APPLICATION OF ADVANCED DATA ANALYTICS TO IMPROVE METAL LOSS TOLERANCE SPECIFICATIONS

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Introduction:

In-line inspection (ILI) has been a key tool in the assurance of pipeline integrity for decades and has been continually evolving over that time. Increases in sensor density and performance seen, for example, in the Baker Hughes MagneScan™ SHR+ and VECTRA HD tools (see Figure 1, Figure 2) have allowed ILI tools to gather ever more data; however, the primary inspection technology is based on magnetic flux leakage (MFL) and this remains an indirect measurement technique. As such, analysis of data from these tools requires truth data to develop sizing models of metal loss to enable assessment of pipeline integrity.

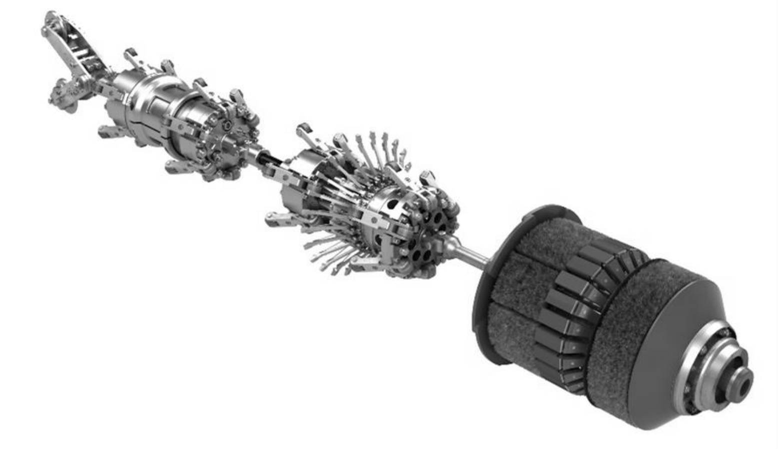

Figure 1: Baker Hughes Magnescan SHR+ ILI tool

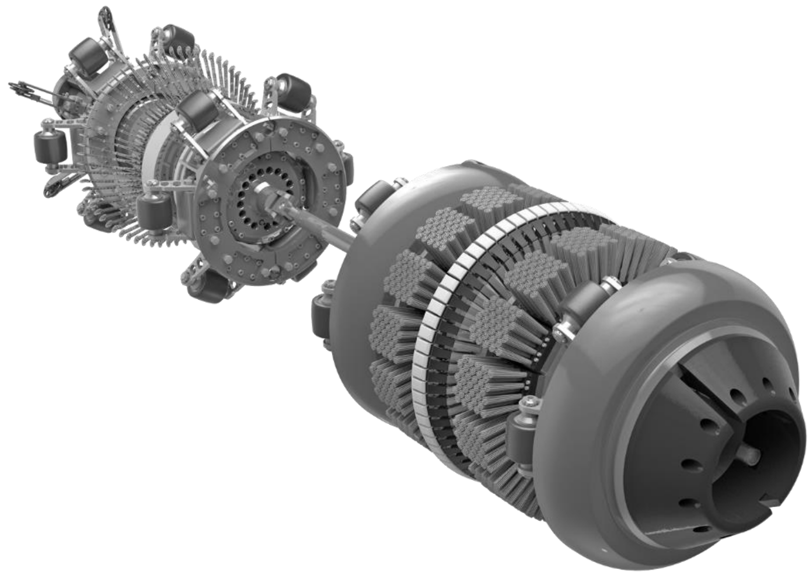

Figure 2: Baker Hughes VECTRA HD ILI tool

In parallel to the developments in ILI tools, there have been advancements in the volume and accuracy of dig verification "truth data" gathered by pipeline operators. A single dig using high resolution laser scanning tools can generate hundreds of thousands of high accuracy depth measurements of corrosion features. This has resulted in an exponential increase in the amount of truth data available to ILI tool operators.

