This document was downloaded from the Penspen Integrity Virtual Library

For further information, contact Penspen Integrity:

Penspen Integrity
Units 7-8
St. Peter's Wharf
Newcastle upon Tyne
NE6 1TZ
United Kingdom

Telephone: +44 (0)191 238 2200
Fax: +44 (0)191 275 9786
Email: integrity.ncl@penspen.com
Website: www.penspenintegrity.com

Can Limit States Design be Used to Design a Pipeline Above 80% SMYS?

T.J.E. Zimmerman, Ph.D., P.Eng. [1]
A. Cosham, [2]
P. Hopkins, Ph.D., C Eng. [2]
and
N. Sanderson, Ph.D., C Eng. [3]

1. C-FER Technologies Inc.
Edmonton, Alberta
Canada
2. Andrew Palmer and Associates
(a division of SAIC Ltd.)
Newcastle upon Tyne
United Kingdom
3. BP Exploration Operating Company Ltd.
Sunbury on Thames, Middlesex
United Kingdom

ABSTRACT

This paper contains the results of a preliminary study, undertaken by C-FER and Andrew Palmer and Associates, for BP Exploration, to demonstrate the feasibility of utilizing limit states design procedures for the design of large diameter, onshore pipelines in remote areas. The objective of the study was to determine if a higher design factor can be justified than that currently specified for such a region; specifically if an increase in the basic design factor, *F*, from approximately 0.72 to 0.85 could be justified, thereby allowing the pipeline wall thickness to be reduced and a substantial weight saving to be achieved. The work included reliability analyses for three limit state failure scenarios: burst of undamaged pipelines, burst of corroded pipelines and burst of pipelines containing dents and gouges. Results presented show: (1) the calculated probability of rupture for a new pipe (i.e., with no damage, corrosion or other forms of deterioration); (2) the probabilities of failure for pipes containing corrosion or dent/gouge defects; and (3) the effects of a higher design pressure for each limit states scenario. The paper discusses the results, comments on the feasibility of justifying higher design factors and discusses the importance of an appropriate pipeline maintenance management system for monitoring and controlling structural integrity for the full life of a pipeline.

INTRODUCTION

Limit states, reliability-based design methods are currently being used by the pipeline industry as an alternative approach for designing against the various potential failure modes (*e.g.*, yielding, burst, collapse, fracture), taking into account the uncertainties that exist in establishing pipeline design loads and the resistance to failure. In some circumstances, these techniques can be used to justify less conservative design factors, and as the basis for evaluating various design and inspection options and remedial activities, which provide comparable, and acceptable, degrees of safety and reliability.

The traditional code approach to pipeline design, based on design factors, is believed to give a conservative design; although in fact, the operator may have little understanding of the vulnerability of the pipeline to the various failure mechanisms. Reliability-based limit state pipeline design offers the operator the potential for a complete understanding of the reliability of the pipeline. Some operators have used reliability-based limit state techniques to re-assess traditionally designed pipelines, allowing greater throughputs to be achieved through operating at higher pressures by reducing the redundancy in the original design.

Previous studies have considered the probability of the burst of defect free pipe as a basis for the use of less conservative design factors (*e.g.*, Sotberg and Leira, 1994a, and 1994b). There has been relatively little work assessing the implications of higher design factors on the likelihood of failure due to, for example, time dependent deterioration and external interference. An analysis of failures in onshore transmission pipelines in North America (Eiber *et. al*., 1995) indicates that the most common causes of failure are external interference and corrosion.

The work presented here uses limit states design concepts and reliability analysis to determine, for pipe designed using normal internal pressure design criteria, the probabilities of: (1) burst of a defect free pipe; (2) burst of a pipe containing corrosion defects; and (3) burst of a pipe containing dents and gouges.

It should be noted that the preliminary nature of this work required that assumptions be made concerning the size, distribution and rate of growth of defects in the pipeline. While every effort was made to select reasonable values for these parameters, results of this work should be viewed in that context, given the importance of these parameters.

Finally, while the work focused on what are believed to be the two most important failure causes in the context of this study (external corrosion and outside force damage), other secondary causes, which were not considered in detail, also require consideration. Despite these limitations, it is believed that this work is sufficient to demonstrate feasibility and describe the basic methodology.

LIMIT STATES AND RELIABILITY-BASED DESIGN

Brief Overview

Reliability-based design is a probabilistic design process where the loads and the strengths of materials and sections are represented by their known or postulated distributions, defined in terms of distribution type, mean and standard deviation. The probability of failure (P_f) for a specific design case is calculated as the probability that the maximum total load effect exceeds the resistance to failure, using reliability analysis techniques such as the first order reliability method (FORM) or Monte Carlo simulations. For instance, the probability distributions for internal pressure, material and section properties, and failure model error are all considered in determining the reliability (defined as 1- P_f) of a pressurized pipe, as shown in Figure 1.

Limit states design (LSD) is somewhat different. It is a semi-probabilistic design process in which the probabilistic aspects are treated at the code development stage (using reliability-based design methods) in order to define characteristic values and partial safety factors for load and resistance that are used to ensure, on average, an acceptably low probability of failure across a full spectrum of design cases. LSD is used as a practical method of incorporating reliability methods in the normal design process.

