Investigate Fundamentals and Performance Improvements of Current In-Line Inspection Technologies for Mechanical Damage Detection

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Phase II: Final Report

BLADE ENERGY PARTNERS

16225 Park Ten Place; Suite 450
Houston, TX 77095

281 206 2000 (phone)
281 206 2005 (fax)

www.blade-energy.com

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Purpose:

This final report provides a comprehensive and in-depth review of the current status of in-line inspection technologies including, but not limited to, Magnetic (Axial MFL, Circumferential MFL), and Geometrical (Caliper) methods in terms of their capabilities, limitations and potentials in detection, discrimination and characterization of various forms of pipeline mechanical damage, such as dents, dents with corrosion, and dents with cracks, gouges and dents with gouges. Capabilities of current technologies presented herein are based on validation data supplied by PRCI members.

Prepared for:

PRCI & USDOT/PHMSA

Authors:
Ming Gao, Ravi Krishnamurthy, Rick McNealy

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1. Executive Summary

This report reviews and summarizes research regarding the capabilities of current in-line inspection (ILI) based technologies for the detection and discrimination of mechanical damage conducted by Blade Energy Partners in cooperation with participating ILI vendors and PRCI member pipeline operators. This research was conducted in two phases. The first identified the current deployed ILI technologies, vendor claims for capability and performance determination with validation data provided by the ILI vendors. Standardized performance measures were also developed and applied. The Phase I research was presented in a report, PR-328-063502 Document # 8469 posted, by PRCI in May 2008. Limitations in understanding of capabilities due to issues such as data population size and inspection attributes were noted in that report with a second phase subsequently executed addressing those issues with those results presented herein.

During Phase II research, a total of 256 mechanical damage features were obtained from four operators using three technologies. The three technologies are Technologies J (Caliper + MFL Combo), Technology E (Tri-axial MFL), and Technology K,N +MFL. Evaluations of dent sizing performance of these technologies were first conducted on the depth. Then limited analysis of length and width was performed for Technology E and Technology K,N +MFL because data are available only for these two technologies. For dent with metal loss (DML), since only three features were reported and field validated for Technology K,N +MFL, DML analysis was not performed on these features alone but combined with the Phase I data.

Phase II research of the operators' data showed that Metal Arm Caliper technologies, on a combined basis, exhibited depth sizing tolerance within +/- 1.1%OD at 80% certainty and 95% confidence level for Tech J (Caliper+MFL combo) and +/-1.53%OD for Tech K,N,MFL with depth correction for bottom-side dent (Caliper+MFL). The MFL multi-axis technology demonstrated capability to provide dent depth with a performance of +/- 0.95%OD after depth correction for bottom-side dents. By comparing with the Phase I operators' data, these three technologies showed higher tolerances in the range between +/-1.6%OD and +/-4.48% OD at the same certainty and confidence level. The progress made in Phase II study was mainly due to the better quality with more recent technologies and information of the data gathered from the operators, which allowed filtering the top-side and bottom-side dents from the total populations.

For dents with coincident metal loss, the combined discrimination performance for all of the MFL technologies exhibited a probability of detection of 83% with a probability of identification of 91%. Critical comparisons were obtained and presented individually for the identified technologies. Understanding of performance measures is largely influenced by the size of the validation population. 908 total mechanical damage features were obtained, of which 708 features were validated by the pipeline operators and ILI vendors for dent with metal loss discrimination performance. Among them, 59 dent with metal loss features had both ILI and in-ditch sizing for coincident metal loss, which provided a statistically usable population for evaluating depth sizing performance, but were insufficient to provide for critical comparisons. While some (but not all) ILI vendors reported conditional capability to discriminate corrosion from gouge, the current in-ditch protocols lacked consistent discrimination to providing sufficient populations for evaluation and discrimination. Improvements to in-ditch protocols with respect to standardized characterization for gouges coupled with ILI assessments taking advantage of mechanical damage evaluation would likely improve the sample populations to the point where critical comparisons for dent with gouge performance should be possible.

The performance for ILI based mechanical damage technologies can be affected by variance in tool measurements, in-ditch validation measurement error and changes in dent dimensions due to removal of indenter restraint (re-rounding) upon excavation. No attempt was made to quantify in-ditch related error but a well controlled atmospheric pull test with Technology G was conducted and used to illustrate the effect of these errors and suggest improved protocols for performance validation. Good agreement for depth sizing was obtained as compared with laser profilometry profile data.

The current technologies claimed capability for mapping detailed axial and circumferential dent profiles suitable for strain assessment. However, profiles are not routinely requested and in-ditch profiles were found to be routinely obtained, but not archived. Therefore, critical performance comparison was not possible. When laser profilometry technology was applied and compared with the pull test data, good agreement for shape profiles and strain calculations was obtained, which demonstrated that the high resolution geometry ILI tool could provide accurate dent profile and comparable strain values.

Characterization of metallurgical change continues to be a challenge for the current MD ILI technologies with no capability claimed to both detect and discriminate severity. MFL technologies were shown to be capable for detecting magnetic anomalies but low-level dents (< 6%OD) upon re-rounding and pressure cycling can form cracks that escape detection by MFL technologies unless multiple technologies with conditional capability for crack detection are employed.

As a result of this research, improvements to in-ditch protocols for both measurement methods and data attributes were identified and recommendations are presented for future research in order to improve understanding of mechanical damage tool performance.

2. Introduction

Effective integrity management depends on understanding the capabilities of in-line tools in order to apply appropriate technologies in response to potential pipeline threats. The governing integrity regulations and codes describe mechanical damage and prescribe acceptable limits for conditions detected by integrity assessments. Models for predicting the severity of mechanical damage that could affect oil and gas pipelines have also been under development within the pipeline industry. The prescriptive requirements and the assessment models, along with supporting analytical tools, enable pipeline operators to decide whether indicated damage could be a threat to a pipeline on the basis of information from an in-line inspection (ILI) and other data sources. However, the researchers developing these assessment models have depended on assumed capabilities for current in-line inspection technologies to detect and discriminate mechanical damage. The Pipeline Research Council International, Inc. (PRCI) and USDOT Pipeline and Hazardous Materials Administration (PHMSA) sponsored research to identify the current ILI technologies employed to detect and discriminate mechanical damage (MD) and validate their capabilities [1, 2]. This is the Phase II final report concluding research for a two-phase project that evaluated current technologies for detecting mechanical damage of pipelines. This project was conducted for the Pipeline Research Council by Blade Energy Partners Ltd under contract PR-328-063502 and PHMSA transaction agreement DTPH56-06-000016 Project #204. The overall objectives of this Project included:

- Identification of current capabilities of mechanical damage inspection technologies used in the pipeline industry
- Evaluation of the capabilities of deformation and MFL based inspection tools in detecting, sizing and possibly discriminating mechanical damage
- Data to validate assessment capability of in-line inspection tools while tying these results back to fundamentals and performance characteristics

The execution of this research reflected a collaborative effort between the ILI vendor community and pipeline operators to integrate field data with the data provided by ILI tools such as caliper, MFL and other MD tools.

The Phase I research provided a comprehensive and in-depth review of the current status of in-line inspection technologies in terms of their capabilities, limitations and potentials for detection,

discrimination and characterization of various forms of pipeline mechanical damage, such as dents with corrosion, dents with cracks (and other secondary features), gouges and dents combined with gouges. These technologies included, but were not limited to, Geometrical (Caliper) methods, Magnetic (Axial MFL, Circumferential MFL), Ultrasonic (UT), and Electromagnetic Acoustic Transducers (EMATs). Phase I reported that deployed mechanical damage technologies were limited to magnetic flux leakage and caliper tools with integration of data from these tools and manual analysis by subject matter experts. Validation data, where available, were provided by the inspection vendors in order to evaluate the capabilities of these technologies. Performance measures were limited by insufficient data in some instances.

The vendors reported that deformation inspections using the current technologies can report dent size as low as 0.5% OD, but reporting limits are often specified by the customer. In the absence of customer-specified limits, the typical reporting limit for dents by caliper technology is 2.0% OD. The MFL technologies are sensitive to anomalies that can be a result of other mechanical damage features, but are associated with dents. For this reason, pipeline operators often specify how they wish such features to be reported, either as dents or/and MD anomalies coincident with dents. While all caliper type technologies utilize mechanical arms, some of them augment the arm tips with electromagnetic sensors (EM), either Hall or eddy current type, making them capable of detecting dent with metal loss.

The current deployed ILI-based technologies identified by the Phase I research with validated capability for detecting and discriminating dents and dents with metal loss are summarized in

Table 1.

Table 1: Capabilities to detect and discriminate dents and dents with metal loss condition from Phase I research

		Dent				Metal Loss			
Phase I Technology Code	Generic Technology Type	Depth	Length	Width	Strain	Depth	Length	Width	Gouge/ Corrosion Discrimination
A+B	Caliper (EM) + MFL Combo	X	X	X	X	X	X	X	ML Only
C	Caliper (EM) + MFL Combo	X	X	X	X				Limited
E	MFL (3 axis)	X	X	X		X	X	X	Limited
(F,G) + (H,I)	Caliper (EM) + MFL	X	X	X	X	X	X	X	Limited
J	Caliper + MFL Combo	X	X	X	X	X	X	X	Limited
K+L Phase I	Caliper + MFL (Circ Magnet)	X	X	X	X	X	X	X	Limited
K+N	Caliper + MFL	X	X	X	X	X	X	X	Limited

The overall project scope originally anticipated that validation data performed by pipeline operators would be available for release by inspection vendors. A second phase was then planned in which important validation data identified by Phase I would be solicited from participating PRCI member pipeline operators. These data represented validation measurements obtained from recent mechanical damage digs which were likely to have been identified by the current technologies.

The difficulties associated with validating deformations due to multiple sources of error are well documented; consequently, a laboratory pull test using Technology G was performed and analyzed against LaserScan measurement during the course of Phase II study. The purpose of the pull test was to investigate ILI deformation tool performance in a situation where all other error sources, namely, re-rounding, re-bounding and direct examination, have been minimized.

In this report, the newly collected data during Phase II are presented and analyzed. If data support, top and bottom side dents are analyzed separately. For bottom side dents, spring back (re-bounding) corrections are applied using literature-available models. Then, the pull test data are summarized and analyzed in terms of ILI dent sizing performance. This set of data perhaps provides the most accurate correlations between ILI and direct measurement. Finally, the Phase II data are combined with the Phase I data and further analyzed, which completes the evaluation of the capabilities of the most widely deployed current mechanical damage technologies (based on in-line inspection tool data) to detect and discriminate the above listed features. Limitations of the study and gaps for further study are identified.

3. Data Received

Two sets of new data were collected for Phase II study (1) eight operators' validation data and (2) one vendor's pull test data.

3.1. Data from Operators

PRCI member pipeline operators were surveyed in 2008 and 2009 to obtain mechanical damage direct examination data from excavations identified by the current ILI based mechanical damage technologies from the Phase I research (Post 2005 ILI assessments). A total of 256 mechanical damage features were obtained from four liquid and four gas pipelines operators provided ILI and validation data with three technologies, namely, Technologies J (caliper + MFL, combo) Technology K,N (caliper + MFL) and Technology E (Tri-axial MFL). Additionally, data for specific inspection attributes were requested as important for evaluation of performance measures:

- Pipeline/inspection Run Identification
- ILI technology(s) employed
- Validation measurement Method
- Pipeline OD, nominal wall thickness, SMYS, MAOP
- Pipeline operating pressure at time of excavation
- Mechanical damage feature circumferential orientation
- Deformation dimensions (depth, length, width)
- Coincident features (metal loss: corrosion or/and gouge, or Cracking)
- Coincident feature sizing (depth, length and width)
- ILI Predictions of mechanical damage Features
    - Type, location and sizing

Together with Phase I study, the total mechanical damage data set (dents and dents with coincident metal loss) is summarized in Table 2.

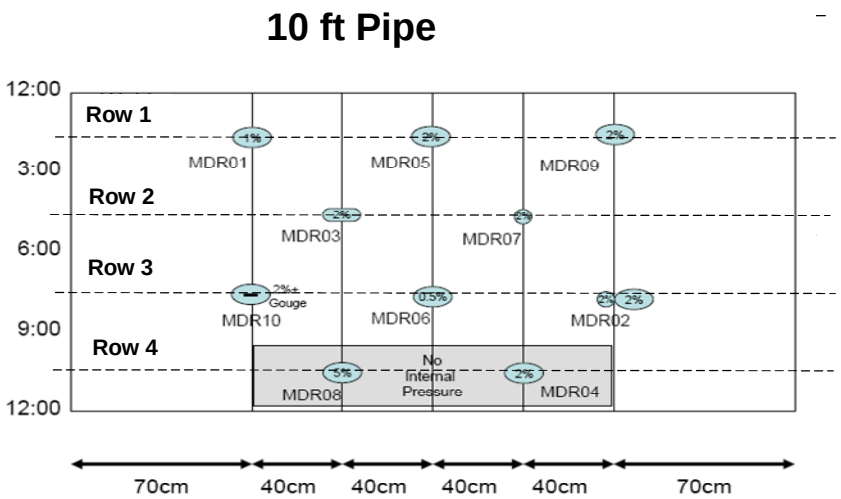
Table 2: Combined mechanical damage feature data set, Phase I and Phase II

Feature Types	# of Features
Total number of sizing and discrimination validation features	909
Dent features sized (ILI)	675
MD features validated for DML discrimination performance	719
ILI reported DML features	466
DML features with ILI and In-ditch sizing	59

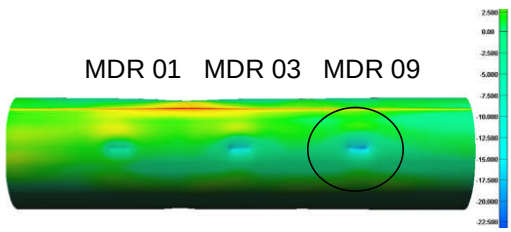
3.2. Pull Test Data (Technology G)

It has long been recognized the difficulties associated with validating deformations due to multiple sources of error. Consequently, a laboratory pull test was performed and analyzed against LaserScan measurement. The purpose of the pull test was not only to eliminate the errors resulted from re-rounding and re-bounding, but also to minimize uncertainties in direct measurements.