Finally, in the pursuit of ever more effective integrity management plans, operators and integrity service providers have developed analyses which consider not only the reported depth and severity of the feature under assessment but also the tolerances of the sizing model used to process the ILI data.

Hence, the opportunity arises to utilise this expanding set of in-field truth data to develop improved models of defect sizing tolerance. This approach can provide meaningful benefits to pipeline operators' integrity management programs.

Background:

This paper describes the process undertaken by Baker Hughes to utilise its library of truth data to improve the sizing models and tolerances for defects identified with VECTRA GEMINI and MagneScan MFL inspection tools.

Previously, metal loss sizing models were developed using calibration joints of various wall thicknesses with machined defects (see Figure 3). These spools were pull tested multiple times at various speeds to generate sizing models and estimates of the variability of those measures. These models were typically based on hundreds of measurement points and provided reliable performance within the defined confidence levels. The shortcomings of these models were that they were based on small sample sets of idealised features (both in morphology and lack of interaction) and, as such, wider tolerances were necessary to reliably represent model performance when exposed to real world defects.

Figure 3: A variety of smaller diameter calibration spools

The tolerances for the sizing models developed in this way were formulated using a categorisation developed by the Pipeline Operators Forum (POF) which grouped all defects into seven categories based on length and width (see Figure 4). Whilst the geometric interpretation of these seven categories makes logical sense when considering the fundamental physics governing axial MFL performance, the boundaries of these categories are, necessarily, arbitrary. The POF categorisation allows for a maximum of seven tolerances to cover all features and only discriminates based on length and width. This creates a non-smooth function where small changes in the length or width of a feature can result in significant changes to the reported tolerances. This behaviour is inconsistent with a mechanistic assessment of the situation.

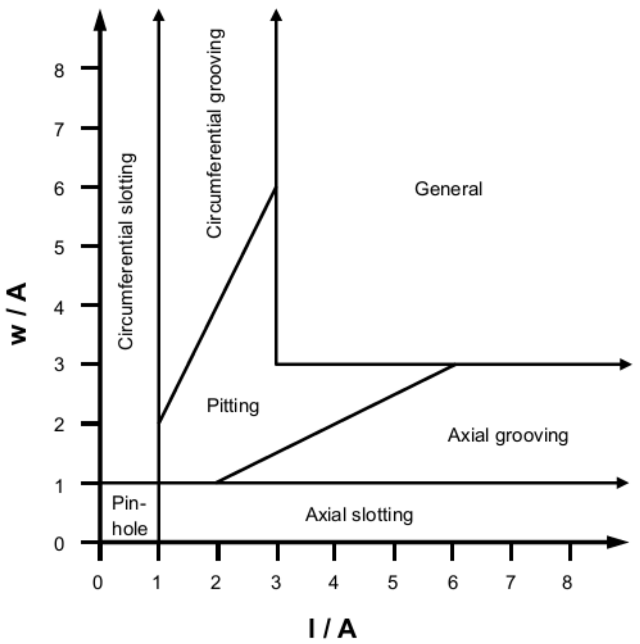

Figure 4: POF categorisation of features

In the approach reported in this paper, sizing models are still developed using machined defects in calibration spools. However, this simulated data is augmented with potentially tens of thousands of additional data points captured from real-world, in-ditch measurement of actual corrosion features. Machine learning techniques are used to develop both sizing models and defect-specific tolerances. These tolerances are not constrained by being expressed only based on length and width, nor by any arbitrary categorisation. Rather, the tolerance model is evolved using a decision model to provide a model without the constraints of categories by using a sufficient but not excessive number of critical parameters; the limitation on parameters being necessary to prevent the overfitting of the model. The result of this approach is to allow Baker Hughes to provide a specific sizing tolerance for each defect. These defect-specific tolerances are more considerate of real-world defect morphologies and in many cases tighter than could be promised under the POF formulation.

