HSE
Health & Safety
Executive

Reliability assessment for containers of hazardous material RACH

Prepared by
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for the Health and Safety Executive

OFFSHORE TECHNOLOGY REPORT

2000/095

Reliability assessment for containers of hazardous material RACH

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HSE BOOKS

First published 2001

ISBN 0 7176 2014 X

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1. SUMMARY

RACH has found that corrosion and erosion are still a problem in offshore process plant even in plain pipes but that under ideal circumstances (bare metal pipe and appropriate scanning patterns) UT thickness measurement can control the problem. It is not always possible to obtain these ideal conditions.

It has been shown that a probabilistic approach to corrosion reliability inspection scheduling is possible but that probability of detection (POD) data, produced in realistic samples, and corrosion modelling data are essential prerequisites. RACH Produced the first accredited POD data for some eight techniques including sizing accuracy trials but there is still a need for a larger defect sample and further trials for X-ray equipment and some of the newer electromagnetic and long range UT systems.

RACH coded the appropriate limit state functions, corrosion modelling data and POD information and utilised these in case studies and field trials. Some success was achieved but the field trials showed that a broad range of defect production scenarios exist and that further corrosion modelling and validation work would be needed before probability based corrosion reliability inspection can be confidently used.

2. INTRODUCTION

Oil and Gas processing plant used topside on offshore platforms experience a harsh environment which can lead to corrosion, erosion and possibly failure. Avoidance of problems requires periodic inspection and, cost-effective inspection scheduling so that the integrity is maintained with minimum expenditure.

Inspection for corrosion is a major inspection activity often involving removal of coatings, insulation etc. In more recent constructions the inspection may have to be through fire protection coatings. In order to schedule inspection and / or take advantage of newer rapid inspection systems it is desirable to have quantified information on the inspection reliability. This requires the production of Probability of Detection and Probability of Sizing data for currently available corrosion inspection systems. It is also desirable to be able to utilise this information within Reliability Based Inspection Scheduling that incorporates probabilistic analysis.

The aim of the Project (RACH) was to produce inspection reliability data from a range of existing and prototype techniques for corrosion detection and measurement in process plant. This data was then applied with selected corrosion degradation models to produce inspection schedules using reliability analysis to ensure consistent probability of failure levels.

3. OBJECTIVES

One of the major industrial hazards that exists is the potential rupture of piping or welded pressure vessels used for processing. The UK Offshore Operators Association (UKOOA) issued a list of probable mechanisms of failure [2], which were generally combined under three headings; internal corrosion fatigue, thermal fatigue and creep. Such an event could result in the escape of potentially damaging materials, and this is unacceptable. These mechanisms are relevant to onshore and offshore process plant but are particularly important for offshore plant because of the consequences of failure on offshore platforms. The main objective of the RACH project was to show that a Reliability Assessment for Containment of Hazardous material in the offshore process plant was possible and to demonstrate how cost effective safety could be achieved given the advances in inspection reliability, failure modelling and incorporation of POD into rational based inspection scheduling.

Criticality Ranking of assets identifies those areas of low risk equipment requiring little more than on stream monitoring of the product, to ensure no change in chemistry likely to effect a change in rate of deterioration, and secondly those assets with a moderate to high risk in which the deterioration is both detectable and measurable. Current inspection practice is often to examine at intervals prescribed by the criticality ranking in accordance with a code of practice. However, the possible methods of inspection vary in their cost and capability, and it is not clear when one method can be replaced by another.

Low risk situations can be dealt with relatively simply by looking at the remaining life in terms of corrosion predictions, the impact on the operation if the vessel fails or is taken out of service, and the associated hazard in terms of pressure, temperature, toxicity, etc.

Medium and high risk situations require more detailed quantitative analysis linking all the elements of Risk Based Non-intrusive Inspection Management. These include, for example, the following aspects.

Degradation Modelling, predicting and defining the deterioration mechanisms, deterioration rates, defect morphology, i.e. pitting corrosion, general corrosion, grooving, etc and by a study of the construction of vessels and / or piping, identification of specific damage location, e.g. vessel top or bottom, oil / water / gas interface, nozzles etc.

Inspection Method to be applied, combined with procedures and reliability.

Statistics to establish the extent of Inspection coverage and scanning patterns.

Defect tolerance, geometries, critical length, depth and width.

These will allow the development of Inspection programmes defining where to inspect, when, how, and how much. A key area requiring quantitative data is that of inspection reliability for detection of corrosion. For this reason RACH included the conduct of Probability of Detection (POD) trials on corrosion detection and mapping systems.

Many inspection techniques are now available and will aid inspection for corrosion if they are implemented correctly. Used conjointly these techniques could identify corrosion and / or cracking. Thus it is technically possible to inspect for all likely failure mechanisms. However all require rigorous trials to establish the relevant POD. This was a major part of the RACH project.

4. BACKGROUND FOR THE RACH PROJECT

Offshore process plants are made up of pressure containment vessels, pipework and valves. The pressure vessels may vary in size in terms of length and wall thickness and have many different operating parameters and design constraints. Depending on whether the process is oil, and or, gas producing, these vessels will have different roles. They may be high-pressure thick wall vessels used for processing and will be subject to mechanical and thermal fatigue especially at the support welds for internals and, if the gas is sour, there could be the additional problems of hydrogen sulphide attack. The oil process vessels will have similar problems that may additionally be aggravated by the contents of the crude oil.

The pipework can be manufactured from a number of products, all of which can suffer from a number of different failure modes. General internal and external corrosion and erosion are the major forms of failure but pitting corrosion can also occur. Other modes of failure would include, weld erosion/ corrosion, stress corrosion and corrosion fatigue, weld fatigue, and cavitation.

It was recognised in the early days of oil and gas production that corrosion played a major role in the cause of failure in oil process plants. Even in the mid 1980s visual inspection and corrosion inspection were still the main forms of topside inspection. Programmes were built around visual inspection walkabouts looking for telltale signs of obvious damage to insulation, rust signs and leaks [3]. This was combined with large programmes of ultrasonic wall thickness measurements using mainly, manual inspection of key areas. Key area inspection is useful in monitoring the rate of corrosion in areas which are known from past history to be susceptible to corrosion or erosion but scanning of an area is much more useful when detection of pits and local corrosion or erosion is required. With the former it is important to have accurately calibrated equipment and always return to the same key points. Where scanning of an area is required various mechanised ultrasonic inspection systems are available but the majority of them are dedicated to specific inspection tasks such as weld inspection. In 1986 a survey was carried out on the available mechanised ultrasonic systems that could be used for corrosion detection and four systems were identified as being capable of meeting specified criteria.

Although emphasis has been put on the use of ultrasonic wall thickness measurement other techniques have been applied more recently to the problem of inspection through coatings. The major problem here is two fold the cost of removal and replacement of the coating and the decision as to where to inspect in order to achieve the most economic and reliable information from the inspection. Techniques have been developed in an attempt to resolve these problems. The inspection can be separated into the inspection through thin coating and the inspection through thick coatings or insulation.

Profile radiography has been used for some years to inspect through insulation to determine the extent if any of wall thinning by erosion or corrosion and conventional radiography has been used to detect stress corrosion and corrosion fatigue cracking in steam lines. The problem is that only small areas are inspected at any one time and that radiation safety means that areas have to be cleared of personnel which can affect production. Real time systems have now been developed which by using small radiation sources, collimated beams and real time imaging it is now possible to scan long sections of insulated pipe work and detect areas affected by corrosion. Some of these systems have video to record the images and densitometers to give indications of depth.

Electromagnetic systems have also been developed for inspection through insulation. The Transient Electro Magnetic Probe (TEMP) system, for example, uses a pulsed eddy current technique to penetrate the insulation and the pipe. The resultant magnetic field produces a signal, which changes depending on the penetration of the pipe wall, which has occurred. This change is recorded using a receiver coil and the time taken for the change to occur is compared with the results obtained with the calibration piece. The system then calculates the wall thickness. The system calculates general wall thinning not localised pitting

Some of the coatings are used for fire protection and these are cementatious which in itself produces inspection problems. These coatings have little mechanical strength and require steel hangers, supports and wire mesh to increase their integrity. If water ingress occurs then these can corrode and cause failure. Only one technique has been proven successful at being able to detect pitting beneath this coating and also to be able to determine the existence of the wire mesh. This is a radiation back scatter system developed for the inspection of aircraft components but which has been used in trials to detect pits and the breakdown in the integral mesh.

Inspection through thin coatings, i.e. up to 6mm, is also necessary and several techniques have been developed for this purpose. Ultrasonic techniques can be used to measure both wall thickness and to detect the length and depth of surface breaking cracks using creeping wave and Time of Flight Diffraction (TOFD). Both of these techniques have limitations. The creeping wave technique can only measure length and the TOFD technique is more sensitive to cracks greater than 3mm deep. The TOFD technique has proved very useful in the detection of weld root erosion and has been applied manually. When thicker coatings of the neoprene or coal tar variety are being used then normal shear waves generated by EMATS can be used. Various eddy current techniques have also been used to detect surface breaking cracks beneath epoxy coatings. The lift off effect produces a rapid deterioration in sensitivity when pencil probes are being applied but this is reduced when more appropriate coils are selected. The ACFM technique has also been developed to inspect through coatings to detect and characterise surface breaking cracks.

Some preliminary trials were carried out at University College London using the creeping wave ultrasonic technique, a multi coil eddy current technique and the ACFM technique to inspect through epoxy coatings. The results showed that all of the techniques could detect the cracks through the coatings. The creeping wave ultrasonic technique also provided length information and the ACFM technique could detect and size the cracks.

Magnetic Flux Leakage techniques have also been used to detect and size pits through coatings up to 6mm thick. The equipment comes in various forms but can be used to scan small localised areas of a pressure vessel or plate or to scan pipe sections. These systems are calibrated using known diameter pits and using appropriate software can then map and size corrosion as they are scanned along the pipe wall.

Radiographic techniques using X or gamma radiography have been identified that can be used to inspect through thin coatings for the detection of defects such as cracks and corrosion pits using conventional techniques. Profile and flash radiography can also be used to measure wall thinning.

The above shows that techniques are now available to detect both wall thinning and cracking in thin coated pipework and structures and that techniques are being developed that can be used for the inspection of thickly coated pipework and structures and the coatings themselves.

There are a number of varied forms of defects present in offshore process plant but there are also a large number of inspection techniques becoming available, which if they are applied correctly and sensibly can provide an effective and economic solution to the inspection programme. One method of applying these techniques is by using risk based inspection based on criticality ratings and this is used to decide what to inspect and when. Criticality rating systems have been produced by various organisations and they have the same basic guidelines based on, defining the area of the process, identifying the hazards, assessing the consequence and probability of failure, formulating an inspection programme, reviewing the results and finally modifying the programme after reviewing the results.

By using the information from past surveys internal corrosion rates can be determined and criticality ratings given to certain sections of the plant. High risk would be 1mm/ year, medium risk 0.3mm/ year and low risk less than 0.3mm/ year. One of the other major corrosion problems is corrosion under insulation. External corrosion of carbon steel pipe work located under insulation, which has been damaged allowing the ingress of moisture, is accelerated as the temperature of the pipe work increases. This means that process plant above a temperature of 30°C should be classed as high risk. With this knowledge it is possible to plan inspection programmes and scheduling.

The introduction of new techniques which provide information which was not available in the past has allowed these risk based programmes to be implemented but the programmes should not be limited to areas which have a large inventory because an initial small failure can have great consequences. For example, platforms have been shutdown because of failures in a small bore stainless steel and duplex pipework. The Piper Alpha disaster in 1988 was caused by one failure leading eventually to complete loss of the platform. The subsequent report issued by Lord Cullen was designed to improve all aspects of offshore safety especially those related to pressurised systems typical of those located on the topsides of offshore installations. One of the recommendations made by Lord Cullen was that the regulatory body should set up and maintain a database of hydrocarbon leaks, spills and ignitions and that the data should be made available to industry. A database was set up by HSE and is a valuable source for identifying areas at risk. Significantly HSE have recently reported that around 13% of all hydrocarbon releases are due to corrosion/erosion with a majority occurring in piping. The main findings of this HSE report are given below.

