum value inspection interval can be selected.

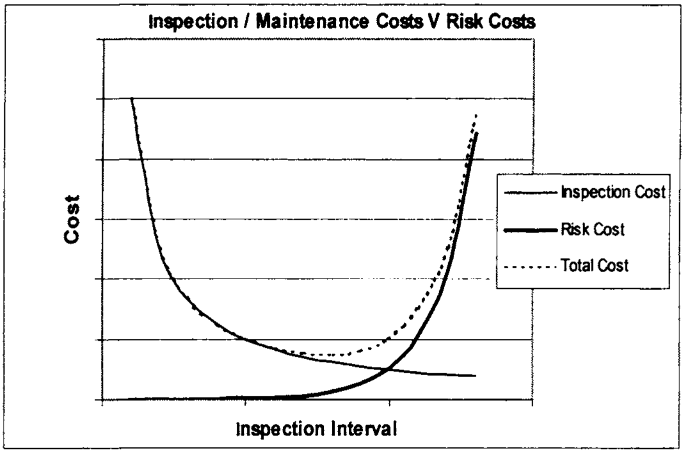

Figure 40.7 Maintenance costs verses risk costs.

40.10 Example 1: Risk Analysis for a Subsea Gas Pipeline

40.10.1 General

This risk analysis example will evaluate the risk acceptance and risk estimation of a North Sea pipeline transporting dry gas. This example will cover all aspects of the risk methodology developed in the chapter. By firstly determining the gas release for different hole sizes it is then possible to determine the potential effects on each type of risk.

40.10.2 Gas Releases

In order to provide an analysis that can be considered representative for the entire pipeline, the release rates have been estimated (conservatively) on the assumption that the water depth is 300m. This leads to a differential pressure at the site of loss of containment of ≈ 250 bar.

Representative hole sizes

Potential hole sizes will be modeled through the use of three representative hole sizes with diameters of 20mm, 80mm, and 200mm. The 20mm and 80mm hole sizes have been selected to provide ease of comparison with the hole sizes considered in the PARLOC database. The largest hole size considered is 200mm. This is considered to be a conservative upper bound to the equivalent hole size caused by major structural damage to the pipeline.

Discharge

Release rates have been estimated using SPILL. This is part of the HGSystem suite of programmer. The rates predicted for these hole sizes are given below. Indicative duration's for these releases are also shown below. These durations are based on the time required to blow down the pipeline through the hole and it is assumed that the mass release rates decrease linearly with time.

20mm hole	14.6 kg/sec	6000 hours
80mm hole	233.2 kg/sec	375 hours
200mm hole	1457.1 kg/sec	60 hours

The durations given above do not take into account emergency response actions initiated following the detection of a loss of containment. Hazard durations have therefore been assumed based on the time that it is expected to take for the existence of a release to be detected. These durations have been assumed to be 168, 48 and 6 hours, respectively. It should be noted that these times represent hazard duration's rather than leak duration's, i.e. they are estimates of the time required for the detection and location of a leak and for the imposition of measures to exclude shipping traffic from the affected locality. It should also be noted that the risk analysis results are not sensitive to the value assumed for the hazard duration for 20mm holes, since these do not result in flammable releases.

Subsea plume

The effect of a subsea gas release may be modeled as an inverted conical plume with a half cone angle of between 11 and 14 degrees in a zero current velocity situation. Assuming the most conservative case, this results for a 150m diameter release zone at the sea surface for the assumed 300m water depth.

Airborne dispersion

Airborne dispersion will be modeled using the program HEGADAS-S, part of the HGSystem suite. This program assumes that the gas evolves as a momentumless release from a rectangular pool. The pool has been taken to be 150m by 150m, so as to reflect the release into the atmosphere of the subsea plume.

Effect of water depth

Releases from greater depths will result in somewhat reduced mass flow rates. This is due to the increased seawater pressure at the site of loss of containment. Subsea dispersion over a greater depth will result in a larger gas evolution zone at the surface. These effects mean that the surface concentrations, and hence the dispersion distances and hazard zone dimensions will reduce with increasing release depth. The assumption of a 300m release depth for all loss of containment incidents is therefore conservative.

Stability

Pasquill stability classes define meteorological conditions from very unstable, A, to moderately stable conditions, F. These parameters are used in the Modeling of airborne dispersion. Two values of the Pasquill Stability Class have been used; these are Class D (Neutral Stability) and Class F (Moderately Stable Conditions). Class D is appropriate for night time and overcast day time, and has therefore been assumed to be representative of 75% of the time, with Class F being representative of the remaining 25%.