Influences on feature sizing:

Baker Hughes screened 57 potential parameters for inclusion in the tolerance model. These parameters broadly fell into four categories:

- Predicted Anomaly Measurements: the output of the sizing model (length, width, depth).
- Raw Signal Characteristics: triaxial sensor data and other associated data.
- Fitting Interactions: proximity to and interaction with fittings reported in the pipeline.
- Defect Interactions: proximity to and interaction with other defects reported in the pipeline.

From these 57 parameters a sub-set of key parameters was selected to achieve an optimal trade-off between model sensitivity and overfitting potential. It is of interest to note that length and width were not the strongest predictors in this set.

Proof of concept:

A key client approached Baker Hughes to produce refined tolerance models to improve the prioritisation of the digs on two critical lines containing 40,000 features. Baker Hughes started by developing individual models for the two pipelines with a further six pipelines being added in due course.

Modelling was performed on each line individually with the results evaluated firstly by the proportion of tolerance which were found to be tighter than the standard POF tolerances and secondly, by the impact of the revised tolerances on the integrity programme of Baker Hughes' customer.

Over the eight lines on which modelling was performed, the defect-specific tolerances were tighter than the relevant POF tolerance in 89% of cases.

The practical impact of this work for the client's dig program was measured against three criteria. Firstly, the number of digs in the next ten years, the number of digs prior to the next scheduled inspection and the impact on the risk-indicated reinspection year. As seen in Figure 5, the tighter tolerances removed nearly 600 risk-indicated digs from the 10-year dig program and 23 prior to the next scheduled inspection. On 3 of the pipelines the impact was such that the risk-indicated reinspection period could be extended.

	10-year growth period	Prior to re-inspection year	Re-inspection year
NPS	Reduction of digs	Reduction of digs	Increase in re-inspection year
8	12	4	1
12	-3	-1	0
20	294	14	0
24	43	6	3
30	90	2	0
30	117	-2	1
30	40	0	0
42	0	0	0
Total	**593**	**23**	**–**

Figure 5: Impact on the integrity program

This performance is broken out in more detail in Figure 6 and Figure 7 where it is observed that, on the majority of pitting and general corrosion defects and the vast majority of pinhole defects, the Baker Hughes sizing algorithms outperform the stated POF specification and still but to a lesser extent the defect-specific tolerances. Firstly, this demonstrates the accuracy of the Baker Hughes sizing model. Secondly, these graphs show the potential reduction in conservatism that can be achieved using the defect-specific models Baker Hughes has developed. It can be seen in Figure 6 that, in a small percentage of cases, the tolerance for an individual pitting or general corrosion feature was wider than the POF tolerance. The same effect is seen in Figure 7 for pinhole features but to a lesser extent. This was not considered a negative outcome as the overall goal of any pipeline inspection is to direct integrity management effort to those areas which pose the greatest risk, either because of the absolute magnitude of the defect or because of a lower ability of the tool to accurately characterise it.