From the HSE database it has been reported that the average number of hydrocarbon leaks due to corrosion/erosion over the period Oct 1992-Sept 1998 was 27 per year with no discernible trend. The majority were gas leaks (36%), followed by oil (29%), 2 phase (19%) and condensate (15%).

The incidents reported to HSE by no means represent all the corrosion related incidents that may have actually occurred. On one installation alone, it was discovered that in one year four small hydrocarbon leaks and 24 incidents involving corrosion leaks in drains and various water systems had also occurred. Hence the real scale of the corrosion problem is greater than that represented by the incidents reported above.

Analysis of the data [4] revealed that flowlines, separation, processing and export systems were affected most by corrosion/erosion. A majority of the incidents were related to piping. In particular, a large proportion involved small bore piping. There could be a number of reasons for this, including, failure to include them in the inspection programme, difficulty in carrying out non destructive testing or visual inspection due to access problems, failure to appreciate their vulnerability to corrosion, a thin wall that can corrode fairly quickly and result in a leak, etc.

The other significant finding was that 30 of the piping incidents involved erosion which represents 26% of all piping incidents and indicates the importance of controlling erosion damage as well as corrosion. This was illustrated further by the valve incidents where the damage was predominantly due to erosion.

In order to determine the underlying causes, 35 incidents were subjected to a more thorough evaluation.

For the incidents examined, design errors and the associated failure to carry out adequate hazard studies were identified as being responsible for 44% of the total contribution to the failures. Lack of maintenance and failure to adequately monitor and inspect for corrosion made a 46% contribution to the failure causation. The failure of an inspection regime could be attributed to lack of knowledge of corrosion rate and location compounded by inadequate appreciation of the limitations of conventional techniques.

If inspection (rather than design) is chosen as a route to reduce incidence of leaks, it is important to have a preventative inspection philosophy in place for the plant operation. This usually takes the form of Risk Based Inspection (RBI). It is clear that the risk of a corrosion failure has previously been underestimated, especially in small bore pipe work.

To carry out a proper analysis for an inspection plan it is necessary to know:

a) The rate and type of defect growth

b) The type of NDT techniques suitable for the application

c) The capabilities and limitation of the inspection technique

d) Value of inspection compared to risk

RACH was designed to solve these problems and, given the HSE analysis, concentrated the majority of trials on 6” diameter pipe work with some limited trials on bends of 4” diameter. This sample was used with both internal and external corrosion defects to assess the performance of currently available NDT systems.

5. SAMPLE AND DECECT MANUFACTURE

5.1. TRIAL SAMPLE

A corroded pipe sample was produced for the RACH project. This included 168mm diameter straight pipe of 7.1 and 14.3mm wall thickness (44 specimens), coated pipe (14 off) of the same size, and a variety of pipe bend specimen (17 off) obtained from an old platform. The straight pipe specimens were manufactured from new pipe and had internal and external defects. The details of this sample are given below.

i. 22 off, 6" nominal bore, schedule 40 pipe (OD 168.3mm, WT 7.1mm), 2.2-2.6 metres long.

ii. 22 off, 6" nominal bore, schedule 120 pipe (OD 168.3mm, WT 14.3mm), 2.2-2.6 metres long.

iii. 4 off coated pipes, 6" nominal bore (2 off schedule 40, 2 off schedule 120), 2.6 metres long.

iv. 9 off, 4" (114.3mm OD) and smaller diameter pipe bends, WT 5.5-6.0mm.

v. 8 off, 8" (219.1mm OD) pipe bends, WT 7.0-9.3mm.

Samples (i) and (ii) were manufactured from new pipe and defects were introduced either on the internal or external surfaces. Two defect-free straight pipe samples were also included, one of each wall thickness. During the trials, the samples containing external defects were thermally insulated with 50mm thickness pre-formed mineral wool sections and an outer 0.7mm thickness stainless steel protective sheeting.

Samples (iii) were new pipe with an external epoxy paint coating, nominal thickness 400 microns. Defects were introduced on the internal surfaces. One defect-free pipe was also included in the trials.

Samples (iv) were steel pipe removed from service and had internal corrosion introduced on the bends.

Samples (iv) were steel pipe removed from service and had corrosion introduced at the circumferential weld roots.

5.2. METHOD OF DEFECT MANUFACTURE

5.2.1. Internal Defects: Straight Pipe

Internal defects were produced by using a reverse polarity corrosion cell in saline solution. Defects are formed where the solution is sprayed onto the pipe internal surface, and where it forms pools in front of the wooden supports for the spray.

The defects manufactured in this way were random, circular or elliptical in shape. The water was sometimes heated to speed up the corrosion process. The position of the defects was varied between pipes by adding more supports and changing the position of the copper spray pipe. All the defects were located at, or close to, the 6 o’clock or 12 o’clock circumferential positions.

5.2.2. External Defects: Straight Pipe

The external defects were made using specially constructed tanks, which contained the corrosion cell. This method produced defects of two types, one approximately 100mm along the circumference by 50mm longitudinal and the other approximately 50mm along the circumference by 100mm longitudinal. Defects were randomly positioned along the pipe and were either on the same circumferential position or diametrically opposed.

5.2.3. Internal Defects: Bends

To produce internal defects in bends, a pool of saline solution was made in the bend, and an electrode placed in this pool to provide the corrosion cell.

5.2.4. Weld Root Defects

These were produced by firstly making a groove with a small grinding wheel, then making a bath using a commercial sealant, and finally creating the corrosion cell as described above.

5.2.5. Defect Monitoring During Manufacture

For the internal defects, defect monitoring was carried out using a standard *Steelgauge* ultrasonic thickness gauge. Measurements were carried out on a 10mm grid over the expected defect area. An adapted vernier gauge was used to monitor the external defects, also on a 10mm grid.

5.2.6. Definitive Defect Measurement

For the internal defects, the T-scan method was used to produce the characterised data results. The external defects were measured using a vernier gauge at 10mm grid intervals. The bends were characterised using a 5mm grid with the thickness gauge. The root defects were measured by making a replica with dental moulding material and then taking physical measurements from this mould.

6. TRIALS

The RACH trials were conducted at TWI over a period of 23 months. A total of 15 separate trials were conducted on selected pipe samples using 10 different equipment types. Figures 1-9 show the general trial arrangement, scanning equipment and instrumentation. In most cases, trials were carried out by personnel employed by the equipment manufacture. In all cases, measures were taken to ensure that information on the corrosion defects contained in the pipe samples was not available to personnel conducting the trials.

Table 1 contains details of the samples inspected by each equipment type. The number of pipes inspected is given in the Table. It should be noted that most of the pipes contained several defects hence the number of defects is much greater than the number of pipes. Some of the pipes had no defects. These pipes were used to influence the expectation of inspectors during the trials.

6.1. TRIAL DOCUMENTATION

Prior to conducting each trial, Bureau Veritas (BV) required the following documentation to be provided. A *Trial Notification* advising the proposed schedule (to allow BV to attend as necessary), a *Test Plan* containing essential details of the trial including the type of samples to be tested and a *Test Procedure* document produced by the inspection teams for use of their particular equipment.

Inspection Equipment Type	Uncoated Internal Flaws	Coated Internal Flaws	Insulated External Flaws	Bends Internal Flaws	Bends, Weld Root Flaws
T-scan	22	4	N/A	N/A	N/A
A-scan	22	4	N/A	9	N/A
Magnetic Flux Leakage	19		N/A	N/A	N/A
Creeping Wave	22	4	N/A		N/A
Long Range U/T (A)	7	4		N/A	N/A
Long Range U/T (B)	8			N/A	N/A
Pulsed Eddy Current (A)	N/A	N/A	18	N/A	N/A
Pulsed Eddy Current (B)	N/A	N/A	11	N/A	N/A
Differential Magnetic Probe	N/A	N/A	22	N/A	N/A
MicroMap	9	4	N/A		N/A
TOFD	N/A	N/A	N/A	N/A	8(16welds)
Long Range U/T (C)	7				

Table 1 Details and number of pipe samples inspected

B) Indicates a repeat trial of A

C) Indicates the use of a different manufacturers equipment to A and B

Figure 1 A-Scan equipment in RACH Trial

Figure 2 MFL Pipescan in RACH Trial

Figure 3 CHIME in RACH Trial

Figure 4 Incotest RACH Trial

Figure 5 LORUS RACH Trial

Figure 6 DMP RACH Trial

Figure 7 Micromap RACH Trial

Figure 8 TOFD RACH Trial

Figure 9 Teletest RACH Trial

After completion of each trial, BV required the following documentation to be provided. A *Trial Report* containing details of any changes or revisions to the Test Plan or Test Procedure, and a set of the *Trial Results* produced by the inspection teams.

7. POD RESULTS

Trials were undertaken at TWI under the supervision of BV. The data obtained was in terms of defect detection and defect sizing. The sample size was chosen so that in excess of 90 defects were available allowing three groups of 29 defects to be assessed giving three points on the basic POD curve. From this data the POD at a confidence level of 95% could be determined for the bare pipe trials. For the coated pipe, insulated pipe and bend trials, a reduced set of defects was used. Tables 2-5 show the main results from the trials.

Table 2 shows the results for the bare pipe trials using A-scan, A-scan with a computerised positioning system, magnetic flux leakage and creeping wave.

		POD Value(%) for individual defect size ranges in (mm)			
Trial No.	Technique	1.3 – 1.8	1.9 – 2.2	2.3 – 2.9	3+
1	A-Scan	33	43	74	90
2	Computerised A-Scan	31	67	100	100
3	Magnetic flux leakage	52	48	35	45
4	Creeping Wave	63	86	84	90

Table 2 POD results for bare pipe

Table 3 shows the results for a second group of trials but this time using coated pipes and a reduced sample of defects. The techniques tested included A-scan, A-scan with a computerised positioning system, and creeping wave. Different defect size ranges were necessary for Table 3 otherwise the groups would have been too small.

		POD Value(%) for individual defect size ranges in (mm)	
Trial No.	Technique	1.2 – 2.0	2.1-4.2
5	A-Scan	23	79
6	Computerised A-Scan	85	93
7	Creeping Wave	77	71

Table 3 POD results for coated pipe

Table 4 shows the results for a third group of trials where inspection was attempted through insulation. Only two techniques were used for these trials namely Incotest and the differential magnetic probe. Again different groupings have had to be used because of the restricted sample used.

		POD value (%) for individual defect size (or %wall thickness) ranges		
Trial No.	Technique	0-34%	35-45%	45%
8	Incotest*	25	40	75
		1.4-2.8mm	2.9-4.5mm	4.6+mm
9	Differential Magnetic Probe	23	29	56

* Reduced set of defects (only defects consisting of wall thinning over a significant area)

Table 4 POD results for insulated pipe

The final series of trials involved inspection techniques that could be used for relatively long range inspection. These included LORUS and Teletest and the results are given in Table 5.

		POD value (%) for individual defect size range (%wall thickness or defect size mm)		
Trial No.	Technique	0-34%	35-45%	45%
10	LORUS	60	40	60
		<3mm	>3mm	
11	Teletest	25	60	

Table 5 Long range inspection data

During the trials it was also possible to measure defect size with some of the inspection systems. Figures 10-12 show the results on bare pipe taken during Trials 1,2 & 4. In each case the trial data is compared to the characterised data obtained prior to trials. Thus the y-axis is the ratio of trial data to characterised wall thickness and the x-axis is the depth of the defect as measured in the characterisation work prior to trials.