Wind speeds

Since there are no fixed installations at hazard as a result of subsea releases from the pipeline, wind direction is not required as an input to the risk assessments. Wind speeds are however required, since they determine the extent of the flammable gas clouds that may be generated by a release. The wind speeds and relative frequencies used to determine the hazard ranges associated with various releases are summarized in Table 40.3.

Table 40.3 Relative frequency of representative wind speeds.

Wind Speed Range (m/s)	Representative Wind Speed (m/s)	Relative Frequency
0 to 5	2	0.26
5 to 11	8	0.49
11 to 17	14	0.21
over 17	20	0.05

Hazard ranges

Hazard ranges are calculated in terms of the extent of the lower flammability limit (LFL) for different release rates, wind speeds and water depths. A concentration of 5% by volume has been used to represent the LFL. A total of eighteen gas dispersion analyses have been undertaken. These results are combined, using the data for relative frequency of Pasquill Class and wind speed, to provide an estimate of the hazard area associated with each of the three hole sizes. These are shown in Table 40.4.

Table 40.4 Average hazard areas for different hole sizes.

Hole Size	Hazard Area (m^2)
20 mm	0
80 mm	4900
200 mm	18650

40.10.3 Individual Risk

Acceptance criteria

The risks to which workers will be exposed are compared with the maximum operational FAR of 10 fatalities per 10^8 hours worked.

Cause analysis

Statistics of dropped object frequencies have been obtained from the 1992 Offshore Reliability Data Book, OREDA-92. This data source records a total of 7 dropped objects against a total calendar time of 648,200 hours or an operational time of 22,800 hours. Assuming an average lift duration of 5 minutes this is equivalent to 0.42 lifts per hour with a probability of a dropped object of 2.56×10^{-5} per lift.

Two lifting operations have been assumed at each work location, corresponding to one lift for installation of structures and one lift for pigging operations.

Assumptions

The following assumptions are made in addition to those stated earlier in the chapter.

1. Water depth has been assumed to be 300m.
2. The probability that the hazard zone resulting from a loss of containment coincides with the dropping vessel is assumed to be 0.5.
3. The probability of ignition has been taken as 0.3.
4. It is assumed that 50% of the persons on the vessel are working at any one time.

Consequence analysis

It is assumed that all persons on the vessel are at risk, the FAR is then a function of the proportion of persons on the vessel who are working, not of the total number of persons on the vessel.

Risk Estimation

The number of ignited releases per working location is given by:

$$f_{lift} \times p_{drop} \times p_{imp} \times p_{haz} \times p_{ign} = 2 \times 2.56 \cdot 10^{-5} \times 0.016 \times 0.5 \times 0.3 = 1.23 \cdot 10^{-7}$$

If the vessel remains on location for 48 hours and has n persons on board then this would result in x fatalities, as a result of 24n hours worked. The FAR is therefore equal to 0.51 x 10^{-8} (1.23 $\times 10^{-7}$ divided by 24). This is far less than the acceptance criteria established.

40.10.4 Societal Risk

Acceptance criteria

The acceptance criterion is 10^{-3} deaths per year.

Initiating incidents

Fishing interaction

Damage frequencies due to trawl gear interaction have been extracted from the PARLOC database. These are considered to be conservative, since the failure frequencies given in the PARLOC report are where no failures have been experienced. This is based on a theoretical analysis that does not take into account the robustness of the pipeline.

Merchant vessels

Because the minimum water depth for the pipeline is approximately 275m, emergency anchoring has not been considered. Incidents initiated by passing merchant vessels have therefore been restricted to dropped containers and sinking vessels. The initiating incident frequency data adopted is given in Table 40.5.

Table 40.5 Initiating incident frequencies.

Incident	Frequency	Hazard Distance
Dropped Container	5.15 × 10^{-6} per hour	15m
Sinking Vessel	2.11 × 10^{-7} per hour	150m

Construction vessels

Loss of containment incident frequencies, as a result of construction vessel activities, is given in PARLOC. However, while it is accepted that construction activities contribute to the overall loss of containment frequency for pipelines it is not considered to be appropriate to treat such incidents as initiating for societal risk calculations. This is because the presence of construction vessels will of itself exclude the presence of merchant shipping.

