# Pigging Run Comparison and Prediction

## Anthony Wickham, Andrew Palmer and Associates

## 1 SYNOPSIS

During a pipeline's lifetime, inspection technology developments can radically change the preferred survey methods and their accuracy. Reconciling results from disparate inspections while accounting for all uncertainties is a problem which has not been widely addressed, results from individual inspection campaigns typically being reviewed in isolation.

The paper describes an approach which allows all relevant inspection results to be analysed holistically. The methodology explicitly accounts for all the uncertainties associated with metal loss inspection data. It can be extended to incorporate uncertainties in pipeline corrosion rate predictions, (for example fluid corrosivity, inhibition effectiveness, inhibitor availability and local pitting) as well as systematic variations in temperature, pressure, and flow regime.

The approach provides risk based point-in-time estimates of the pressure capacity of the pipeline, together with statistical estimates of the remnant life of the pipeline. The analysis identifies the criticality of all of the metal loss defects analysed, and also predicts the failure mode for each of the defects.

The methodology explicitly accounts for the confidence limits associated with different methods of inspection and it therefore provides a rational basis both for planning inspection intervals and for choosing between alternative inspection technologies.

## 2 INTRODUCTION

Changes in inspection technology and in the preferred methods for, and accuracy of, metal loss surveys may make it difficult to reconcile different sets of inspection results taken over the lifetime of a pipeline. Even where multiple inspections are undertaken using nominally identical tools the error bands associated with those tools impedes the analysis and understanding of the inspection results. The result is that asset managers may be forced to ignore some data and rely only on the findings of later inspections.

The only practical method for determining the magnitude of corrosion metal losses throughout an entire pipeline is by means of an intelligent pig inspection. However, unless metal loss is proceeding rapidly, the uncertainty in the change in wall thickness at a given location will typically be of the same order as the metal loss itself. Only when the metal loss is very rapid will the uncertainty in the derived corrosion rate be small with respect to the mean corrosion rate. This means, of course, that confidence in the accuracy of the corrosion rate will be highest when the expected remnant life is low.

Figure 1 shows, as an example, the large uncertainty in the corrosion rate inferred from the results of two intelligent pig surveys undertaken with a five year interval.

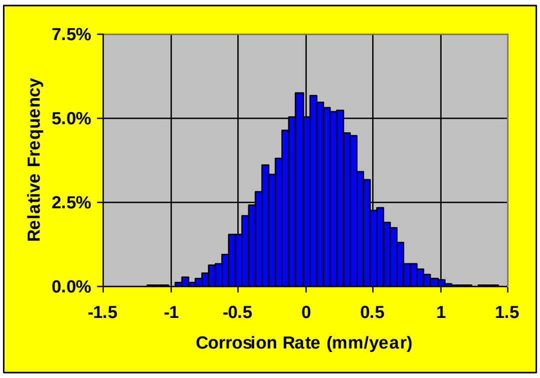

**Figure 1: Distribution of corrosion rate**

To make the best use of the available information it is necessary to establish a comprehensive framework within which the results from a number of disparate inspection campaigns can be appropriately reconciled while taking into account all of the uncertainties associated with the condition of a pipeline. If successful, such a framework will allow all of the relevant inspection results to be analysed holistically, thereby ensuring that optimal use is made of all available inspection data.

Figure 2 shows the reported wall thicknesses at the times of 10 different surveys of the same defect. The error bars show reported wall thickness plus and minus one standard deviation. The surveys involved two different types of MFL pig, one manual ultrasonic survey and three different types of automatic external ultrasonic measurement.