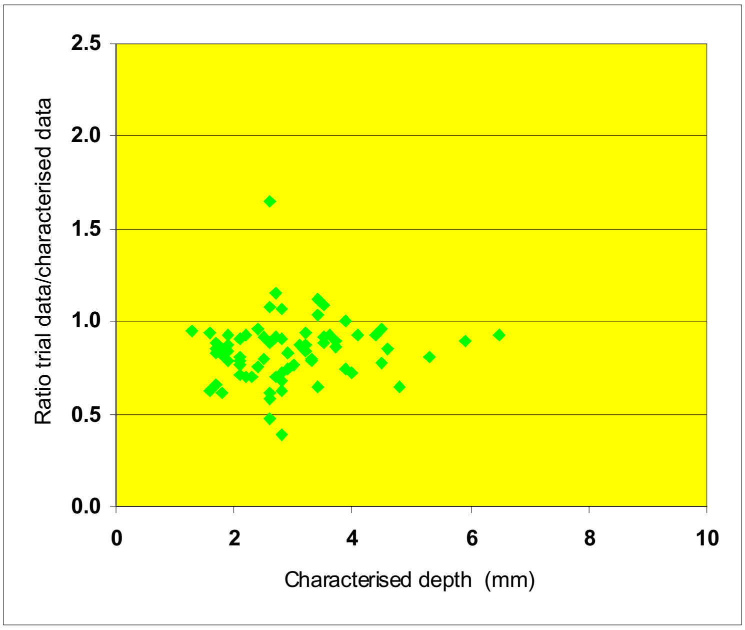

Figure 10 A-Scan Tested on Bare Steel Cumulated Thickness

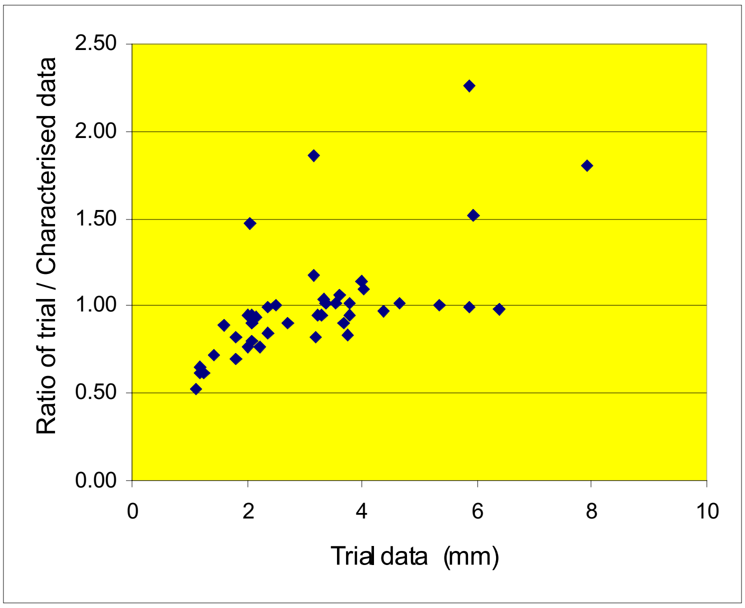

Figure 11 Micromap Tested on Bare Steel Cumulated Thickness

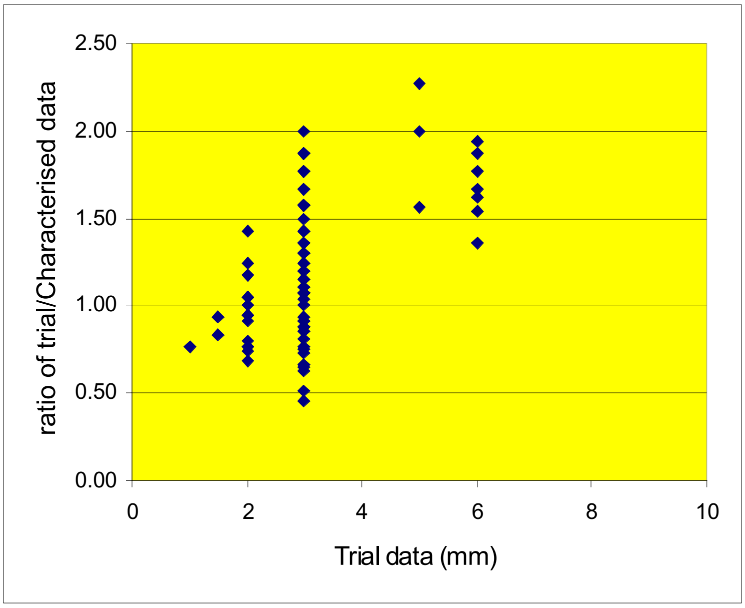

Figure 12 CHIME Tested on Bare Steel Cumulated Thickness

Figures 13 & 14 show the results for coated pipes (Trials 5 & 6) and Figure 15 shows the results for insulated pipe from Trial No. 9.

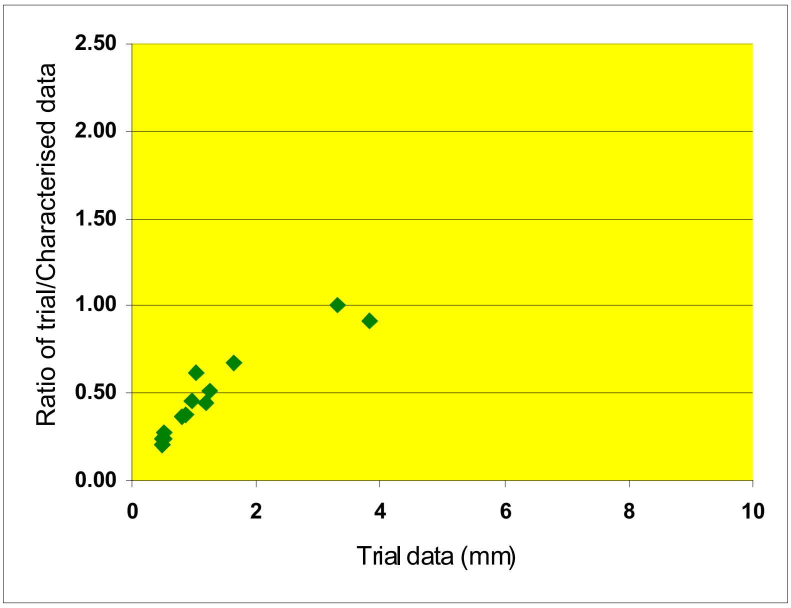

Figure 13 A-Scan Tested on Coated Steel Cumulated Thickness

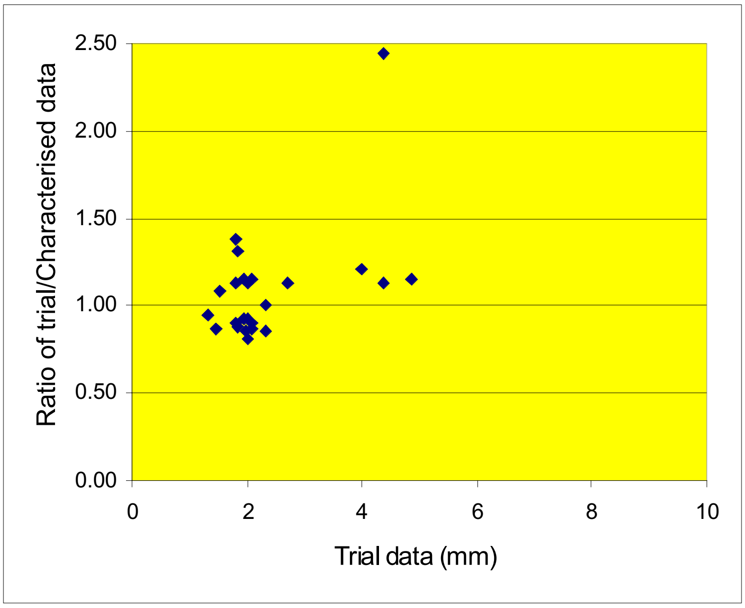

Figure 14 Computerised A-Scan Tested on Coated Steel Cumulated Thickness

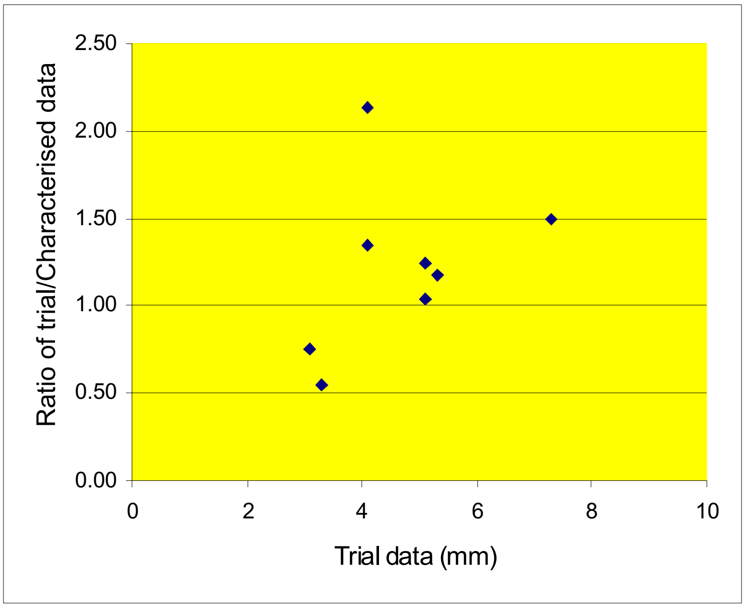

Figure 15 DMP Tested on insulated Steel Cumulated Thickness

Finally a record was kept of any spurious indications for each technique. This information was used to produce reliability operating characteristic plots. Figure 16 shows the results for Trials 1-4 and 11, on bare pipes, and Figure 17 shows the results from coated pipes (Trials 5 & 6). Figure 17 also has the result from Trial No. 9 on insulated pipes.

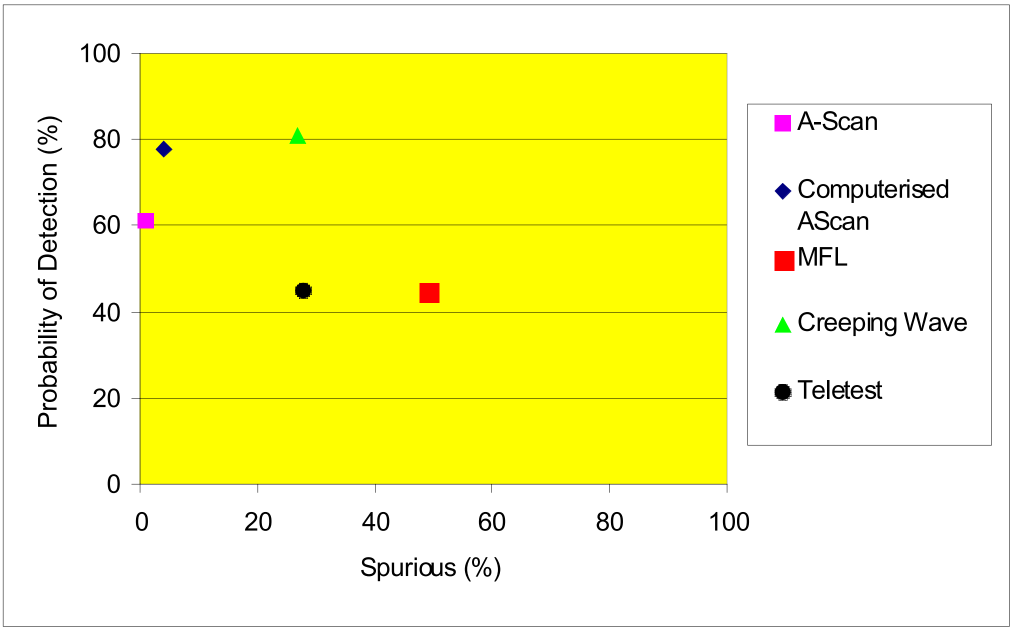

Figure 16 Reliability Operating Characteristic(ROC) for bare Steel Cumulated Thickness