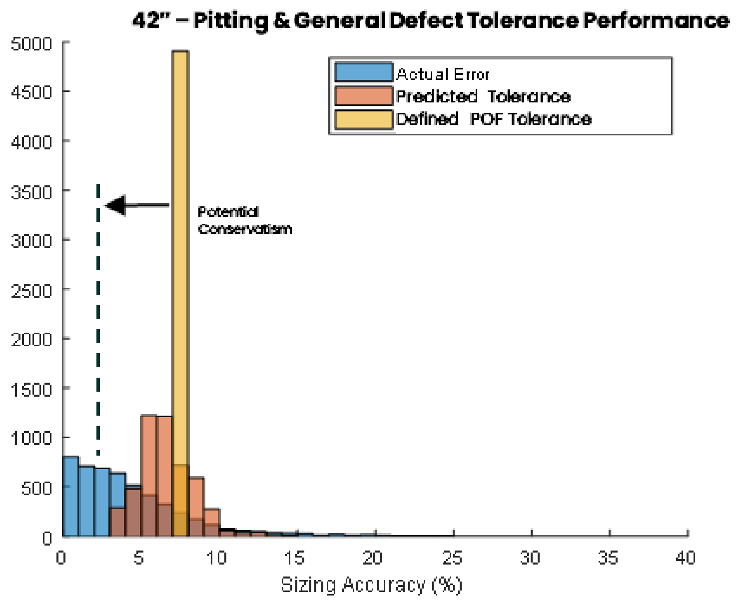

Figure 6: 42" Line-specific model performance for pitting and general corrosion

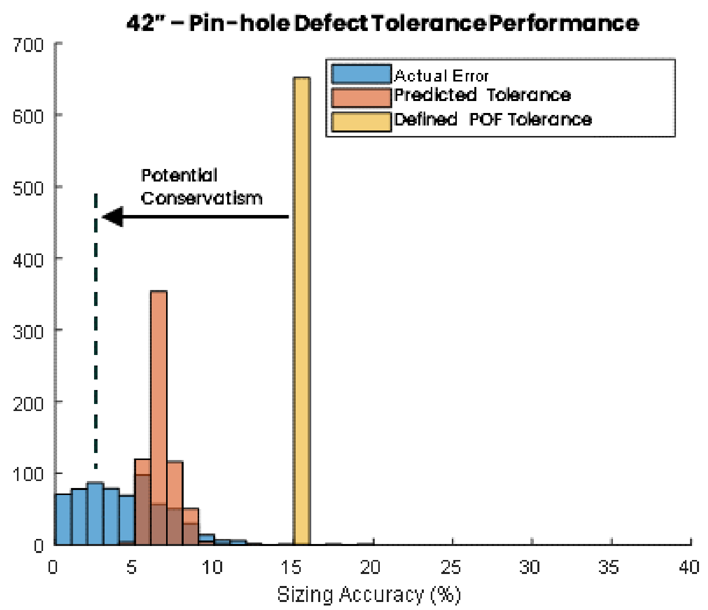

Figure 7: 42" Line-specific model performance for pinholes

In the second, practical, assessment of the impact of revised tolerances a positive effect on the effectiveness of the client integrity program was observed. Firstly, in no instance did the application of these tolerances remove from consideration a known critical defect. However, the tightened tolerances allowed our client to reduce the number of digs required before the next inspection by 62% and to extend the risk-based inspection window on three of the eight pipelines.

Extension to a general model

With the success of the line-specific modelling described above, the next step was to attempt to produce a single unified tolerance model for general application. A generalised model can be applied to all lines without requiring line-specific training data. If such a model were feasible i.e., retained sufficient accuracy over the entire input space, then it would allow more cost-effective application of improved tolerances than the line-specific model.

Initial analysis of the eight line-specific models indicated a high level of consistency in the parameter weightings which was cause for some optimism for the generalised model. To create the general model the model structure identified previously was reoptimized on a set of laser-scan data selected from the Baker Hughes Dig Verification database. This data set covered all pipe diameters and a range of depths per Figure 8. This data included data gathered by both the VECTRA and MagneScan tools, sized using all levels of sizing accuracy offered by Baker Hughes.