Random failures

Material and corrosion defect failure rates have been taken from PARLOC. Once again this data is considered to be conservative, particularly with respect to corrosion failure rates for export gas pipelines with a diameter > 10". It should, however, be understood that the corrosion defect failure rates used here can only be considered to be conservative provided that the pipeline is operated under the design conditions (i.e. dry). If the pipeline is to be frequently or continuously operated under wet conditions then the corrosion related failure rates would be significantly higher. The failure rates obtained from PARLOC are appropriate for the localized spot corrosion which may be experienced (often in association with a pre-existing defect) in a normally dry gas line in which corrosion is actively controlled and monitored on an ongoing basis.

Cause and consequence analysis

The total number of trawler crossings of the pipeline per year has been determined. It has been assumed that 50% of the trawlers will have a crew of 5 persons and 50% will have crews of 10 persons. It has been assumed that 15 people will on average be at risk per merchant vessel. This value is based on a population at risk of 10 people for 95% of vessels and 100 people for 5% of vessels.

In the absence of knowledge concerning the intensity of future 3rd Party construction activity it is not possible to predict the Societal Risks that will be associated with those activities. These risks will be subject to control by the 3rd Party concerned, and will contribute to the individual risks (the FAR) for those specific activities. In the absence of detailed information concerning the density of merchant vessel shipping, it has been assumed to be high. A merchant vessel crossing frequency of 29 per km year has been assumed.

The assumptions made with respect to the relative frequency of holes of different sizes are shown in Table 40.6.

Table 40.6 Calculated trawl impact frequencies.

Trawl Impact Frequency	Total Area	Pipeline
$f_{imp}/(\text{year} \times \text{km})$	2.63	0.42

Risk estimation

The expected number of 3rd party fatalities per year is 9.75×10^{-6} for the various scenarios considered. In view of the conservative nature of the calculations undertaken it is considered that the societal risks associated with the pipeline are acceptable.

40.10.5 Environmental Risk

No risk is posed since the material being transported is dry gas.

40.10.6 Risk of Material Loss

Initiating incidents

All incidents considered as initiating in the assessment of individual and societal risks are considered to be initiating for the purposes of determining the risks of material loss posed by the pipeline.

In addition any incidents occurring during construction and installation and having the potential to result in damage to and/or delay in the construction of the pipeline are considered to be initiating with respect to Risks of Material Loss.

Consequence analysis

Both repair cost and lost production cost have been assumed to be linearly related to the time taken for repair. Material costs for repairs have been neglected. Costs assumed are as follows:

- lost production 20 MNOK per day
- cost of repair spread 1 MNOK per day
- cost per fatality 100 MNOK

Time required for the repair of small or medium damage is assumed to be 16 days (clamp repair), time required for repair of large damage (new spoolpiece installed using mechanical connectors) is assumed to be 30 days. 3 days vessel mobilization has been assumed in each case. The costs (based on the above assumptions) incurred as the result of different sizes of damage are shown in Table 40.7. A discount factor of 7% is used to determine Net Present Values (1998 NOK) of future costs. The frequencies of incidents resulting in loss of containment are summarized in Table 40.8.

Table 40.7 Contributions to overall loss of containment rate.

	Small	**Medium**	**Large**	**Total**
Trawlers (Sinking)	0	0	$5.7\text{x}10^{-10}$	$5.7\text{x}10^{-10}$
Merchant (Sinking)	$1.3\text{x}10^{-8}$	$3.7\text{ x}10^{-9}$	$4.51\text{x}10^{-8}$	$6.18\text{x}10^{-8}$
Material Defect	$4.92\text{ x}10^{-7}$	$4.92\text{ x}10^{-7}$	$4.92\text{x}10^{-7}$	$1.48\text{x}10^{-6}$
Corrosion	$3.14\text{ x}10^{-6}$	0	0	$3.14\text{x}10^{-6}$
Trawl Impact	$1.16\text{ x}10^{-6}$	$2.91\text{x}10^{-7}$	0	$1.45\text{x}10^{-6}$
Subtotal (per km year)	$4.80\text{ x}10^{-6}$	$7.86\text{x}10^{-7}$	$5.60\text{x}10^{-7}$	$6.13\text{x}10^{-6}$
Maintenance/ Workover (per year)	$5.37\text{ x}10^{-7}$	$5.37\text{x}10^{-7}$	$5.37\text{x}10^{-7}$	$1.61\text{x}10^{-6}$
Total	$6\text{ x}10^{-4}$	$9.9\text{ x}10^{-5}$	$7.1\text{ x}10^{-5}$	$7.7\text{ x}10^{-4}$

Table 40.8 Costs of repairs.