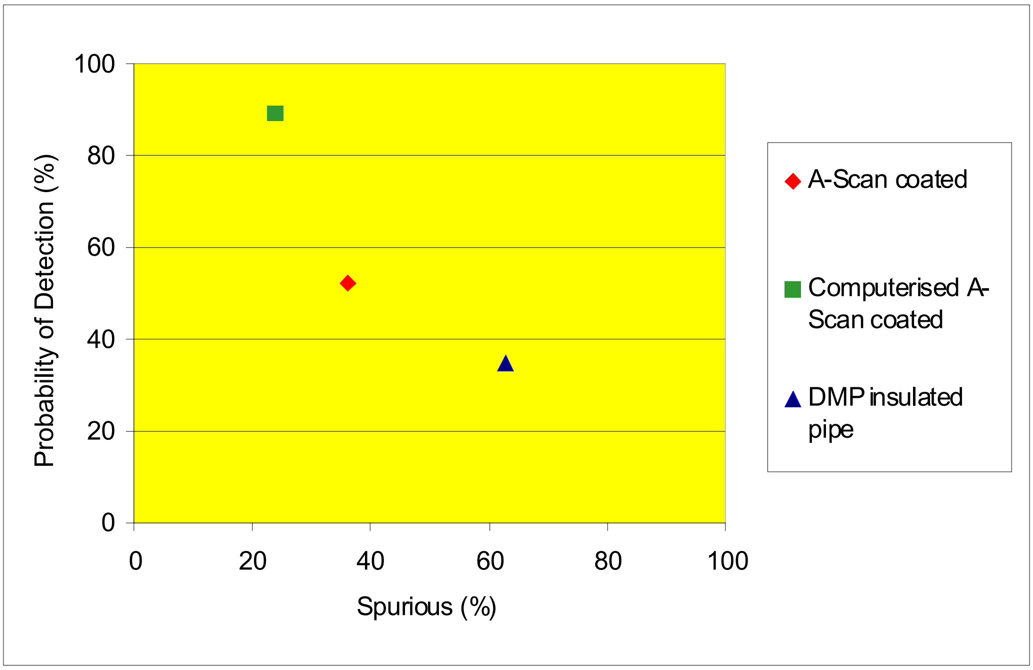

Figure 17 Reliability Operating Characteristic

8. CORROSION RELIABILITY ANALYSIS

Reliability analysis is required in situations where values of quantities used in calculations are not known accurately. Instead of a simple value, a central tendency and spread are used to describe these quantities.

In corrosion it is necessary to consider two variables, load and strength and estimate both in probabilistic terms. Figure 18 shows a typical case where the strength exceeds the load in most circumstances but there is an overlap, the shaded area, and this possible failure region is regarded as the probability of failure (POF).

The expression (strength – load) >0 represents the situation where a component or structure is safe and is called the limit state function. These functions can be expressed in terms of defect size.

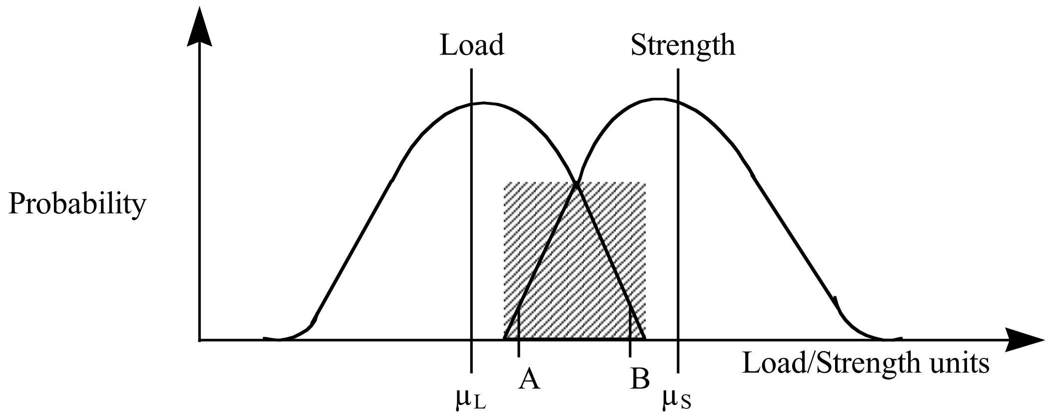

Figure 18 Basic Structural Reliability

In practice the POF will almost always be a small value (e.g. $<10^{-3}$) and this needs to be calculated for a structure or component in terms of how it varies due to degradation in service. Often a related parameter, the reliability index β, is calculated for convenience. The method of derivation is explained below.

The reliability graph shown in Figure 18 can be redrawn as a graph of load against strength, as shown in Figure 19.

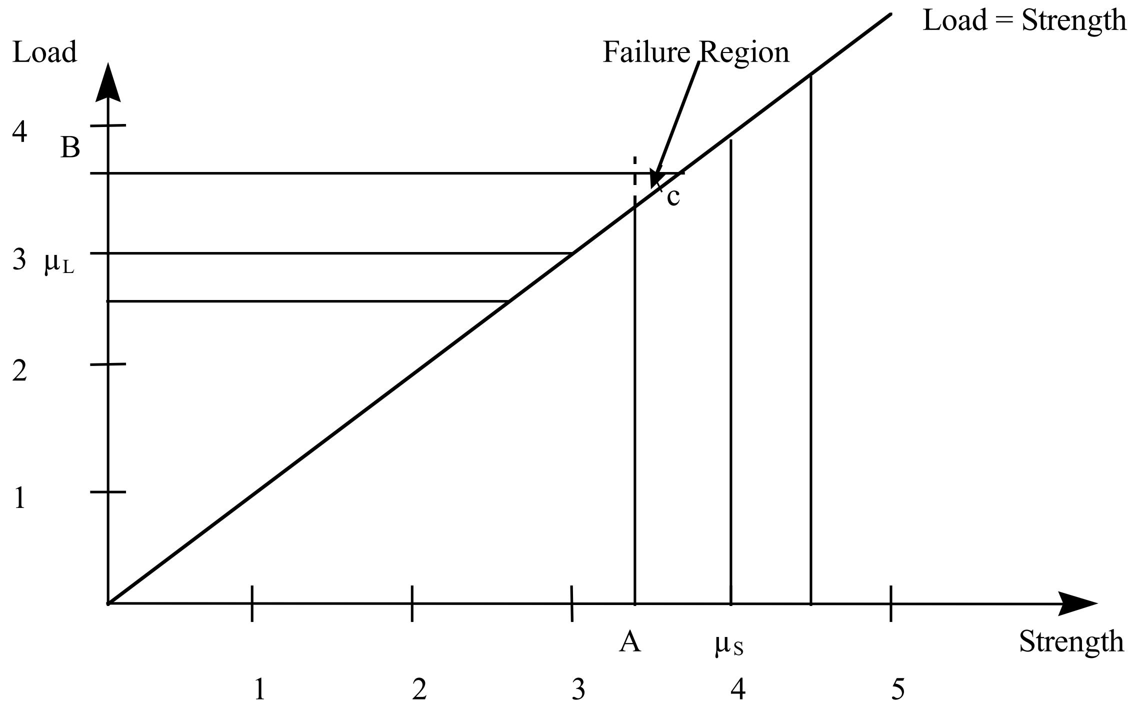

Figure 19 Load versus strength reliability diagram

Anywhere that the load is greater than strength (i.e. to the left of the *load = strength* line) is the failure region. In the particular case of Figure 19 this is represented by the small triangle shown (ignoring the tails of the distributions, for simplicity). Again, it can be seen that decreasing strength or increasing spread increases the area of the triangle and the POF.

If the origin of this graph is set at the central tendency values of load and strength, the *load = strength* line is displaced, as shown in Figure 20.

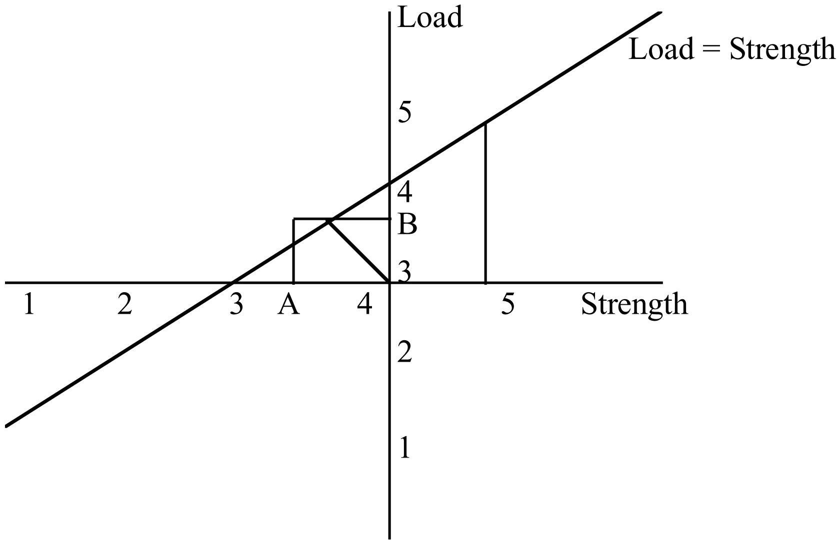

Figure 20 Reliability diagram with axes displaced to central tendency values

The effect of inspection is to provide a new estimate of the reliability based on a re-calculated structural strength. The sensitivity and accuracy of the techniques affect the reliability calculations.

The reliability is said to be updated by the inspection process. The updating can be a static case (i.e. simply recalculated at the new inspection time) or may include degradation models. The latter are needed to produce inspection schedules. Use of knowledge of the degradation process also allows the possibility of Bayesian updating. This uses a preliminary predicted value of the reliability based on the degradation model from initial conditions or from the last inspection, and performs a different calculation to produce the updated reliability.

The distance of the *load = strength* line from the origin can be calculated. Clearly this distance will decrease as the strength reduces; beta will also become smaller.

The procedure for calculating the reliability index, β, for a component subjected to corrosion can be illustrated as follows. In this example the probability distributions for the strength, and load are given and assumed to be normal. The example particularly illustrates how time dependent degradation processes such as corrosion can be implemented in the estimation of the reliability index for a give set of defined variables.

For the standard case involving two distributions of load (L) and strength (S) and where L and S are uncorrelated, the reliability index, β, can be calculated from;

$$\beta = \frac{\mu_S - \mu_L}{\sqrt{\left(\sigma_S^{\ 2} + \sigma_L^{\ 2}\right)}} \tag{1}$$

where μ_S and μ_L are the mean strength and mean load respectively while σ_S and σ_L are the standard deviations for the strength and load respectively. This definition of β is invariant to the definition of the failure function and it is only applicable where the failure surface depends only on two standard variables S and L. In practice, often the failure surface depends on more than just two variables but these are often correlated, and the correlation coefficients must be used in determining the reliability index. Where several variables are involved it is still possible to linearise the safety margin provided that the correlation between any pair of basic variables are accounted for by using the appropriate correlation coefficients.

The example of this procedure is based on a pipe subjected to corrosion. It assumes that the distribution of strength per unit cross sectional area, s, for a pipe is normally distributed $N(\mu_s = 20, \sigma_s = 6)$. In this case it is assumed that *A* is also normally distributed, $N(\mu_A = 1, \sigma_A = 0.44)$. These two standard uncorrelated variables can be used to determine the overall distribution of strength, *S*, which will also be normally distributed with the following parameters.

$$\begin{aligned} \mu_{SA} &= \mu_A \mu_s \qquad = 20 \\ \sigma_{SA} &= \sqrt{\left(\sigma_A^{\ 2} \sigma_s^{\ 2}\right)} = 2.64 \end{aligned} \quad ? \; ? \tag{2}$$

This overall distribution of strength is shown in Figure 21, where it is compared with a normally distributed load $N(\mu_L = 10, \sigma_L = 2)$.

