Reliability based design for pipeline construction and operation

V. Pistone, P. Bonandrini

Snam S.p.A., Technical Dept.
Piazza Santa Barbara 7, 20097 San Donato Milanese
ITALY

Abstract

Risk assessment, risk based inspection, and similar words are nowadays widely used in plant and pipeline operation, but they have widely different meanings. On one side qualitative models to support prioritisation decisions for pipelines maintenance are widely used, at the opposite extreme very seldom applied are quantitative analysis as a basis for negotiation with Authorities.

Within this context the paper will elaborate on the use of quantitative models for fracture probability calculation as tool for rational design and maintenance choices. Special problems, like earthquake or landslides, very severe environments, like pipeline construction an operation in Arctic regions make traditional design against internal pressure via safety factor choice, rather inadequate. Reliability analysis is an appealing tool to account in a quantitative way for the different failure modes relevant to pipelines in different environments.

Introduction

This paper deals with reliability based design and presents two case studies where the methodology is used. To understand the role of reliability based design a very simple overview of safety issues has been placed before.

Design and maintenance choices related to pipeline safety are confronted on one side with requirement from Authorities and public pressure and on the other side on the Company pressure to keep costs under control or reduce them. An excursus over the safety issue is then been deemed necessary. Acceptance criteria expressed as maximum allowed risk are presented for two countries in Europe where they have been enforced by law.

On the same ground of decision tools for maintenance there are also decision supports model using on ranking algorithms based on expert judgement. They appear to have a different use than reliability based design because they allow assessing the impact of alternatives only in a limited way. Also examined briefly here is the use of historical failure data, sometimes used to assess the validity of design choices.

Two case studies are then presented where the reliability approach is used allowing preliminary conclusions.

Pipeline safety

The approach to pipeline safety contained in the British law called "The Pipelines Safety Regulations 1996" [1] considers natural gas transmission at a pressure exceeding 8 bar as a "dangerous fluid" and requires the operator to prepare a document demonstrating that:

* all hazards relating to the pipeline have been identified;
* the risks arising from those hazards have been evaluated;
* the safety management system is adequate;

* arrangements for audits have been established.

No specific way of calculating the risks is specified, but of course in Great Britain there exists an Health and Safety Executive to check and agree the risk analysis. A specific level of tolerable risk is not defined. The safety approach is "securing that, so far as is reasonably practicable, persons are protected from risk to their health and safety".

A possible way of quantifying the so called ALARP (As Low As Reasonably Practicable) has recently been proposed [2] as shown in figure 1 where on the x-axis the calculated risk is indicated and in the y-axis there is the cost per risk averted, that is the reduction in risk obtained by a given activity with a given cost. In figure 1 the acceptance regime of a maximum tolerable risk is given by a vertical line, while linking cost and risk would be represented by some function, in this case a straigth line is given as an example, bounded by a lower limit, a certainly acceptable risk level to the left, and an unacceptably high risk on the right side. In between this approach would require to spend more to lower higher risks

In the Netherlands there is a precise quantitative target of a individual risk together with a societal risk criterion that the product $F N^2 < 0.01$ where F is the frequency and N the number of casualties. In the paper [3] recently presented at the Pipeline Technology Conference in Brugge an application for a 36" is given, where a safety distance of 35 m from the pipeline centreline is defined, based on the 10^{-6} yr^{-1} individual risk criterion, and a 115 m evaluation distance where the individual risk should not exceed 10^{-8} yr^{-1} is used as a basis for the class location definition.

The risk assessment procedures used for such an approach must of course be fully quantitative, take into account all possible failure modes and combining them in a single figure. The models for an accurate analysis are not yet available and a large amount of assumptions has to be made, so that for the same scenario very different figures are calculated by different specialists. Care should then be used in agreeing with Authorities precise safety targets.

Methods for prioritizing pipeline maintenance

At the opposite of the fully quantitative risk assessment methodologies seen above we find the scoring techniques used in setting of maintenance priorities. Several methods have been developed, among them PIMAR, prepared by Battelle for the Pipeline Research Committee of AGA in 1990 [4]. The basic idea is to make the maintenance decisions more rational by setting a scoring method and applying to all part of a network, coming then to a ranking not affected by personal like or dislike, specific previous experiences of the expert in charge of analysing a specific area and so on.

The method is in fact based on expert judgement on a number of parameters affecting pipeline integrity combined in a ranking algorithm together with a simplified calculation of the consequences of a failure, both in terms of population exposure and loss of service. The strength lies in its very simple structure, PIMAR uses only 28 parameters, all rather easy to evaluate, like good girth welds or poor girth welds or earthquake present or not present.

Similar ranking methods are widely used, and they have been expanded to include the need for intelligent pigging inspection and the time interval between inspections. These methods appear useful for complex system, either because a single plant contains a large number of items, or because a network is composed of a large number of lines. Using this approach to decide maintenance activities for just a couple of lines is useless, the operators know a lot more than is included in the model.

Failure statistics

A frequently used approach to assess the risk associated to a pipeline is to estimate the failure probability on the basis of the existing statistics of pipeline failures. The method is simple and avoids the problem associated with modelling and data distributions needed for a quantitative risk analysis, but is of little use to evaluate the impact on risk of the specific environment or design criteria. It is useful to examine some available information at least to have a feeling of the order of magnitude of failure frequencies.

According to the European incident data base of EGIG [5] no injuries have been reported causing fatalities or injuries on a natural gas transmission pipeline. The total exposure in the 1970 to 1998 period is 2.09 million kilometres-years, so that the probability of dying due to a gas transmission pipeline failure is lower than $4.8\ 10^{-7}$ per km yr. The frequency of incidents is $4.8\ 10^{-4}$ per km yr over the whole period, but drops to $2.1\ 10^{-4}$ per km yr when only the last five years are considered. No explanation for this decrease has been given in the paper, but it is seen in general as improvement in pipe construction and maintenance techniques, introduction of pigging allowed better avoidance of corrosion failures for example, and in an increased awareness of the public about existence and risk related to the gas transmission network, limiting the amount of failures due to mechanical damage.

Apart from these general figures the failure statistics can be used to assess the relevance of problems and to give generic failure estimates using more specific data sets. Figure 2 shows the failure frequency per type of incident (initiating cause) over the total period (1970-1998) and the performance only over the last five years (1994-98). External interference is by far the largest cause of failures followed by construction/material defects and corrosion. It is interesting to notice that corrosion results in nearly only pinhole leaks, while ruptures, defined as a break of length equal or exceeding one diameter, are due to external interference, ground movement and material defects.

Other interesting considerations can be made examining failure frequency divided by pipe diameter, wall thickness, or year of construction. Figure 3 for example shows a strong influence of the pipe diameter over the failure frequency due to mechanical damage. Smaller diameter lines, laying more often in urban or suburban areas and with thinner pipe wall thickness are significantly more affected by mechanical damage than large diameter pipelines.