Hole Size	**Small**	**Medium**	**Large**
Cost of repair (MNOK)	19	19	33
Cost of lost production (MNOK)	380	380	660

40.10.7 Risk Estimation

The expected discounted lifetime cost of incidents is deemed acceptable, as it is only a small percentage of the steel cost of the pipeline.

40.11 Example 2: Dropped Object Risk Analysis

40.11.1 General

This calculation is used to present an assessment of the risk posed by dropped objects hitting spools, umbilical and flowline sections around a template. This example will concentrate on the determination of the probability of dropped objects hitting subsea installations.

40.11.2 Acceptable Risk Levels

There is a need to distinguish SLS (Serviceability Limit State) and ULS (Ultimate Limit State). For this example, SLS is assumed as a dent damage larger than 3.5% of the pipe diameter, while ULS corresponds to bursting due to internal over pressure and combined dent and crack defects. The pipeline will not burst unless a large dent and a certain depth of cracks exist simultaneously.

The principle used in establishing the acceptance criteria is that the recovery time (for the most sensitive population) after an environmental damage incident should be insignificant relative to the frequency of occurrence of environmental damage. For this example, marine (pelagic) seabirds have been identified as the most sensitive resources during all seasons.

The damage category has been defined as minor for the field. The acceptance criterion is therefore a frequency $<2\cdot 10^{-2}$ for the field as a whole. This can broadly be grouped into three main risk areas; pipelines, templates and topside and risers.

The acceptance criterion for pipelines alone is therefore assumed to be 1/3 of the field specific criterion, namely a frequency $< 7\cdot 10^{-3}$.

40.11.3 Quantitative Cause Analysis

Probability cones

An object dropped at the sea surface is assumed to land within an area on the seabed which is swept out by a cone starting at the drop point. This area is determined by a cone with angle, ϕ.

It is further assumed that the probability of an object hitting a point within the cone follows a normal distribution and can be described as a function of distance x from the cone centerline.

$$p(x) = \frac{1}{\sigma\cdot\sqrt{2\pi}}\cdot \exp\left[-\frac{1}{2}\cdot\left(\frac{x-\mu}{\sigma}\right)^2\right] \tag{40.4}$$

where:

p(x) : probability of hitting a point a distance x from the cone centerline

σ : standard deviation

x : distance from the cone centerline

μ : mean value of x (here = 0)

The cone will sweep out an area with 99% cumulative probability of hit from a dropped object when:

$$X = d \cdot \tan\phi \tag{40.5}$$

where:

X : distance from the cone centerline giving 99% cumulative probability of hit

d : water depth

ϕ : cone angle

σ in Equation (40.4) can thus be determined by solving:

$$\int_{-a}^{a} p(X)dX = 0.99 \tag{40.6}$$

where: $a = X / \sigma$

Probability of flowline or spool hit

The probability of hitting parts of the pipeline or spool consists of three parts:

- Probability of dropping an object
- Probability of object landing within a cone area containing the flowline or spool.
- Probability of object hitting the spool or flowline (inside the cone area).

This is expressed in Equation (40.7).

$$P(\mathrm{hit}) = P(\mathrm{drop}) \cdot P(A_c) \cdot \frac{A_f}{A_c} \tag{40.7}$$

where:

P(hit): Probability of a dropped object hitting flowline, spool and/or umbilical

P(drop):Probability of an object being dropped

$P(A_c)$: Probability of a dropped object hitting the cone area A_c

A_f : Area of flowline, spool and/or umbilical within A_c, assumed = length x 1 m.

Energy absorbed by steel pipe

The energy required for a knife edge indentor to produce a dent in a pipeline may be calculated as follows:

$$E_d = 25 \cdot SMYS \cdot t^2 \cdot \sqrt{\frac{\Delta^3}{OD}} \tag{40.8}$$

where: t : wall thickness;

SMYS : Specified Minimum Yield Strength;

Δ : dent depth, assumed max. 3.5% of OD based on serviceability;

OD : outside diameter.

The effect of coatings and surface area of the falling object is conservatively neglected in Equation (40.9).

Basic data and assumptions for risk analysis

This example will consider the hit probabilities for a generalized L-spool. Table 40.9 presents the basic data for these calculations.