Having reduced the initial variables to two standard uncorrelated variables, the reliability index can now be calculated such that;

$$\beta_1 = \frac{\mu_{SA} - \mu_L}{\sqrt{\left(\sigma_{SA}{}^2 + \sigma_L{}^2\right)}} = \frac{20 - 10}{\sqrt{\left(2.64^2 + 2^2\right)}} = \frac{10}{3.31} = 3.02$$

Further exposure of the pipe to the corrosive environment will lead to a reduction in the load bearing area for the pipe and hence its load carrying capacity. In practice this type of degradation can be obtained by using an appropriate degradation model or by carrying out service measurements to establish the loss in section due to corrosion. Whichever way this information is obtained the possible effect on the load bearing area is shown in Figure 22. This loss of section will lead to an overall reduction in the strength of the pipe as shown in Figure 23 which shows the resulting strength distribution and the original distribution. This resulting strength distribution, $N(\mu_{SA} = 19, \sigma_{SA} = 3.0)$, is also compared with the original load distribution ($N(\mu_L = 10, \sigma_L = 2)$ in Figure 21 which shows a higher degree of overlap between the strength and load distributions. This effectively will reduce the reliability index now given based on the parameters of the two standard distributions such that,

$$\beta_2 = \frac{\mu_{SA} - \mu_L}{\sqrt{\left(\sigma_{SA}{}^2 + \sigma_L{}^2\right)}} = \frac{19 - 10}{\sqrt{\left(3.0^2 + 2^2\right)}} = \frac{9}{3.61} = 2.50$$

In practice a degradation function is used to predict, from the start of service, the variation of _ with time. The reliability index can be recalculated during service given the information coming from inspection. The inspection data used for updating must be used with appropriate assumptions of variability.

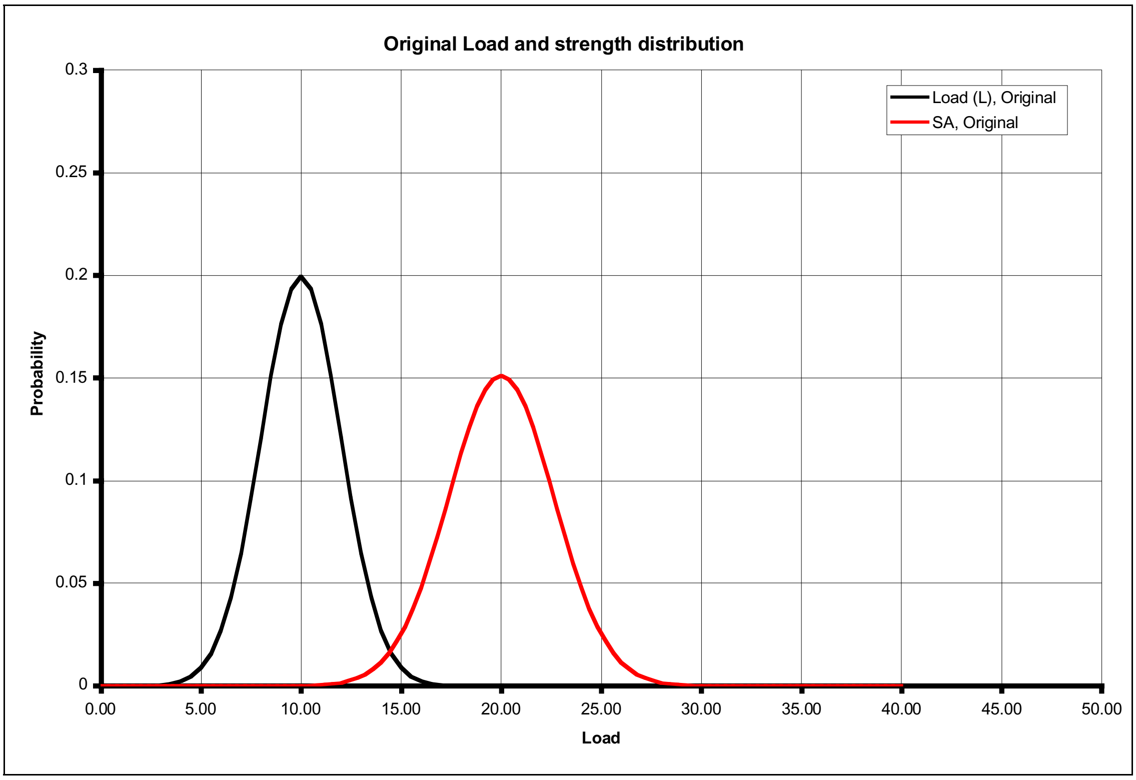

Figure 21 Distribution of standard variables used in calculating β_1

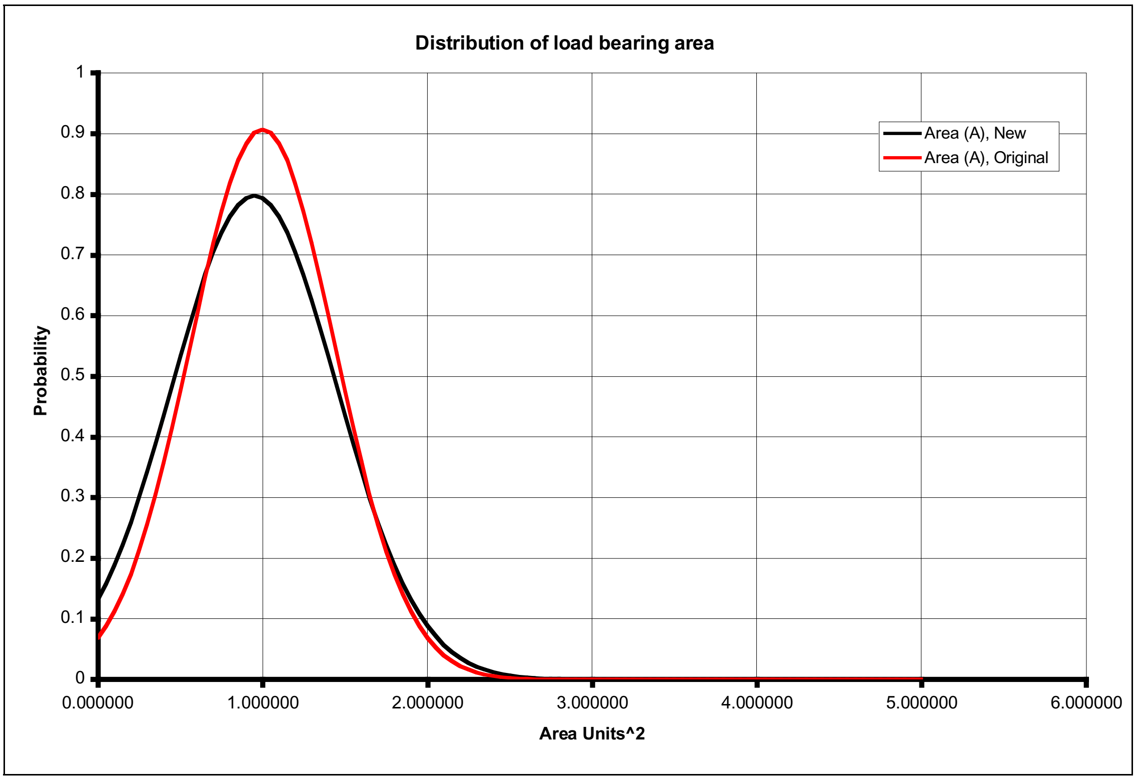

Figure 22 Effect of degradation on the distribution of load bearing area for β_2

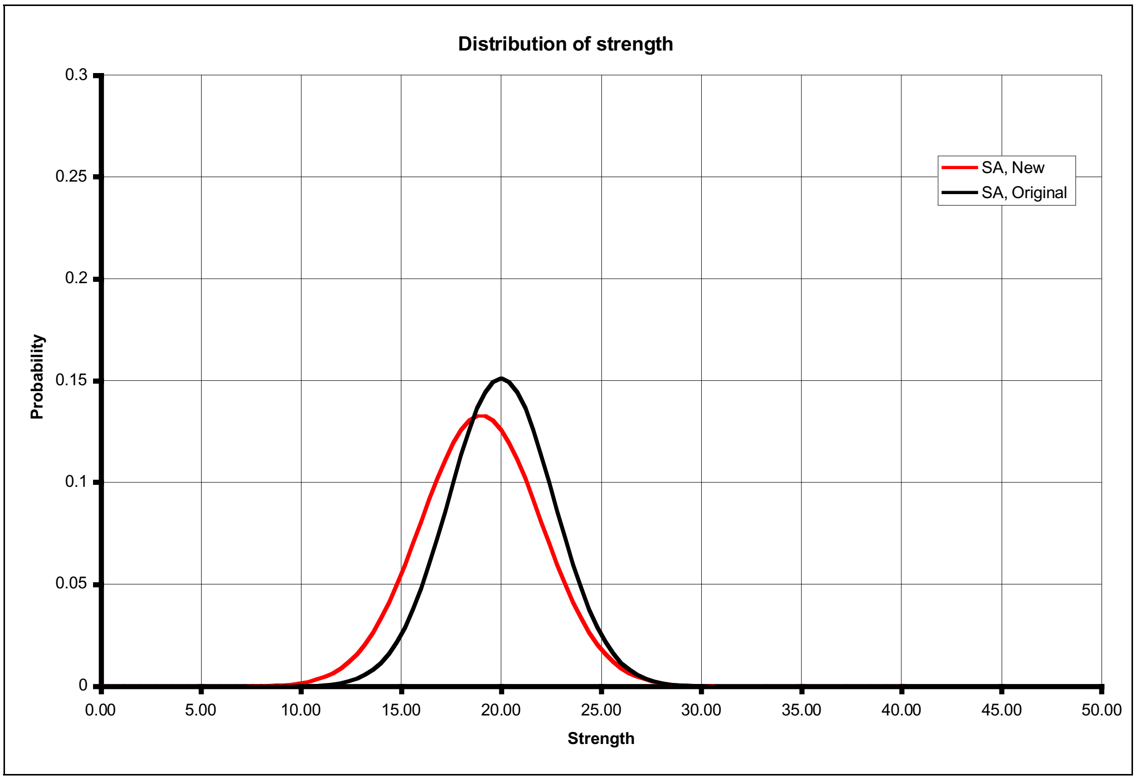

Figure 23 Effect of degradation of distribution of strength for β_2

Software such as Strurel or Comrel [5] is available for the calculation of β and in RACH [6], Comrel was used in conjunction with limit state functions derived from various sources (ANSI B 31G [6], RSTRENG) and a corrosion pit growth model.

The aim of the analysis is to quantify the time dependent failure probability. This requires the use of the time variant form of COMREL (COMREL –TV). This is more complex than the time invariant analysis as it requires the consideration of random processes which are not necessarily stationary with respect to time.

The most important aspects for reliability based inspection scheduling are as follows:

To give assurance of integrity for a given service period (a degradation model is required for this).

Updating of computed reliability using inspection data.

The defect growth model incorporated into RACH is of the form shown in equation (1).

$$\text{Depth of pit (d)} = K\, t^{\,n} \qquad (1)$$

Where t is time and K and n are constants depending on the environment, material etc. This is used in conjunction with either of several limit state functions taken from codes (ANSI B 31G, RSTRENG, or API 579 Level 2 and 3).

For integrity assurance one has to adopt a target reliability level. In addition a predicted reliability curve estimated in terms of service life needs to be produced. This then allows the choice of inspection interval.