The trend is confirmed by a recent analysis of failure incident in the United States, reported in figure 4 [6]. Dividing the failure according to the class locations pointed out clearly that most incidents happens in heavily populated areas. Class location 3 has 46 or more buildings in a strip of one mile (1.609 km) length along the pipeline by 200 m on either side of the pipe, and in class 4 buildings with four or more stories are prevalent.

Use of statistical data to assess the safety of a line or a risk associated with a specific hazard is currently done and has the merit of not needing a detailed analysis and avoiding the associated assumptions. It includes however a very severe assumption, that the line under consideration will behave as the lines used to build the failure data bank. For specific maintenance decisions or design choices it is of little use, it appears however still the more prudent approach to use in dealing with Authorities.

Reliability based design

The Structural Reliability Analysis approach is represented mainly by the offshore design code DNV 96 [7]. The code offers two alternatives: the design based upon limit state and partial safety factors, already calibrated for a given reliability target, or a full structural reliability analysis. The target reliability levels are indicated to be calibrated "against identical or similar Pipeline designs that are known to have adequate safety on the basis of these Rules". As an alternative the target reliability figures are given in the following table.

Table 1. Acceptable failure probabilities vs. Safety Classes according to DNV 96 [7]

Limit States	Probability bases	Safety Class		
		Low	Normal	High
Serviceability limit states	annual per pipeline	10^{-2}	10^{-3}	10^{-3}
Ultimate limit states	annual per pipeline	10^{-3}	10^{-4}	10^{-5}
Fatigue limit states	lifetime per pipeline	10^{-3}	10^{-4}	10^{-5}
Accidental limit states	annual per km	10^{-4}	10^{-5}	10^{-6}

Low Safety Class is defined as not implying risk of human injury and minor environmental and economic consequences, Normal for temporary risk of human injury or significant environmental and economic consequences, High near platforms or in areas with frequent human activity or very high consequences for environment, economical or political.

For an offshore pipeline, interaction with people is unlikely so for most of the lines the relevant failure probabilities are of the order of 10^{-2} to 10^{-3} per pipeline year. For a pipeline of one hundred kilometres this results in 10^{-4} to 10^{-5} per km year, that does not compare favourably with the average European figure of 2.1 10^{-4}. The lower expected failure probability for offshore gas transmission lines can however be justified on the basis of large wall thickness, concrete protection and so on.

Translating these figures to onshore lines appears not realistic. According to DNV rules we should consider pipelines running through inhabited areas as High Safety Class and that would result in a target of around 10^{-5} to 10^{-7} failures per km year for ultimate and serviceability limit states respectively.

The difficulty in providing realistic reliability targets for onshore pipelines has been recognised by the Working Group WG 12 set up by the International Organization for Standardization ISO TC 67 SC2 to prepare a standard on "Reliability Based Limit States Methods" [8], where the offshore section was easily dealt, on the basis of DNV tradition, but the criteria for onshore pipelines are still undefined.

Case study 1. Design of a high pressure long distance pipeline.

Snam and Snamprogetti, in co-operation with other ENI companies, have been involved in a research project on the development of technologies for long distance pipeline construction. Within this frame a feasibility study was prepared considering the transportation of 30 billion cubic metres of natural gas from Chardzou (Turkmenistan) to Bratislava (Slovakia) [9].

Two basic hypotheses have been compared: the tradition pressure level of 75 bar and a higher pressure of 140 bar. The economic evaluation is well in favour of high pressure gas transmission, not quite as regards to the capital expenditure because the higher costs of the high pressure line is compensated by the reduced number of compressor stations needed, but because the gas consumption during operation is lowered from 0.83 to 0.18 billion cubic metres of gas per one thousand kilometres per year. Further cost reductions could be obtained using very high grade steels, so API 5L X80 and X100 steels were considered.

The use of high design pressures is usual for offshore pipelines, but is only slowly becoming accepted for onshore lines. Usual design pressure in North America are around 1000 psi, about 70 bar, but the recently completed Alliance project, a 3000 km line connecting British Columbia and North West Alberta with Chigago, has been designed for 120 bar. In Europe typical design pressure of gas transmission pipelines are in the range from 70 bar to 85 bar.

A significant increase in design pressure has to face the perception that a high pressure line is more dangerous than a traditional line, and this is certainly true as far as failure consequences are concerned. How the failure probabilities of an high pressure line compare with a traditional one is not so clear. Snam, in co-operation with Centro Sviluppo Materiali, a research centre located near Rome, is carrying out a reliability study to assess the hypothetical Chardzou to Bratislava line.

The following calculations refer to this pipeline project, for which five different design options were identified for material grade, operative pressure and design factor.

Table 2. Design alternatives considered for failure probability calculations.

Case	Design pressure	Material grade	Safety factor	Applied stress	Wall thickness
1	70 bar	X70	1.4	72 % SMYS	14.8 mm
2	140 bar	X80	1.4	72 % SMYS	26.0 mm
3	140 bar	X80	1.25	80 % SMYS	23.4 mm
4	140 bar	X100	1.4	72 % SMYS	20.0 mm
5	140 bar	X100	1.25	80 % SMYS	18.7 mm

The probability of failure was estimated up to now for two failure modes only: corrosion and mechanical damage. The data for corrosion defect dimensions were taken from a pig inspection in an old line considered heavily corroded, at least in the Italian gas transmission scenario. It is the case of a line coated over the ditch with polyethylene tapes, with resulting randomly distributed poor adhesion, where even with an effective cathodic protection the corrosion phenomena developed at the interface between the disbonded coating and the pipe surface. To avoid unnecessary computation problems the data with minimum impact on the results have been considered constant, as shown in table 3.

Table 3. Input parameters for the corrosion model.

Variable	Distribution type	Mean	Std. Dev.
Outside diameter	Constant	56 inches	-
Design pressure	Constant	70/140 bar	-
Yield strength	Constant	485/550/690 Mpa	-
Wall thickness	Constant	Table 2	-
Corrosion defect depth	Lognormal	1.50 mm	0.57 mm
Corrosion defect length	Lognormal	33.8 mm	32.5 mm

From the same inspection data set an average density of 100 corrosion defects per km was used in the calculation for humid, that is normally aggressive soils that account for 2000 km of the Chardzou to Bratislava line. Owing to the crossing of large area of desertic or semidesertic climate with little or no water in the soil, an assumption was made of no corrosion defects over the remaining 3045 km.