The basic LSD design equation is given by:

$$fR \geq aL \quad [1]$$

where fR represents the factored resistance, and aL represents the factored load effect. The factored load is determined by multiplying the nominal load, L, by the load factor, a. The factored resistance is determined by multiplying the nominal resistance, R, by the resistance factor, f.

To achieve the required reliability, the load factor, a, is generally ≥ 1.0 and the resistance factor, f, is generally ≤ 1.0 (see Figure 2). The choice of the nominal load values and load factors is dependent on the variability of the load and the model uncertainties associated with calculating it. Once the nominal loads and resistances are defined, the partial factors are used as a means of achieving sufficient separation between the load and resistance probability distributions to keep the probability of failure below an acceptable target value. In general, load effects with high variability (*e.g.*, environmental load effects) have higher load factors than those with lower variability (*e.g.*, gravity load effects). Resistance characteristics with high variability have lower resistance factors than those with lower variability.

In developing a limit states design code, load and resistance factors are not combined into a single design factor, since they are calibrated to provide acceptable safety levels over a wide range of design cases. This can be more efficiently achieved using separate factors. For this work, however, since relatively few design cases were considered, it was convenient to combine the load and resistance factors into a single design factor, F, where $F = f/a$. This also allows a direct comparison with design factors currently being used for pipeline design.

Use and Acceptance of Limit States Design

Limit states design codes have come into common usage over the last twenty years for many types of structures, including buildings, offshore structures, bridges, and nuclear containment structures. More recently, this development has been extended to pipelines. A limit states design approach is used in: the new DnV Rules for Submarine Pipeline Systems (DnV 1996); the Netherlands Requirements for Steel Pipeline Transportation Systems (NEN 3650, 1992); Appendix C, Limit States Design, in the Canadian code, Oil and Gas Pipeline Systems (Z662-96); and Annex G in the draft European Standard, Pipelines for Gas Transmission (prEN 1594, 1994). Most of these codes have yet to be formally calibrated (*i.e.*, partial factors have been selected to match existing design factors, rather than based on reliability analyses). The exception to this is the DnV offshore pipeline code, which was calibrated using reliability analysis methods, with some consideration given to accidental impact, under internal pressure loading (Collberg *et al*., 1997).

With respect to reliability analysis being used to justify higher than code-specified design factors, an important precedent was recently set with the Britannia gas export line (185 km) in the UK North Sea. It will operate at a design factor of 0.81 (*i.e.*, 81% SMYS, based on minimum wall thickness). This operating stress is based on a reliability-based, limit state design which was accepted by the UK pipeline regulatory authority (Health and Safety Executive) on a project specific basis (Mckinnon *et al*., 1996).

Target Reliability Levels

A limit states code is calibrated to ensure that selected appropriate reliability levels, called target values, are attained in design. A reliability target, which normally has a value very close to one (*e.g.*, 0.9999), can also be expressed in terms of its complimentary probability of failure, which is a number very close to zero (*e.g.*, 0.0001), since by definition, reliability is equal to one minus the probability of failure. As already explained, load and resistance factors (or a single design factor) are used as the means of achieving sufficient separation between the load and resistance probability distributions to keep the probability of failure below the acceptable target value.

Target failure probabilities for pipeline design can be established through risk analysis using economic, life safety, and environment criteria. The work recently conducted for PRC*I* (Zimmerman *et al.* 1997) concluded the following with respect to target reliability levels:

- Risk analysis shows that the governing criterion depends on the failure consequences associated with different products. In general, life safety is the critical constraint for gas and HVP pipelines in populated areas, while environmental safety is most important for LVP pipelines.
- Cost optimization (based on average North American failure costs) suggests an average failure probability of 10^{-4} per km per year for the design of both oil and gas pipelines.
- The life safety criterion leads to an average target failure probability of 10^{-5} per km per year for the design of gas pipelines in areas with moderate population densities, and 10^{-4} per km per year for remote areas.

Based on these conclusions, a target reliability level of 10^{-4} per km per year is suggested for this initial phase of work as being appropriate for remote areas.

It should be remembered that the probability of failure is simply a measure of uncertainty and that absolute values should be treated with caution. The strength of the limit states method is that it allows quantitative comparisons to be made. A pipeline with a basic design factor of 0.72 would be 'acceptable' under existing design codes. Increasing the design factor to 0.85, say, increases the probability of failure. The question is whether or not this increase is significant in a remote area, and what additional measures may be required to maintain an 'acceptable probability of failure' (e.g. the implementation of a complimentary pipeline management system).

Credible Failure Modes

The two most common causes of failure in onshore gas transmission pipelines, external interference (mechanical damage) and external corrosion, were selected as the focus for this work.

External interference damage usually results from an incident such as accidental contact with the pipeline of earth moving equipment, agricultural equipment or dropped objects. It can occur during construction or operation and most often takes the form of dents, gouges or punctures of the pipe. While plain dents are not necessarily problematic, dents that contain gouges (*i.e.*, metal loss defects) can be severe, significantly reducing the failure pressure. Combined dents and gouges can have short fatigue lives; this work, however, focused on failure pressure under static load conditions. Protection from external interference damage can be provided by using a pipe wall thickness that is sufficient to resist such damage, or by reducing the probability of a damage event occurring through such measures as surveillance, pipeline marking, one-call systems, or concrete protective slabs over the pipeline.