The purpose of reliability updating is to reduce the knowledge uncertainty by taking into account the most recent observations (inspection data). This needs to include the uncertainty associated with inspection sizing accuracy.

Two problems exist in terms of the inspection data. One is the accuracy of sizing and the other is the likelihood of detection. The second point also has two aspects ie whether the inspection is in control or whether the detection level is poor. Probability of Detection data will be relevant to the last of these two but knowledge of the degradation mechanism is necessary to show which inspection equipment should be used.

The difficulty associated with implementing inspection data into reliability updating, and the advantages of using more accurate measurements, can be visualised from the following example based on three types of inspection data.

Type A produces thickness measurements directly, with a resolution that is expected to be good (1% is shown), and is the type of data expected from ultrasonic thickness gauging. Figure 24 shows an example of a set of readings for one particular application. This type of data is very dependent on the sampling approach used to collect data. Given full (100%) sampling a distribution like Figure 24 is possible.

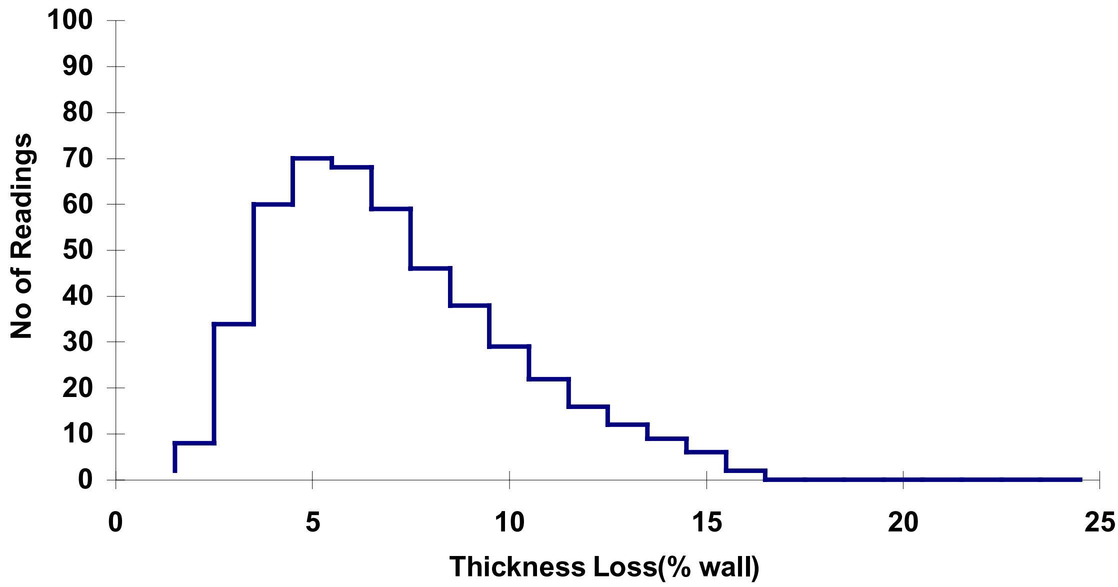

Figure 24 Example of high resolution wall thickness readings

Type B is a system that has a known POD of 1-exp(-0.1221x) (where x is the wall thickness loss). This relationship shows, for example, that the equipment has a POD of approximately 95% at 25% wall loss. Some flux leakage devices, ACFM, the radiography system and the low frequency ultrasonics may have data in a format that can be interpreted in this way.

Type C is a system that separates its received data into 20% wall loss intervals. Due to the low resolution of Type C 20% of the data recorded as being in the 0-20% range is actually 20-40%. In addition 20 % of the data recorded as being in the 20-40% range is actually 0-20% and 20% is 40-60%. Some flux leakage systems produce output in this format.

In order to compare the use of these three different types of inspection data an example of in-service degradation needs to be considered. Figure 25 shows a statistical representation of the result of a particular deterioration mechanism. The graphs show the expected thickness after periods of 5 years. In practice other deterioration mechanisms will give different forms of this graph. The form may be known from previous plant experience but may be less well known in new plant or plant where conditions have or will change.

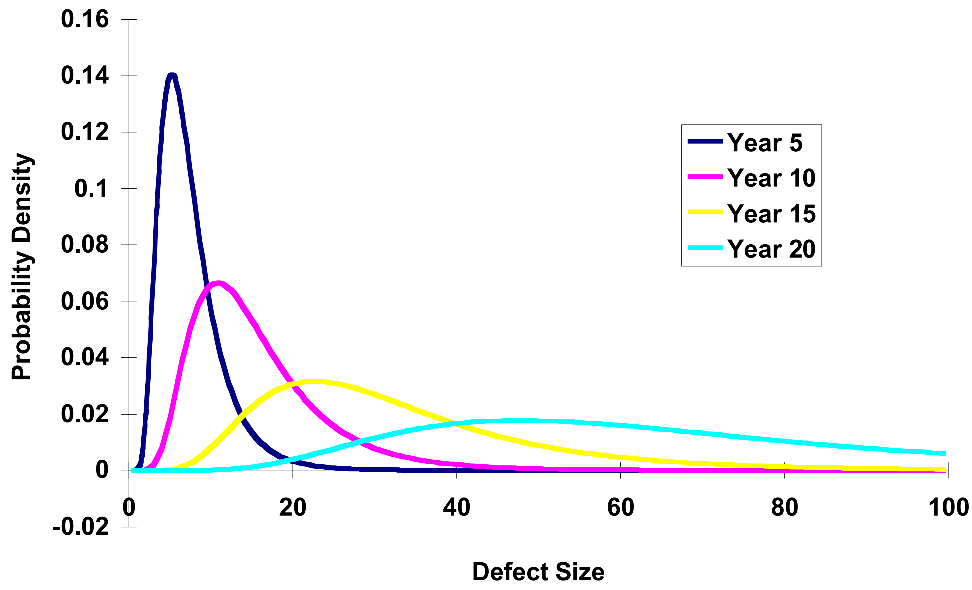

Figure 25 Example of Deterioration Mechanism

As mentioned earlier the limit function can be expressed in terms of defect size. Thus the extra shaded area under the tail of the distribution in Figure 26 can represent the probability of failure.

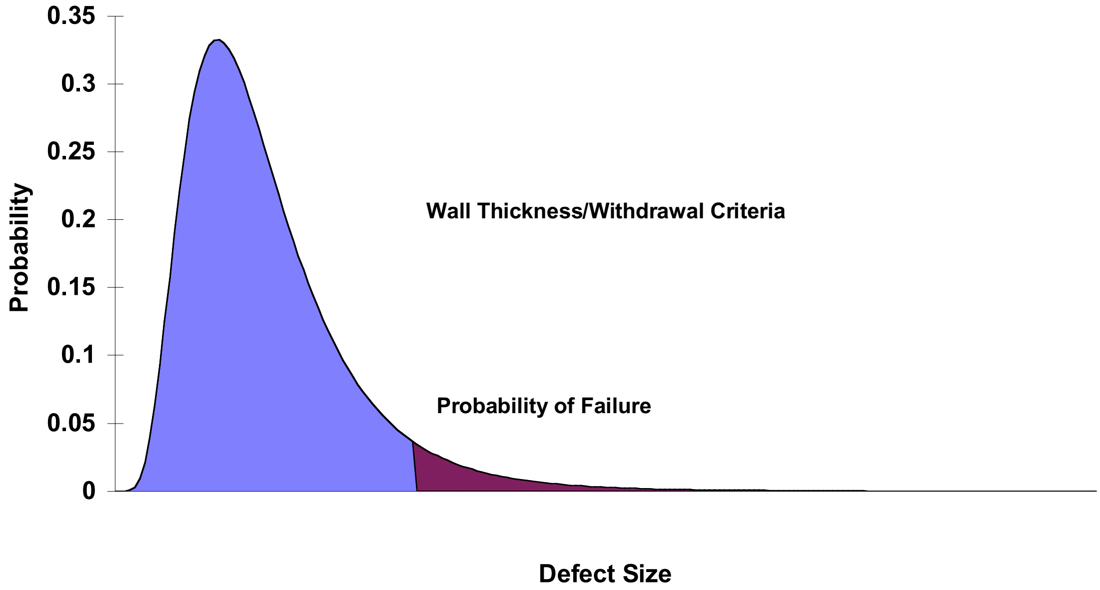

Figure 26 Probability Density of Defect Size showing Probability of Failure

Combining Figures 25 and 26 can give something like Figure 27, which shows how the POF varies with time. A point on this curve may be chosen as the target reliability figure at which it may be necessary to take action (for example probability of failure 10^{-3}).

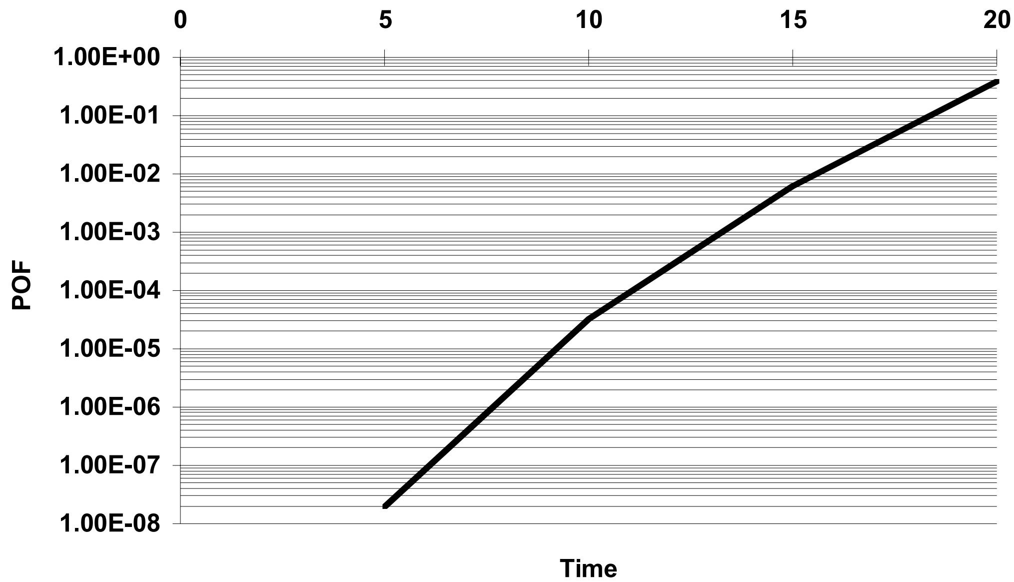

Figure 27 Change of POF with Time

To compare the three types of data the following results are assumed for an inspection at Year 10.

a) Equipment A results are as given in Figure 24.

b) Equipment B results gave no indications of defects.

c) Equipment C results gave 80% of data points in the range 0-20% wall thickness loss and 20% data points in the range for 20-40% wall thickness loss.

Firstly, for equipment A, Figure 25 showing, the expected thickness distribution, can be compared with the measured defect distribution given in Figure 24. It can be seen that the measured distribution agrees closely with the defect distribution after 5 years and the probability of failure estimated after this inspection (from Figure 27) would be $2x10^{-8}$.

To analyse an inspection carried out by Equipment B with no defects detected, it is necessary to consider the probability of a defect being present together with the POD. This may be represented by the diagram in Figure 28. For any particular defect size range, and at any particular time, the probability that there is a defect is given by Area A, and the POD by Area B. Area A will correspond to the probabilities for individual size ranges within the graphs in Figure 25, and Area B will be 0 at zero defect size and increase as the defect size increases.