Figure 6 shows the computed failure probabilities for the different cases for a single defect. Neglecting the crack growth in a year and taking account the defect density one can arrive at the failure probability per km year. Using the figure of 100 defect per km the resulting probability for case 1 (X70 steel and 1.4 safety factor) reaches 3.8 10^{-7}, still very low compared with European failure frequencies. A more accurate analysis of the European data bank shows however that nearly all failures are simple leaks on small diameter lines and nearly no rupture due to corrosion happened as can be seen in figure 2. Assuming that the maintenance of such important line will include intelligent pig inspection the output of the calculations appears reasonable. With higher pressure and resulting larger wall thickness, the calculated failure probabilities are significantly lower.

The probabilities of failure for mechanical damage were estimated not using a generic assumptions or historical data for gouges length and depth, but from an assumed distribution of excavating machines and ploughs. Taking into account distribution of energy of existing operating machines and the interaction with the pipe, the resulting defect dimensions can be calculated. The resulting dent and gouge defect is then evaluated according to current models to evaluate whether it results in a failure or not.

The input parameters are listed in the following table:

Table 4. Input parameters for the dent and gouge model.

Variable	Distribution type	Mean	Std. Dev.
Yield strength	Constant	485/550/690 MPa	-
Outside diameter	Constant	56“	-
Wall thickness	Constant	Table 2	-
Design pressure	Constant	70/140 bar	-
Charpy toughness	Lognormal	129 J	10 J
Charpy fracture area	Constant	60 mm^2	-
Vertical impact angle	Rectangular	0 - 90 deg	
Horizontal impact angle	Rectangular	0 – 180 deg	
Impact energy	Lognormal	40 kJ	30.4 kJ
Dent/gouge energy share	Rectangular	0 - 1	

Figure 7 shows very high failure probabilities but one must remember that these values are the probabilities that a pipe will fail when damaged and they must be corrected to account for the probability that an impact actually occurs. Accurate values of probability of an impact are difficult to evaluate as they are affected by a number of factors: whether is desertic, rural or urban has of course the larger effect, but it is influenced by the existence of legal obligations to inform pipeline operator before digging, the accuracy of marking, the frequency of patrolling and so on. To roughly account for the use of land an impact probability of one in about 4 km every year in urban and industrial area (503 km) is calculated using a model in literature [10]. For agricultural areas and semidesertic regions the damage probability decreases to one in 165 km a year

The factor that has the largest influence on the resistance of the pipe to mechanical damage is the wall thickness. In fact the failure probabilities in figure 7 are ranked in inverse order with wall thicknesses from table 2.

The final results obtained combining the probabilities of failure for corrosion and mechanical damage over the entire pipeline length and accounting for a design life of 30 years in figure 8, indicate that the high pressure by itself do not correspond to higher risk. Quite the contrary high pressure thicker lines are safer than ordinary design even when higher strength steels are used. Decreasing safety factor to 1.25 and using steel grade X100 reduces the benefit of high pressure, but only in the worst case 5 (140 bar, X100 steel and 1.25 safety factor) the fracture probability is nearly equal to the basic case 1 reflecting traditional design choices of 75 bar, X70 steel grade and 1.4 safety factor. In table 5 the detailed calculation for this case are shown.

Table 5. Failure probability calculated for the Chardzou to Bratislava line, considering failure by corrosion and mechanical damage. The values are calculated for case 1 (75 bar, X70 steel grade and 1.4 safety factor) and accounts for 5045 km of pipeline and 30 years design life.

Failure probability for Corrosion		Failure probability for Mechanical damage	
Aggressive areas	$4.6\ 10^{-6}$	Urban and industrial areas	$5.7\ 10^{-3}$
Non-aggressive areas	0	Agricultural areas	$5.9\ 10^{-3}$
Total	$4.6\ 10^{-6}$	Total	$1.1\ 10^{-2}$
Overall failure probability $1.1\ 10^{-2}$			

Case study 2. Rehabilitation choices for an existing line.

The same methodology as above has been applied to analyse the proposal to lower the maximum operating pressure of an existing pipelines with severe corrosion defects. This has been done by comparing the relative importance of the two most common failure modes: corrosion and mechanical damage.

The corrosion defect distribution has been obtained by the inspection with intelligent pig and is the same used in the above case study. For mechanical damage a detailed analysis of the land use has been carried out defining for each area the operating machines likely to be used. The energy of the operating machines has then been characterised as the probability functions reported in table 6.

Table 6. Probability functions of energy of operating machines over the pipeline length.

Area	Length	Distribution	Mean value	Std. Dev.	Impact probability
Urban	0.19 km	Lognormal	24.2 kJ	7.3 kJ	0.18
Industrial	0.11 km	Lognormal	39.8 kJ	12.1 kJ	0.26
Agricultural	80.4 km	Lognormal	8.2 kJ	3.5 kJ	0,0061
Rural	3.4 km	Lognormal	25.3 kJ	7.7 kJ	0,0042

Several calculations have then been carried out varying the pressure and the outcome is shown in figure 9 for corrosion failure and figure 10 for mechanical damage in urban areas. The failure probability for the complete line has been calculated in table 7 for the two alternative pressure values, 64 bar and 54 bar. The effect of a pressure reduction of 10 bar, from 64 bar to 54 bar results in a reduction of a factor of 2 in the probability of failure due to corrosion and only 1.5 for mechanical damage. The overall probability is not then reduced by a very large amount.

It is interesting to notice that the failure probability for industrial and urban areas is very high but, owing to the very small length of pipeline laying in urban areas, its overall effect is limited. The failure probability for this line is controlled by the agricultural land where the probability of damaging the pipe is significantly lower.

Table 7. Failure probability calculated for pipeline, considering failure by corrosion and mechanical damage. The values are calculated for the whole pipeline length and 30 years remaining life.

Failure probability for corrosion	Failure probability for mechanical damage			
	Urban areas	Industrial areas	Agricultural areas	Rural areas
$4.9\ 10^{-3}$	$9.1\ 10^{-4}$	$1.6\ 10^{-3}$	$6.3\ 10^{-4}$	$4.2\ 10^{-4}$
Failure probability for the at 64 bar $8.3\ 10^{-3}$				
Failure probability for corrosion	Failure probability for mechanical damage			
	Urban areas	Industrial areas	Agricultural areas	Rural areas
$2.6\ 10^{-3}$	$6.3\ 10^{-4}$	$1,3\ 10^{-3}$	$2.2\ 10^{-4}$	$2.9\ 10^{-4}$
Failure probability for the at 54 bar $5.1\ 10^{-3}$				

In this case the importance of the two failure modes is nearly equivalent, with one important difference. In this line where an intelligent pig inspection can be run, the chances of a corrosion defect to become large enough to cause failure appear negligible. Mechanical damage on the other side can be little controlled and with time larger operating machines becomes available tha can damage the pipe even buried at a reasonable depth.