Corrosion is a time dependent process that depends on the external and internal chemical environment of the pipeline. The occurrence of internal corrosion depends upon the chemical composition of the product, and is influenced by factors such as temperature and flow rate. External corrosion depends upon the soil properties, humidity and other similar factors, all of which can vary significantly along the length of a pipeline. External coatings, cathodic protection systems and condition monitoring are used to reduce the severity of external corrosion. In this study, internal corrosion was not considered to be a primary consideration.

Other less frequent causes of pipeline failure include stress corrosion cracking, welding defects in the seam or girth welds, design errors, and accidental hot taps. Some of these issues are dealt with through adequate management, inspection, operational and auditing procedures. The precommissioning hydrotest is used to provide a measure of assurance that no gross errors have occurred, such as a major seam weld defect, significant mechanical damage during construction, or the inclusion of a low-strength rogue pipe section in the pipeline. These failure causes were considered secondary to external corrosion and external interference, and were therefore not included in this preliminary study.

RELIABILITY ANALYSES

Undamaged Pipelines

The current design philosophy for internal pressure is to provide sufficient pipe strength to prevent excessive yielding in the hoop direction. The corresponding limit state design requirement can be written as follows:

$$f s_y = \frac{aPD}{2t} \qquad [2]$$

where f = resistance factor for material yield strength;
s_y = yield strength;
a = load factor for pressure;
P = internal operating pressure;
D = outside pipe diameter; and
t = pipe wall thickness.

Since the intention of this work was not to determine separate load and resistance factors, the limit state design equation was reduced to the familiar form:

$$t_{\min} = \frac{PD}{2F s_y} \qquad [3]$$

where $t_{\min}$ = specified minimum pipe wall thickness; and
F = design factor for internal pressure.

Using Equation 3 as the design equation for minimum wall thickness, the probability of failure was determined for a range of design factors.

Probabilistic characteristics of the basic design variables required for the analysis of this limit state are shown in Table 1. Data for material and pipe section properties were based on a limited data set, but are consistent with values used by others for similar analyses (*e.g.*, Sotberg, 1990). There was little information available concerning distribution type or variability related to internal pressure loads; however, Jiao *et al.* (1992) suggested a normal distribution for differential pressure, with a mean/nominal ratio of 1.0 and a COV of 3 percent. That assumption was made here as well, but requires further consideration.

To determine the probability of the hoop stress exceeding the yield strength of the pipe, Equation 3 was used to formulate the following limit state function:

$$s_y - \frac{pD}{2t} \leq 0 \qquad [4]$$

The probability of failure, P_f, was calculated by applying the first order reliability method as implemented in the computer program FORM (Gollwitzer *et al.* 1988). Figure 3 shows the calculated variation of P_f with respect to the design factor, *F*. As can be seen, the target value of 10^{-4} is only exceeded for design factors in excess of 0.9. At a design factor of 0.72 the probability of failure (*i.e.*, yielding) is less than 10^{-16}, which is very small compared to the target value.

To determine the probability of pipe burst, flow stress, rather than yield strength, is used as the limiting stress in the hoop direction. Flow stress, s_f, is defined as the hoop stress at which unconstrained plastic flow occurs in a pressurized cylinder and takes a value somewhere between the yield stress and the ultimate tensile strength. For this work, the flow stress was defined as $1.1 s_y$ (ASME 1991), resulting in the following limit state function:

$$1.1 s_y - \frac{pD}{2t} \leq 0 \qquad [5]$$

The variation of P_f with respect to *F* for this limit state (rupture) is also shown in Figure 3. It shows that the calculated probability of rupture for a new pipe (*i.e.*, with no damage, corrosion or other forms of deterioration) is very small compared to the reliability target.

The extremely low calculated failure probabilities suggest that a higher design factor would be justified if a pipeline could be maintained in an undamaged condition for its entire design life. Since this is not normally a reasonable assumption, the reliability of deteriorated pipe must also be considered. This analysis highlights the need to consider deterioration and the fact that, in this case, the a failure of defect free pipe is not a credible failure mode. This is a conclusion evident from historical data.

Pipelines with Corrosion Damage

The hoop stress at failure for a ductile pipe with a longitudinally oriented metal loss defect can be estimated using a semi-empirical model developed by Battelle (Kiefner 1969), that has been widely used as a basis for estimating the remaining strength of corroded pipe (ASME-B31G 1991). Although the basic format of the model has not changed, there have been attempts to redefine some of the input parameters in order to achieve better accuracy (*e.g.*, Kiefner and Vieth 1989, and Bubenik *et al*. 1992). The model used in this work was developed by C-FER for a different study (subsequently published by Brown *et al*., 1995) as an improvement over the original semi-empirical model. The basic model employed calculates the pressure resistance as a function of time (to account for defect growth) for a pipe with a specific corrosion feature. The probability of failure during a given time interval is calculated as being equal to the probability of failure before the end of the interval, less the probability of failure before the beginning of the interval. The equation used is as follows:

$$R(t) = \frac{2.3 t s_y}{D}\left[1 - C\left(1 - \frac{1-(h_0 + tg_h)/t}{1-(h_0 + tg_h)/(M(t)t)}\right)\right] \qquad [6]$$

where R = pressure resistance;
t = time elapsed
t = wall thickness;
s_y = yield strength;
D = outside pipe diameter;
C = model error;
h_0 = initial average defect depth;
g_h = growth rate of average defect depth; and
M = three-term Folias factor (Folias 1965).