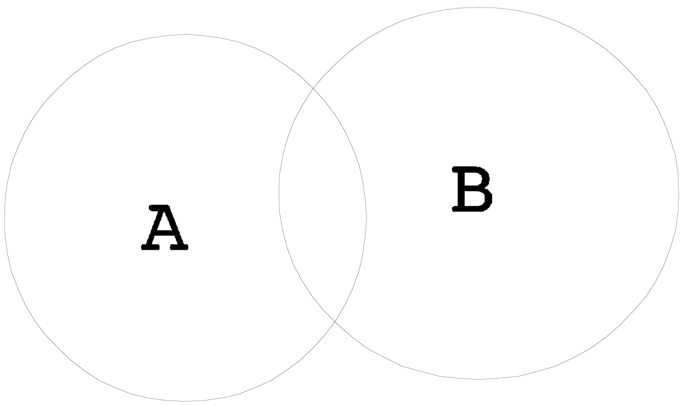

Figure 28 Probabilities for an Inspection at a particular time

A- Probability of defect of certain size being present

B- Probability of Detection for that size

Overlap Area-Probability of a defect being present and detected by the inspection

The overlap of the two is the probability that a defect will be present and detected. The total probability over all sizes can be calculated by summing the values for all size ranges. The probability that a defect will be detected using Equipment B at any inspection time, and therefore the probability that an inspection could be carried out with no defects at each inspection time can be calculated.

If no defects are detected, a choice of an appropriate probability must be made to estimate the year to which the deterioration has progressed. Suppose that a 10% probability is considered acceptable, then, on the basis of the calculations described above, this would give a defect distribution in Year 8 (say) and a POF of $5x10^{-6}$. A consideration of confidence intervals in this data is likely to be most important in this type of analysis.

The situation for equipment C is rather more complex. Suppose an inspection result gives 80% in the range 0-20% wall loss and 20% of results in the range 20-40% loss. Using a correction for the errors as mentioned earlier, a final estimated defect distribution can be calculated.

If the defect distribution curves in Figure 25 are replotted in 20% ranges, the results of the inspection can be compared directly with the defect distribution for equipment C, as in Figure 29. It can be seen that in this case a reasonable correspondence is with the distribution in year 10 (giving a POF of 3×10^{-5}).

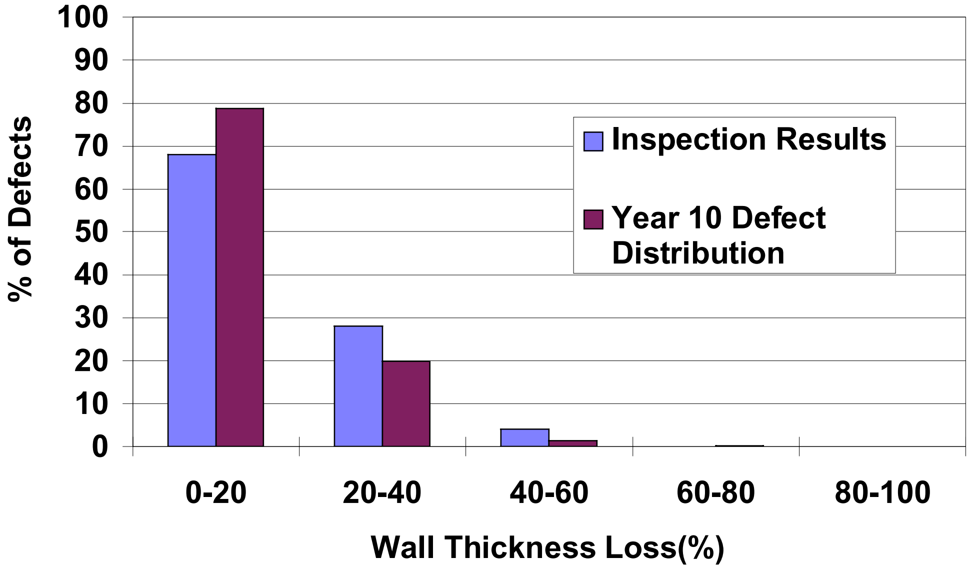

Figure 29 Comparison of Inspection Results and Year10 Distribution

The above data gives some idea of how to estimate the current POF from an inspection result with known inspection reliability data. In order to assess the date of the next inspection the target POF needs to be known together with an existing timescale.

If one takes the target POF to be 10^{-3}, and all the inspections above had been carried out in Year 10 then examination of Figure 30 shows that in the case of the inspection carried out by the high resolution device the deterioration mechanism appears to have not taken place as fast as expected, and the expected progression indicates a life of 8 years before withdrawal. Inspection B shows that the target POF will be in Year 15, and Inspection C reaches the target POF in Year 13.

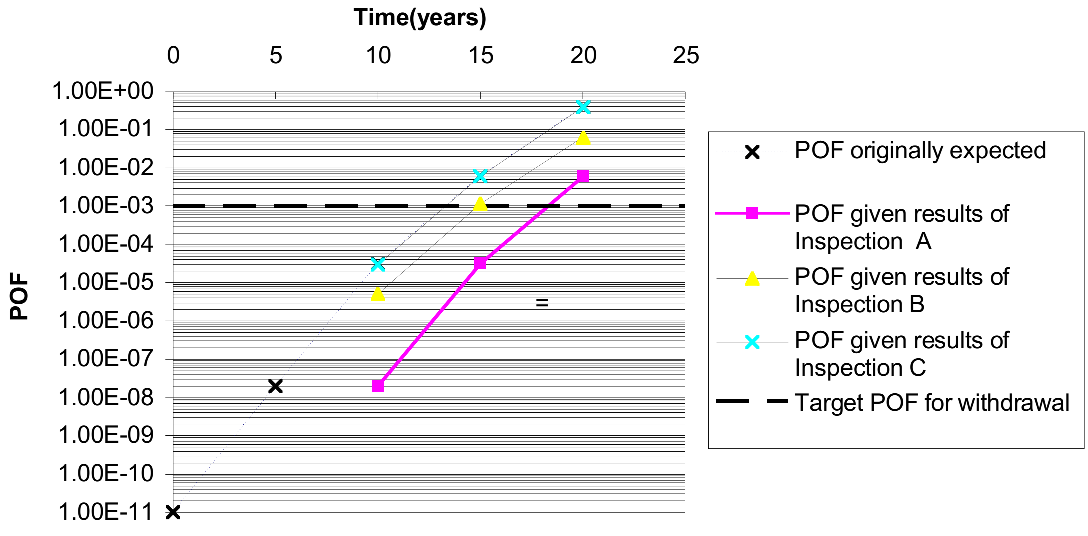

Figure 30 Effect of Inspections on POF and Lifetimes

9. ANALYSIS OF SERVICE DATA

The final example looks at service data and illustrates lack of control in inspection. In RACH a procedure for manual updating for inspection scheduling for corrosion defects was developed. This was used for assessing a service case history. The steps are as follows:

Establish the ‘a priori’ curve for β as a function of time.

Choose a minimum target reliability level (β) and hence decide on the date for inspection.

Specify an inspection method which is able to detect a defect size equal to the one predicted.

Update the predicted defect size by using the inspection outcome and continue the prediction from that point to give an ‘a posteriori’ curve.

The service example is based on a mature system installed in 1983 in the North Sea for a 20 year life. The topside pipework was inspected frequently with A-scan and occasionally with A-scan incorporating a computerised positioning system. Thus two sorts of inspection data are available for analysis representing two inspection strategies. Both strategies are based on UT data but one with a specified grid along the pipe (referred to as UT) the other a detailed measurement of wall thickness for the whole pipe (referred to as μMap)

Annual data using these two approaches is shown in Table 6. Examples of individual sets of data are shown in Figures 31 and 32.

Line Number	Date Inspected	Nominal WT	Minimum Reading Recorded	Technique
1	09/03/1995	9.27	7.2	UT
	30/06/1996	9.27	6	UT
	15/04/1997	9.27	5.79	Map
	28/08/1998	9.27	5.25	UT
	31/08/1997	9.27	4.75	UT
	25/10/1998	9.27	2	Map

2	21/09/1991	7.78	9	UT
	30/06/1996	7.78	8.99	UT
	15/04/1997	7.78	1.79	Map
	28/08/1997	7.78	7.75	UT

Table 6 In-Service inspection data

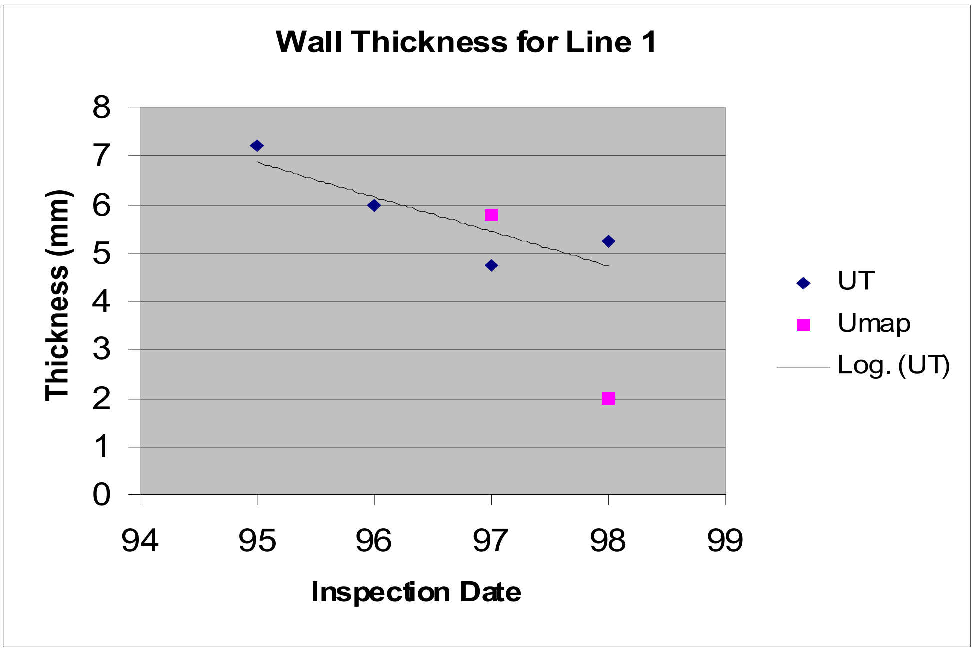

Figure 31 Historical Inspection Data

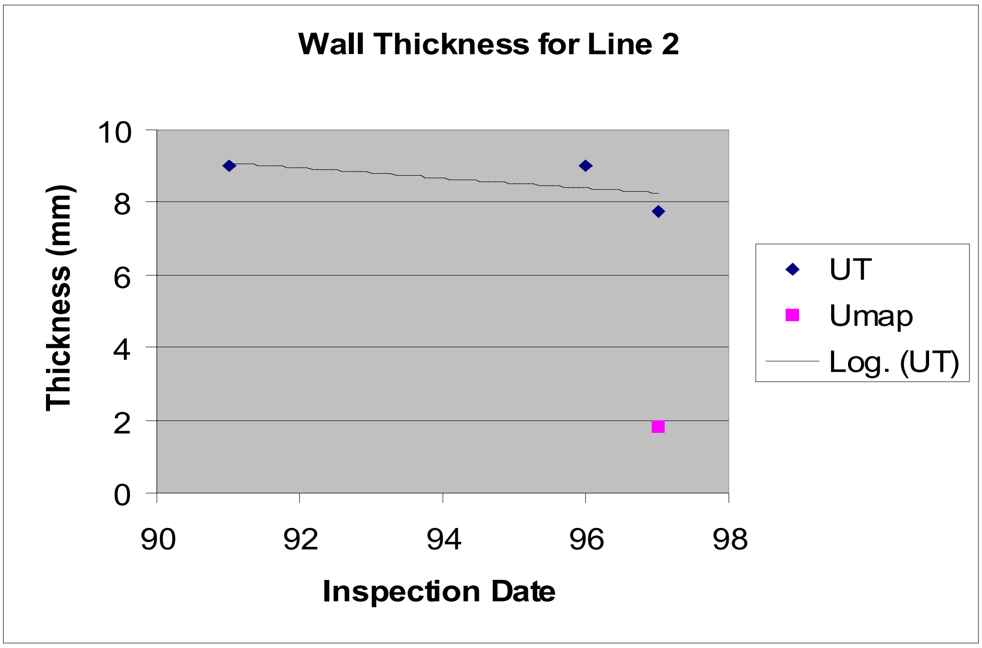

Figure 32 Historical Inspection Data

The historical data can be seen to be very dependent on the inspection strategy. Figures 31 & 32 appear to show two types of behaviour, widespread corrosion or localised corrosion. Line 1 for example appears to give similar results for UT and µMap. Thus even without 100% coverage significant wall loss was detected. The corrosion in the pipe must have been widespread.