Using a model given in the literature [10] for the effect of cover depth on the probability of hitting the pipe, it can be shown , in figure 11, that there is a reduction of failure probability of one order of magnitude lowering the pipe from 90 cm to 1.20 metres. This result has certainly not to be seen as definitive. Better models are needed, taking into account the differences between countries and different locations, allowing to model different choices, not only lowering the pipe, but also building protection, increasing patrolling and so on. But even rough as they are these calculations show that traditional approaches can be improved increasing safety by more effective or less costly maintenance measures.

Conclusions

The methodology shown in these two cases allows detailed calculation of the effect of design alternatives on failure probability. The calculation is precise, but the models are not. For the time being they appear rather rough and the distribution of input parameters is not known with accuracy, too.

An area where reliability based design has found an important role is the calibration of safety factors in design codes. Formerly based on historical records and analysis of failures this key process in drawing a design code is now more and more explicitly done by reliability analysis..

Using the same approach as current engineering tool is certainly more difficult as there is not the time and neither the money available for collecting all the data and developing equations for the failure modes of interest, when they are not available. The methodology appears however worth the effort needed in developing it. Being able to assess the effect of different choices certainly allows a more cost effective maintenance strategy and there are no alternatives available to carry out the same calculations.

The criteria to be used in judging the results of calculations also need development. Nowadays the more reasonable approach seems to be a comparative one, judging a new case towards other similar of known good and bad behaviour, or comparing on the same ground different failure modes or different measures to control a single failure mode.

References

[1] Health and Safety 1996 No. 825 "The Pipelines Safety Regulations 1996"

[2] Joint Industry Project to Develop Guidance for Limit State, Reliability and Risk Based Design and Assessment of Onshore Pipelines, "Derivation of preliminary criteria for determining the structural reliability of onshore pipelines", March 2000

[3] A. Pijnacker Hordijk, F. Noltes, G. Stallenberg and H. van Merriënboer, "How to deal with older pipelines. A Risk Assessment Methodology gives the answers", Pipeline Tecnology Conference, May 21-24, 2000, Brugge, Belgium

[4] P.H. Vieth and J.F. Kiefner, "Methods for prioritizing pipeline maintenance and rehabilitation", Eight Symposium on line Pipe research, September 26-29, 1993, Houston, USA

[5] R. Bolt, "Positive trends in European gas pipeline incidents", 21st World Gas Conference, June 6-9, 2000, Nice, France

[6] B.N. Leis, T.A. Bubenik, R.B. Francini, J.B. Nestleroth and R.J. Davis, "Recent developments in avoiding, detecting and assessing severity of mechanical damage ", Pipeline Tecnology Conference, May 21-24, 2000, Brugge, Belgium

[7] Det Norske Veritas, "Rules for Submarine Pipeline Systems", December 1996

[8] International Organization for Standardization, "Petroleum and Natural gas Industries. Pipeline Transportation Systems. Reliability Based Limit State Methods", ISO WD 16708

[9] E. Donati and D. Ercolani, "High pressure long distance pipelines: technical–economic analysis", 21st World Gas Conference, June 6-9, 2000, Nice, France

[10] Q. Chen, and M. Nessim, "Reliability based prevention of mechanical damage", EPRG/PRCI 12th Biennial Joint Technical Meeting on Pipeline Research, May 1999, Groningen, Netherlands.

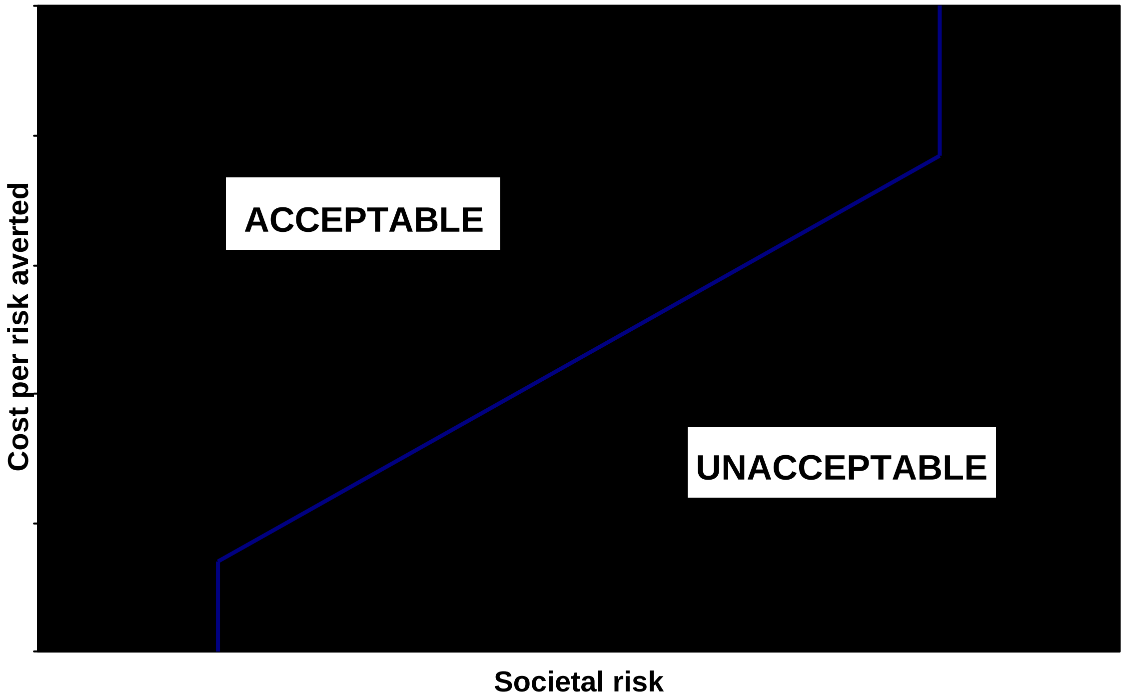

Figure 1. Schematic risk acceptance criteria associated to the ALARP principle.

