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VALIDATION OF AN IN-LINE INSPECTION METAL LOSS TOOL

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INTRODUCTION

Enbridge Pipelines Inc. ("Enbridge"), together with U.S. affiliate Lakehead Pipe Line, operates the world's longest crude oil and petroleum products pipeline system. These companies transport liquid hydrocarbons from their point of supply to refining markets in the Midwestern United States and Eastern Canada.

Enbridge began using first generation high resolution in-line inspection (ILI) technology to inspect for metal loss in 1989. By 1996, Enbridge and Morrison Scientific Inc. were able to further develop and use the software programs Phoenix^{TM} and Tracer^{TM}. Phoenix^{TM} is a suite of programs that matches in-line inspection data from different inspections, and estimates future corrosion severity. Tracer^{TM} was developed for the purpose of comparing metal loss defects reported by in-line inspection tools with field measurements. Both software packages have become fundamental in determining the reliability of in-line inspection tools for sustained integrity management since the first generation tools were used for in-line inspection.

As a liquid operator, Enbridge has taken advantage of the ability to employ both high-resolution ILI magnetic flux leakage (MFL) and ultrasonic technology (UT) tools for metal loss. The ILI tool validation programs have established that each of these inspection techniques have advantages and limitations that can only be appropriately evaluated when considered with respect to the requirements of a specific line.

BACKGROUND

In July 1999, BJ Pipeline Inspection Services (a Division of BJ Services Company Canada) conducted an in-line inspection using their high resolution tri-axial sensor Vectra^{TM} MFL tool in a section of Enbridge Pipelines 34" line (also called Line 3). The purpose of the run was to qualify the tool as a reliable means of metal loss inspection.

As part of the procedure to include the tool in the pipeline system's inspection protocol list, Enbridge requested that Morrison Scientific carry out a validation study to assess the ILI tool's capability in finding and sizing defects. The study was divided into two components:

1. Analysis of ILI data against field data, in this case a bridging bar assembly.
2. Comparison of new ILI tools against existing technologies.

A 27 kilometer section of Line 3 was selected that covered data from a recent in-line inspection and subsequent excavations. This included sections of complex shapes of corrosion to ensure the tool was able to appropriately identify and calculate the failure pressure of not only individual defects but also interactive corrosion.

The results of the first portion of the validation study, the comparison of the ILI tool with the field data, are presented in this paper.

A statistical analysis of the reporting of the field tracing data and the inspection was performed using the procedures given in Bhatia et al. (1998) and Jaech (1981). A brief review of the BJ ILI tool is presented first, followed by the statistical analysis of the comparison between the BJ ILI tool reporting and field measurements obtained on 13 joints of pipe recoated after a previous inspection.

In this paper a box is an individual report of a corrosion defect. Interaction is accounted for and clusters are determined based on the spacing between individual defects. Failure pressure values are given for subclusters, which are the lowest failure pressure portions of a cluster after accounting for interaction. The phrases cluster, subcluster and feature are used interchangeably in this paper.

THE BJ VECTRA^{TM} MAGNETIC FLUX LEAKAGE IN-LINE INSPECTION TOOL

Details of the BJ in-line inspection tool are given in Long et al. (1997), Sutherland and Seibert (1998) and Seibert and Sutherland (1999).

The objective was to create a modern in-line inspection tool that could be used in both gas and liquid transmission lines. At present several tools in a variety of pipe diameter sizes are available.

The mechanical and sensor design of the BJ in-line inspection tool began in 1994. The data analysis, or corrosion feature sizing, portion of the design began in early 1996. A bypass design was incorporated into the tool so it could travel at a speed appropriate for the measurements, without forcing a reduction in the speed of the gas or fluid in the pipeline. Rare earth permanent magnets are used to generate the magnetic field. The three dimensional coordinate system measuring the magnetic field consists of an axial or longitudinal component, a radial component perpendicular to the pipe wall, and a circumferential component. Other MFL tools typically only measure the axial and radial components of the flux.

Hall effect sensors enable the measurement of magnetic flux density over an area of 1 mm by 1 mm, and are very sensitive to small magnetic fields. Other systems, such as some coil sensors, measure over an area of 30 by 70 mm. Hall effect sensors are speed independent, but coils are speed dependent and only measure a flux leakage that is proportional to the flux leakage, therefore coils make relative measurements only.