The pull test was conducted on a 30ft long x 30 inch OD x 0.342 inch wall test piece that contained 10 deformations with varying depths (0.5% to 6% nominal depth) introduced by Battelle for MD 1-1. Figure 1 is a sketch of the 10 deformation features and the LaserSan image of the deformed pipe test piece.



(a)



(b)

Figure 1: Manufactured dents and LaserScan image for the 30-inch pull test specimen: (a) layout of 10 dents on a 10 ft pipe and (b) laser scanned image that contains three dents on Row 1

The ILI tool used for the test was Technology G, DAMC(EM) with a total 72 sensors (sensor spacing = 1.3 in). This ILI tool was repeatedly pulled 12 times with a speed between 0.5 m/s and 1.8 m/s with the majority of tests at 1 m/s to provide statistically significant results. A total of 120 data points (12 data points/dent) were produced and analyzed.

For direct measurement, a laser profilometry, i.e., Nvision 3D scanner, was used. Laser profilometry is known to be a matured technology developed for reversed engineering, which has a spatial resolution of 0.1 mm and a depth accuracy of 0.1mm. Using the laser scanner, not only the 10 MD features but also the entire pipe surface were mapped to determine the center line of the pipe and establish reference points for mechanical deformation analysis. Two features (MDR02 and MDR09) were also scanned from the pipe internal surface. The established dent internal surface profile was compared with its companion (external surface profile) and ILI geometry tool profiling data.

4. Approach Used for Data Evaluation

Similar to Phase I study, two methods were used for data evaluation: (a) binomial and confidence interval methods to determine POD, POI, and tool tolerance at a given confidence level and (b) standard unity graph with linear regression to establish correlations between ILI feature size prediction and field measurement.

4.1. Binomial and Confidence Interval Method

Similar to Phase I study, POD, POI of the tool performance were evaluated using the binomial probability and confidence interval method. This method also allows for estimating tool sizing tolerance based on an assumption that the field measurements are accurate and no other error factors, such as rebounding and re-rounding, are involved. The tolerance determined by this method is a measure of tool sizing performance for a given certainty and confidence level. By using the binomial distribution and confidence interval methods, the following capability of the technologies is evaluated [1]:

- Accuracy of Sizing
  - Tolerance, e.g., ± 10% WT in depth for corrosion or ±1%OD for dent depth
  - Certainty, e.g., 80% of time
  - Confidence level, e.g., 95%
- Probability of Detection for dents with metal loss, DML; (POD)
- Probability of False Calls, DML; (POFC)
- Probability of Identification, DML; (POI)

The details of the binomial distribution analysis and confidence interval method have been discussed in the Phase I report [1] and API 1163 [14], and are briefly described below.

Binomial Distribution Analysis – The method assumes that the validation measurements are independent of each other and the “successful” measurements have a Binomial distribution. The analysis estimates the probability (or certainty) of finding “x” out of “n” measurements within the desired tolerance, or estimates the probabilities of detection and identification for a given confidence level for a relatively small sample.

Confidence Intervals (CI): Confidence intervals for the certainty are the recommended procedure in API 1163, and can also be used to estimate a tool tolerance for a given certainty at a confidence level, or to estimate the probabilities of detection and identification for a given confidence level from a relatively small sample. Many confidence intervals for binomial variables appear in the literature [15,16,17], and the Clopper-Pearson confidence interval is chosen for the study which always gives conservative results [18].

It is noted that traditionally, the ratio of "success of detection" or the ratio of "success of identification" (x) to the total number of samples (n), i.e., x/n, is reported as POD or POI, respectively. Similarly, the ratio of false calls (also denoted as x) to the number of samples (n), x/n is used to represent POFC. Obviously, POD, POFC and POI obtained in this way are not the true probabilities, rather the proportions of detection, false calls and identification. The probability of detection (POD), probability of false calls (POFC) and probability of Identification (POI) used here are values estimated using binomial-probabilistic distribution and statistically based confidence interval method at a given, say 95%, confidence level.

4.2. Unit Graph Method and Rerounding/Rebounding Correction

A standard method for comparing ILI sizing predictions to in-ditch direct measurements was used for this research. In the unity graph, each feature is plotted on an x-y chart with the x-coordinate being the in-ditch validation measurement and the y-coordinate the ILI size prediction. Deviations of data from the unity line could reflect errors and bias due to ILI tool and the in-ditch measurements.

The unity graph method along with statistical analysis (e.g., linear regression) quantifies the correlation and bias between ILI tool/in-ditch measurements, data scattering, and the confidence interval for the empirically established relationship. This is a complementary component to the binomial distribution and confidence interval analysis.

Dent size accuracy can be further complicated due to the potential for dents to re-round due to internal pressure and rebounding due to the removal of an indenter upon excavation as illustrated in Figure 2.

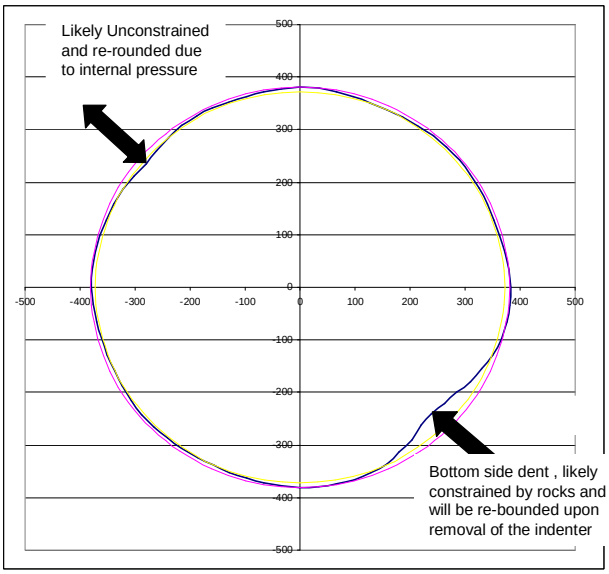


Figure 2: A sketch of circumferential profile of a bottom-side dent (5.8% OD, constrained) and top side dent (1.6% OD unconstrained)

Bottom-side dents are generally formed by rocks acting as the indenters during pipeline construction. Usually, the indenters remained in place at the time of an ILI assessment, but the dent rebounded (sprung back) upon excavation due to the removal of the restraining indenter and rerounded while the pipeline remains under pressure. This rebounding/rerounding allows for possible reduction in depth as compared to what was observed by the ILI tool.

For top side dents, deformations are more likely induced by a third party action such as excavator bucket teeth impacting the pipe wall. It is likely that any spring back and pressure re-rounding would occur immediately after the impact. Such a dent would be un-constrained during ILI assessments with little change expected due to excavation. The shape of dents could also affect the likelihood for re-rounding.

A number of empirical spring back (rebounding) and pressure re-rounding correction factors have been proposed by EPRG and others [3] to predict the original dent depth based on residual dent depth measurement for integrity assessment. The following relationship taken from the EPRG model predicts the residual dent depth at pressure when a dent was induced while the pipe was under internal pressure and the indenter subsequently removed.

$$\frac{H_r}{D} = 0.436\frac{H_p}{D} - 0.282 \qquad (1)$$

where $D =$ pipe diameter, $H_r =$ residual dent depth measured upon excavation at reduced pressure and unrestrained condition, $H_p =$ maximum dent depth during indentation as measured by ILI under restrained conditions, and $\frac{H}{D}$ *is* expressed in %

When significant scatter or bias was observed in the unity evaluations, the relationship in equation (1) was applied to bottom-side dent depth predictions. Assuming the dent depth measured by an ILI tool represented a constrained dent with the indenter in place, the application of equation (1) could predict the residual dent depth upon excavation when the indenter would be removed. The calculated residual depth is then used to compare with the in-ditch validation measurements. As shown later, with this correction the scatter bands are significantly narrowed.

An alternative re-rounding model was proposed by Rosenfeld [4] using the data from a caliper pig to estimate the initial depth. It is based on fitting the displacements to a Fourier series. This technique is for the circumferential profile only and requires displacement readings over the dent profile and these data are not available from archived feature lists or dig data and therefore are not available to this project. In the same reference, a second alternative was cited predicting original depth based on a regression analysis when only dent width and depth were available:

$$
\begin{aligned}
d_o &= \frac{d}{fg} \\
f &= \frac{1.04}{1+0.0875z^{-3.2}} - 0.052 \\
g &= \frac{0.88\frac{D}{w}}{1+0.59\frac{D}{w}+0.041\left(\frac{D}{w}\right)^2} \\
z &= \left(\frac{D}{w}\right)^{0.3}\left(\frac{D}{t}\right)^{-0.7}\left(\frac{P}{E}\right)^{-0.2}
\end{aligned}
\qquad (2)
$$

Where $D =$ pipe diameter, $w =$ dent width, $d_o =$ original, or restrained dent depth predicted from dig measurements, d = residual or in-ditch dig, un-restrained dent depth, $P =$ internal pressure, and $E =$ elastic modulus for line pipe.

The additional data gathered in Phase II allowed for categorization by circumferential orientation with sufficient population sizes for application of performance measures described in the Phase I report.

Conversely, for top-side dents it is assumed that the indenter was immediately removed. The dent depth at the time of passage for the ILI tool should be the same as for in-ditch validation assuming the internal pressure remains constant.

4.3. Pull Test and One-on-One Comparison of Dent Profile

Since the laser scan results provide not only the depth-length-width information but also the 3-D profile of deformation, validation measurements for comparison against the ILI technology predictions can be carried out on a profile-comparison basis, i.e., one-on-one ILI vs laser profile comparison. This comparison avoids errors in depth measurement using the bridging bar method due to some uncertainty in selecting reference points on the deformed pipe. Figure 3 is an example of one-on-one profile comparison between ILI and laser measurements.

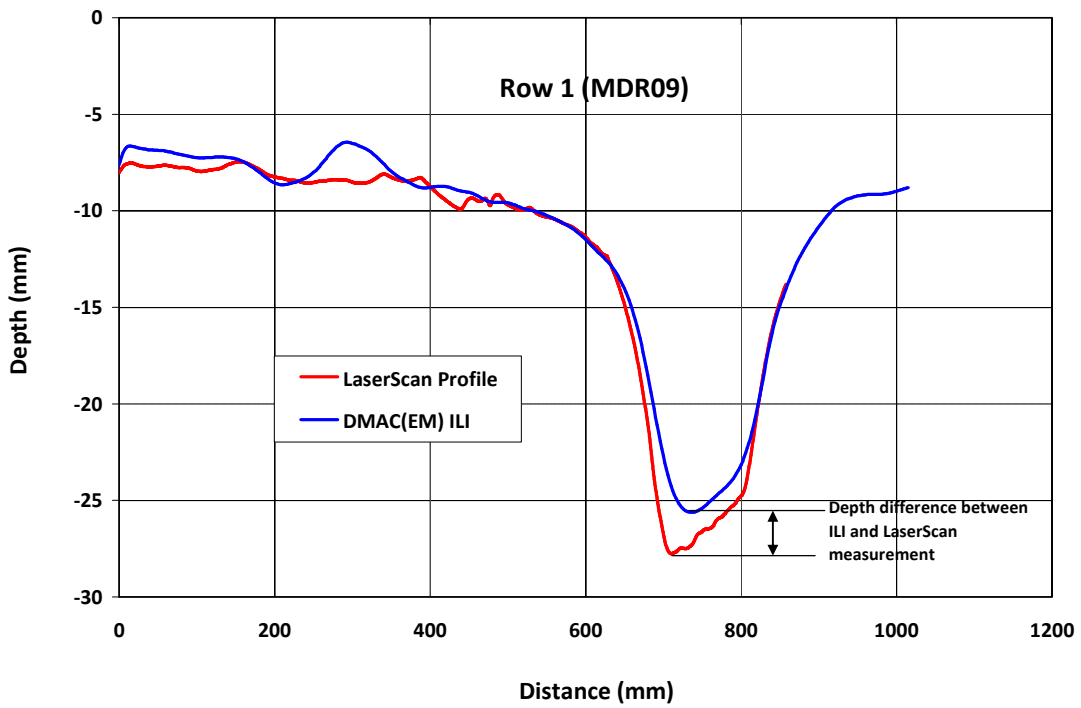


Figure 3: An example of one-on-one comparison of profile between ILI and laser. The difference in depth can be directly measured from the profiles, which minimizes errors resulting for the use of Bridging Bar

The results of one-on-one comparison of more than 100 data points were further evaluated using unity graph and linear regression analysis, which provide a most accurate basis for understanding of the errors, bias, and tool performance.

5. Evaluation Results

The evaluation results are presented in the following two subsections: (1) Evaluation of the Newly Collected Data from Operators and (2) Evaluation of the Pull Test Data.

5.1. Evaluation of the Newly Collected Operators' Data

A total of 256 mechanical damage features were obtained from four operators using three technologies. The three technologies are Technology J (Caliper + MFL Combo), Technology E (Tri-axial MFL), and Technology K,N+MFL. Evaluations were performed on the depth, length and width sizing even though limited data are available only for Technology E and Technology K,N+MFL. For dent with metal loss (DML), only three features were reported by Technology K,N+MFL and field-validated. Because of very small sample size (three points), DML analysis was not performed separately but combined with the Phase I data.

As same as the Phase I study, two methodologies were used for Phase II, namely, binomial probability distribution and confidence interval method and unity graph method. The binomial probability distribution and confidence interval method was used for evaluating tool sizing performance for dent and dent with metal loss, and POD, POI, and POFC for dent coincident with metal loss. The unity graph method was used for evaluating correlations between ILI and field validation, bias, and data scattering for tool sizing.

5.1.1. Performance Evaluation Using Binomial Probability Distribution and Confidence Interval Method

<u>Dent Sizing Performance</u>

The dent depth performance shown in Table 3 was calculated at 80% certainty for 95% confidence using both binomial distribution and the Clopper-Pearson confidence interval method. The dent depth performance specifications claimed by the ILI vendors often vary with pipeline diameter with differences likely a result of sensor arm spacing. The expected performance shown in Table 3 was determined from the vendor specifications for a mid-range size of line pipe in the range of 20 to 26 inch.