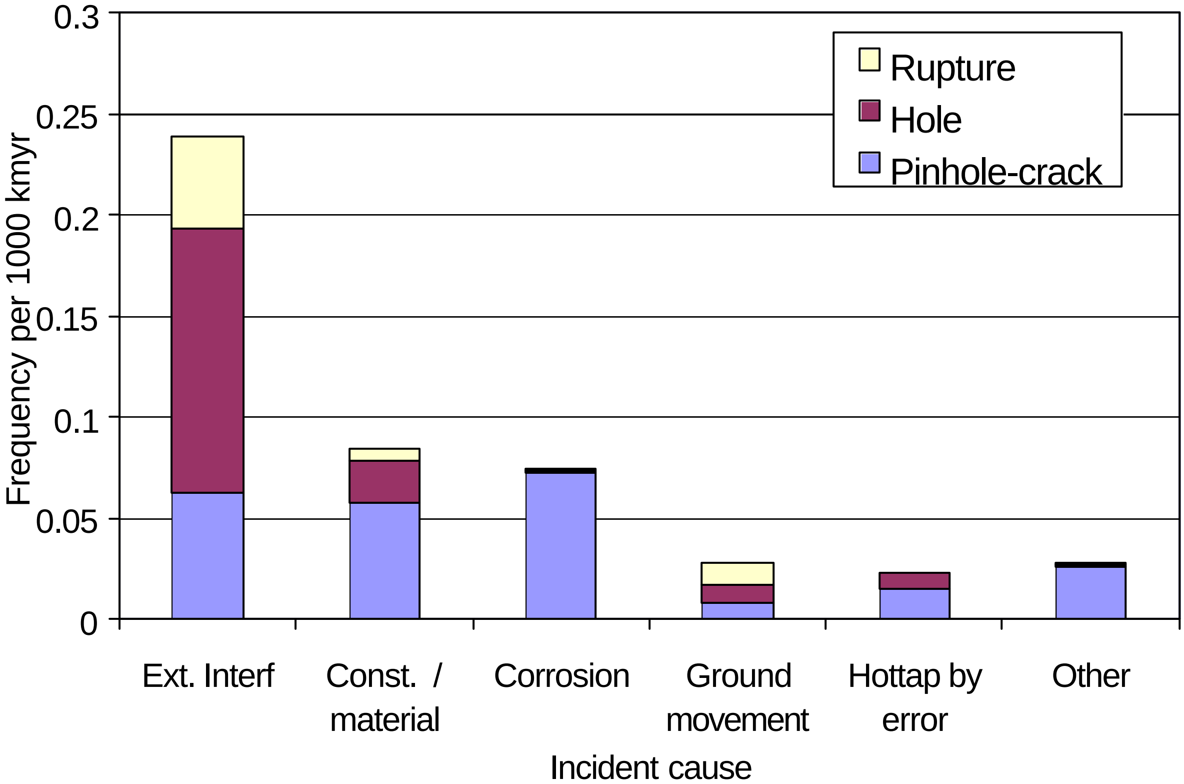

Figure 2. Incidents frequency by cause and type of leak, from the European data bank [5].

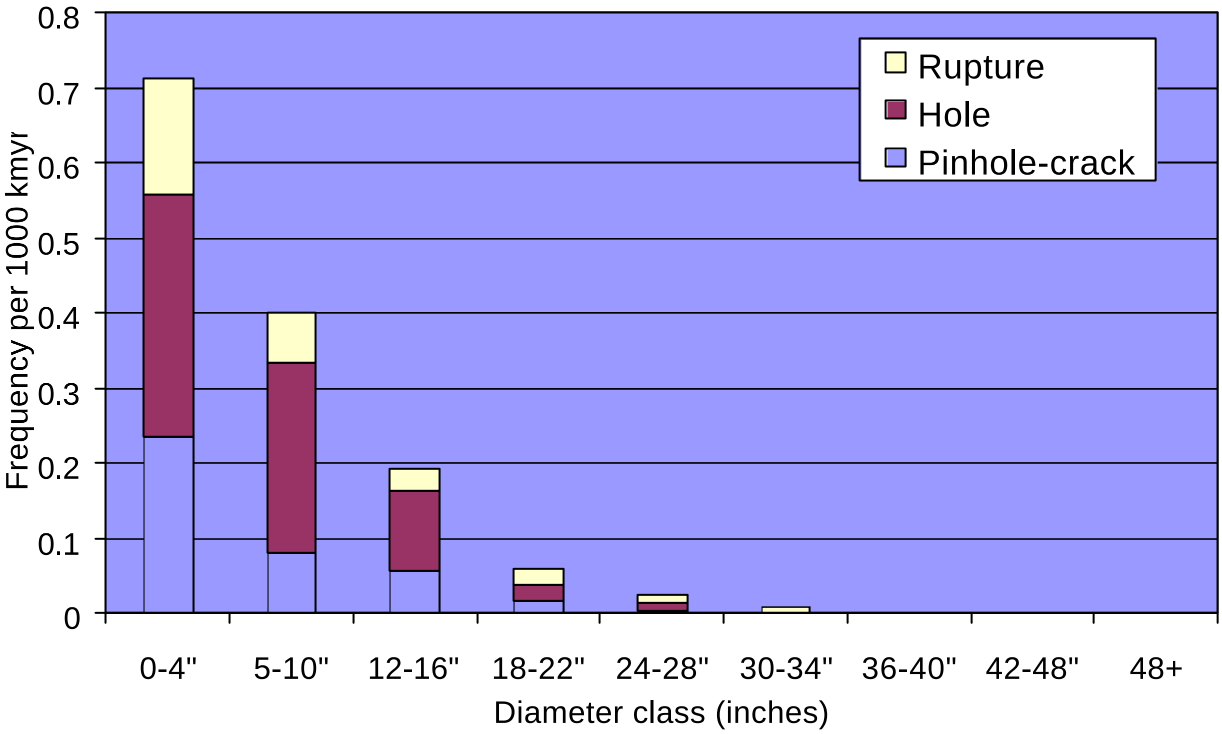

Figure 3. Incidents caused by external interference and frequency per diameter class, from the European data bank [5].

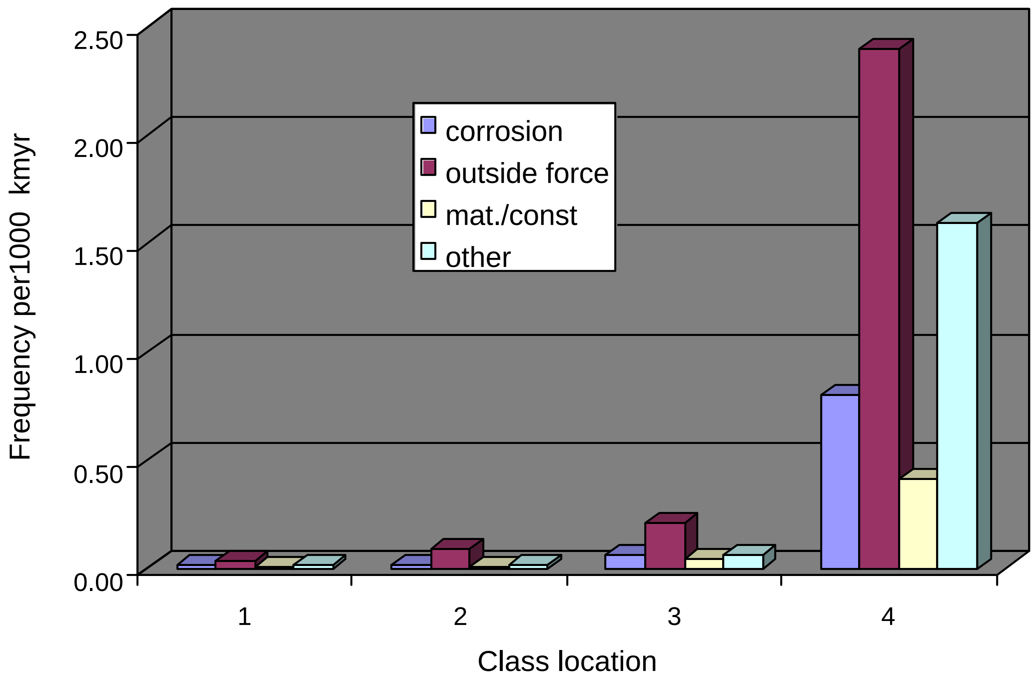

Figure 4. Incident frequency by class location and category, from United States onshore incident data bank, US Department of Transportation [6].