A check on the distribution measured by µMap, seen in Figure 33, confirms this as many defects were detected and the average remaining wall thickness was between 5 and 6mm.

This represents nearly 50% wall loss for the average measurement. Thus even UT was measuring significant corrosion.

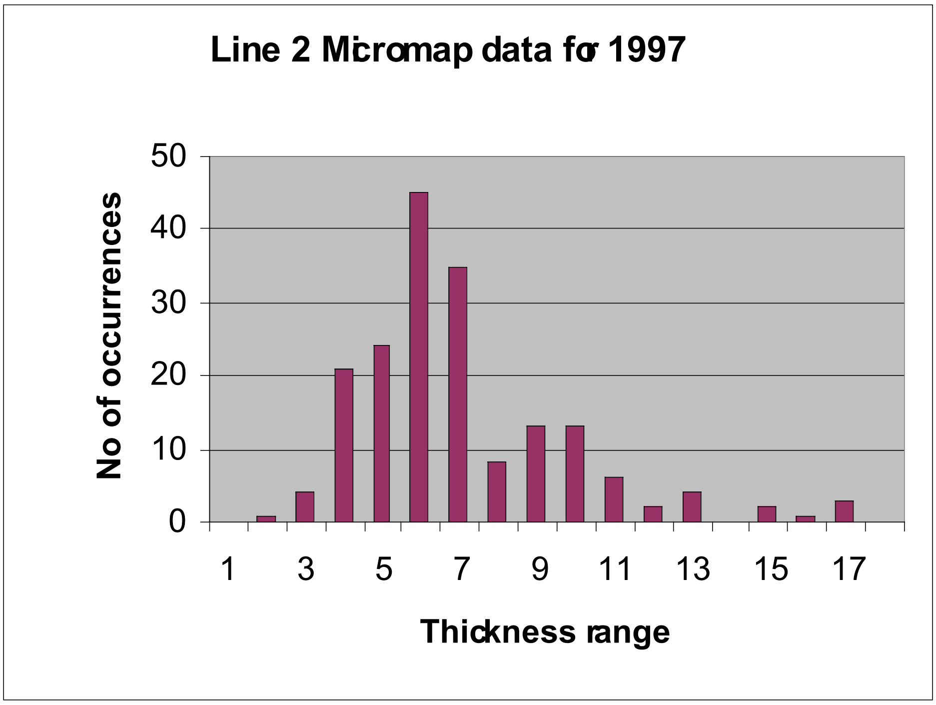

Figure 33 Line distribution of measured wall thickness

In contrast Line 2, Figure 32, shows wide differences between UT and μMap. In these cases the UT inspection was not sufficiently in control and was not detecting the significant flaws. The detailed MicroMap data for 1997 showed that the distribution was very different to that shown in Figure 33 and that only a few were around 2 mm and the normal distribution was centred around 10mm. Thus with only a few measurements the significant defects may be missed.

The analysis can be expressed in a different way using the software developed with RACH for a probabilistic assessment. This can be done in association with the trials data produced for the μMap technique.

The trials data showed that wall thickness loss in excess of say 2.5 mm could be detected with a very high POD at a high confidence level. In addition the accuracy of wall loss prediction approached a very high accuracy at about 3 mm loss. Thus periodic use of μMap on line with a corrosion allowance of 3.2 mm (as in the present case) would ensure detection before failure.

A-scan trials data showed that a wall thickness loss nearer to 4 mm is needed before reaching a very high POD and that in combination with a persistent underestimate of 20% the periodic use of this technique would not guarantee detection within the corrosive allowance of 3.2 mm.

Given appropriate choices for the degradation model it is also possible to produce the relevant β values necessary for inspection scheduling. Figure 34 shows this scheduling data for Line 2, produced using the RACH software.

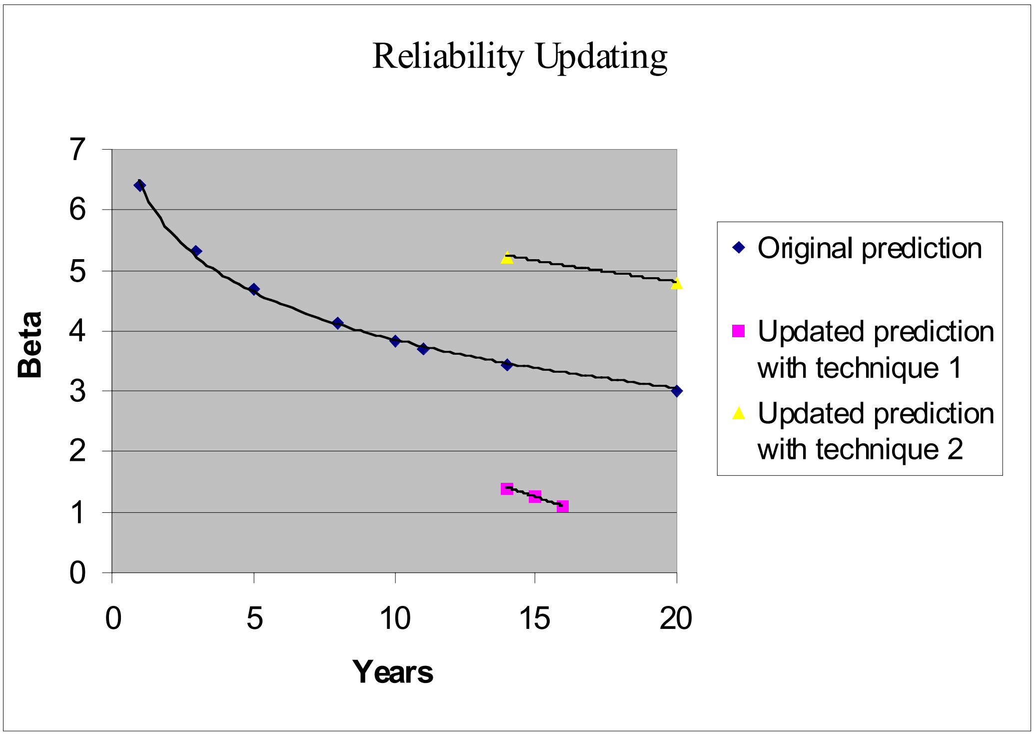

Figure 34 Reliability Updating for Line 2

Figure 34 shows that only µMap appears to be in control of the process and that the corrosion process appears to have been underestimated. Thus for Line 2 only µMap is an appropriate inspection tool.

10. SUMMARY AND CONCLUSIONS

10.1. SUMMARY

The initial reviews and the information received from the Health and Safety Executive, Shell and Marathon showed that the project needed to address the problem of corrosion and erosion in pipework. This is still a cause for concern and can give problems including the release of hydrocarbons.

Corrosion modelling identified three types of corrosion (general, local metal loss, and pitting corrosion) and produced typical growth rate equations. These together with the limit state functions were coded into the COMREL reliability program to give corrosion reliability inspection scheduling. The version used in this work was the Time Variant so that updating from in-service data was possible. In essence this program produces the value of β for a particular situation (where β is related to the failure probability and for scheduling is a more convenient program output).

β values are produced in a particular case for specific intervals in a service life, and, given a target value of β for safety purposes, an inspection schedule is constructed. The unknown or unforeseen possibilities of damage in service are taken into account by the calculated values of β based on in-service data. Thus an updated β curve can be compared to the original β curve and amendments made to the inspection schedule based on a comparison of these curves.

Demonstration trials involved, inspection reliability trials, laboratory trials and field trials. The preliminary survey of POD data revealed that there was nothing suitable for the detection of isolated local metal loss or pitting and, given the importance of this data for probabilistic based inspection scheduling, POD trials were necessary.

The trials were conducted under the supervision of BV, in order to give manufacturers assurance of impartiality, at the facilities of TWI using the sample produced at UCL. Strict control of data and interpretation was enforced by BV and the results are given on significant first step in the provision of quantitative data on inspection reliability for corrosion.

The results showed that 100% inspection with UT could, in the best circumstances, give excellent results in terms of defect detection and sizing. Other results also showed that some of the newer techniques although promising in terms of economic use still required further development before they could achieve the benefits of low cost and high quality data.

Laboratory trials and field trials were based on the data produced in the project especially the information on corrosion modelling and corrosion reliability inspection scheduling. For the laboratory trials advantage was taken of the corrosion pit production for the POD sample. Attempting various inspection schedules was possible in this laboratory based work and could be verified given the access to real defect growth rates. Two particular inspection systems were utilised and compared using the predicted values. The basic difference between the inspection systems was that in one case the scanning pattern for thickness measurement was quite broad giving the possibility of missing or undersizing some corrosion pits. The results showed that for the broad scanning pattern the β values were insensitive to the defect population and were invariably low in value, something akin to loss of control of the process. The ideal scanning pattern of the other system gave good results and a consistent updating behaviour. The results also showed that both of the limit state functions coded gave relatively similar predictions.

The field trials were based on a Marathon platform and produced an interesting variety of situations. The most frequent situation was of single mode behaviour in that normal sampling showed how the defect population varied with time in service. However bimodal behaviour also existed and caused problems for the operator. It was necessary in these circumstances to have two inspection systems, conventional thickness mapping and μ Map a more intense and elaborate survey. μ Map located and sized defects in both populations, general corrosion and local metal loss / pitting. It was clear from this work that any occasional periodic check with μ Map linked to more regular conventional wall –thickness surveys could give control of the degradation process.

10.2. CONCLUSIONS

The RACH project has provided data and analysis methodology suited for rational inspection scheduling. The defect sample and POD trials results together with defect growth rate models and limit state functions used in conjunction with COMREL –TV, has allowed the development of corrosion reliability analysis.

The results show that thickness measurement can be very accurate but that sampling pattern have a strong influence on the detection of corrosion.

All of the information on NDT equipment and procedures is stored on the RACH database together with the inspection reliability results [8].

a) Corrosion and erosion are still a problem in offshore process plant even in plain pipes.

b) A wide range of NDT equipment is now available for detection of wall loss and with 100% inspection and removal of cladding very good results can be obtained. In more difficult situations such as inspection through thick coating improvement in NDT equipment is still needed.

c) Probability based inspection scheduling is now possible but requires information on the defect distribution and the change in distribution during service life. In service measurements are necessary to provide the input but this needs to be done through consideration of the probability of detection.

d) Eight techniques were subjected to rigorous trials to give POD and sizing accuracy data. Of these the 100% thickness measurement UT systems used on bare metal were very successful. It was not possible to include X-ray techniques and this work is still necessary.

e) Corrosion modelling was studied and reviewed and typical growth rates and limit state functions were coded for corrosion reliability inspection scheduling. Field trials showed that the software based on COMREL-TV could be applied to service data in principal but that the nature of corrosion could be quite complex leading to a combined distribution of defects. Further modelling and validation work is required before the probability based corrosion reliability inspection can be confidently used.

11. ACKNOWLEDGEMENTS

The RACH Partners would like to acknowledgement the financial support of the EU DGXVII (THERMIE Programme), Shell UK Exploration and Production, Marathon Oil UK Limited and the Health and Safety Executive.

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ISBN 0-7176-2014-X

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