It should be noted that the results presented in Table 3 are based on an assumption that the field measurements were accurate, and there were no other factors (or at least, no major factors) that could affect the measurement reliability, such as change in dent depth between ILI and field measurements. Obviously, these assumptions have not been validated. Therefore, the numbers presented in Table 3 are informative for discussion. Based on experience learned in the past for bottom-side dents, some corrections were made to account for spring-back due to removing the constraint during excavation. The results are also presented in the table for comparison.

Table 3: Dent depth performance for the Phase II ILI technologies

Technologies for Dents		Data Source	# of Dent Features Evaluated	Mid-range size Caliper Specifications		Validation of Depth Tolerance %D at 80% Certainty and 95% confidence Level	
				LOD, %D @90% POD	Depth Tolerance, +/- %D @80-96% Confidence Level	Binomial Distribution Method	Clopper-Pearson Confidence Interval Method
J	Caliper + MFL Combo	Phase II	All 135 Dents	1.00	±0.50	±1.07	±1.08
J	Caliper + MFL Combo	Phase II	Top Side 25 Dents	1.00	±0.50	±1.00	±1.20
J	Caliper + MFL Combo	Phase II	Bottom Side 110 Dents, Uncorrected	2.00	±0.50	±1.10	±1.10
J	Caliper + MFL Combo	Phase II	Bottom Side 110 Dents, Corrected*	2.00	±0.50	±1.32	±1.32
E	MFL (3 axis)	Phase II	All 26 Dents	0.50	±1.00	±2.40	±2.88
E	MFL (3 axis)	Phase II	Top Side 6 Insufficient #	0.50	±1.00	NA	NA
E	MFL (3 axis)	Phase II	Bottom Side, 20, Uncorrected	0.50	±1.00	±2.88	±3.00
E	MFL (3 axis)	Phase II	Bottom Side, 20, Corrected*	0.50	±1.00	±0.95	±1.00
K,N, MFL	Caliper + MFL	Phase II	All 95 Dents	0.60	±0.80	±5.30	±5.34
K,N, MFL	Caliper + MFL	Phase II	Top Side 1 Insufficient #	0.60	±0.80	NA	NA
K,N, MFL	Caliper + MFL	Phase II	Bottom Side , 94, Uncorrected	0.60	±0.80	±5.34	±5.34
K,N, MFL	Caliper + MFL	Phase II	Bottom Side, 94, Corrected*	0.60	±0.8	±1.51	±1.52

*Bottom side dent depth corrected for spring back using EPRG recommend equation

From the table, it is seen that Technology K,N+MFL exhibits a very large depth tolerance: i.e., ±5.34% OD at 80% certainty and 95% confidence level. This is because there were about 35 features (out of 95 total), having the error between tool prediction and field measurement greater than 4%OD. These features are all at the bottom (i.e., 6 o'clock) of the pipe, and were constrained. By applying ERPG [3] correction to the 94 bottom-side dents, the tolerance considerably reduced down to ±1.52%OD. Similarly, Technology E also had a large percentage of bottom-side dents with large errors between ILI and in-ditch measurement, and EPRG correction effectively reduces the tool tolerance from ±2.88%OD to ±0.95% OD. On the contrary, though the percentage of bottom-side dents (80% of 135 dents) were comparable to Technology E (84% of 26 dents). Technology J exhibits a much smaller tool tolerance (±1.08%OD) that is about 5 or 3 times smaller than that of Technology K,N+MFL or Technology E, respectively. The reason for this pronounced difference might be associated with smaller spring-back error in the field measurement for Technology J. The evidence is that, unlike Tech

E and K,N+MFL, EPRG spring-back correction does not reduce but increases the tool tolerance for Technology J from 1.10 %OD to 1.32%OD.

Overall, the tool tolerance for these three technologies is in the range between 1.0%OD and 1.5%OD at 80% certainty and 95% confidence level after making bottom-side dent depth correction.

Similar evaluations may be conducted for ILI measurements of dent length and width. The ILI vendors all reported their technologies had the capability to measure length and width, but validation data sets were too small to evaluate performance for each technology. Table 4 lists the dent length and width performance using the binomial distribution and Clopper-Pearson confidence interval technique for Tech E and Tech K,N+MFL. There is no length and width report for Tech E. From the table, it seems that the length and width tolerances are over the range 15 inch to 20 inch, which is quite large. However, except that there are no claimed or expected performance specifications from the ILI vendors.

Table 4: Dent length and width performance for the Phase II ILI technologies

Technologies for Dents		Data Source	# of Dent Features Evaluated	Validation of Length and Width Tolerance, inch, at 80% Certainty and 95% confidence Level	
				Binomial Distribution Method	Clopper-Pearson Confidence Interval Method
Length Assessemnt					
K,N, MFL	Caliper + MFL	Phase II	28	±17.00	±17.00
E	MFL (3 axis)	Phase II	12	±14.70	NA
Width Assessment					
K,N, MFL	Caliper + MFL	Phase II	23	±15.00	±21.00
E	MFL (3 axis)	Phase II	12	±20.00	NA

AS mentioned previously, the data presented here may reflect multiple sources of error and bias, such as:

- Errors from the ILI tool itself
- Error in in-ditch validation measurement
- Variability inherent in the pipe, most notably, variability in shape and size of deformations due to changes in internal pressure (re-rounding) and changes in external confining forces (re-bounding)

Coincident Damage Discrimination Performance[1]

Only three features were reported by Technology K,N+MFL during Phase II. Because of small sample size (three point), analysis was performed in combination with Phase I data. The results are shown in Table 5. A ±12% wt depth sizing tolerance is determined at 80% certainty and 95% confidence interval. This is generally consistent with the MFL tool tolerance for corrosion, i.e., ±10% wt @ 80% of time.

Table 5: Dent with metal loss performance for a combined Phase I and Phase II ILI technologies

Technologies for Dents with ML	Data Source	# of Dent Features Evaluated	Validation of ML DepthTolerance %wt at 80% Certainty and 95% confidence Level	
			Binomial Distribution Method	Clopper-Pearson Confidence Interval Method
Tech C, Tech H,I, Tech K,N,MFL, Tach K,L TFI		Phase I 56, & Phase II 3	±12.00	±13.00

Coincidence Damage Performance (POD), (POI), and (POFC)[2]

Coincident damage such as gouge or corrosion within dents was evaluated using the detection and discrimination performance measures described above. Figure 4 is an example of a dent with metal loss (DML) feature that was a gouge. Some of the ILI vendors indicated limited capability for their MFL based technologies to discriminate gouges from corrosion using rule based decision criterion. The decision criteria include feature aspect ratio, shape, orientation and magnetic halo patterns seen with the analysis software, etc..

[1] Additional data was received from one operator which showed issues with ML sizing performance by ILI tools one day prior to release of this report. The data in this report is not updated with that data however will be incorporated in data analyses in MD1-4.

[2] Additional data was received from one operator which showed inconsistent results for ML POD and POI performance one day prior to releasing this report. Therefore, the report is not updated but the data will be included in the MD1-4 report

Figure 4: Dent coincident with gouge and interaction with a girth weld

A review of in-ditch dig reports within the Phase II research indicated there is no consistent protocol for characterizing coincident dent with metal loss damage. Criterion, such as definitions for scratches, moved metal and gouges and mill type surface defects, is needed. The lack of consistent in-ditch protocol for characterization of coincident damage limited the evaluation of discrimination performance to a general category of dents coincident with metal loss where any corrosion, gouge, crack or mill defect constituted a successful DML identification. The vendor and operator supplied ILI predictions and dig validation results were evaluated using the following definitions:

Total Investigations
Number of mechanical damage investigations (excavations) reported, not just DML

ILI Reported DML
Number of ILI predictions of Dents with Metal Loss, DML

Correct Calls (DML)
Prediction= Dent w/ Metal Loss, Field= Dent w/ Metal Loss
Prediction= Dent w/ Metal Loss, Field= Dent w/ corrosion
Prediction= Dent w/ Metal Loss, Field= Dent w/ gouge
Prediction= Dent w/ Metal Loss, Field= Dent w/ crack

Prediction= Dent w/ Metal Loss, Field= Dent Like Signal [ID restriction or mismatch (anything that results from a sensor lift-off)] w/ metal loss

True Calls (DML)
Dent w/ Metal Loss= Dent w/ Metal Loss (gouge or corrosion)

Number of Missed Calls (DML)
Plain Dent Call= Field DML
ML Corrosion Call= Field DML
Nothing or 0= Field DML

Number of False Calls (DML)
DML= Field Plain Dent
DML= Field ML corrosion, 0 deformation
DML= Field Nothing

Table 6 lists the statistics and results for probabilities of detection (POD), identification (POI), and false calls (POFC) of DML for the three MFL based ILI technologies participating in this research for Phase II.

Table 6: Performance evaluation for three technologies for detecting, identifying, and false call of dent coincident with metal loss (DML)

Technologies for Dents and Dents with Metal Loss		Project Phase Data Source	Total Investiga- tions	ILI reported DML (Exc. based on ILI Call)	Correct Calls (including type of DML)	True Calls (not including type of DML)	Number of Missed DML	Number of false calls	Dent with Metal Loss Performance																	
									POD						POFC						POI					
									Proportion	n	x	POD @ 95% Confidence Level			Proportion	n	x	POFC @ 95% Confidence Level			Proportion	n	x	POI @ 95% Confidence Level		
												Binomial, p, @ 95% Conf for given x,n	Confidence Interval					Binomial, p, @ 95% Conf for given x,n	Confidence Interval					Binomial, p, @ 95% Conf for given x,n	Confidence Interval	
													Lower	Upper					Lower	Upper					Lower	Upper
E	MFL (3 axis)	Phase II	26	4	4	4	3	0	57%	7	4	34.0%	22.5%	87.1%	0.0%	4	0	1.5%	0.0%	52.7%	100.0%	4	4	47.3%	47.3%	100.0%
J	Caliper + MFL Combo	Phase II	135	135	54	54	0	82	100%	54	54	>94.6	94.6%	100.0%	60.7%	135	82	67.8%	53.3%	67.8%	100.0%	54	54	>94.6	94.6%	100.0%
K+N	Caliper + MFL	Phase II	94	81	33	33	0	3	100%	33	33	>91.3%	91.3%	100.0%	3.7%	81	3	2.4%	1.0%	9.3%	100.0%	33	33	>913%	91.3%	100.0%

From the table, it is seen that the Technologies J and K,N,MFL have POD and POI greater than 90% at 95% confidence level while Technology E has only 34% and 47.3%, respectively for dent coincident with metal loss. However, Technology J poses highest POFC, i.e. 67.8% as compared to Technologies E and K,N,MFL, *that is*, 1.5% and 2.4%, respectively.

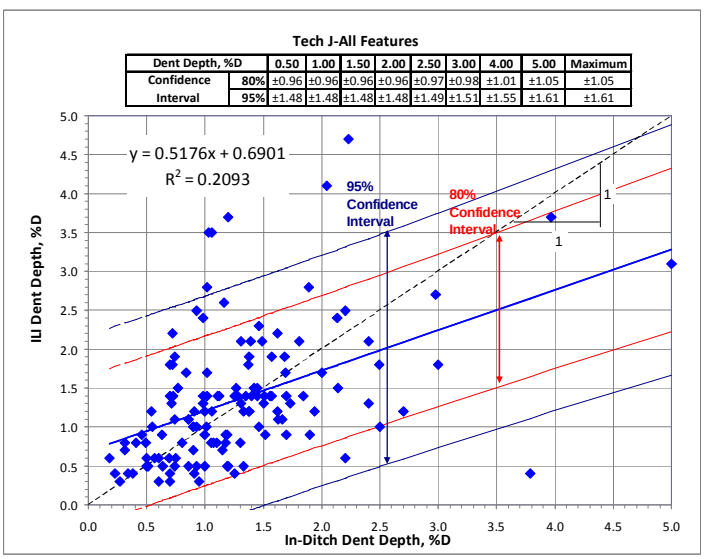
5.1.2. Tool Performance Evaluation Using Unity Graph Method

Technology J (Caliper & MFL Combo) 135 dents were identified and sized by both ILI and excavations. Figure 5 is a unity graph of total samples without bottom side dent re-bounding correction. The x-axis represents in-ditch measured dent depth and y-axis represents the ILI predicted depth. The blue line in the figure is the regression line that is established from the

data points using the least square linear regression method and represented by a linear equation $y = \beta_o x - \beta_1$, *i.e.*, $y = 0.5176x - 0.6109$ in this case. Deviations from the unity line (i.e., $y = x$, the dash line) could reflect errors and bias due to ILI tool and the in-ditch measurements. By quantifying the deviation of the regression line from the unity line, tool performance in sizing can be evaluated.

From the figure, it is seen that the deviations of the regression line (slope β_o =0.52 and intercept β_1 =-0.619) from the unity line ($y = x$) is significant, implying errors either from ILI predictions or in-ditch measurements are large. Such error could be attributed to the in-ditch measurement protocol or to change in the feature dimensions between ILI tool passage and excavation.

Furthermore, in the figure there are lines representing upper and lower bounds of 80% and 95% confidence intervals. The upper and lower bounds of the confidence interval, along with the variance R^2 value, reflect the scatters of the data around the regression line. The larger the confidence interval and the smaller the R^2 value is, the larger the data scatters are. From the figure, the R^2 is very low and the maximum intervals are ±1.05%OD @ 80% confidence interval (cl) and at ±1.61%OD @ 95%cl, suggesting the data scatters are significant.