Knowledge of the size of the feature is a necessary component of the estimate of penetration. Use of the sensitive Hall effect sensors enables the measurement of the small circumferential field. The better width estimation based on the circumferential field yields a better penetration estimation.

It was decided to analyze the data recorded by the sensors using a neural net procedure. The neural net(s) were trained using approximately 200 features that were electrochemically machined into steel. A linear test rig was developed that used features machined into steel plate. NAEC (narrow axial external corrosion) like features and complex corrosion like features were also constructed in pipe, and were measured at a pullthrough facility located in Calgary. Different neural net architectures and training sets were used to gain experience in using the neural net procedures, and new types of features have been included in the training data sets. As well, during the past three years, empirical and other methods have been used to analyze the data so as to keep the analysis procedures robust, and there is always ongoing research for improvements in the data analysis.

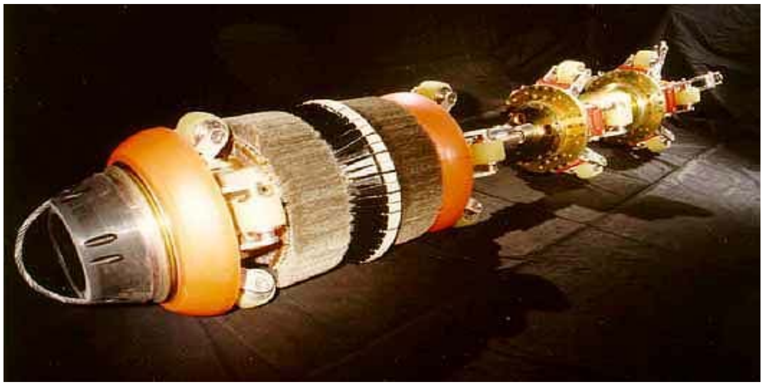

Figure 1. THE BJ PIPELINE INSPECTION SERVICES MFL INSPECTION TOOL

The first use of the tool occurred in June 1996 on a 24" pipeline. Validation digs on this pipeline showed the analysis procedure was capable of determining the penetration of features with measurement errors within the ±10% wall thickness bounds.

In Figure 1 the BJ Vectra^{TM} ILI tool is shown. The magnetic field sensors are located on the ring between the brushes, which transfer the magnetic field from the permanent magnets to the pipe.

An example of some of the diagnostics of the analysis software is given in Figure 2.

One of the most difficult aspects of using magnetic flux leakage technology is that if the corrosion geometry on a pipeline is not similar to that of the training data set, the corrosion parameter estimates will be different than those of the corrosion features. One can imagine vertical walls, spiral corrosion, huge and complicated features, and proximity to girth and seam welds causing problems for the analysis procedure, as these are not typically included in a training set. When possible, new types of features should be included in the training data set. With respect to the neural nets, one has to be careful to not under train nor over train the neural net.

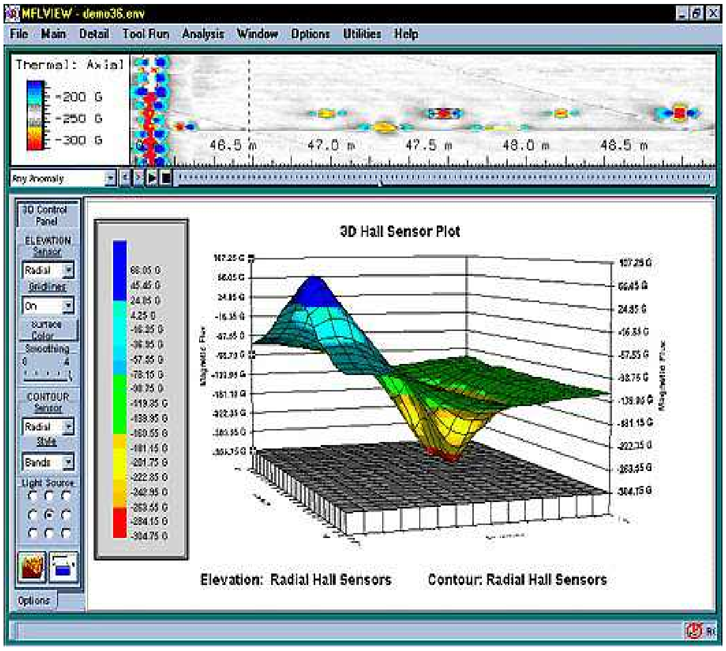

Figure 2. SOME OF THE DIAGNOSTIC CAPABILITIES OF THE BJ PIPELINE INSPECTION SERVICES OUTPUT SOFTWARE

THE VALIDATION

The two most important aspects of estimating the corrosion severity on a pipeline are the maximum penetration and failure pressure.