The Folias factor, *M*, is given by:

$$M(t) = \sqrt{1 + 0.6275\frac{(L_0 + tg_l)^2}{Dt} - 0.003375\frac{(L_0 + tg_l)^4}{D^2 t^2}} \qquad [7]$$

for $\frac{(L_0 + tg_l)^2}{Dt} \leq 50$

$$M(t) = 0.032\frac{(L_0 + tg_l)^2}{Dt} + 3.3 \qquad [8]$$

for $\frac{(L_0 + tg_l)^2}{Dt} > 50$

where L_0 = initial maximum defect length; and
g_l = growth rate of maximum defect length.

The model represented by these equations was favoured over the standard ASME-B31G criterion because it is more accurate and less conservative.

Finally, the failure condition can be defined by subtracting the applied pressure, *P*, from the resistance, leading to the limit state function:

$$\frac{2.3 t s_y}{d}\left[1 - C\left(1 - \frac{1-(h_0 + tg_h)/t}{1-(h_0 + tg_h)/(M(t)t)}\right)\right] - P \leq 0 \qquad [9]$$

Dividing the total failure probability into probabilities of small leak and pipe body failure (large leak or rupture) at any point in time was done using a probabilistic model that was developed by C-FER's proprietary PIRAMID corrosion research project (Nessim and Hong, 1996).

Probabilistic characteristics of the basic design variables required for the analysis of this limit state are shown in Table 2. For this work, a more recent source was used to estimate the variability related to internal pressure (Sotberg and Leira, 1994a, 1994b); again however, this assumption requires further verification. The model error, *C*, was assigned a normal distribution with a mean value of 0.062 and a standard deviation of 1.362.

The values shown for corrosion defect length and depth were based on a limited amount of data. While in general the corrosion depth growth rates are considered reasonable for high, medium and low rates of corrosion respectively, they should be substantiated for conditions representative of the particular region being considered. In addition, the corrosion defect data given in Table 2 pertain to a single significant corrosion feature, of which there were assumed to be one per kilometer of pipeline.

The results of the corroded pipe reliability analyses are shown in Figures 4, 5 and 6. Figure 4 shows the total annual probability of failure (combined leaks and ruptures) for the three different corrosion growth rates (severe, moderate and low) and for two different design factors (0.72 and 0.85) over a thirty year time period. Figure 5 shows the calculated split between leaks and ruptures for severe corrosion rates. Figure 6 shows the effect of a higher pressure (for the same design factor) on the probability of failure.

The following observations can be made from these results:

1. The rate of corrosion has a much greater effect on the probability of failure than does the choice of design factor;
2. The total annual probability of failure (combined leaks and ruptures) exceeds the reliability target (10^{-4}) in approximately five years for a severe rate of corrosion and in approximately thirteen years for a moderate rate of corrosion. For low corrosion rates the total probability of failure does not exceed the target value after twenty years of operation;
3. The time to a given failure probability is not significantly reduced by increasing the design factor from 0.72 to 0.85;
4. Leaks are the dominant mode of failure, with the probability of a leak being one to two orders of magnitude greater than for 'ruptures' for most conditions; and
5. A higher design pressure (1550 psi vs. 1050 psi) results in a reduced probability of failure (due to the greater length of time it takes corrosion to grow through the pipe wall).

Subject to the limitations of this work, these results demonstrate that it is possible for a pipe designed using a design factor of 0.85 to meet target reliability levels for this failure mode, provided that corrosion rates are not severe, and that an appropriate inspection and maintenance program is in place to identify, locate and repair critical corrosion features that do occur.

Pipelines with Dent-Gouge Damage

The nominal hoop stress at failure of a pipeline containing a smooth dent and a gouge is best described by a fracture model proposed by British Gas (Hopkins, 1992). This failure criterion for combined dents and gouges is a mean predictive model; it does not give a lower bound prediction of the failure stress. The model is semi-empirical.

The basic model calculates the hoop stress at failure for a pipe with a specific dent-gouge feature using the following set of equations (given in imperial units):

$$s_f = C_1 \frac{2\bar{s}}{p} \cos^{-1}\left[\exp - \left\{ \frac{1.5pE}{\bar{s}^2 Ad} [Y]^{-2} \exp\left[\frac{\ln(C_v) - K_1}{K_2} \right] \right\} \right] + C_2 \qquad [10]$$

where

$$\bar{s} = 1.15 s_y \left(1 - \frac{d}{t}\right) \qquad [11]$$

$$Y = \left[Y_1 \left(1 - \frac{1.8 D_0}{2R}\right) + Y_2 \left(10.2 \frac{RD_0}{t.2R}\right) \right] \qquad [12]$$