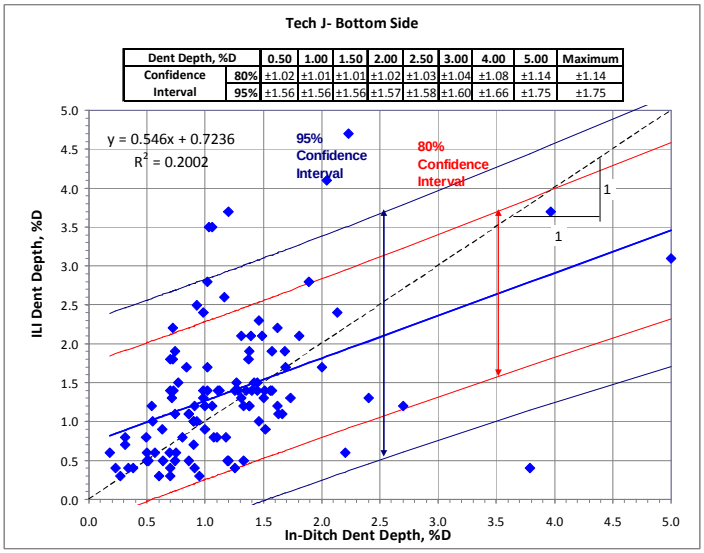


Dent Depth, %D		0.50	1.00	1.50	2.00	2.50	3.00	4.00	5.00	Maximum
Confidence	80%	±0.96	±0.96	±0.96	±0.96	±0.97	±0.98	±1.01	±1.05	±1.05
Interval	95%	±1.48	±1.48	±1.48	±1.48	±1.49	±1.51	±1.55	±1.61	±1.61

Figure 5: Unity graph and linear regression analysis of 135 dent depth reported by Technology J

It is noted that, out of the 135 dents, 110 dents are on the bottom side of the pipe. A plot of the filtered 110 bottom-side dents on the unity graph shows slightly larger scatters and wider error bands, Figure 6. However, the slope, intercept, R^2 value are comparable to those of unfiltered

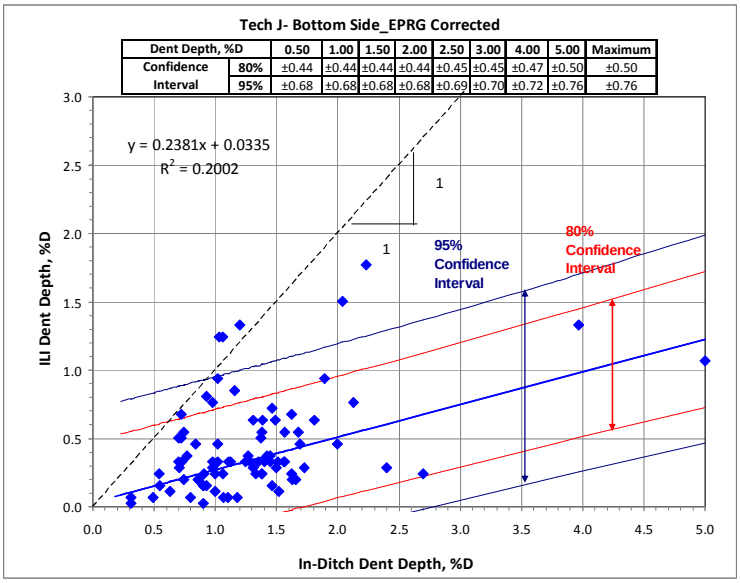
dent data, suggesting that the tool sizing performance is predominated by the bottom side dents.



Dent Depth, %D		0.50	1.00	1.50	2.00	2.50	3.00	4.00	5.00	Maximum
Confidence Interval	80%	±1.02	±1.01	±1.01	±1.02	±1.03	±1.04	±1.08	±1.14	±1.14
	95%	±1.56	±1.56	±1.56	±1.57	±1.58	±1.60	±1.66	±1.75	±1.75

Figure 6: Unity graph and linear regression analysis of 110 bottom-side dent reported by Technology J

Assuming that all the 110 bottom-side dents were constrained during ILI inspection and have been spring-backed during excavation due to removal of the constraint for the measurement, a correction is made using Equation 1 (EPRG's equation). The results are shown figure 7.



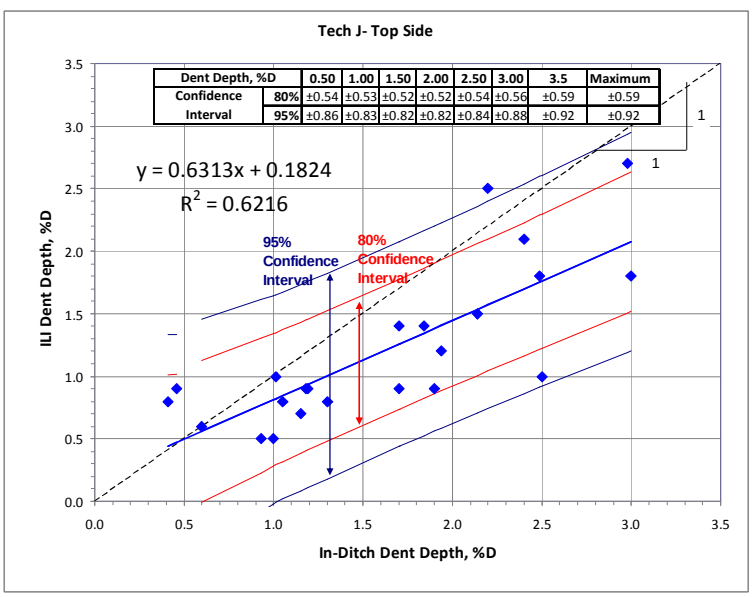
Dent Depth, %D		0.50	1.00	1.50	2.00	2.50	3.00	4.00	5.00	Maximum
Confidence Interval	80%	±0.44	±0.44	±0.44	±0.44	±0.45	±0.45	±0.47	±0.50	±0.50
	95%	±0.68	±0.68	±0.68	±0.68	±0.69	±0.70	±0.72	±0.76	±0.76

Figure 7: Unity graph and linear regression analysis of 110 bottom-side dent with correction made using EPRG equation (Eq. 1 in the report)

From the plot, it is seen that the confidence interval bands are significantly narrowed. The maximum confidence interval at 80% and 95% confidence level is ±0.48%OD and ±0.74%OD, which is almost one half of the tolerance without correction.

However, it is noted that the slope of the regression line is also considerably reduced by a factor of more than two, appearing that the tool, after correction, is further deviated from the unity line. This reflects that the equation may be overly simple which does not account for the magnitude of spring-back as a function of dent depth– relatively, less spring-back for deeper dents, or other factors. A better correction model is needed to account for spring-back and re-entrant due to pressure reduction for excavation as well.

For the remaining 25 top-side dents, a better correlation between ILI and in-ditch examination was observed. Figure 8 is the unity graph plot of the top side dent depth ILI vs validation data. The calculated maximum confidence interval at 80% and 95% confidence level is ±0.56%OD and ±0.88%OD, respectively. The slope of the linear correlation equation is 0.63, which is less than 1, but is slightly better than the unfiltered bottom-dent data, implying that the tool underestimated the dent depth, in particular for deeper dents, based on an assumption that the field measurement was accurate. However, literature data also suggest if a linear regression best fit line through the data has a slope < 1, a significant error in the validation measurements is likely [20]. Such error could be attributed to the in-ditch measurement protocol or to changes in the feature dimensions between ILI tool passage and excavation.



Dent Depth, %D		0.50	1.00	1.50	2.00	2.50	3.00	3.5	Maximum
Confidence Interval	80%	±0.54	±0.53	±0.52	±0.52	±0.54	±0.56	±0.59	±0.59
	95%	±0.86	±0.83	±0.82	±0.82	±0.84	±0.88	±0.92	±0.92

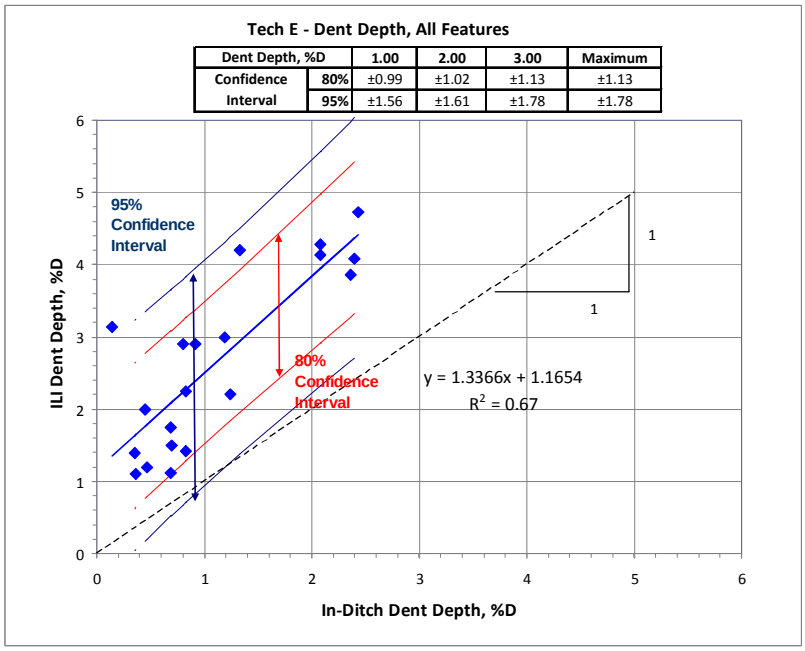
Figure 8: Dent depth validation data of Technology J, top side dents, without corrections applied

The better correlation between ILI and validation data may be understood in terms that the top-side dents are unlikely constrained and therefore, no spring-back error is involved, except for some degree of re-entrant due to pressure reduction during excavation.

Technology E (Tri-axial MFL)

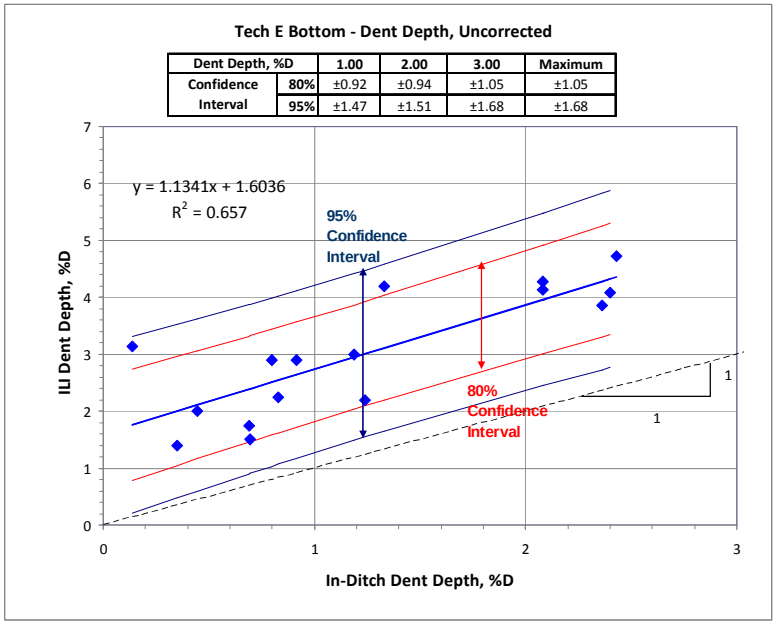
A total of 26 validation data are available for the analysis. Figure 9 shows the three unity graph plots of ILI vs validation data, namely, (a) all 26 data, (b) bottom-side data without correction and (c) with correction.

The results on the 26 features showed that the confidence interval for scatter bands is ±1.13 %OD @ 80% conf. level and ±1.78%OD @ 95% conf. level. The confidence interval for bottom-side dents only is ±1.05 %OD @ 80% conf. level and ±1.68%OD @ 95% conf. With the EPRG correction, it resulted in a much smaller confidence interval (tool tolerance), *that is*, ±0.46%OD @ 80% conf. level and ±0.73%OD @ 95% conf. level. Again, the correction also reduced the slope of the correlation equation from 1.33 to 0.49. This makes that the tool significantly underestimates the dent, suggesting that an investigation of the correction model is needed for improvement.

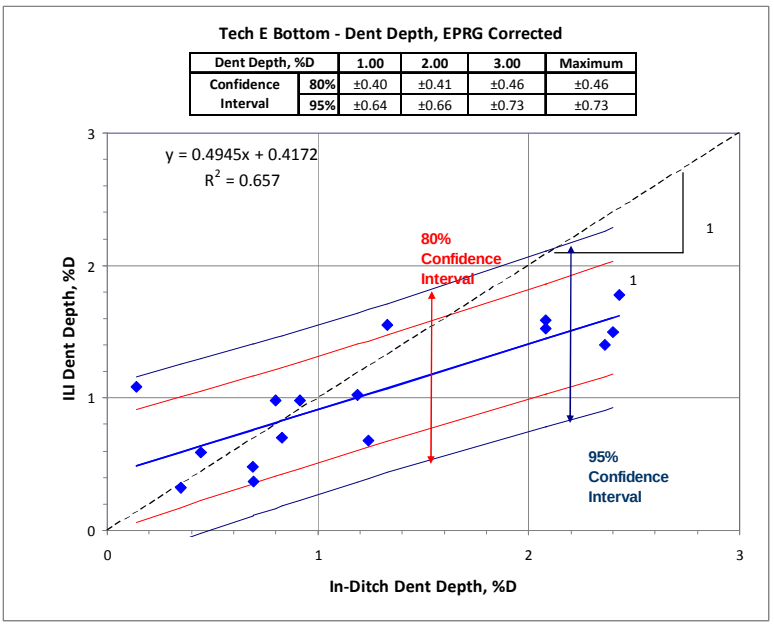


Dent Depth, %D		1.00	2.00	3.00	Maximum
Confidence Interval	80%	±0.99	±1.02	±1.13	±1.13
	95%	±1.56	±1.61	±1.78	±1.78

(a) All 35 features



(b) Bottom-side dents without correction



(c) Bottom-side dents with EPRG correction

Figure 9: Dent depth validation data of Technology E: (a) all 26 features, (b) bottom-side dents without correction and (c) bottom-side dents with depth correction using EPRG equation.

For the top-side dents, in contrast to Technology J, Technology E exhibits much larger scatter and wider error bands, Figure 10. The very large confidence interval (±1.62 OD at 80% conf. and ±3.69% OD at 95% conf.) may be partially attributed to the small sample size (4 data points).