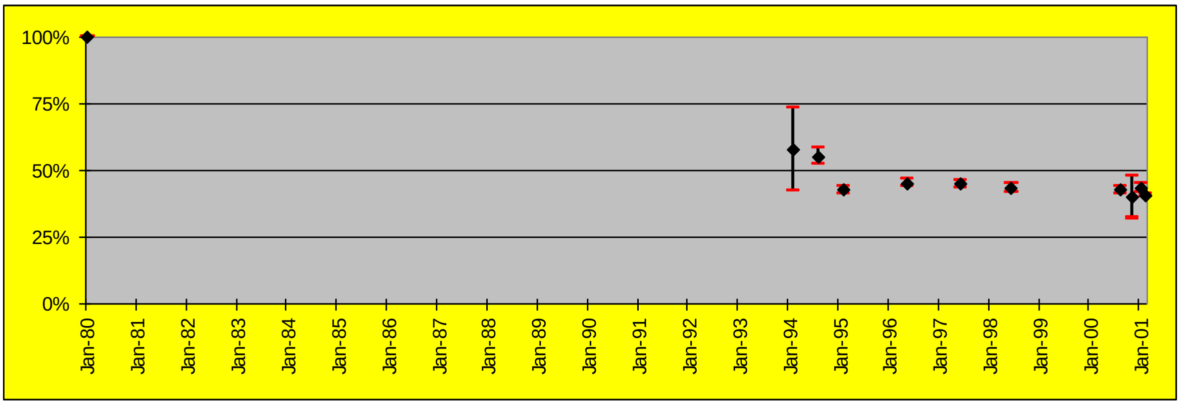

**Figure 2: Reported wall thicknesses at 10 surveys over lifetime**

The paper describes an approach that has been developed to deal with this type of problem, and that allows all the well-known sources of uncertainty associated with corrosion rate predictions in pipelines to be taken into account. These include large scale factors (such as the corrosivity of the transported fluids and the effectiveness of the inhibition regime), medium scale factors (such as temperature, pressure and flow regime) and small scale factors such as local pitting and the uncertainties associated with inspection data.

The methodology was developed to allow continuous updating of corrosion predictions on the basis of all available information such as the findings from multiple general and local inspections. The fact that the defects being analysed have not failed at the time of the analysis is also taken into consideration. The resulting remnant life predictions are therefore always consistent with the known condition of the pipeline.

This methodology is demonstrated using survey data obtained for a range of pipelines including pipelines in gas, oil and multiphase service. The majority of the pipelines have been subject to two surveys using intelligent pigs, however one pipeline had only been intelligently pigged once, and the remnant life assessment was therefore based on this survey and the original as-built wall thickness.

Within the context of the analysis, some operational benefit is derived if the intelligent pig runs are carried out by the same contractors since this leads to consistency in the reporting format and makes the task of comparing the pigging results less onerous. It should be emphasised however that this is not a requirement of the methodology presented here, and indeed one of the strengths of the methodology is that it is able to reconcile the results obtained using different instruments.

In one of the assessments undertaken the first (magnetic flux) intelligent pig inspection survey reported approximately 32000 individual metal loss features having a depth in excess of 10% of wall thickness. The second (ultrasonic) pig inspection was undertaken approximately 2.5 years later. This survey reported approximately 4000 individual internal metal loss features. The significant reduction in the number of individual features reported is caused by three main factors:

- The difference in accuracy and sensitivity between the two tools used;
- The additional corrosion resulting in the accretion of many small defects into a smaller number of larger defects with more complex morphologies;
- Inconsistent defect definition and reporting between the two inspections.

## 3 ACCURACY OF DEFECT DEPTH SIZING

The accuracy with which the depths of metal loss defects can be determined is dependent on the technology employed. In the case of ultrasonic inspection it also depends on both the defect size and the speed of the inspection vehicle. Typical claimed accuracies are given in Table 1 below.

| Survey Methodology | Tolerance | Confidence Interval |
|---|---|---|
| Ultrasonic (TOFD) | +/- 0.1 mm | 90% |
| Ultrasonic (IP) | +/- 0.2 to 0.3 mm | 90% |
| Ultrasonic (manual) | +/- 0.5 mm | 80% |
| MFL | +/- 10% to 20% wall thickness | 80% |

**Table 1: Typical claimed accuracies for defect depth sizing**

In the absence of any contradictory information it is usual to assume that random measurement errors follow a normal distribution. Assuming that the errors are normally distributed, the accuracies given in Table 1 correspond to the standard deviations given in Table 2.

| Survey Methodology | Standard Deviation |
|---|---|
| Ultrasonic (TOFD) | 0.06 mm |
| Ultrasonic (IP) | 0.12 to 0.18 mm |
| Ultrasonic (manual) | 0.4 mm |
| MFL | 1.25 to 2.5 mm [1] |

**Table 2: Derived Standard Deviations for errors in depth sizing**

[1] Based on a nominal wall thickness of 15.9mm

## 4 CONDITION AT TIME OF SURVEY

The observed metal loss, $V_o$, at a given location, say x km along the pipeline, at the time of the survey, say t, can be expressed as the actual wall thickness plus the random measurement error:

$$V_o(x,t) = V(x,t) + \mathit{error} \qquad 1$$

Because the error is a random quantity this means that for any value of the actual metal loss, V, there is a random distribution of potential observed values, only one of which will be realised during the inspection. Once the observation has been realised there is of course an equivalent random distribution of actual values of the metal loss which could, in combination with a random measurement error, have given rise to the observed value, i.e.:

$$V(x,t) = V_o(x,t) + \mathit{error} \qquad 2$$

An intelligent pig survey provides a snapshot of the observed values of the metal loss along the pipeline at a point in time. Using a Monte-Carlo analysis it is straightforward to generate samples of the metal loss profile along the pipeline which correspond to the observed metal losses and the known distribution of the measurement error.