A 100m section of rockdump is assumed to follow directly after each spool. The hit probabilities are calculated for two areas:

- Probability of hitting the spool between the template and the start of the rockdump;
- Probability of hitting the pipeline outside the rockdump, but inside the 99% cone area.

The probability of the line being hit outside the 99% cone is considered negligible. Two flowlines and one umbilical are assumed for each template. The probability calculated considers a hit on any of these three items, for simplicity it is modeled as a total hit area of 3 x (one generalized spool length) x (a 1m corridor around each item).

The assessment is based on objects being dropped through the moon pool of the drill rig. Although objects may be dropped from the cranes, drops through the moon pool are assumed to be the worst case, as these will normally happen closest to the spools. A drill rig will be present on the field for the whole lifetime of the field (20yrs). A total of 17 templates has been assumed. This means that the time spent on one template will be 20yrs/17 ≈ 425 days. 75 days is added to this to account for increased drilling activities in the pre- and early production phase, after the lines are installed, giving a total of 500 days of drilling operations. There will be an average of 20 lifts/day during these 500 days, giving a total of 10000 lifts/20 years.

Table 40.9 Basic data and assumptions.

Item	Unit	Value
Water depth	m	300
Cone angle	°	30
P(drop)	-	$3\cdot10^{-5}$
Rig activity:	rig days/template/20 years	500
	Number of lifts/rig day	20
Design life	Years	20
Pipeline Outside Diameter	mm	259.8
Pipeline Wall thickness	mm	15.6

40.11.4 Results

Probabilities

Cone radii are found using simple geometric principles.

Cone radius, end spools: $(30^2 + 30^2)^{1/2} = 42$

Cone radius, end rockdump: $(130^2 + 30^2)^{1/2} = 133$

$X = 300\text{ m} \cdot \tan 30 = 173.2\text{ m}$

From Equation (40.5) and Table of the standard normal distribution:

$\sigma = X/2.575 = 67.2$ m (In a normal distribution; $P(-2.575<x<2.575) = 0.99$)

The cone area of the cone section encompassing the spools is:

$A_c = \pi \cdot (42)^2 = 5542\ m^2$

The spool area within this cone area is:

$A_f = 60m \cdot 3 \cdot 1\ m = 180\ m^2$ (length of pipe & umbilical within A_c with a 1m corridor)

Probability of hit within A_c:

42 m/67.2 m = 0.625 $\Rightarrow P(-0.625<x<0.625) = 0.468$

$$
\begin{aligned}
P(hit) &= 3 \cdot 10^5 \cdot 180/5542 \cdot 0.468 \\
&= 4.6 \cdot 10^7/\text{lift} \\
&= 4.6 \cdot 10^7/\text{lift} \cdot 20\ \text{lifts/rig day} \cdot 500\ \text{rig days/ 20 years/template} \\
&= 4.6 \cdot 10^3/20\ \text{year/template} \\
&= 2.3 \cdot 10^4/\text{year/template} \cdot 17\ \text{templates} \\
&= 3.9 \cdot 10^3/\text{year}
\end{aligned}
$$

To calculate the probability of a dropped object hitting the flowlines outside the rockdumped area, the procedure above is repeated considering the cone section between the end of the rockdump and the end of the 99% cone area, giving:

$A'_c = \pi \cdot (173.2^2 - 133^2)^{1/2} = 38670\ m^2$

$A'_f = 3 \cdot (173.2-133) \cdot 1m = 120.6\ m^2$ (length of pipe & umbilical within A_c with a 1m corridor)

Probability of hit within A'_c:

133 m/67.2 m = 1.979 $\Rightarrow P(-1.979<x<1.979) = 0.952$

$P(\text{hit within } A'_c) = 0.99-0.952 = 0.038$

$$
\begin{aligned}
P'(hit) &= 3 \cdot 10^{-5} \cdot 120.6/38670 \cdot 0.038 = 3.6 \cdot 10^{-9}/\text{lift} \\
&= 3.6 \cdot 10^{-9}/\text{lift} \cdot 20\ \text{lifts/rig day} \cdot 500\ \text{rig days/20 years/template} \\
&= 3.6 \cdot 10^{-5}/20\ \text{years/template} \\
&= 1.8 \cdot 10^{-6}/\text{year/template} \cdot 17\ \text{templates} \\
&= 3.0 \cdot 10^{-5}/\text{year}
\end{aligned}
$$

Energy absorbed by steel pipe

The energy required to produce a dent of 3.5% of OD is found to be 5.2 kJ. Only items of approx. 1 tonne will have an impact energy less than 5.2 kJ. It is assumed that most dropped objects will be heavier than this, and consequently also assumed that all dropped objects will damage the spool/flowline enough for repair to be required.