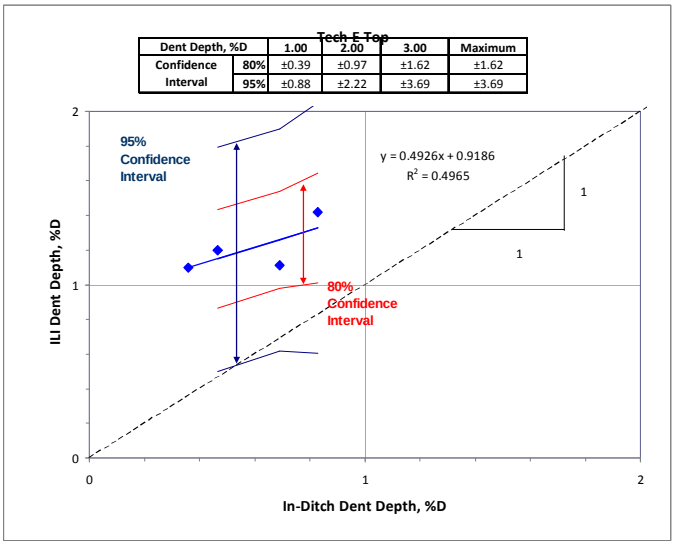


Figure 10: Dent depth validation data of Technology E, top-side dents, with no corrections applied

In addition to the depth validation data, Technology E also provided the length and width validation data. The length validation data (11 data points) showed that correlation between ILI and validation is fairly good, Figure 11. However, the error bands are large mainly due to the small sample size (9 data points only) and possibly some uncertainties in tool predictions [20].

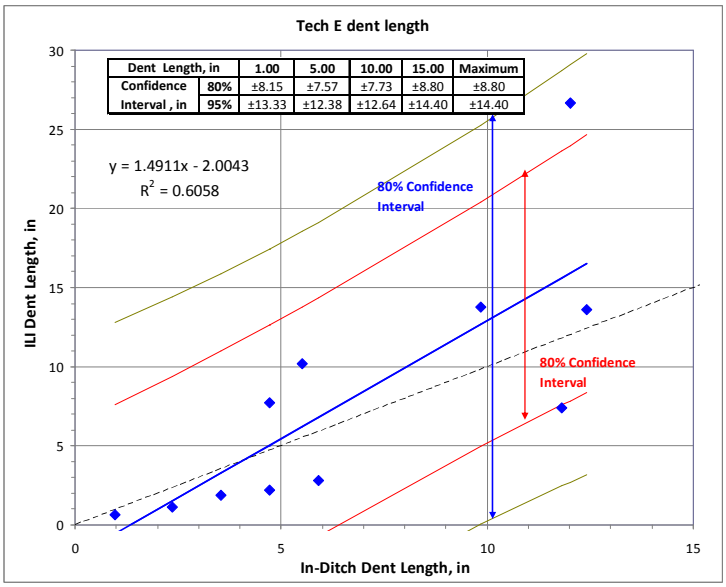
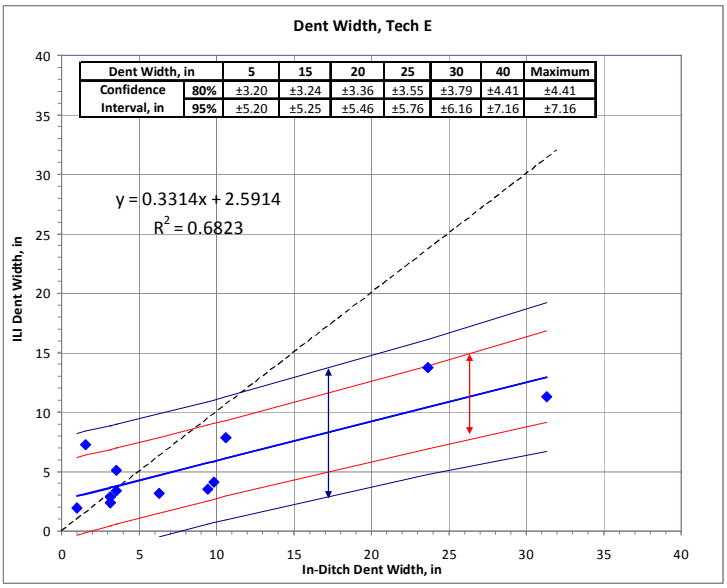


Figure 11: Dent length validation data of Technology E

From the width validation data (12 data points), the 80% confidence interval is ±4.4 in, Figure 12. The correlation between ILI and in-ditch measurements appears to be not as good as the length correlation. The tool significantly underestimated the width, in particular, for wider dents.

Such error might be related to the technology itself. For example, the tool could become insensitive to the change of dent width for wider dents. Certainly, in-field measurement error may also be involved. As previously quoted, when the data has a slope < 1, a significant error in the validation measurement is likely [20]. Such error could be attributed to the in-ditch measurement protocol or to changes in the feature dimensions between ILI tool passage and excavation.

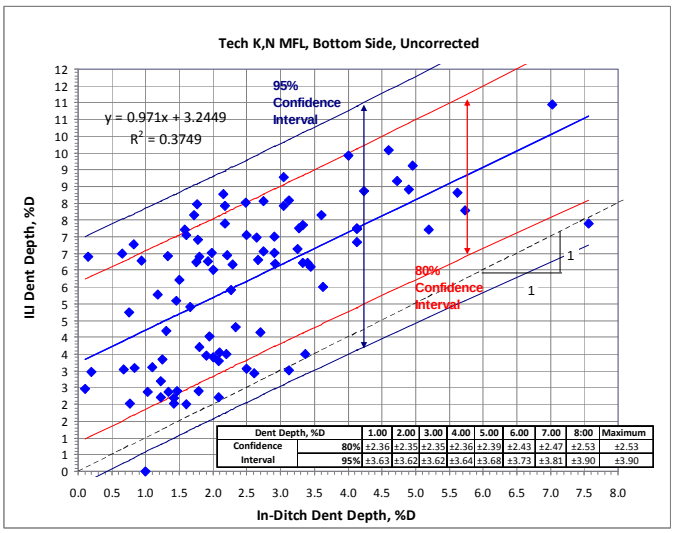


Dent Width, in		5	15	20	25	30	40	Maximum
Confidence Interval, in	80%	±3.20	±3.24	±3.36	±3.55	±3.79	±4.41	±4.41
	95%	±5.20	±5.25	±5.46	±5.76	±6.16	±7.16	±7.16

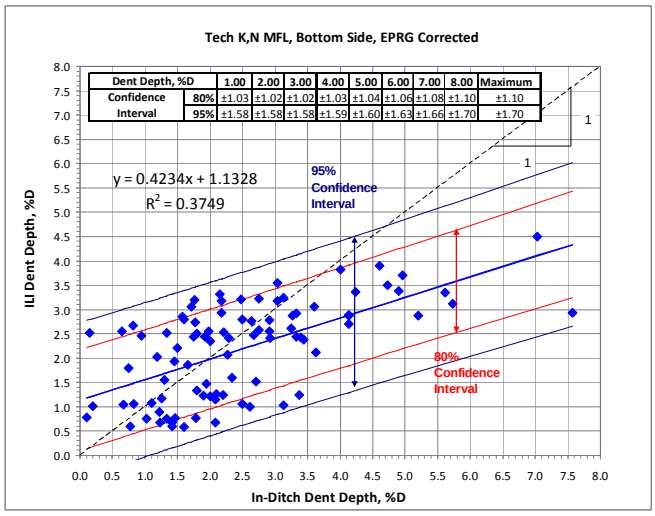
Figure 12: Dent width validation data of Technology E

Technology K,N + MFL

A total of 95 validation data was received from two pipeline operators. All except one are bottom-side dents. Therefore, no top-side dent validation data are analyzed. The results are shown in Figure 13. Figure 13 (a) is the unity graph plot showing the bottom-side data without correction and (b) is the same data with EPRG Correction. The EPRG corrected data shows greatly improved confidence interval, however, the reduction of slope by a factor of more than two is still a challenge. As stated previously, a better correction model is needed.



(a) Bottom-side dents without correction



(b) Bottom-side dents with ERPG correction

Figure 13: Dent depth validation data of Technology K,N+MFL (a) bottom-side dents, uncorrected and (b) bottom-side dents, EPRG corrections applied.

In addition to the depth validation data, Technology K,N+MFL also provided the length and width validation data. The length validation data, Figure 14, showed that correlation between ILI and validation is very poor. It appears that there are two outliers where the ILI predictions are 9" and 8" while the field measurements are 26" and 30" respectively. The reason for the outliers is not known, however, by removing the outliers, the correlation between ILI and field validation could be improved.

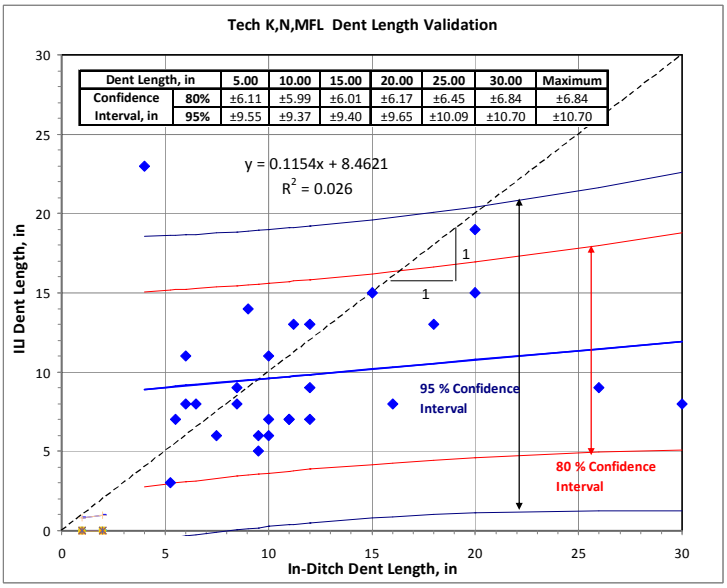


Figure 14: Dent length validation data of Technology K,N+MFL

From the width validation data (23 validated data points), it appears that correlation between ILI and validation is also quite poor, Figure15. One outlier is noticeable where the ILI prediction is 39.5" while the field measurement is 14", Implying that tool significantly underestimated the width for wider dents. Similar to Technology E, such error might be related to the technology itself, for example, the tool could become insensitive to the change of dent width for wider dents.

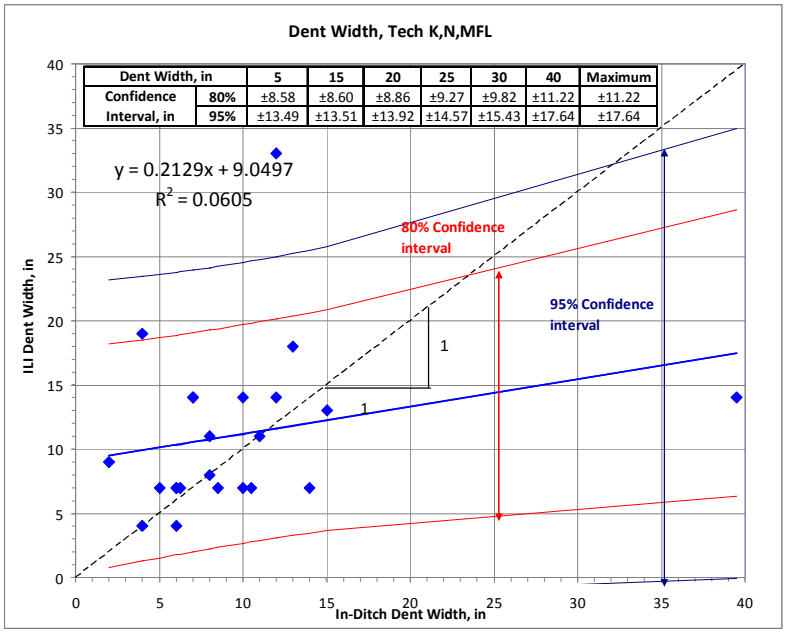


Figure 15: Dent width validation data of Technology K,N+MFL

Below is a summary of the tool sizing performance for the three technologies evaluated during the Phase II study, Tables 7-9.

Table 7: Summary of depth sizing performance for three technologies, Phase II

(a) All dents (not filtered in terms of bottom-side and top-side dents)

Technology	Slope	Intercept	R^2 value	80% C.I.	95% C.I.
J, Caliper + MFL Combo, 135	0.518	0.690	0.21	±1.05	±1.61
E, Tri-axial, 26	1.337	1.165	0.67	±1.13	±1.78
K,N,MFL, Caliper+MFL, 95	0.917	3.245	0.38	±2.58	±3.97

(b) Bottom-side dents without correction

Technology	Slope	Intercept	R^2 value	80% C.I.	95% C.I.
J, Caliper + MFL Combo,,110	0.546	0.724	0.20	±1.14	±1.75
E, Tri-axial, 21	1.341	1.165	0.66	±1.05	±1.68
K,N,MFL, Caliper+MFL, 92	0.917	3.245	0.38	±2.53	±3.90

(c) Bottom-side dents with correction

Technology	Slope	Intercept	R^2 value	80% C.I.	95% C.I.
J, Caliper + MFL Combo,,110	0.238	0.035	0.20	±0.50	±0.76
E, Tri-axial, 21	0.495	0.417	0.66	±0.46	±0.73
K,N,MFL, Caliper+MFL, 92	0.423	1.133	0.38	±0.48	±0.74

(d) Top-side dents without correction

Technology	Slope	Intercept	R^2 value	80% C.I.	95% C.I.
J, Caliper + MFL Combo,,110	0.631	0.182	0.62	±0.59	±0.74
E, Tri-axial, 21	0.493	0.919	497	±1.62	±3.69
K,N,MFL, Caliper+MFL, 92	NA	NA	NA	NA	NA

Table 8: Comparison of length sizing performance for two technologies, Phase II

Technology	Slope	Intercept	R^2 value	80% C.I.	95% C.I.
J, Caliper + MFL Combo, 0					
E, Tri-axial, 11	1.491	-2.004	0.656	±8.80	±14.40
K,N,MFL, Caliper+MFL, 26	0.115	8.462	0.026	±6.55	±10.23