$$Y_1 = 1.12 - 0.23\left(\frac{d}{t}\right) + 10.6\left(\frac{d}{t}\right)^2 - 21.7\left(\frac{d}{t}\right)^3 + 30.4\left(\frac{d}{t}\right)^4 \qquad [13]$$

$$Y_2 = 1.12 - 1.39\left(\frac{d}{t}\right) + 7.32\left(\frac{d}{t}\right)^2 - 13.1\left(\frac{d}{t}\right)^3 + 14.0\left(\frac{d}{t}\right)^4 \qquad [14]$$

and
s_f = hoop stress at failure (lbf/in^2);
$\bar{s}$ = plastic collapse stress of an infinitely long gouge (lbf/in^2);
s_y = yield strength (psi);
A = Fracture Area of Charpy (0.083 in^2 for a 2/3 Charpy specimen);
E = Young's Modulus (30,000,000 lbf/in^2);
C_v = 2/3 Charpy toughness (ft lb f);
d = gouge depth (in);
D_0 = dent depth at zero pressure (in);
t = pipe wall thickness;
R = outside radius of pipe (in);
K_1 = 1.9 (non-linear regression parameter);
K_2 = 0.57 (non-linear regression parameter);
C_1 = multiplicative model error; and
C_2 = additive model error.

The model uses the dent depth at zero pressure (this is the basis on which it was developed), which is assumed to be 1.43 times deeper than the dent depth in a pressurized pipeline due to "spring back".

The fracture model assumes that the gouge is located at the point of maximum stress concentration within the dent and that it is infinitely long (i.e., it does not incorporate a defect length term - many of the experimental tests were on pipe 'rings' containing slots which simulates an infinitely long defect).

Probabilistic characteristics of the basic required design variables are shown in Table 3. The values for pipe dimensions, yield strength and operating pressure are the same as those used for the corroded pipe analysis. Characteristics for the CVN energy were taken from other work (Zimmerman *et al.* 1997). The model uncertainty was established based on a data base of test results collated by the European Pipeline Research Group. The multiplicative model error parameter, C_1, was assigned a deterministic value of 1.1; the additive parameter, C_2, was assigned a normal distribution with a mean value of -4.83 ksi and a standard deviation of 8.1 ksi.

The values shown for both dent and gouge depths were based on a limited amount of data. While in general the defect depths are considered reasonable for deep and shallow gouge depths respectively, they should be substantiated for the particular region being considered. The deep gouge depth is considered more severe than would be expected for a pipe of this diameter and wall thickness. The dent depth was assumed to be that remaining in a pressurized pipeline after an external interference incident (i.e. the dent depth measured at pressure).

The defect data given in Table 3 pertain to a single significant dent-gouge feature. In order to calculate the total probability of failure, the assumption was made that the probability of occurrence of such a defect is 1/100 per kilometer of pipeline per year. This is another assumption that, while considered reasonable, requires verification.

Reliability analyses were conducted for two gouge depths (1.5 mm and 0.5 mm) and two design pressures (1050 psi and 1550 psi) for a range of design factors from 0.61 to 0.85. The results are shown in Figures 7 and 8. Figure 7 shows the probability of failure, given the existence of a dent-gouge damage feature. Figure 8 shows the probability of failure for an assumed probability of occurrence of 1/100 per kilometer per year. The target probability of failure (10^{-4} per km per yr.) should be compared to the latter figure.

The following observations can be made from these results:

1. An increase in design factor from 0.72 to 0.85 results in an increased probability of failure of between one and two orders of magnitude (although for shallow gouges they are below the target value even for the higher design factor);
2. A higher design pressure (1550 psi vs. 1050 psi) reduces the probability of failure by approximately one order of magnitude for dents with deep gouges, and by from one to three orders of magnitude for dents with shallow gouges;
3. Conditional probabilities of failure (given the occurrence of damage) range from as high as 0.1 per km per yr. for the thinnest walled pipe with a deep gouge, to as low as 1×10^{-7} for the thickest walled pipe with a shallow gouge; and
4. Probabilities of failure (for a probability of occurrence of 1/100 per km per yr.) for dents with a shallow gouges are below the target (10^{-4}) level for all design factors.

Subject to the limitations of this work, these results demonstrate that it is possible for a pipe designed using a design factor of 0.85 to meet target reliability levels for this failure mode, provided that adequate measures are taken to limit the magnitude and frequency of external interference damage to levels below those assumed in this work, and that an appropriate inspection and maintenance program is in place to identify, locate and repair critical damage features that do occur.

IMPLICATIONS FOR OPERATION AND MAINTENANCE

This work has indicated that pipeline reliability is very sensitive to damage incident rates, initial defect sizes and time-dependent defect growth rates. It is therefore important to ensure that the defect distributions assumed at the design stage are not exceeded during a given operational period of time. Adequate testing, inspection and audit procedures must be specified to ensure that the required tolerance limits are not exceed. A pipeline management system (Hopkins and Cosham, 1996) that combines an incident database with an interactive maintenance plan provides a method of monitoring and controlling the long term integrity of the pipeline.

A maintenance strategy must be used that ‘tracks’ the condition of the pipeline to ensure that all the criteria used at the design stage, and all key assumptions used (including the ‘credible failure modes’), are valid throughout its design life. Such a system also offers the potential to assess the effect of the maintenance strategy in a qualitative sense.