An assessment of the pressure retention capacity of the pipeline at the time of the survey then consists of evaluating the minimum burst pressure corresponding to each of the sample metal loss profiles. Figure 3 below shows the distribution of a pipeline's burst pressure derived in this way.

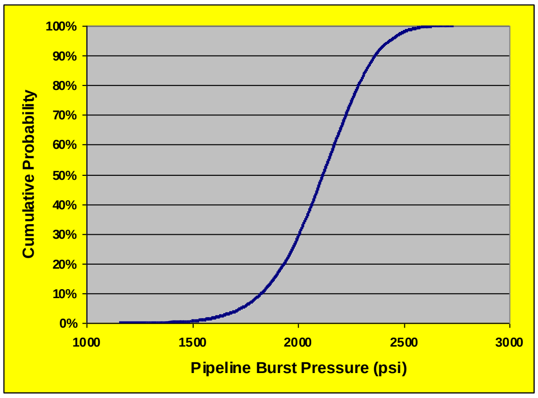

**Figure 3: Distribution of Burst Pressure**

This approach is readily adapted for sensitivity analyses. The repetition of the analysis with either individual defects, or groups of defects corresponding to specific sections of the pipeline, excluded will show the change in the burst probability at any specified operating pressure. This is illustrated in Figure 4 below.

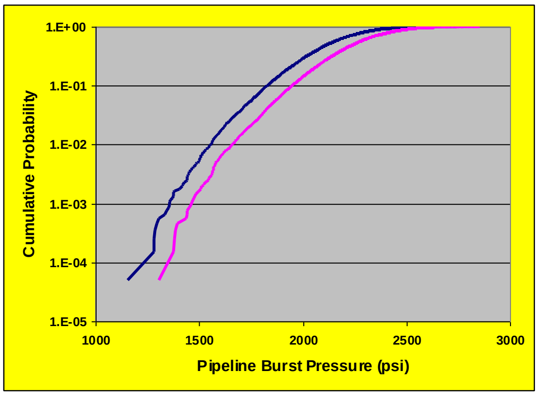

**Figure 4: Sensitivity to selected defect**

# 5 REMNANT LIFE PREDICTION

There are a number of approaches that could be used to assess the remnant life of a pipeline. The simplest of these is to use the wall thicknesses obtained from two surveys to determine local (pitting) corrosion rates for each identified defect site. Simple extrapolation would then provide an estimate either of the wall thickness at the time of the analysis, or the expected time to through wall penetration or ligament failure. This approach will of course yield only a deterministic assessment of the time to failure (or leak), and therefore would provide minimal input to the decision-making processes relating to the future management of the asset.

Other drawbacks of this approach will be familiar to everyone who has undertaken an analysis of this type. The dates at which individual defects will penetrate through wall are easily defined but confidence limits in those dates are less easy to determine. Data for some defects has to be ignored because the later measurement reports a greater wall thickness than the earlier measurement. Finally, if the analysis is performed some time after the last set of readings was obtained, then individual defects may be predicted to have reached through wall penetration when no leak has been detected.

Perhaps the most significant drawback however is that this type of analysis, although consistent on a defect by defect basis, provides little information with respect to the pipeline as a whole. Asset managers are only concerned with corrosion rates local to individual defects to the extent that they impact on the overall condition of a pipeline. Their real concern is with respect to the remnant life of the pipeline as a whole (or of defined sections of the pipeline). In order to achieve this some assumptions have to be made concerning the statistical independence of the remnant life predictions at each defect.

Assumptions of either complete dependence or of complete mutual independence between defects will allow the analyst to solve the problem. Unfortunately neither assumption can be justified in practice. In reality the real corrosion rates acting within a set of significant defects in a single pipeline will be significantly correlated (all of the defects being subject to attack from the same corrosive fluid and being subject to the same corrosion inhibition regime). The measured corrosion rates will be somewhat less correlated than the real corrosion rates, given that the measured corrosion rates are the real corrosion rates modified by the random measurement errors associated with the pipeline inspection tools.

# 6 BASIS OF ANALYSIS

## 6.1 Reconciliation of survey measurements

The survey estimates of wall thickness are subject to random errors as described above. For some of the defects, the difference between the observed remnant wall thicknesses at the two surveys is small enough that the error bands of the measurements overlap each other to a significant extent, see Figure 1. It follows that an assumption of complete independence between the statistical distributions cannot be justified, since this would lead to the possibility that the wall thickness increased between surveys. In order to avoid this outcome it is necessary to reconcile each set of wall thickness observations corresponding to a single location by updating the probability distributions for the measurement errors.