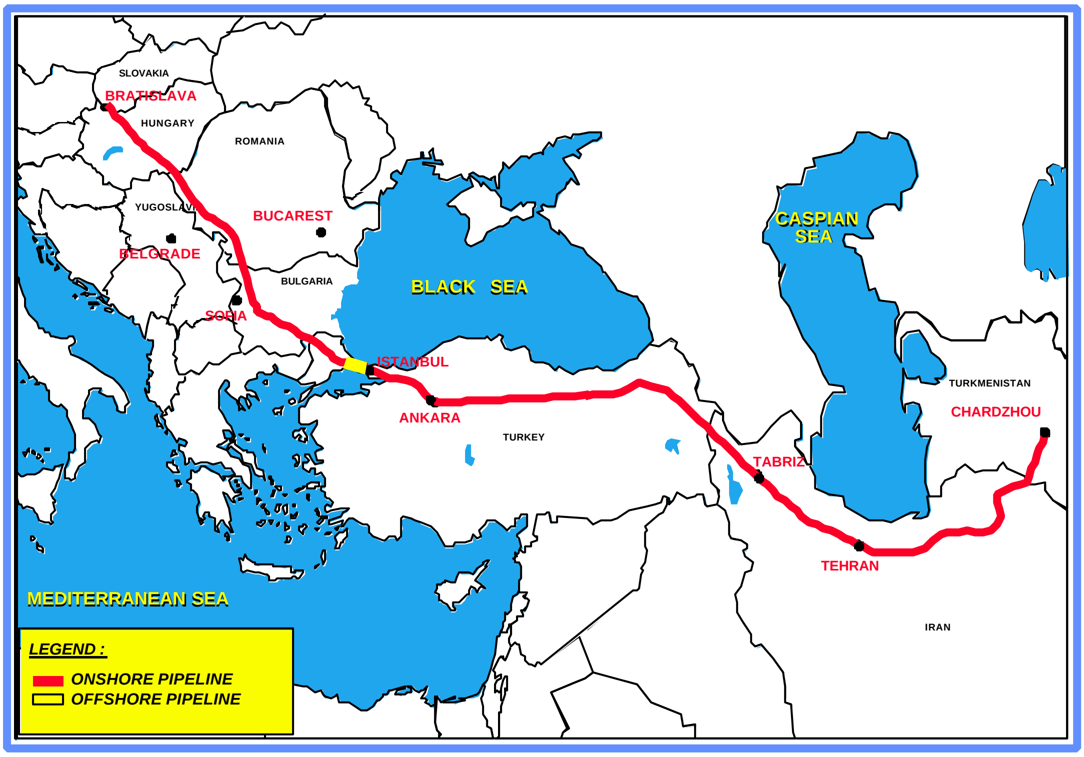

Figure 5. Route of the hypothetical Chardzou to Bratislava line.

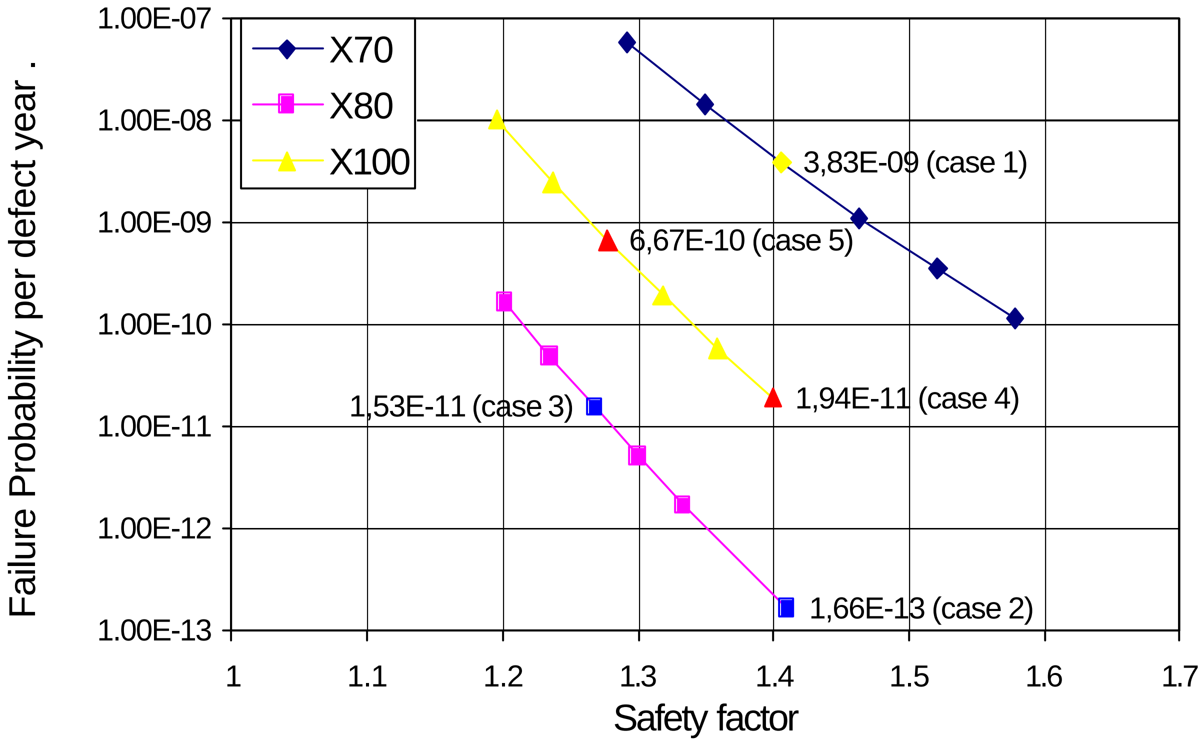

Figure 6. Conditional failure probability for a single corrosion defect.