CONCLUSIONS AND RECOMMENDATIONS

This paper has demonstrated that, subject to the limitations of this work, it is potentially feasible to use reliability-based design procedures to justify an increase in the basic design factor, *F*, from approximately 0.72 to 0.85, for a large diameter pipeline in a remote area. The results have also demonstrated that the burst of defect free pipe is not a credible failure mode and that it is essential to consider damage and time dependent deterioration.

The increased design factor can be justified provided that: 1) corrosion rates are not severe; 2) adequate measures are taken to limit the magnitude and frequency of external interference damage; and 3) an appropriate inspection and maintenance program is in place with the ability to identify, locate and repair critical damage features that do occur.

The importance of a pipeline management system is emphasized. Such a system should combine an incident database with an interactive maintenance plan in order to provide a method of monitoring and controlling the long term integrity of the pipeline. Given the sensitivity of pipeline reliability to damage incident rates, initial defect sizes and time-dependent defect growth rates, it is important to ensure that the defect distributions assumed at the design stage are not exceeded during a given operational period of time. Adequate testing, inspection and audit procedures must be specified to ensure that the required tolerance limits are not exceed.

The scope of this initial study was limited to identifying potential benefits and to clearly demonstrating the LSD methodology. A company wishing to apply limit states design methods to a particular project would need to undertake a more detailed phase of work to provide a sound design basis. Recommended additional work includes:

1. Project-specific cost optimization work in order to verify the target reliability level of 10^{-4} per km per year that was selected for this work, and including consideration of time dependency and multiple limit states;
2. Comparison of the proposed design with a traditional design that would be ‘acceptable’, to determine whether the increase in the probability of failure is significant;
3. Gathering relevant, site-specific information in order to verify the assumptions made in this initial work related to: the size, distribution and rate of growth of defects in the pipeline; the frequency of occurrence of external interference; and the variability in line pressure, including the frequency and magnitude of over-pressure events;
4. Repeating the reliability analyses conducted here, using the new site-specific information obtained;
5. Reliability analyses for other failure modes (*e.g.*, fatigue of dent/gouge features), that the initial work classified as secondary, but that should be considered in order to rigorously consider all potential failure sources; and
6. Detailed development of a pipeline management system that will ensure the long term integrity of the pipeline.

REFERENCES

American Society of Mechanical Engineers (ASME) 1991. ASME B31G Manual for Determining the Remaining Strength of Corroded Pipelines. A Supplement to ASME B31 Code for Pressure Piping.

Brown, M., Nessim, M. and Greaves, H. 1995. Pipeline Defect Assessment: Deterministic and Probabilistic Considerations. Second International Conference on Pipeline Technology, Ostend, Belgium, September.

Bubenik, T.A., Olson, R.J., Stephens, D.R. and Francini, R.B. 1992. Analyzing the Pressure Strength of Corroded Line Pipe. Proceedings of the Eleventh International Conference on Offshore Mechanics and Arctic Engineering, Volume V-A, Pipeline Technology ASME.

CSA-Z662 1996. Oil and Gas Pipeline Systems. Canadian Standards Association, Rexdale, Ontario.

Collberg, L., Bjørnsen, T. and Mørk. K.J. 1997. An Introduction to the DNV 1996 Rules for Submarine Pipeline Systems, ISOPE-97, Honolulu.

DnV 1996. Rules for Submarine Pipeline Systems. Det Norske Veritas Classification AS.

Eiber, R.J., Miele, C.R. and Wilson, P.R. 1995. An Analysis of DOT Reportable Incidents on Gas Transmission and Gathering Lines for June 1984 Through 1992. Topical Report to Line Pipe Research Supervisory Committee of the Pipeline Research Committee of the AGA, NG-18 Report No. 213, July.

Folias, E.S. 1965. An Axial Crack in a Pressurised Cylindrical Shell. International Journal of Fracture Mechanics, Vol. 1 Part 1, pp. 20-46.

Gollwitzer, S., Adbo, T. and Rackwitz, R. 1988. First Order Reliability Method. RCP GmbH, Munich, Germany.

Hopkins, P. 1992. The Application of Fitness-For-Purpose Methods to Defects Detected in Offshore Transmission Pipelines. Conference on Welding and Weld Performance in the Process Industry, London.

Hopkins, P. and Cosham, A, 1997. How Do You Manage Your Pipeline? Seventh International Conference on Pipeline Risk Management and Reliability, Houston, USA, November.

Jiao G., Sotberg, T. and Bruschi, R. 1992. Probabilistic Assessment of the Wall Thickness Requirement for Pressure Containment of Offshore Pipelines. Offshore Mechanical and Artic Engineering Conference, Calgary, June.

Kiefner, J.F. and Vieth, P.H. 1989. Project PR 3-805: A modified Criterion for Evaluating the Remaining Strength of Corroded Pipe. A Report for the Pipeline Corrosion Supervisory Committee of the Pipeline Research Committee of the American Gas Association.

Mckinnon, C., Bell, G., Patel, J. and Hawkins, P. 1996. A Case Study of the Britannia Gas Export Pipeline Reliability Based Limit State Design. Risk and Reliability and Limit States in Pipeline Design and Operations Conference, Aberdeen, May.