This assumption is conservative because the falling object area (the object will not necessarily indent the pipe in a "knife edge" fashion) and the protection offered by the flowline coating is neglected.

40.11.5 Consequence Analysis

As stated earlier this example analysis pays little attention to the consequence of pipeline failure. The only consequence which is considered is the environmental damage that could be suffered. The damage category which the environment is likely to suffer is 'minor'.

40.12 Example 3: Example Use of RBIM to Reduce Operation Costs

40.12.1 General

The above RBIM approach can be used in the following aspects:

1. To optimise the intervals between planned shut-downs and the amount of inspections: the optimisation can be conducted through us of a cost-benefit analysis and/or structural target reliability levels, particularly where all costs cannot be accounted for.
2. To select inspection methods: An inspection method that yields most of the return for the dollars spent for safety and business is to be selected.
3. To prioritise the areas where risks are highest: for safety/business critical elements, it is necessary to accept additional inspection costs.
4. To prevent un-planned shut-downs: the cost associated with loss of production and transportation as a result of un-planned shut-down can be reduced by focusing inspection effort on safety/business critical elements.
5. To maintain the capacity of oil and gas transportation. Most of business risk is due to reduced value of maximum allowable operating pressure.

These targets are achieved through the establishment of inspection programs in which basic questions like what to inspect, when to inspect and how to inspect are answered.

The cost saving through the use of RBIM needs to be balanced with the costs of applying the RBIM. Much of the inspection expenditure is to satisfy prescriptive legislative requirements and many operators are concerned as to the value derived from such frequent inspection regimes. Risk Based Inspection (RBI) is increasingly becoming an interesting and profitable alternative to traditional, frequently performed inspections, which may bring little added value. An optimum interval of inspection may be obtained by minimising the total costs. The selected interval of inspection should, however, be less than that determined by the requirements of regulatory and company's safety and business criteria.

Use of RBI also allows operating expenditure to be focused on a few "critical elements" that will give the greatest return on expenditure.

40.12.2 Inspection Frequency for Corroded Pipelines

The spreadsheet tool receives processed defect data similar to the format below. The safe operating pressure, safety index and failure probability is calculated for each defect over the remaining life of the line and presented graphically in the spreadsheet as shown overleaf. The future corrosion damage in this case is predicted based on de Waard et al.'93 and considered process operating conditions. The individual defect failure probabilities are combined to give the failure probability for each segment and the pipeline as a whole.

The nominal P_{safe} is calculated from the equation below, using nominal calculated / measured values of X_A and X_L:

$$P_{safe} \equiv \frac{1}{\gamma} .2. \sigma_f . \frac{t}{D} . \frac{1 - X_A}{1 - \left(1 + 0.6275 .XL + 0.003275 .XL^2\right)^{-0.5}}$$

$= 137.6$ barg

where,

$$X_A = \frac{0.66\, L.d}{L.t} \equiv 0.33 \quad \& \quad X_L = \frac{L^2}{Dt} \equiv 0.4$$

P_{safe} is the operating pressure that gives an acceptable/desirable safety index (γ) i.e. probability of burst for the individual defect considered ($P_{burst} = \gamma \cdot P_{safe}$).

Input Data

Pipeline Section Properties			
Section Diameter	D	(m)	1
Section Nominal Wall thickness	Wt	(m)	2.50E-02
	δ_t	(m)	0.0005
Factor of Safety (New Criteria)	γ		2
Usage Factor	F		0.72
	SMYS	(MN/m^2)	445
Ultimate Tensile Strength	UTS	(MN/m^2)	553
MAOP	P	(MN/m^2)	16.02
		Bar	160.2
	P_{yield}	Bar	222.5
Pipeline Section Corrosion damage Parameters			
Type (Spiral, Pit, Groove, Circum Weld)			Groove
Measured max defect depth.	d_o	(m)	5.E-03
Stand Dev.	σ_{do}	(m)	5.E-04
Average Corrosion Rate	r	(m/yr)	4.00E-04
Stand Dev.	σ_r	m/yr)	4.0E-05
Measured Width			0.05
Spiral Angle			90.00
Measured Corrosion Length	Lm	(m)	0.05