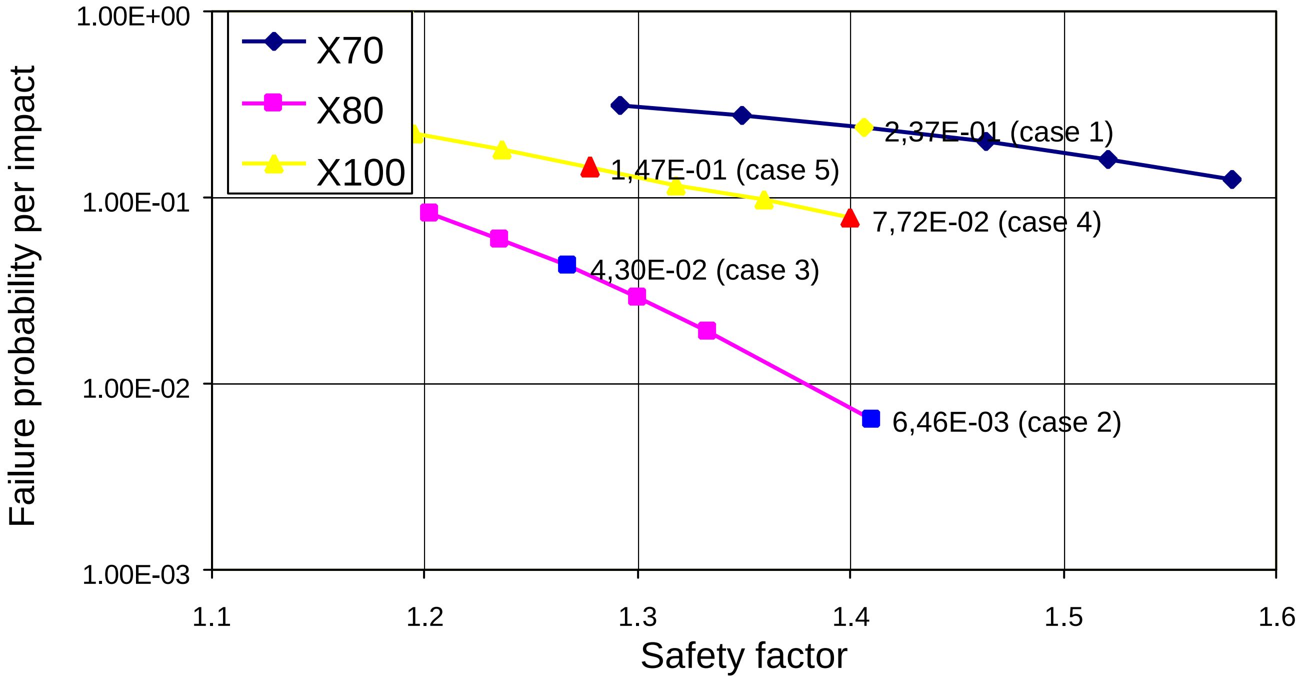

Figure 7. Conditional failure probability due to mechanical damage.

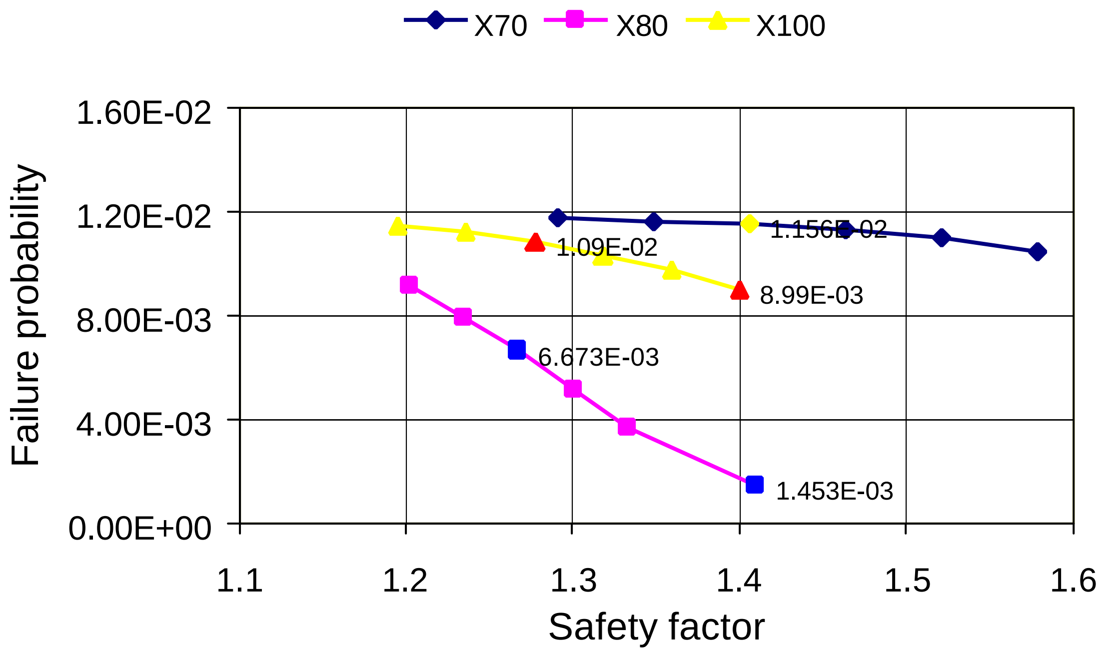

Figure 8. Failure probability for the Chardzou to Bratislava line, considering corrosion and mechanical damage and for a design life of 30 years.