NEN 3650 1992. Requirements for Steel Pipeline Transportation Systems. NNI (Netherlands). September.

Nessim, M.A. and Hong, H.P. 1996. Optimization of Metal Loss Corrosion Maintenance - PIRAMID Technical Reference Manual No. 6.0. Confidential to C-FER's Pipeline Program Participants, C-FER Report 96008, December.

prEN 1594. 1994. Pipelines for Gas Transmission. European Committee for Standardization. October.

Sotberg, T. and Leira, B.J. 1994a. Pipeline Design and Code Calibration. Offshore Pipeline Technology Conference, Oslo, Norway, 1994.

Sotberg, T. and Leira, B.J. 1994b. Reliability-Based Pipeline Design and Code Calibration. Proceedings of the Thirteenth International Conference on Offshore Mechanics and Arctic Engineering, Vol. V, pp. 351 – 363, 1994.

Sotberg, T. 1990. Application of Reliability Methods for Safety Assessment of Submarine Pipelines. Dr. Ing. Thesis, Division of Marine Structures, Norwegian Institute of Technology, Trondheim, Norway.

Zimmerman, T.J.E., Chen, Q. and Pandey, M.D. 1997. Limit States and Reliability-based Pipeline Design. C-FER Report No. 95027, submitted to PRC International.

Table 1 Probabilistic Data for Undamaged Pipe Failure Analysis

No.	Variable	Mean/Nominal or Mean/Specified	COV (%)	Distribution Type
1	Yield strength (X70)	1.10	3.5	Normal
2	Pipe diameter	1.0	0.06	Normal
3	Wall thickness	1.01	1.0	Normal
4	Operating pressure	1.0	3.0	Normal

Table 2 Probabilistic Data for Corroded Pipe Failure Analysis

Variable	Nominal or Specified	Mean/Nominal or Mean/Specified	COV (%)	Distribution Type
Yield strength (MPa)	483	1.1	3.5	Normal
Pipe diameter (mm)	1219	1.0	0.06	Normal
Wall thickness (mm)	10.8 to 18.7	1.01	1.0	Normal
Operating pressure (MPa)	7.24 and 10.7	1.07	3.0	Gumbel
Initial defect depth (mm)	0	0	-	Deterministic
Defect depth growth rate (mm/yr)				
high	0.25	1.0	60	Weibull
medium	0.10			
low	0.05			
Initial defect length (mm)	40	1.0	50	Weibull
Defect length growth rate (mm/yr)	1.0	1.0	50	Deterministic

Table 3 Probabilistic Data for Dent/gouge Failure Analysis

Variable	Nominal or Specified	Mean/Nominal or Mean/Specified	COV (%)	Distribution Type
Yield strength (MPa)	483	1.1	3.5	Normal
Pipe diameter (mm)	1219	1.0	0.06	Normal
Wall thickness (mm)	10.8 to 18.7	1.01	1.0	Normal
CVN (Joules)	129	1.25	23	Weibull
Operating pressure (MPa)	7.24 and 10.7	1.07	3.0	Gumbel
Dent depth (mm)	20	1.0	25	Weibull
Gouge depth (mm)		1.0	60	Weibull
deep	1.5			
shallow	0.5			