Table 9: Comparison of width sizing performance for three technologies, Phase II

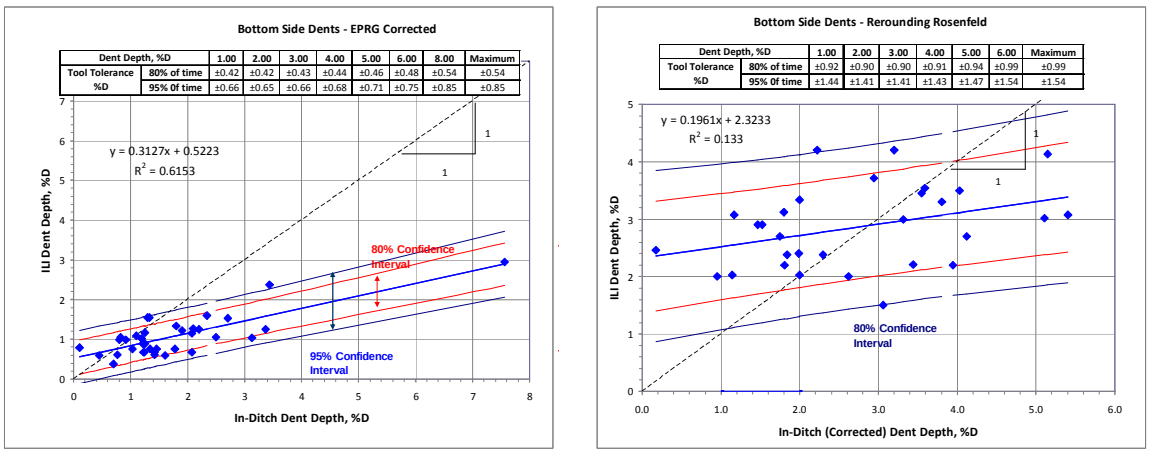
Technology	Slope	Intercept	R^2 value	80% C.I.	95% C.I.
J, Caliper + MFL Combo, 0					
E, Tri-axial, 11	0.331	2.591	0.682	±4.41	±7.16
K,N,MFL, Caliper+MFL, 23	0.213	9.05	0.061	±11.22	±17.64

From the tables, it is seen:

- Tech K.N+MFL has a slope = 0.917, which is close to one, but a low R^2 value = 0.38 and the large confidence interval (3.97%OD @95% confidence level). The slope and R^2 value of Tech E are higher (1.337 and 0.67, respectively), but confidence interval is lower (1.78%OD @95% confidence level), while Tech J poses the lowest slope = 0.518 and R^2 value = 0.21, and the lowest confidence interval (1.61%OD@95% confidence level). It seems that Technology E have a better performance than the other two, based on higher R^2 value and lower confidence interval.
- The similar trend can be seen for the filtered but uncorrected bottom-side dents.
- After correction using EPRG equation, the confidence interval essentially becomes the same for all three technologies, i.e., (±0.46% ~ ±0.50%%OD) @ 80% confidence interval and (±0.73%OD ~ 0.76%OD) @ 95% confidence interval, while there is no change in R^2 values. The understanding of this observed concurrency in confidence interval after EPRG correction is not straightforward and requires more data for support.
- Corrections using EPRG equation to the bottom-side dents significantly reduced the slope and intercept, implying that the correction makes the data significantly deviate from the unity line and underestimates the dent depth.
- The slopes of the regression lines for the bottom side dents all showed less than one, which may be understood in terms of dent re-bounding (spring-back) upon removal of the constraint from rocks. The deeper dents may have greater re-bounding than the shallow ones, however, additional investigation is needed to confirm.
- Since errors with both ILI and field measurements are not known and are further complicated by the change in dent dimensions between ILI passage and excavation, it makes analysis of the data quite difficult. Fundamentally, a more “clean” measurement under well defined conditions is desired to facilitate the understanding of errors and finally resolve the long standing complicated issue.
- Technology E appears to have a better length and width sizing performance than Technology K,N+MFL based on the slope and R^2 values (Table 4,5).

It should be noted that there wasn’t adequate data for all the diameter ranges to assess the effect of pipe diameter and wall thickness (t/D) on the correlation between ILI and field measurement. The nominal OD and wall thickness covered by this study is 20-36” and 0.218-0,5”, respectively.

Finally, a comparison of the correction equations for bottom-side depth between EPRG and Rosenfeld methods was made. The analysis was performed on the combined Technologies E and K,N+MFL data, making a total 35 points available. The results are presented in Figure 16. From the figure, it is seen that EPRG correction provides higher R^2-values (0.61), higher slope (031), and small confidence interval (±0.85% @95% confidence level) as compared to Rosenfeld's. The respective values from Rosenfeld are R^2-values = 0.13, Slope = 0.19 and confidence interval = ±1.54% @95% confidence level. However, the comparison does not mean that the EPRG correction is better that Rosenfeld's because errors and uncertainties in the data set used for analysis are unknown.



(a) EPRG Correction **(b) Rosenfeld Correction**

Figure 16: Comparison between EPRG and Rosenfeld corrections for bottom-side dent depth

Coincident Damage Sizing Performance[3]

The sizing of coincident metal loss was reported by some ILI vendors to be offered on a best effort basis with no publication of expected performance. Normally, high resolution MFL tools can be expected to size metal loss (corrosion) depth +/- 10 to 20 % wt with 80% certainty. The performance for metal loss within dents is affected by the shape of the dent affecting the ride of the MFL sensors over the dent. Fifty-six (56) validation data were available in the Phase I, the Phase II data gathering effort increased the ML population for ML depth sizing to 59 features.

[3] Additional data was received from one operator which showed inconsistent results of ML depth sizing, POD and POI performance one day prior to releasing this report. Therefore, the report is not updated but the data will be included in the MD1-4 report

Only three features reported by Technology K,N+MFL. Because of small sample size (three point), analysis was combined with Phase I data. A unity graph for metal loss depth sizing for combined data is given in Figure 17. The data points with red circles are the three new DML features obtained during Phase II study, showing that they are fairly in agreement with the Phase I data.

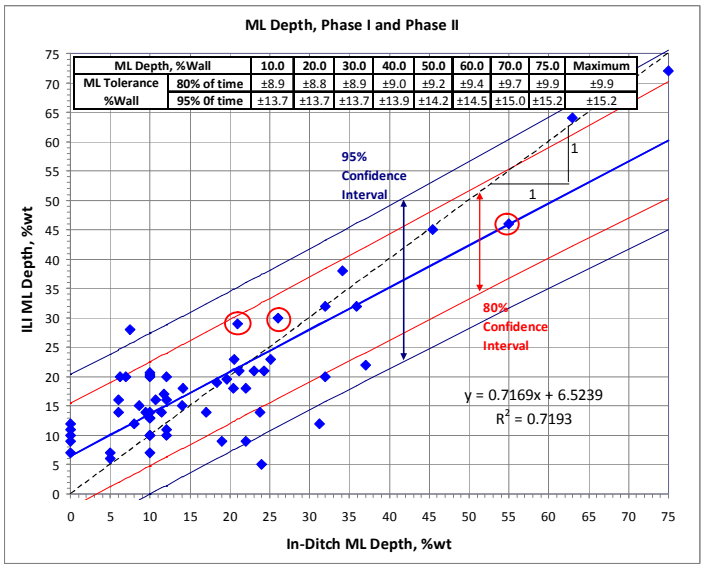


Figure 17: DML validation data from Phase I and II. The data points circled with red are the data collected from Phase II.

Figure 17 shows that the slope of the regression line is 0.72 is not significantly deviated from the unit line. The confidence intervals are ±9.9%wall @ 80% confidence level and ±15.2%wall @ 95% confidence level with the R^2-value = 0.72, suggesting the data scatters are reasonably small. This depth sizing performance is slightly better than 10.6%wt @ 80% confidence level and 16.4% @ 95% confidence level obtained from Phase I study. This is generally consistent with the MFL tool tolerance for corrosion, i.e., ±10% wt @ 80% of time.

5.2. Pull Test Data Analysis (Technology G)

Technology G pull tests were conducted at travel speeds between 0.5m/sec and 1.8 m/sec. The sensor deflection data from the 12 pull tests were provided by the ILI vendor. The evaluation was performed using the linear regression best fit against the laser profilometry validation measurements.

5.2.1. Performance Evaluation Using Profile One-on-One Comparison

To avoid errors due to using different reference points for the depth measurement between ILI and laser, a one-on-one comparison of ILI and LaserScan profile method was used. The dent depth was directly measured from the overlapped profiles with the same reference points. Figure 18 is an example that illustrates how the measurement and comparison were made.

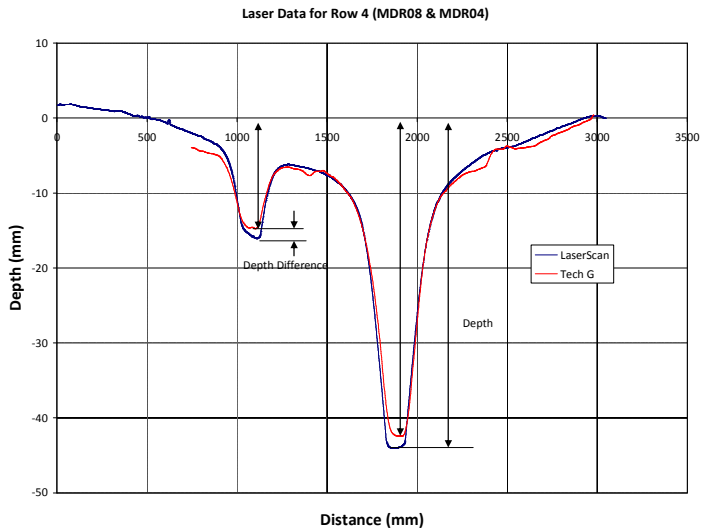


Figure 18: ILI and LaserScan profile one-on-one comparison

Figure 19 is the unity graph of the ILI dent depth prediction against LaserScan validation.

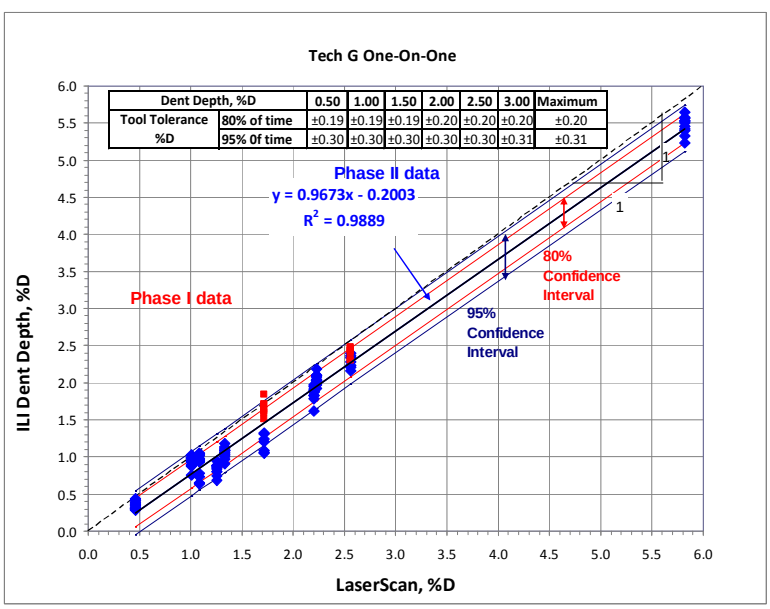


Figure 19: Dent depth validation of Technology G, DAMC (EM) using one-on-one profile comparison method, 12 times repeating pull tests. The blue symbols represent the depth data for

Laser Scan that was performed on the external surface of the pipe. The red symbols are of the Laser data scanned on the internal surface of the pipe

From Figure 19, it is seen:

- The linear correlation between ILI and LaserSan data is extremely good with the R^2 value = 0.9889
- The slope of the regression line is very close to one (0.9673), implying little bias of the ILI prediction
- There is a small shift of the regression line from the unity line, indicating the ILI tool underestimate of the dent depth by 0.20%OD. This systematical shift can be readily corrected. The reason for this shift is unclear and required the vender for further investigation.
- The confidence interval for the 12 sets of repeating tests is ±0.20% at 80% and ±0.31% at 95% confidence interval. By comparing the vendor specification for this caliper technology +/- 0.5%OD at 95% of time, the tool performance is justified.
- The red symbols (internal dent surface LaserScan) in the plot is higher vertically as compared with the blue symbols (external dent surface LaserScan), implying a better correlation between ILI pull test and internal LaserScan data. The better correlation can be readily understood in terms of both ILI and internal LaserScan measuring the same surface, i.e., from interior of the pipe as opposed to the external LaserScan. It is expected that the deformation response of external and internal surfaces to the applied force during denting process is different, such as local contact stress induced deformation, wall thinning, etc.. However, the difference is relatively small.

The above results appear to be very promising. It suggests that with the minimized error from field measurement and with no re-rounding and rebounding involved, the tool's "true performance" can be evaluated. The evaluated results can be served as a basis for assessing errors of ILI prediction from various sources.

It is important to note that the use of LaserScan technology could make it possible to not only minimize the field instrumentation error, but also reduce human errors on the measurement. With this technology, errors related to re-rounding and rebounding can be more precisely evaluated.

5.2.2. Performance Evaluation Using Laser Axial Bridge Reference Line

Evaluation of the depth performance was also conducted using the depth data obtained from an *Axial Bridge Reference Line*, which is similar to that used in-ditch field measurement. The results are shown in Figure 20.