The following example shows how the reconciliation process works in practice. The example is for a single defect in a pipeline with an as-built wall thickness of 15mm. Two surveys performed after 15 and 20 years of operation record wall thicknesses of 12.5 and 12.3mm respectively. Each survey has a measurement uncertainty with a standard deviation of 1.24mm.

Figure 5 shows 5000 randomly generated samples of the wall thicknesses at the dates of the two surveys. Figure 6 shows the corrosion rate derived from the samples plotted with the wall thickness samples corresponding to the 20 year survey.

It is clear by inspection that the samples on which Figures 5 and 6 are based are invalid. Figure 5 shows wall thicknesses in excess of the as-built wall thickness of 15mm and Figure 6 shows samples with negative corrosion rates. The means of the samples are indicated by the crossed horizontal and vertical lines.

The wall thickness distributions corresponding to each of the surveys have to be updated in order to reconcile them with each other, and to reconcile both of them with the known as-built wall thickness.

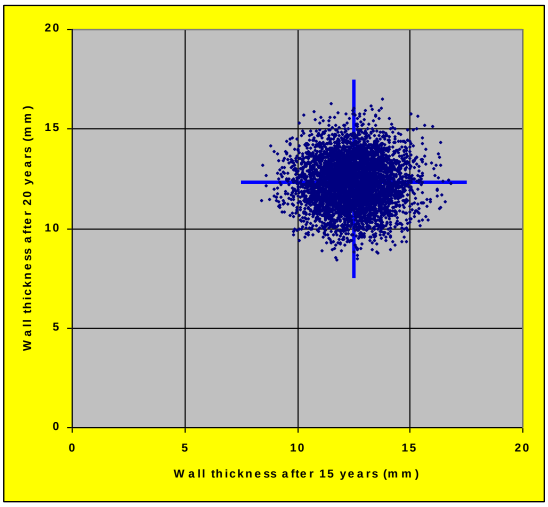

**Figure 5: Wall thickness samples**

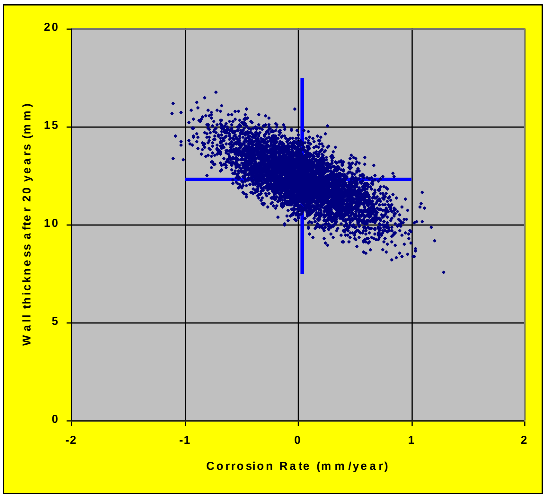

**Figure 6: Wall thickness vs. corrosion rate**

The best estimates of the actual wall thicknesses at the times of each of the surveys are modified by knowledge of the observed thicknesses and associated errors at the time of the other survey.

In practice, the effect of the reconciliation of the two sets of survey results leads to an increase in the average corrosion rate over the rate that would be predicted from a deterministic assessment. This increase is greatest where two measurements are close (i.e. where the overlap in the error distributions is greatest).

The methodology used to reconcile the survey data utilises a Bayesian (1) approach, which updates the probability distributions used to model each thickness determination. The methodology used is "symmetric in time" in that all defect depth measurements obtained at a specific location are updated by all other depth measurements made at the same site. The methodology used is general in that it allows an unlimited number of measurements made at a particular location to be reconciled. Implicitly it also allows the concept of "no leak here today" to be automatically incorporated into the analysis.

Figure 7 shows the updated wall thickness samples for the two surveys. The valid sample points are shown highlighted. The Figure shows that updating process has resulted in an increase in the mean of the wall thickness distribution for the earlier survey and a reduction in the mean of the wall thickness distribution for the later survey.