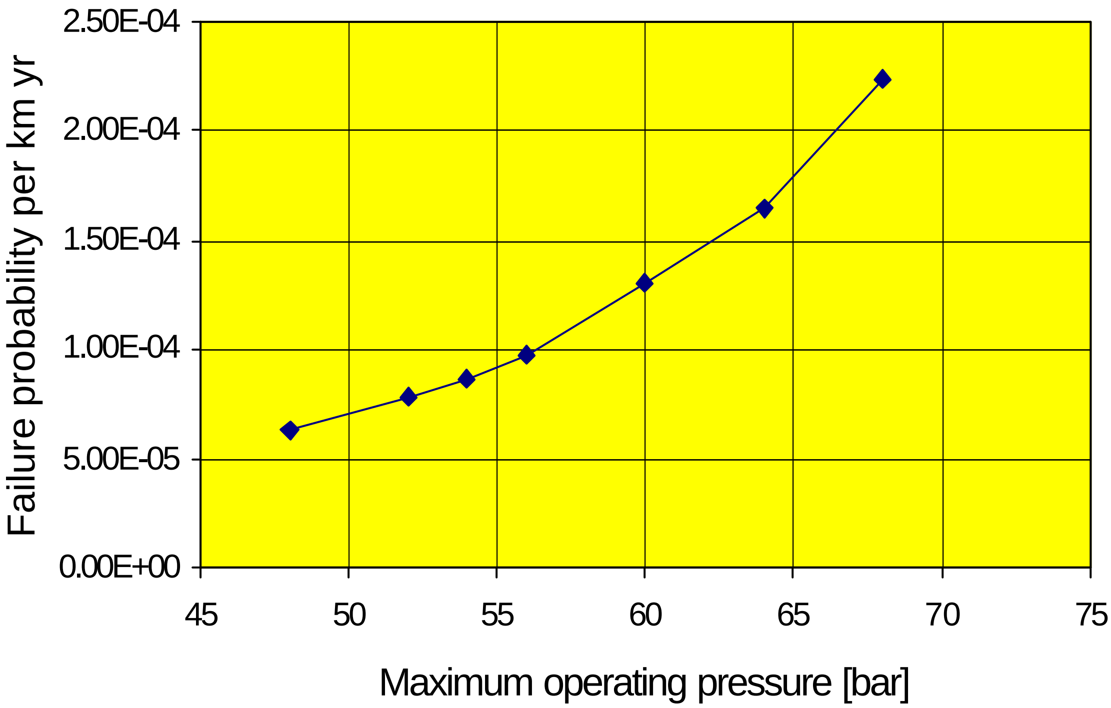

Figure 9. Effect of variation in maximum operating pressure of an existing pipeline, on the failure probability for corrosion.

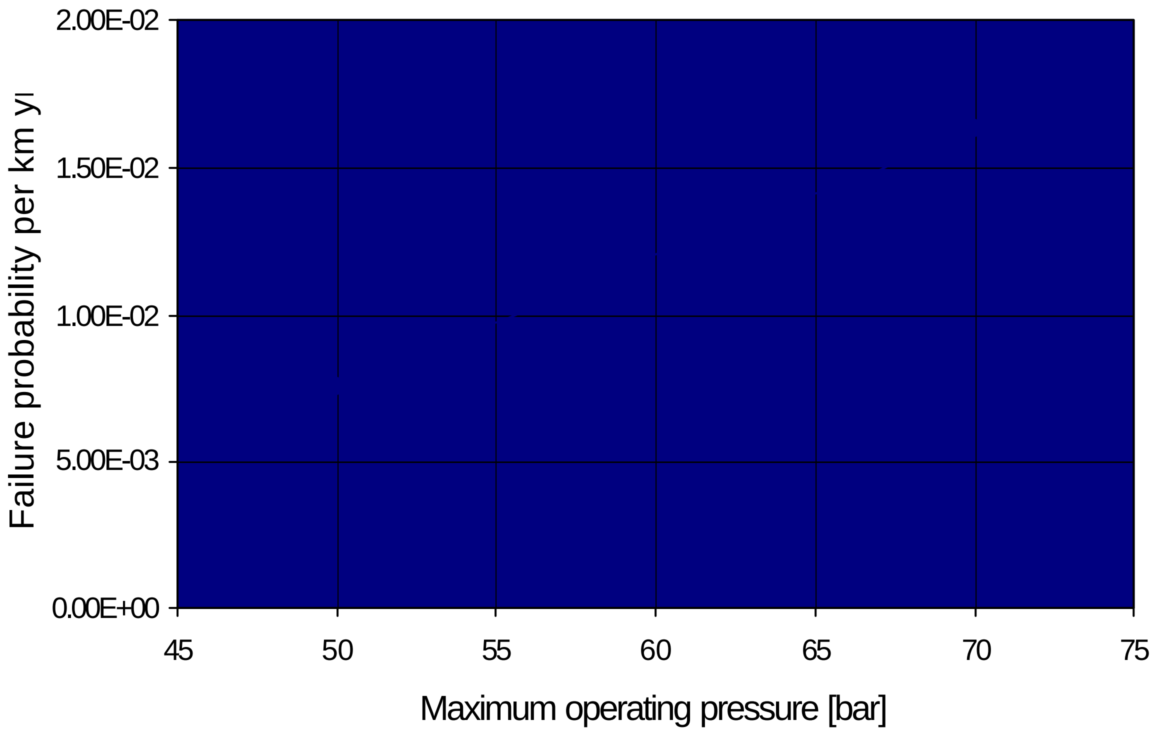

Figure 10. Effect of variation in maximum operating pressure on the failure probability for mechanical damage in urban areas.

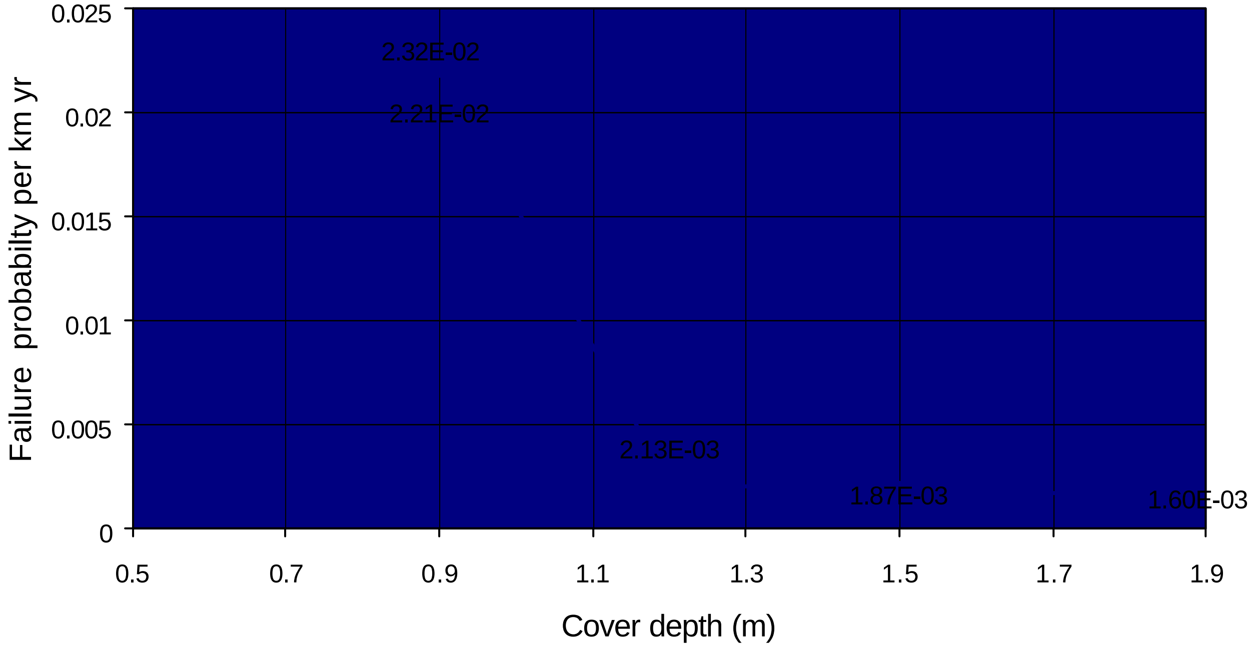

Figure 11. Effect of the variation in cover depth on the failure probability for mechanical damage in urban areas.