In the comparison of the 1999 inspection data with the field data, corrosion features under steel sleeves were omitted from the analyses. This made the comparison portion of the data set consist of those features with penetrations greater than about 10% and less than about 40% of the wall thickness. In all, 217 corrosion features were analyzed.

Use of the Tracer Software

As part of the examination of the joints experiencing corrosion identified during the earlier inspection of Line 3, tracings were made of each joint and measurements of the penetration of each corrosion feature were determined using a bridging bar assembly. A set of 13 tracings of NAEC and general corrosion on some of the recoated joints were compared with the 1999 inspection for the purposes of determining errors in the field data and the 1999 inspection.

The field tracing data gives the best estimate of the severity of corrosion around the long seam weld of the pipe. Penetration and failure pressure estimates were prepared from the field data and the in-line inspection data.

The field tracing is scanned and an electronic picture file of the tracing is obtained. Some of the tracings can be over 10 metres long. The ILI tool box or cluster sizes and locations are overlayed on the picture of the tracing at the same scale, enabling accurate comparison of the ILI tool and the field data. It is possible in this fashion to make the comparisons of the ILI data and the field data as close as possible, with a minimum amount of arbitrariness introduced into the comparison. The user makes field boxes around the individual measurements on the tracing and the software produces a "Morrison Scientific" format file of the box length, width, penetration and location, which can then be analyzed by other software as desired.

The Statistical Comparison

Two types of confidence intervals were determined in this portion of the study. The Type I interval is the 80% confidence interval for the BJ tool and the bridging bar based on the estimated variance of the measurement errors from the present set of data. The Type II interval is the 80% confidence interval for the BJ tool and the bridging bar based on the upper bound of the variance of the measurement errors that one could have from many such comparisons, if repeated. The Type I confidence interval is to be compared with the 80% confidence interval of ±10% of the wall thickness that appears to be a standard in the industry. The Type II interval is an estimate of the possible range of the Type I interval and is added here for completeness.

The maximum penetration comparison is given in Figure 3 and the failure pressure comparison is presented in Figure 4. In each figure the Type I 80% overall confidence intervals for measurement error for each tool compared, the correlation, and the number of clusters in the data sets are given. Only those features reported by both the BJ tool and the bridging bar are included in the analysis.

In Figure 3 the BJ peak penetration is given on the left axis and the field peak penetration is given on the bottom axis. The three lines on the graph represent the "equal" line, and lines at ±10% of the wall thickness. A slight jittering of the data (of less than 2% of the wall thickness) has been used to illustrate the density of measurements, otherwise many of the points would lie upon each other. Treating the field maximum penetrations as accurate, it is seen that in general there appears to be a slight underestimation of penetration, on the average, of about 2 to 3% of the wall thickness, by the BJ tool.

The scatter in the penetration plot has been analyzed and split into two components, one for the field data and one for the ILI tool reporting. These estimates are obtained following the method due to Grubbs (1948) (which are the Case V estimators in Bhatia et al. (1998)), and are used when two instruments measure the same object only once.