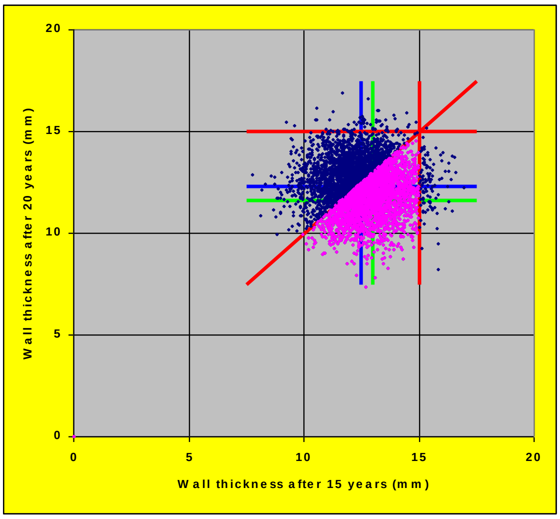

**Figure 7: Updated wall thickness samples**

Figure 8 shows the update of the plot in Figure 6. The updating process gives an average wall thickness for the 20 year survey of 11.6mm instead of 12.3mm, and an average corrosion rate of 0.28mm/year instead of 0.04mm/year.

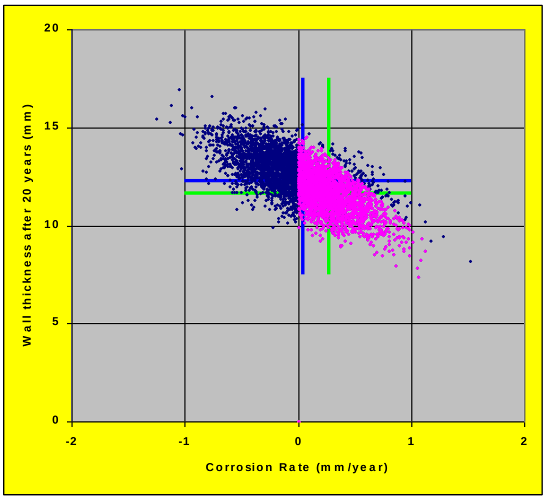

**Figure 8: Updated corrosion rate**

### 6.2 Determining the remnant life

Where only two sets of survey measurements are available the remnant life of the pipeline can be estimated directly by extrapolating the pairs of updated wall thickness measurements. A constant corrosion rate is assumed and the time required for either through wall penetration or burst (2) is established. The probability of through wall penetration for the example presented above is shown in Figure 9.

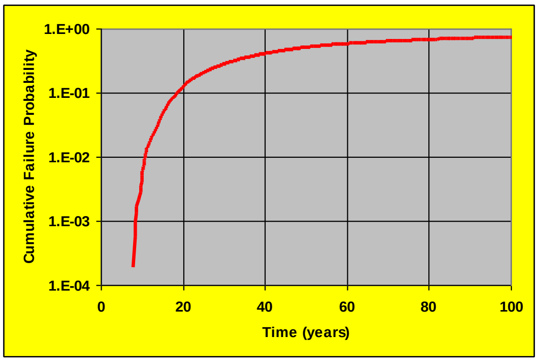

**Figure 9: Probability distribution for remnant life**

Where more than two sets of inspection results are available the corrosion rate is established for each set of updated wall thickness samples using a weighted least-squares best fit.

### 6.3 Variations in operating conditions

Throughout a pipeline system, the occurrence of the conditions required for corrosion (water wetting of the pipe wall) is dependent on both the flow velocity and the flow regime. If flow velocities are high enough to prevent water dropout, corrosion will be negligible. If flow is slugging two-phase, corrosion conditions may occur. If the flow rate is negligible, resulting in near stagnant conditions, significant water dropout will occur and corrosion will be expected. Where wetting of the pipe wall is expected corrosion inhibition is the only protection against high levels of metal loss.

If operating conditions in the pipeline have been uniform, and are expected to remain uniform for the foreseeable future, then carrying out predictive corrosion calculations will not add any value. However, if operating conditions are known to have varied significantly, or are expected to vary in the future, then these calculations are required in order to calibrate the remnant life predictions.

A corrosion rate prediction model can be used to estimate both the historic cumulative corrosion over a specified time interval and the predicted future corrosion rate under assumed operating conditions. The ratio between the predicted average corrosion rate over the time interval between inspections and the predicted corrosion rate based on assumed future operating conditions provides a calibration factor. This is used to modify the predicted remnant life to take account of changes in the corrosivity of the transported fluids.

### 6.4 Corrosion inhibition

Variations in the corrosion inhibition regime may also need to be considered, particularly where a pipeline is known, or believed, to have experienced corrosion because of a deficiency in the inhibition regime.

The historical effectiveness of the corrosion inhibition regime can be deduced by comparing the predicted uninhibited corrosion rate with the general corrosion rate observed in the pipeline.

## 7 REMNANT LIFE ASSESSMENTS OF OIL & GAS PIPELINES

The methodology described here has been programmed into a software tool using Microsoft Visual Basic and Excel.