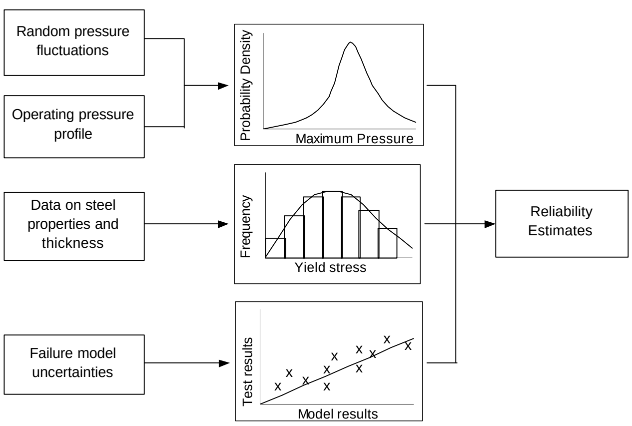

Figure 1 Reliability-based Design Concept for Internal Pressure

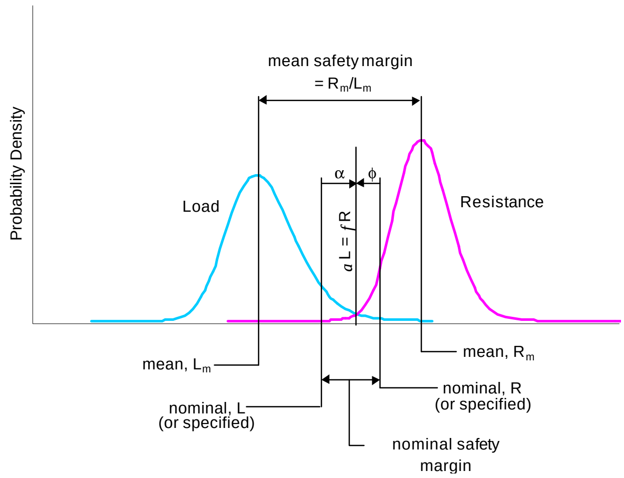

Figure 2 Load and Resistance Probability Distributions

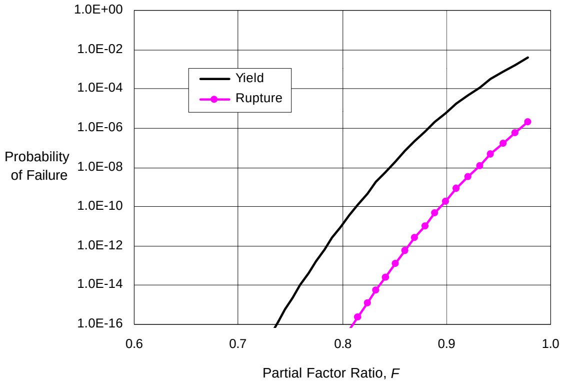

Figure 3 Annual Probability of Failure Due to Internal Pressure of New Pipe

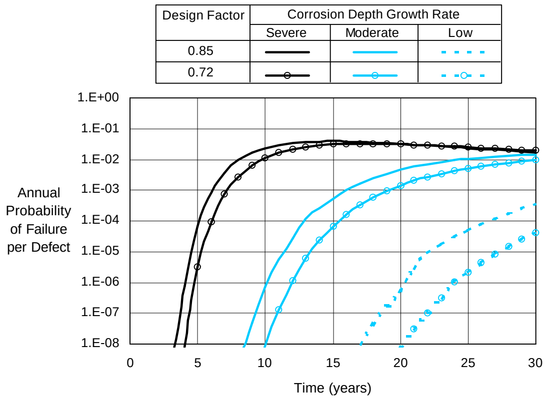

Figure 4 Annual Probability of Failure of Corroded Pipe (Combined Leaks and Ruptures)

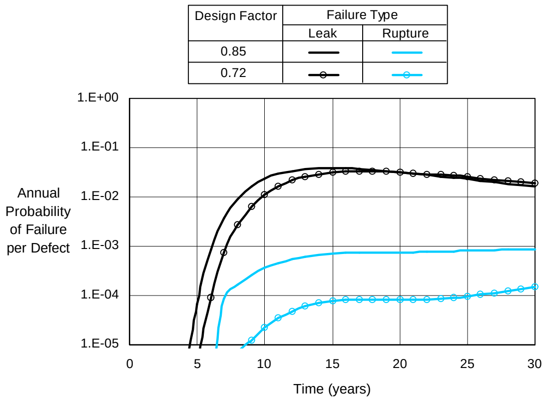

Figure 5 Annual Probability of Failure - Severe Corrosion Rate (0.25 mm/yr)

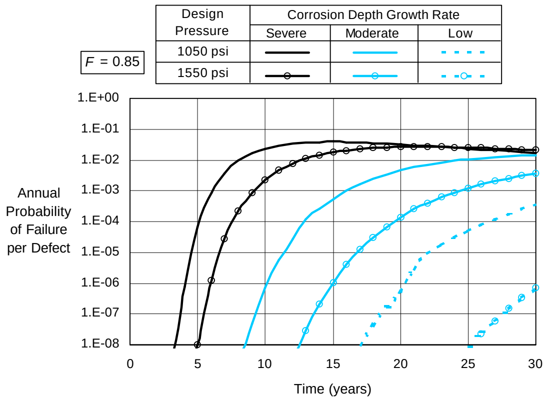

Figure 6 Annual Probability of Failure - Effect of Higher Pressure (F = 0.85)

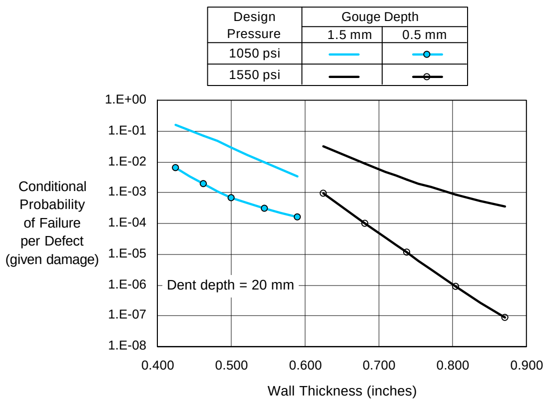

Figure 7 Conditional Annual Probability of Failure of Dent/Gouge

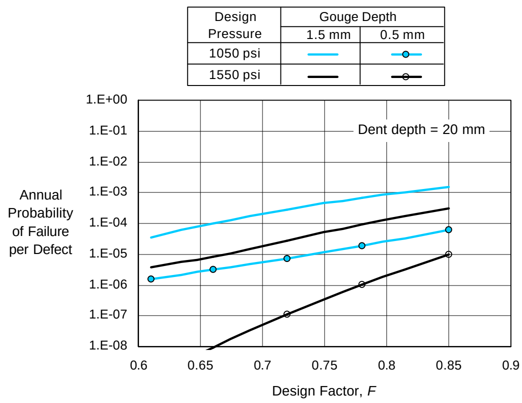

Figure 8 Annual Probability of Failure of Dent/Gouge