$$80\%\ \text{BJ CI}:\ \pm 1.28\sqrt{\text{Var(BJ)}\ -\ \text{Cov(BJ, Field)}}$$

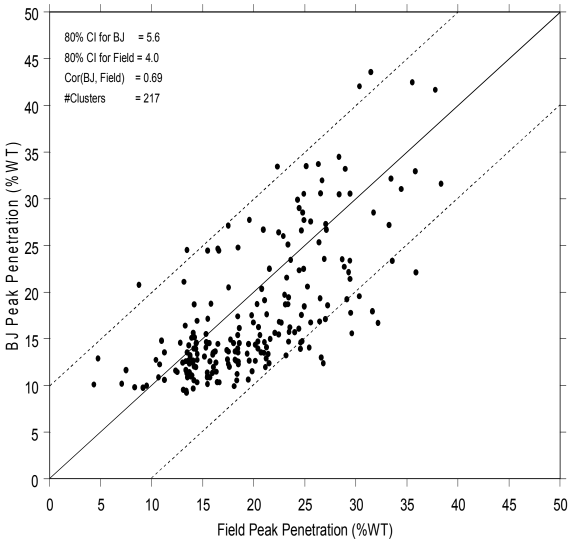

Figure 3. BJ PEAK PENETRATIONS VS. FIELD PEAK PENETRATIONS

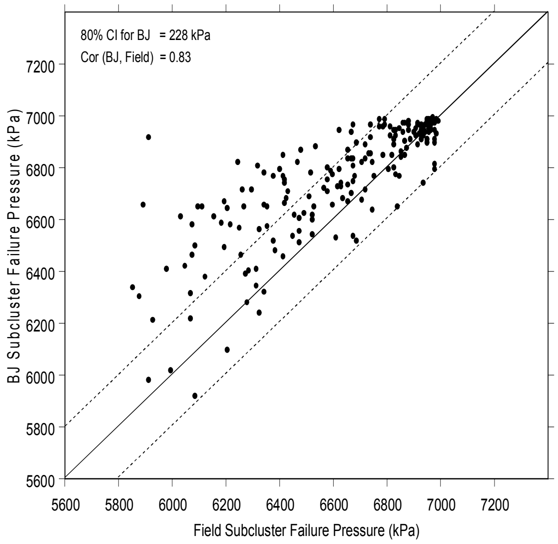

Figure 4. BJ FAILURE PRESSURES VS. FIELD FAILURE PRESSURES

$$80\% \text{ Field CI}: \ \pm 1.28\sqrt{\text{Var(Field)} \ - \ \text{Cov(BJ, Field)}}$$

CI stands for confidence interval, Var for variance and Cov for covariance. The value under the square root is the variance of the estimated measurement error for the particular tool. The square root of the variance is equal to the standard deviation, and the 80% confidence interval is obtained by multiplying the standard deviation by 1.28.

The value under the square root is sometimes negative, therefore the confidence interval for the tool in question cannot be obtained using Grubbs method. Thompson (1962) suggested that the whole scatter could be assigned to the tool with variance is greater than the covariance term. The other tool is treated as being perfect (i.e. having no measurement error), thus penalizing the tool whose variance is greater than the covariance term. In these situations the constrained expected likelihood estimator (CELE) proposed by Jaech (1981) can be used. The CELE estimates have to be checked to see if they are reasonable. When the tool expected to have the larger error fails the Grubbs estimator, it can be assigned an unrealistic low CELE error estimate. In these cases there is no alternative and one has to follow Thompson's (1962) suggestion.

The overall Type I confidence interval for penetration for the BJ tool is ±5.6% of the wall thickness, and for the field data it is ±4.0% (Table 1). Compared to the ±10% confidence interval that appears to be a standard in the industry, this is an excellent and small amount of scatter.

Table 1. 80% CONFIDENCE INTERVAL FOR PEAK PENETRATION MEASUREMENT ERRORS FOR THE BJ AND FIELD TOOLS

Penetration Range	No. of Features	80% CI for Measurement Error of the Tools		Correlation Coefficient
		BJ	Field	
All	217	5.6	4.0	0.69*
Field <= 20%	123	4.3	3.4	0.25*
Field > 20%	94	7.9 (C)	1.9 (C)	0.57*
Field > 25%	40	9.1 (C)	2.1 (C)	0.45*
Field > 30%	13	9.8 (C)	2.4 (C)	0.45(NS)

* Significant at 95% probability level of significance
NS stands for nonsignificant
C means CELE was used as Grubbs estimator yielded negative measurement error values for the field tool

The Type II confidence intervals have been obtained following Thompson (1963). The Type I interval gives the best estimate of the variability of the tool for the present set of data. The Type II interval, on the other hand, gives some idea of the variability of that estimate if several sets of data are compared under the same conditions. In simple language, it provides the minimum lower limit and maximum upper limit of the confidence intervals for the measurement errors. The Type II intervals are ±10.1% for BJ and ±8.3%