As expected, when taking structural failure into account the estimated remnant life is less than when considering through thickness penetration only. It should be noted however that there is more uncertainty associated with the ligament failure estimates because they depend not only on the data obtained in the various surveys but also on assumptions about the pressure in the pipeline and the failure stress in the ligaments (1).

The tool has been used to predict the remnant lives of a range of pipelines including oil, gas and multiphase pipelines. Some of the graphical output is given in Figures 10, 11 and 12. Figure 10 shows the probabilities of failure against time for a number of individual defects in the pipeline (i.e. the most critical defects as defined by the ERF). Figure 11 shows the probability of occurrence of one, two, three, four or five failures plotted against time. Figure 12 shows the probability of failure plotted against time for each of the 43 defects identified in a section of a pipeline, while Figure 13 shows the predicted criticalities of this same set of defects.

## 8 CONCLUSIONS

### 8.1 General

The paper has described an approach that was developed to deal with the problem of reconciling disparate inspection results. The methodology described takes account of all significant sources of uncertainty associated with corrosion rate predictions in pipelines.

The approach presented here has taken account of these issues in a statistically rigorous manner.

An assessment of this type, using all available data, results in an increased confidence in the understanding of the current and future state of the pipeline. This understanding directly supports the decision making that then follows concerning monitoring, and repair and/or replacement schedules for the pipeline.

### 8.2 Capabilities of MDRLP

Multiple Defect Remnant Life Prediction is able to:

- Reconcile survey data from disparate sources;
- Explicitly account for survey precision;

- Simultaneously perform analysis of a large number of defects; and,
- Account for future changes in operating conditions and inhibition regime.

### 8.3 Implications for Inspection Strategies

The approach explicitly accounts for uncertainty in inspection results and therefore contributes to a better understanding of the likely outcome of an inspection. Importantly it allows rational planning of inspections, and provides a basis for performing a cost benefit analysis as part of the process of selecting the inspection technology.

It also allows asset managers to:

- Establish the safe interval until the next inspection; and,
- Optimise inspection intervals to minimise post-inspection uncertainties.

## 9 REFERENCES

1. Bayes, T.; ‘Essay towards solving a problem in the doctrine of chances’, Philosophical Transactions of the Royal Society of London, London 1764.
2. Rosenfeld, M. J., Kiefner, J. F.; 'Proposed Fitness-for-Purpose Appendix to the ASME B31.8 Code for Pressure Piping - Section B31.8, Gas Transmission and Distribution Systems', Kiefner and Associates, Worthington, Ohio, Jan. 1995.