The mean P_{burst} is calculated by substituting into the nominal P_{burst} equation above, the mean X_A and X_L values, which are obtained by multiplying the measured value by its bias i.e. X_A

$_{\text{mean}} = X_{A\ \text{nominal}} \cdot B_{XA}$. The bias being obtained from analysis of experimental data and for the case in question given above. The equation is further multiplied by the P_{burst} model bias X_M and normalized by dividing through by the SMYS. Thus the normalized mean P_{burst} (R_m) is given by:

$$P_{safe} \equiv .2 \cdot \sigma_{f.} \frac{t}{D} \cdot \frac{1 - X_A}{1 - \left(1 + 0.6275 \cdot XL + 0.003275 \cdot XL^2\right)^{-0.5}} . B_{XF} \cdot B_{XM}$$

= 336 barg. The mean load is taken to be 137. barg multiplied by the load bias 1.05 giving a mean Load of 144.5 barg.

The variance of the mean resistance R_m is estimated from the variances of X_A, X_L X_F X_M, values of which are given above, thus $V_{Rm} \sim (V_A^2 + V_L^2 + V_F^2 + V_M^2)^{0.5} \sim 0.212$. The variance for the load (S_m) is taken from Bai '99 as 0.02. The Safety index β is calculated as $[\ln(R_m/S_m)/\sigma_{\ln RS}]$ where:

$$\sigma_{\ln RS} = ((\ln((R_m + V_{Rm}.R_m)/R_m))^2 + (\ln((S_m - V_{Sm}.S_m)/S_m))^2)^{0.5} = 0.19$$

Thus $\beta = \ln(336.0 / (137.6 \times 1.05)) / (0.19) = 4.56$ and the probability of failure $P_f = 1 - \Phi[\beta] = 2.33\text{x}10^{-6}$. This is well below the Ultimate Limit State acceptance criteria of $1\text{x}10^{-4}$. Thus if only this defect exists the safety factor of 2 can be reduced. For year 0, the following Safety levels are calculated for lower safety factors:

Safety factor	P_{safe}	Safety index	P_f
1,8	152.2	4	$3.1\text{x}10^{-5}$
1,6	171.2	3.75	$8.61\text{x}10^{-5}$

Note: for $\gamma = 1.6$ $P_{\text{operating}} = 160$ barg.

P_{burst}, P_{safe}, and safety index are predicted for the service life of the pipeline as illustrated in Figures 40.8 and 40.8 below. This analysis is repeated for every defect considered and an overall failure probability established.

If a safety factor greater than 1.6 is required then the cost of repairing the defect(s) verses reducing the operating pressure needs to be evaluated. However the defect(s) may be located near the export end of the pipeline such that the local operating pressure is much less than P_{safe}.. Thus depending on the relative costs, pressure protection systems may be put in place to prevent the local pressure exceeding P_{safe}, without reducing the inlet pressure and thus transport rates. If a safety factor of 1.6 is adequate (e.g. few significant defects), then initially no pressure derating is required. After approximately 5 years the ULS acceptance criteria is exceeded. At which point, either an intelligent inspection is performed to verify the predicted corrosion damage or the pressure is reduced (to a level that accounts for the uncertainty in predicted corrosion damage), depending on the relative costs. If many defects exist, the particular defects and segments can be ranked in terms of contribution to failure probability. Alternatively the line could be inspected when the predicted failure probability falls below $1\text{x}10^{-4}$ to establish whether the predicted corrosion rates are correct.

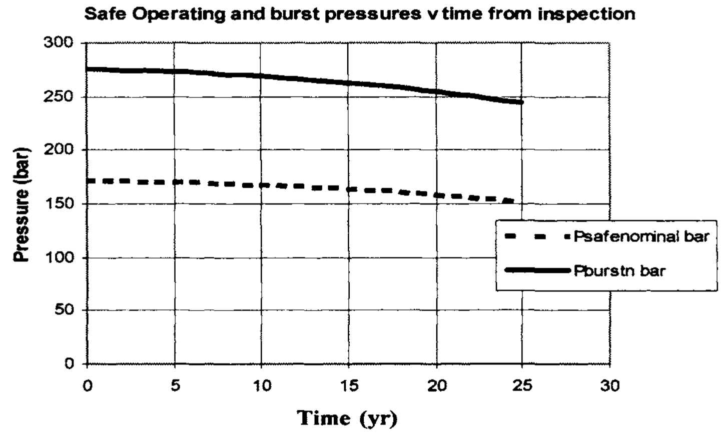

Figure 40.8 Operating and burst pressure vs. time from inspection.