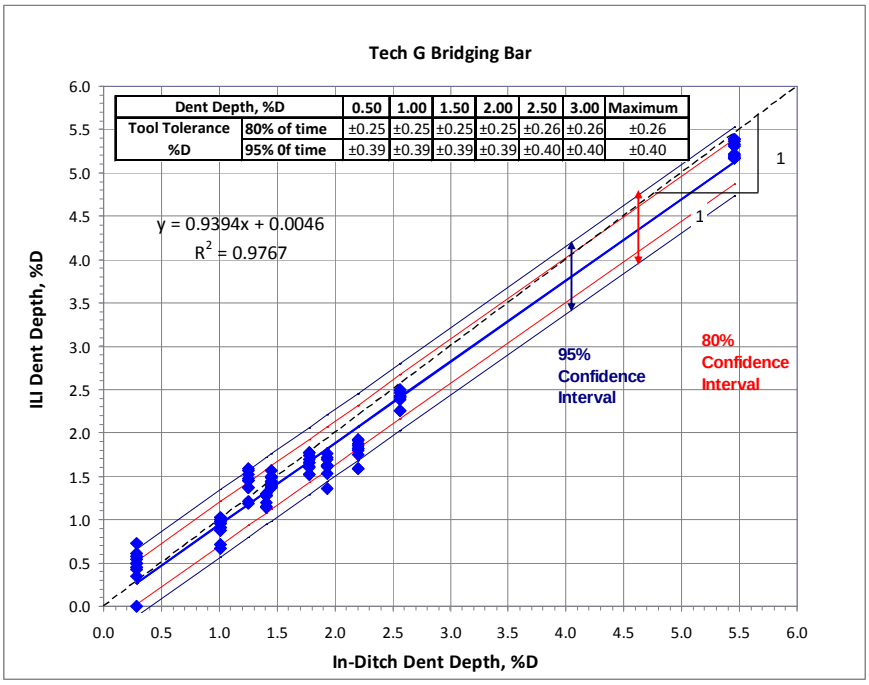


Figure 20: Dent depth validation of Technology G, DAMC (EM) using ILI prediction against LaserScan Axial Bridge Reference line measurement, 12 times repeating pull tests

By comparing Figure 20 with Figure 19, a slight increase in bias and confidence interval is seen. It should be noted, however, that the error of actual filed bridging bar measurement would be higher and vary significantly due to many other factors, including human factor. Since the profile one-on-one comparison provides the best correlation and can be automated, the one-on-one comparison is recommended for future use.

5.2.3. Comparison between Phase I and phase II data

It is noted that the Phase I data provided by the ILI vendor for Technology G were also from a pull test but on a different diameter pipe specimen. The validation method consists of manual micrometer measurements using an axial bridging bar. The Phase I results are overlaid on the unity graph in Figure 20. A large bias was observed as compared to the Phase II pull test data. More scatter was evident in the manual bridging bar data lending support to the earlier assertion

that in-ditch measurement error likely plays a significant role for all of the validation results using dig validation data.

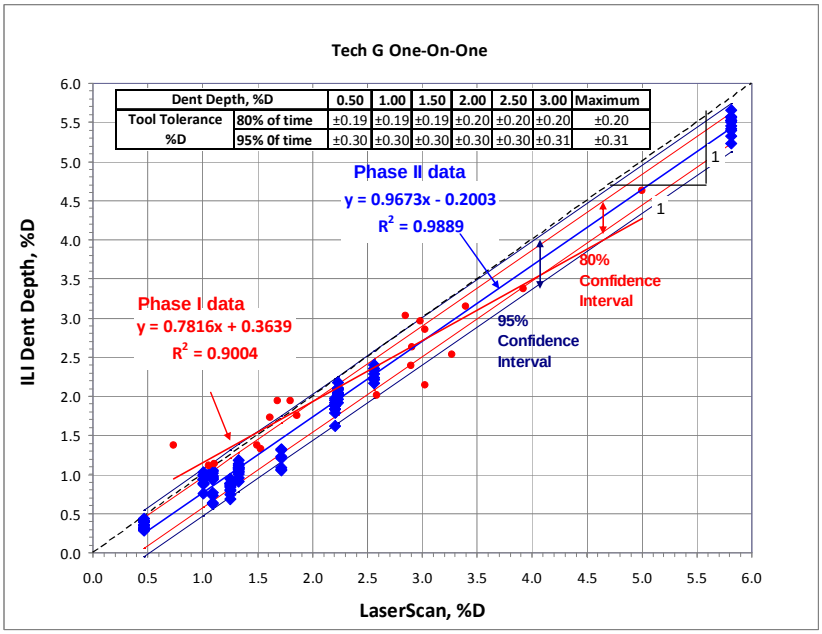


Figure 21: A comparison between Phase I and Phase II data, Technology G

6. Discussion

6.1. Summary of Phase I and Phase II Results

POD, POI and POFC for DML Characterization

The Phase II study of dent coincident with metal loss has increased the total sample size from 452 to 708. From the 708 samples, the overall tool performance for characterization of DML has been established to be POD = 83%, POI = 91% and POFC = 37.1% at 95% confidence level using the binomial distribution method and POD = 83.2%-89.8%, POI = 90.9%-96% and POFC = 36.9%-44.6% using the Clopper-Pearson confidence interval method. Table 10 summaries the results of Phase I and II studies.

Table 10: Performance evaluation for the current ILI based technologies for detecting, identifying dent with metal loss (DML)

Technologies for Dents and Dents with Metal Loss		Project Phase Data Source	Total Investigations	ILI reported DML (Exc. based on ILI Call)	Correct Calls (including type of DML)	True Calls (not including type of DML)	Number of Missed DML	Number of false calls	Dent with Metal Loss Performance																	
									POD						POFC						POI					
									Proportion	n	x	POD @ 95% Confidence Level			Proportion	n	x	POFC @ 95% Confidence Level			Proportion	n	x	POI @ 95% Confidence Level		
												Binomial, p, @ 95% Conf for given x,n	Confidence Interval					Binomial, p, @ 95% Conf for given x,n	Confidence Interval					Binomial, p, @ 95% Conf for given x,n	Confidence Interval	
													Lower	Upper					Lower	Upper					Lower	Upper
A+B	Caliper (EM) + MFL Combo	Phase I	138	82	27	27	18	55	60%	45	27	49.0%	46.7%	72.3%	67.1%	82	55	75.6%	57.6%	75.6%	100.0%	27	27	>89.9%	89.5%	100.0%
C	Caliper (EM) + MFL Combo	Phase I	34	26	25	25	0	1	100%	25	25	89.0%	88.7%	100.0%	3.8%	26	1	17.0%	0.2%	17.0%	100.0%	25	25	>88.71%	88.7%	100.0%
E	MFL (3 axis)	Phase II	26	4	4	4	3	0	57%	7	4	34.0%	22.5%	87.1%	0.0%	4	0	1.5%	0.0%	52.7%	100.0%	4	4	>47.3%	47.3%	100.0%
(H,I)+ (F,G)	Caliper (EM) + MFL	Phase I	26	23	20	16	3	3	87%	23	20	75.0%	69.6%	96.3%	13.0%	23	3	30.4%	3.7%	30.4%	80.0%	20	16	66.0%	59.9%	92.9%
J	Caliper + MFL Combo	Phase I	61	58	52	49	3	6	95%	55	52	89.0%	86.5%	98.5%	10.3%	58	6	19.4%	4.6%	19.4%	94.2%	52	49	88.4%	85.8%	98.4%
J	Caliper + MFL Combo	Phase II	135	135	54	54	0	82	100%	54	54	>94.6%	94.6%	100.0%	60.7%	135	82	67.8%	53.3%	67.8%	100.0%	54	54	>94.6%	94.6%	100.0%
J	Caliper + MFL Combo	Combined	196	193	106	103	3	88	97%	109	106	94.0%	93.0%	99.2%	45.6%	193	88	51.8%	39.5%	51.8%	97.2%	106	103	94.0%	92.8%	99.2%
K+L Phase I	Caliper + MFL (Circ Magnet)	Phase I (Operator L2)	63	56	26	22	7	30	79%	33	26	67.0%	63.8%	89.6%	53.6%	56	30	65.1%	41.8%	65.1%	84.6%	26	22	72.7%	68.2%	94.6%
K+N	Caliper + MFL	Phase I (OperatorG1)	27	8	6	6	3	2	67%	9	6	45.0%	34.5%	90.2%	25.0%	8	2	60.0%	4.6%	60.0%	100.0%	6	6	>65.1%	60.7%	100.0%
K+N	Caliper + MFL	Phase I (OperatorG2)	114	37	31	30	5	6	86%	36	31	76.0%	73.0%	94.4%	16.2%	37	6	29.5%	7.3%	29.5%	96.8%	31	30	90.8%	85.6%	99.8%
K+N	Caliper + MFL	Phase II	94	81	33	33	0	3	100%	33	33	>91.3%	91.3%	100.0%	3.7%	81	3	2.4%	1.0%	9.3%	100.0%	33	33	>91.3%	91.3%	100.0%
K+N	Caliper + MFL	Combined	235	81	70	69	8	11	90%	78	70	83.9%	82.3%	94.8%	13.6%	81	11	19.4%	7.8%	21.5%	98.6%	70	69	96.0%	93.4%	99.9%
All	Current ILI (MFL based) MD Technologies	Combined	708	462	278	258	42	188	87%	320	278	83.5%	83.4%	89.9%	40.7%	462	188	37.1%	36.9%	44.6%	92.8%	278	258	91.2%	89.7%	95.2%

In the absence of prescriptive jurisdictional repair requirements, the EPRG criterion is applied assuming all metal loss is gouge and metal loss depth data are available from ILI data. If corrosion vs gouge discrimination is available, corrosion is evaluated separately using B31G or RSTRENG. The current MFL technologies evaluated in this research demonstrated capabilities to detect and discriminate metal loss within otherwise smooth dents.

For any integrity assessment, the ideal technology would exhibit a high probability of detection (POD) with a low probability of false call (POFC) and high probability of identification (POI) to insure the all dent with metal loss conditions could be detected with unnecessary excavations minimized. The combined performance for current MFL based mechanical damage

technologies resulted in a probability of detection for DML of 83% with a probability for false call of 37.1% with a probability of identification of 91%. Individual technologies exhibited higher POD of 94%, but with POFC increasing to 68%. Comparison of the final results with the preliminary performance measures from the Phase I research indicated sensitivity to size of the evaluation populations and the SME evaluation applied to the assessments. The Phase I operators' data was of a vintage when current mechanical damage SME evaluation was unlikely while for the Phase II data the potential for SME analysis required for current mechanical damage technologies was more likely but not validated.

Validation of Sizing Performance of the Current MD ILI Technologies

During Phase I study, significant data scatters and bias were observed for the validation populations obtained from the operators. Progress was made in reducing the data scatters during Phase II study due to the better quality and information of the data gathered from the operators, which allowed filtering the top-side and bottom-side dents from the total populations. For the bottom-side dents, attempts have been made to apply corrections. The improved validation data are presented in the Figures in Section 5.1.2. The table below is a summary of Phase I and II depth validation data from the pipeline operators.

Table 11: Depth validation data and depth sizing performance obtained from Phase I and II study

Technologies for Dents		Data Source	# of Dent Features Evaluated	Mid range size Caliper		Validation of Depth Tolerance	
				LOD, %D @90% POD	Depth Tolerance, +/-%D @80-96% Confidence Level	Binomial Distribution Method	Clopper-Pearson Confidence Interval Method
Ao	DAMC(EM)	Phase I	28	0.5	±1.00	±1.60	±1.60
Co	Caliper (EM)+MFL Combo	Phase I	58	0.5	±0.10	±4.48	±4.65
Jo	Caliper + MFL Combo	Phase I	17	1	±0.50	±1.63	1.63
J	Caliper + MFL Combo	Phase II	All 135 Dents	1.00	±0.50	±1.07	±1.08
J	Caliper + MFL Combo	Phase II	Top Side 25 Dents	1.00	±0.50	±1.00	±1.20
J	Caliper + MFL Combo	Phase II	Bottom Side 110 Dents, Uncorrected	2.00	±0.50	±1.10	±1.10
J	Caliper + MFL Combo	Phase II	Bottom Side 110 Dents, Corrected*	2.00	±0.50	±1.32	±1.32
E	MFL (3 axis)	Phase II	All 26 Dents	0.50	±1.00	±2.40	±2.88
E	MFL (3 axis)	Phase II	Top Side 6 Insufficient #	0.50	±1.00	NA	NA
E	MFL (3 axis)	Phase II	Bottom Side, 20, Uncorrected	0.50	±1.00	±2.88	±3.00
E	MFL (3 axis)	Phase II	Bottom Side, 20, Corrected*	0.50	±1.00	±0.95	±1.00
K,N, MFL	Caliper + MFL	Phase II	All 95 Dents	0.60	±0.80	±5.30	±5.34
K,N, MFL	Caliper + MFL	Phase II	Top Side 1 Insufficient #	0.60	±0.80	NA	NA
K,N, MFL	Caliper + MFL	Phase II	Bottom Side , 94, Uncorrected	0.60	±0.80	±5.34	±5.34
K,N, MFL	Caliper + MFL	Phase II	Bottom Side, 94, Corrected*	0.60	±0.8	±1.51	±1.52

Numerous references are made in literature to an industry standard reporting threshold of 2%D for dents by caliper inspection [4] [8]. Current caliper technologies claimed, within this research, limits of detection and reporting as low as 0.5%D, however, multiple vendors did report their standard reporting limits for dent depth were 2.0%D unless otherwise specified by the customer. The validation data did substantiate capability to detect and report shallow dents of 0.5%D for the current caliper based technologies.

One MFL based dent depth technology (Tech E) evaluated in this research claimed a dent depth limit of detection of 0.5%D and depth sizing capability with validation data provided (see Figure 9) supporting the claim. The DOT/PHMSA regulations for integrity management of pipelines affecting High Consequence Areas consider the limited application of MFL technology for mechanical damage. The liquid integrity management rule [9] recognizes the ability of MFL technology to detect the presence of dents in FAQ 6.17, advising the use of an MFL tool without concurrent deformation tool would be acceptable if the ILI vendor is specifically directed to identify all potential dent signals and all such potential dents are excavated and examined. ANSI B31.8S, section 6.2 is incorporated by reference in the gas pipeline integrity rule [10] governing ILI tool selection depending on the threats identified for the pipeline segment. This Code cites limited success identifying third party damage using MFL ILI tools but not useful for sizing

deformations. These regulations do not differentiate MFL technologies, as in this research, where one specific type of MFL technology demonstrated with validated capability for depth sizing. Another MFL technology (Tech K) reported capability in the literature for discriminating dent severity based on a strain based criterion and will be discussed later in the assessment model.

The validated dent depth performance for current caliper based ILI technology categories varied from +/- 0.9%D to +/- 1.2%D. The nature of dent feature populations implies that a caliper dent reporting threshold of 2%D may detect only one-quarter of the dents in a pipeline detected by MFL signals [4]. The application of a 2%OD caliper reporting threshold without consideration of dent depth performance implies that dents greater than 2%D might not be reported therefore justifying a caliper dent depth reporting threshold of 0.5%D to 1.0%D.