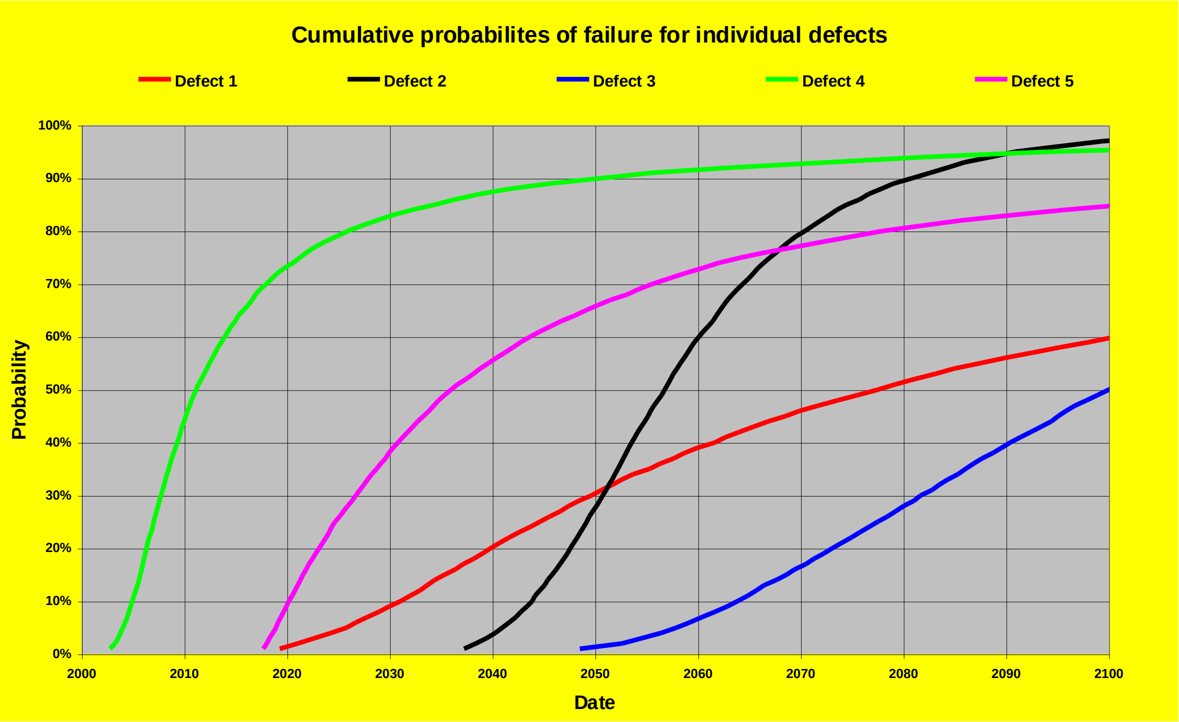

Figure 10: Probabilities of failure for individual defects

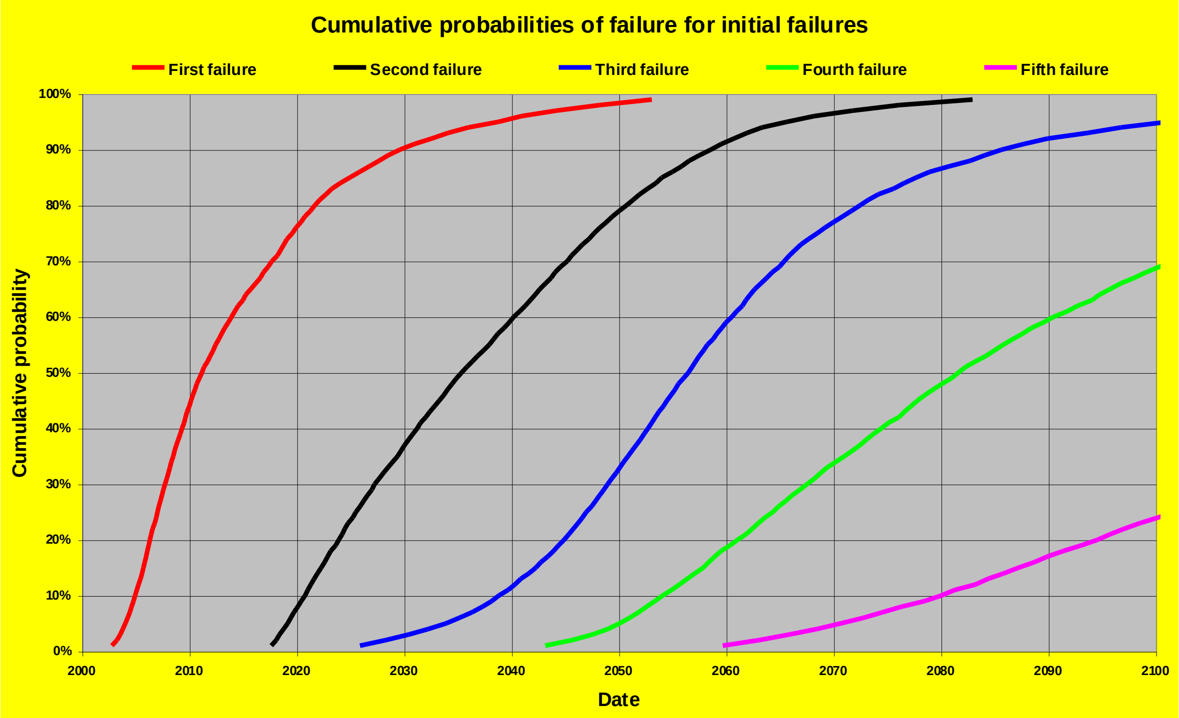

Figure 11: Probabilities of failure for initial failures