Table 2. 80% CONFIDENCE INTERVAL FOR FAILURE PRESSURE MEASUREMENT ERRORS FOR THE BJ AND FIELD TOOLS

Penetration Range	No. of Features	80% CI for Measurement Error of the Tools		Correlation Coefficient
		BJ	Field	
All	217	NA <-----	228 (T)	0.83*
Field <= 20%	123	NA <-----	118 (T)	0.78*
Field > 20%	94	126	231	0.70*
Field > 25%	40	210	192	0.56*
Field > 30%	13	340	202	0.30(NS)

* Significant at 95% probability level of significance

NS stands for nonsignificant

NA means not available because Grubbs estimator fails, CELE gave unrealistic small values for BJ, thus Thompson (T) estimator had to be used

for the bridging bar.

The failure pressure confidence intervals are given in Table 2. In the first two lines NA's are present for the BJ tool. The constrained expected likelihood procedure associated an unrealistic small confidence interval value to the BJ tool. In these two situations the Thompson (1962) estimator was felt to be more realistic and the total scatter was associated with either tool. The arrows in the table indicate this assumption. The overall Type I 80% confidence interval for the BJ tool is ±228 kPa (about ±230 kPa). This is also a very small confidence interval.

The scatter in the penetration graph appears to be consistent for the range of the data. On the other hand, the scatter in the estimated failure pressures appears to depend on the failure pressure itself.

Based on the overall confidence interval obtained in this study, the BJ tool is capable of estimating both the maximum penetration and failure pressure of these most difficult features with a small amount of error.

CONFIDENCE INTERVALS OF MEASUREMENT ERRORS AS A FUNCTION OF PENETRATION

The break-up of the confidence intervals for measurement error for maximum penetration and failure pressure as a function of penetration are also given in Tables 1 and 2. The width of the confidence interval for the BJ ILI tool increases as the penetration of the features increases.

For field measured features of penetration less than 20%, the Type I confidence interval for maximum penetration is ±4.3% for the BJ tool. For field penetrations greater than 20%, it becomes ±7.9%, and for features with field measured penetrations greater than 30% the value increases to ±9.8%.

A similar increase in the confidence interval for the failure pressure is also present as a function of increasing maximum penetration. The Type I 80% failure pressure confidence interval for the BJ tool for field penetrations less than 20% is ±118 kPa (if the bridging bar failure pressures are assumed accurate). It increases to ±210 kPa for field measured maximum penetrations greater than 25%, and increases to ±340 kPa for field measured maximum penetrations greater than 30%.

One major reason for the increase in confidence interval is that features with deeper penetrations are typically surrounded by shallower features, making penetration estimation more complicated when the data are sent to the processing software.

The statisticians also have a reason for the increase of measurement error with increasing penetration. For shallow features the measurement cannot be less than zero, somewhat limiting the negative large measurement errors of the tool. For deeper features, it is possible for the measurement to be in error by large positive and negative amounts. Thus, for deeper features, the measurement error can be larger. This phenomenon is observed not only in this study, rather it has been noticed in earlier studies also.

It is therefore recommended that the confidence intervals for measurement error be reported as a function of penetration, as this highlights the capabilities of the ILI tool for different ranges of penetration.

SUMMARY

The BJ magnetic flux leakage in-line inspection tool has been shown to size corrosion features with a small amount of error when compared with the bridging bar field data. The measurement of the flux leakage in three dimensions makes sizing more accurate, especially long, narrow corrosion, either near or far away from the long-seam weld of a joint of pipe.

The confidence intervals of the corrosion sizing and failure pressure estimation by the BJ tool are very good. The overall 80% confidence interval for maximum penetration is about ±5.6% of the wall thickness, and the failure pressure estimate is approximately ±230kPa.

Even for the deeper features the BJ tool's performance is good. For features more than 30% deep the confidence interval for maximum penetration is ±9.8% and for failure pressure it is ±340 kPa.

For ILI tools, the confidence intervals for penetration and failure pressure should be reported as a function of penetration. Reporting in this fashion better highlights the capabilities of the ILI tool. Similarly, though not discussed for this study, confidence intervals for length and width of features should also be broken-down as functions of length and width respectively.

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