Case B represents the situation where the operating pressure is reduced to P_{safe}.

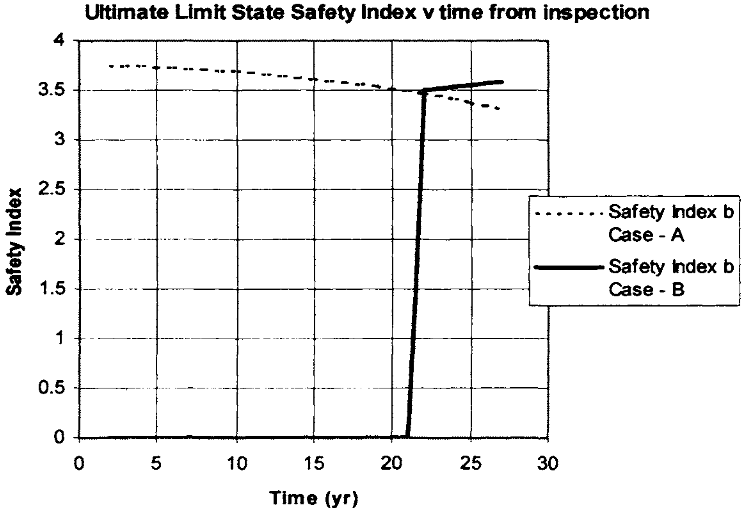

Figure 40.9 ULS safety index vs. time form inspection.

40.12.3 Examples of Prioritising Tasks

The RBIM tools can also be used to prioritise which areas to inspect and repair or other corrective actions to take. For a pipeline system all pressure containing parts that cannot be readily isolated (so that their failure does not affect the overall system) are generally equally critical and cannot be prioritised by this means. However supporting structures and equipment such as rock supports, protection structures and riser supports etc. will have varying criticality levels which can also be used to rank their inspection and maintenance requirements.

From the previous example, the failure predictions for each defect location are plotted verse location and time and compared to required reliability targets, see Figure 40.10.

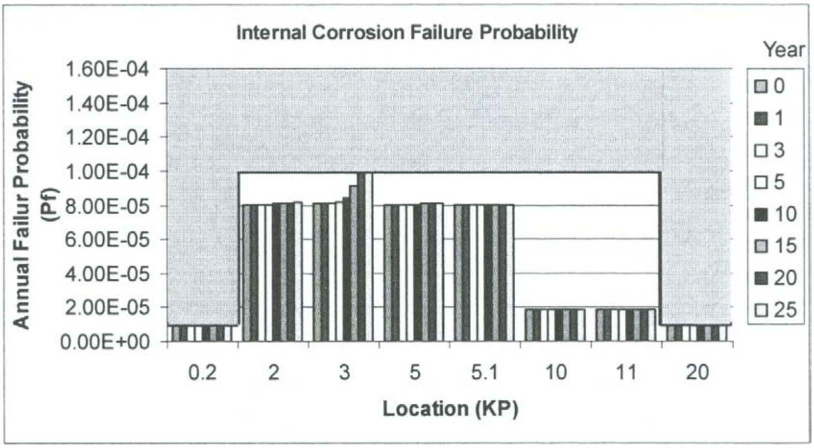

Figure 40.10 Specific defect/location failure probability with time.

Due to the high safety risks within the platform safety zone, the target ULS reliability is $1\text{x}10^{-5}$/yr compared to $1\text{x}10^{-4}$/yr for the midline. Thus it can be seen that the defects at KP 0.2 need to be repaired soon and that the export pressure needs to be reduced until the repair has been carried out. For the defect/segment at KP 20 also within a safety zone, it also needs to be repaired shortly unless the local operating pressure can be kept below P_{safe}.

For the midline section, all defects are within the acceptance criteria, though that at KP 3 indicates that it could develop into a concern. Also overall these defects exceed the acceptance criteria, thus those that pose the greatest likelihood of failure can be repaired first e.g. KP 2–5.1.

The local failure predictions can also be converted into local fatality, material loss and environmental damage risks and compared against risk acceptance criteria. This paper has presented a number of examples and approaches of applying a pipeline Risk Based Inspection and Integrity Management (RBIM).

40.13 References

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