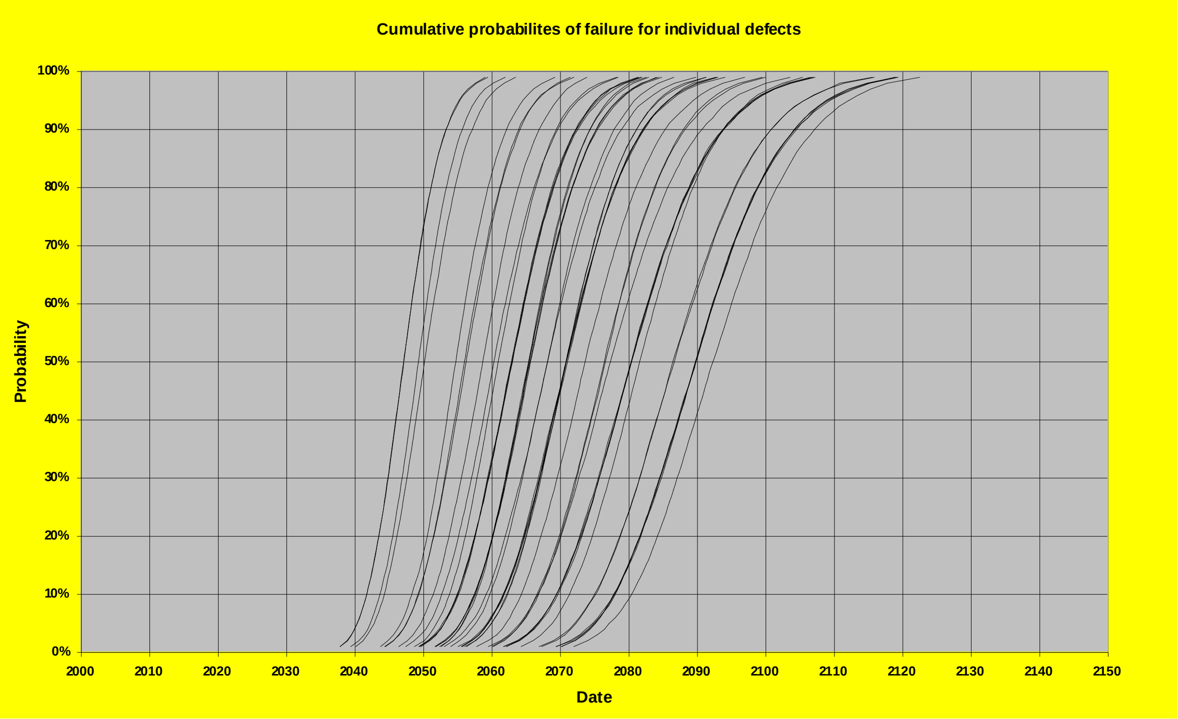

Figure 12: Probabilities of failure for individual defects (based on one inspection plus as-built data)

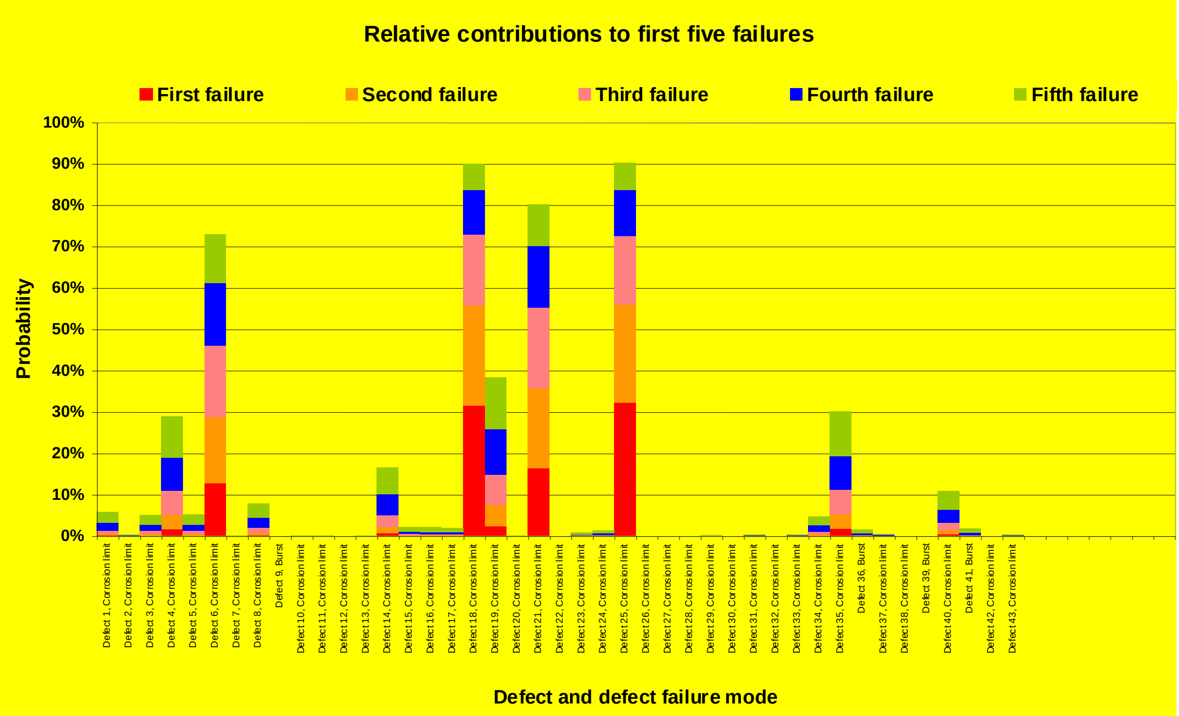

Figure 13: Example of defect criticality output