High resolution MFL has evolved and is capable of reporting metal loss below 10%wt; however it should be recognized that reporting thresholds and data filters are routinely employed for MFL in-line inspections. The application of a 10%wt metal loss reporting threshold in conjunction with a 2%D reporting threshold for dents could fail to detect integrity conditions in pipelines where mechanical damage threat has been validated. The adjustment of caliper reporting thresholds respecting dent depth performance in combination with an appropriate metal loss reporting limit would provide for an understanding of the risk of missing critical dents with metal loss conditions. This research showed that validated dent depth performance is affected by the size of the evaluation population and errors associated with the in-ditch measurements.

The metal loss depth sizing performance for the MFL technologies validation, in general, supported a capability for discriminating metal loss within dents equivalent to that expected for high resolution MFL technology in un-dented pipe (+/-10%wt with 80% certainty). The vendors reported case study metal loss sizing validation data for three MFL + Caliper based technologies. The amount of operator source validation data from Phase II indicated that while some MFL + Caliper technologies can size coincident metal loss, the pipeline operators may not be widely applying this capability or the in-ditch protocols may not provide for measurement and reporting. Raw feature list data was not provided by either the ILI vendors or the pipeline operators therefore a good understanding of the current implementation of coincident metal loss sizing was not possible within this research. There are established differences in the magnetic behavior of gouges and corrosion metal loss features and sizing performance could be affected.

While some in-ditch inspection protocol provided for discrimination of gouge versus corrosion the data set was not large enough to evaluate sizing performance for these two types of metal loss.

The Phase I research was able to record only 43 of 301 dents with both dig and ILI dent length measurements. The Phase II research increased the number of length validation features to 70 for performance evaluation, of which two technologies were represented (Tech E and Tech K). Tech K was a direct measuring arm caliper (DAMC) while Technology E was a MFL based technology. The dent length performance for these two technologies is shown in Figures 11 and 4 in Section 5.1.2. There is no established protocol for defining the periphery of dents measured directly compared with the detection limits for in-line tools.

Dent width validations are more difficult to determine than axial length measurements due to difficulties in development of an appropriate circular reference form for un-deformed pipe. The Phase II research increased the number of plain dent features with width validation measurements. The dent width validation for Technology K (DMAC Caliper) and Technology E (MFL) are shown in Figure 12 and Figure 15, Section 5.1.2.

However, the data provided by pipeline operators were characterized by small numbers of validations where dent lengths and widths were both reported by ILI and recorded by in-ditch validation and likely affected the performance measures obtained in this research.

6.2. Pull Test and Laser Profilometry Validation

The pull tests of Technology G conducted in this research have demonstrated that, by minimizing validation measurement error using laser profilometry, the standard error for differences between ILI predictions and laser validations was ±0.15 %OD and therefore ±0.31% at 95% confidence level which is close to the claimed depth sizing capability for the technology tested (+/- 0.5%OD). Since the laboratory pull test conditions eliminate any error from pipe re-rounding/rebounding, the errors in validation as shown in the unity plot provided in Figure 19 should be limited to the ILI tool and/or the laser profile based measurements. More recently, calibration of LaserScan technology has shown that the errors resulted from leaser profilometry measurement is in order of magnitude of several thousands of an inch. Thus the use of this technology will greatly increase the accuracy and reliability of field measurements, and as a

result, not only the effect of re-rounding/re-bounding on the measurement error can be better quantified but also the correlation established between ILI and on-depth measurement can be more reliably applied for integrity assessment.

Within the Phase II research, the following gaps were identified between ILI predictions and field validations:

- Lack of a consistent protocol for in-ditch measurement, which has produced wide scatters in data and inconsistent results of evaluating ILI mechanical damage performance
- A simple straight bridging bar for the dent depth and length measurement could bring significant human errors due to the difficulties in selecting appropriate reference points

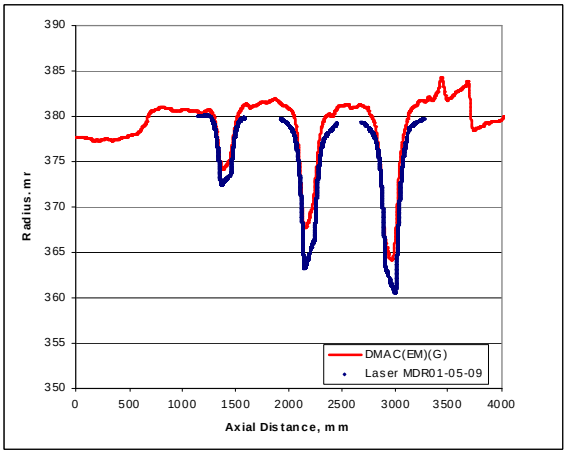
Accordingly, efforts should be made to fill the gaps in the future:

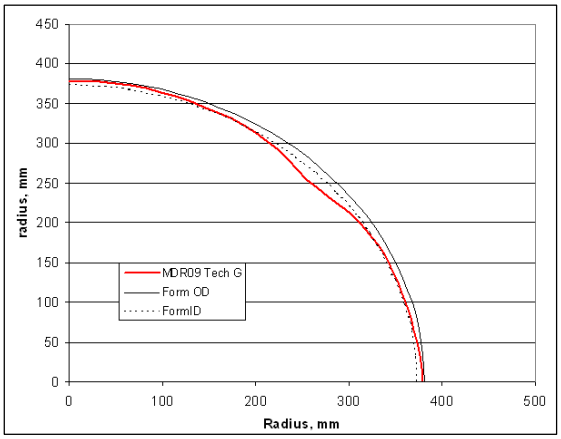
- Develop a well defined and comprehensive in-ditch assessment protocol
- Develop a new in-ditch measurement tool that allows for orders higher in measurement accuracy and is capable of comparing the den profile with ILI prediction on a one-on-one basis.

Plain dents with depths greater than 2%D but less than 6%D do not require investigation or repair under most pipeline integrity regulations or standards. However, recent improvements in strain predictions from profile data have highlighted the conditions where shallow plain dents can exhibit significant plastic strain, most notably in the case of small diameter punching type indenters. The Phase I research cited work done by Gao et al. and Dawson et al. in accurately estimating strain from ILI data [11], [12]. The Phase I and Phase II research demonstrated that profile data suitable for strain assessment is routinely available from the current caliper based ILI technologies. This research also noted that in-ditch strain assessment from direct measurement profile data was also routinely applied by pipeline operators [13]. However, this research did not find validation data where both ILI based and in-ditch based measurements were taken, which enables validation of strain predictions. The laboratory pull test for one caliper technology (Tech G) provided an opportunity to compare ILI profiles and strain predictions with external profiles from laser profilometry and resulting strain predictions. There was good agreement between the shapes obtained from the ILI technology with laser profiles.

Predictions of strain from ILI data, in order to prioritize and schedule excavation response, have been proposed as part of the proposed mechanical damage assessment model. Maximum

equivalent stain was calculated for the three dent features shown in Figure 22 and compared with strains calculated from direct examination laser data as shown in Table 12. The results demonstrate, for the single technology tested, that accurate strain results from ILI data are possible.





(a) Axial dent profiles **(b) Circumferential dent profiles**

Figure 22: Comparison of ILI and Laser profiles for three dents from Technology G pull tests

Table 12: Comparison of strains predicted from ILI data and by laser profilometry validation measurement

	ILI Data Predictions		Laser Validation	
Dent ID	Depth, % OD	Max ε_{eqv}	Depth, % OD	Max ε_{eqv}
MDR 09	2.10	5.1%	2.6%	5.7%
MDR 05	1.50	5.0%	2.2%	5.7%
MDR 01	0.78	3.1%	0.1.0%	3.1%

7. Conclusions

This research concluded that current, deployed, ILI technologies for detection and discrimination of mechanical damage rely on application of caliper and magnetic flux leakage (MFL) technologies combined with subject matter expert interpretation of the integrated data streams. These technologies were characterized by differences in technical attributes such as sensor types, locations inside and outside of primary magnetizers and combination of data streams from separate or integrated tools. The ILI vendors reported some application of ultrasonic sensor technologies but the extent of trials has not yielded enough data for validation of capabilities at this time.

During Phase II research, a total of 256 mechanical damage features were obtained from four operators using three technologies. The three technologies are Technologies J (Caliper + MFL Combo), Technology E (Tri-axial MFL), and Technology K,N +MFL. Evaluations were performed on the depth, length and width sizing even though limited length and width data are available only for Technology E and Technology K,N+MFL. For dent with metal loss (DML), three features were reported by Technology K,N+MFL and field-validated. Because of small sample size, DML analysis was combined with the Phase I data.

Validation data obtained in this research documented the capability for detection and discrimination of dents and dents with metal loss. Greater than 80% certainty of detecting and 90% certainty of identifying dents with metal loss for combined MFL and caliper technology was claimed by combined MFL plus caliper technologies. The validation data evaluated thus far in thin research indicates that such a claim may be reasonable for these technologies, however, the size of validation data sets may have significant impact on results and this effect will be further studied after the conclusion of this research. Some vendors claimed the capability to discriminate corrosion and gouges but there was insufficient validation data to validate those claims. One MFL plus caliper technology claimed a probability of identification for gouges between 50% and 90%. Some capability for detection and discrimination of cracks was also claimed. However those vendors pointed out these capabilities are subject to limitations and are offered on a “best effort” basis. Case study examples for gouge and crack discrimination were provided by the ILI vendors to illustrate this capability but not enough data was available (ILI predictions with associated validation data) to quantify performance. Minimum sample sizes between 25 and 29 are required depending upon the desired level of certainty and

improvements or standardization of in-ditch protocols are needed to provide for reliable validation discrimination records for gouge and/or cracks.

The probability for false calls, or calling a dent with metal loss from ILI data and finding no metal loss or minor surface mill or construction features is becoming an important issue for pipeline operators in terms of un-necessary excavations and cost. The participating ILI vendors stressed the importance of largely manual subject matter expert data interpretation in discriminating metal loss within dents as a significant factor affecting probability of identification and probability of false calls. Appropriate application of metal loss feature filtering and/or size reporting thresholds should be considered in conjunction with mechanical damage risk and threat assessment. Metal loss depth measurement protocol and characterization criterion for in-ditch validations was found to be limited. A consistent in-ditch protocol could improve the performance measures (POD,POFC,POI) in order to determine if there are significant differences between the current technologies and to benchmark improvements of future technologies.

For plain dents, four technology categories were identified. Validation from vendors' data from Phase I research showed that Metal Arm Caliper based technology augmented with electromagnetic sensors (eddy current or hall sensors) at the contact arm tip exhibited a depth sizing performance of +/- 0.90%OD while the indirect or non-contact eddy current technology exhibited dent depth performance of +/- 3.0%OD (80% certainty with 95% confidence level). By comparison, Phase II research from operators' data showed Metal Arm Caliper technologies, on a combined basis, exhibited +/- 1.1%OD for Tech J (Caliper+MFL combo) and +/-1.53%OD for Tech K,N+MFL with depth correction for bottom-side dent (Caliper+MFL). A MFL multi axis technology demonstrated capability to provide dent depth with a performance of +/- 0.95%OD after depth correction for bottom side dents

The depth sizing performance for metal loss within dents was found to be essentially consistent with body of pipe metal loss, about 10%wt, but, as the vendors point out, the "ride" of sensors over complex shape or severe deformations can adversely affect detection and sizing performance. Reporting thresholds are expected to be identified by the pipeline operators and this research suggests that caliper and MFL reporting thresholds should be jointly considered based on the assessment criterion expected to be employed and the expected level of mechanical damage threat.

The validation for these technologies was subject to the potential errors (ILI tool, in-ditch and pressure re-rounding errors) but a laboratory pull test indicated the critical comparison between these technology classifications may be valid.

All of the current technologies for caliper based dent inspection have capabilities for reporting axial and circumferential profile data. Reporting of profiles is finding increasing use in strain based assessment of plain dents but is generally not offered as standard reporting. This research demonstrates, for the one technology tested, that accurate strain results from ILI data are possible. An alternate strain assessment model has been proposed [5, 19] based on dent length, width and depth predictions. The validated dent length and width performance was limited due to small validation data sets. The length and width tolerances that could be accepted were in excess of +/- 10 inch and with that level of performance the implementation of this alternative assessment model may also have limited value. An understanding of sizing rules employed by the vendors for dent length and width as part of the in-ditch protocol would likely result in improved performance validation.

The performance of in-ditch dent profile protocol was not part of this research; study of these errors could be a subject of future research to more fully understand the capability of current technology to size dents and assess severity considering ILI tool errors. A more complete understanding of performance for current mechanical damage technologies could benefit from understanding of in-ditch measurement errors (profiles and coincident damage characterization). It is clear that increased numbers of validation data points provides for higher confidence for performance measures. The PRCI has a developmental road map for future research addressing these issues. Laser validation showed promise in helping to minimize in-ditch validation measurement errors leaving only corrections for re-rounding required to determine in-line tool performance.

The validation of full profile capability (length, width and shape) was limited to the single technology pull tested. The measurement of in-ditch profiles, in order to calculate strain, was found to be a routine activity. However the retention of profile data was not found to be a standard practice. ILI profile data, while available on request, was found to not be routinely reported. Therefore, no rigorous validation of profile capabilities and critical comparisons was possible within this research.

The current mechanical damage technologies have limited capability for detecting cracks. Case study data was provided and the vendors claim capability for detecting cracks largely dependent on crack orientation, size and sensor ride for both MFL and ultrasonic technologies. Future research providing sufficiently large validation data sets particularly for MFL residual field sensors, multi axis MFL sensors, combined circumferential MFL data streams or ultrasonic technology together with a recording protocol for all required attributes as described in this report would allow for determination of performance and critical comparison for these technologies.

The detection of metallurgical changes such as re-rounded dents continues to be a challenge for the current mechanical damage technologies with no capability claimed to both detect and discriminate severity. MFL technologies were shown to be capable for detecting magnetic anomalies but low level dents (< 6%D) upon re-rounding and pressure cycling can form cracks that escape detection by MFL technologies unless multiple technologies with conditional capability for crack detection are employed. Future research focusing on reported magnetic anomaly signatures and application of in-ditch techniques capable of discriminating metallurgical changes such as strain hardening, harness and micro-cracks could benefit the understanding of capabilities for both current and developmental technologies.

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