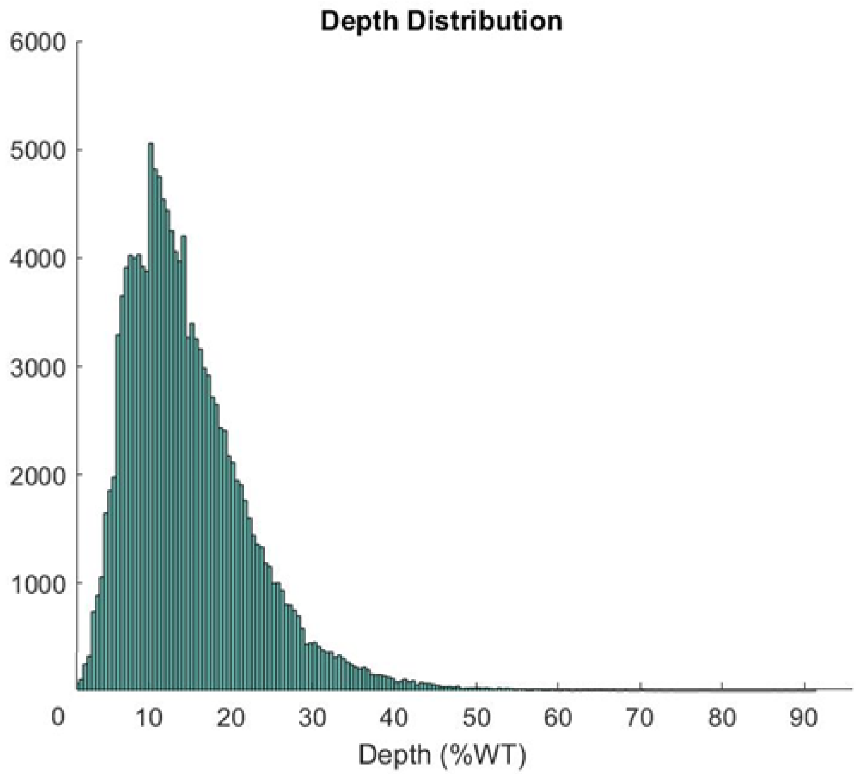

Figure 8: Depth distribution of generalised model training data set

In developing more conservative tolerances, one key performance criterion was to maintain or reduce the risk of understating the potential sizing error for a given defect. Figure shows a comparison between the actual sizing error on the y-axis and the stated tolerance on the x-axis. Tolerances calculated by the defect-specific model are shown in green and tolerances derived from the POF model are shown in red. Any defect falling within the 45-degree unity lines has an error that falls within the tolerance bounds. Defects above the upper unity line are out of specification but shallower than the lower tolerance bound would predict. The critical area of safety outliers, those where the upper tolerance is exceeded by the actual error, is below the lower unity line. In this area, the defect is deeper than would have been predicted by adding the upper tolerance to the measured depth. For both the revised and original POF specifications, there are defects in this area. However, analysis of the population of defects outside the unity lines shows that the defect-specific model reduces the proportion of defects in these areas compared to the POF tolerances.

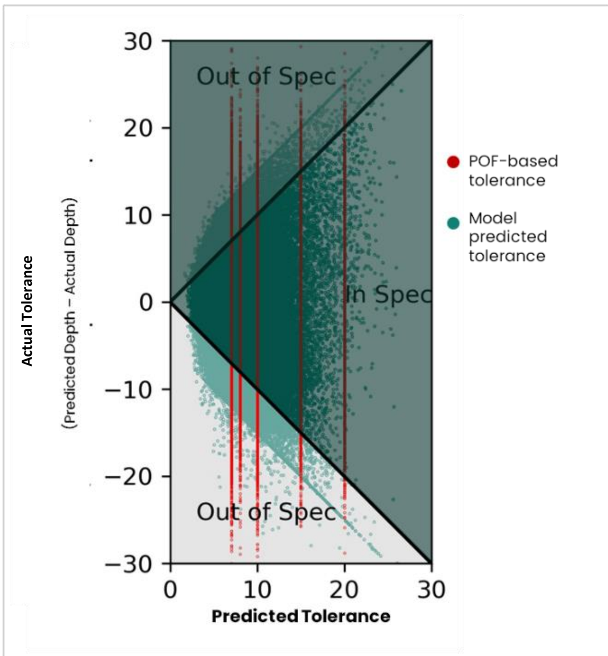

Figure 9: Tolerance unity plot for the generalised model

The relative conservatism of the generalised model tolerances in comparison to the POF tolerances can be seen in Figure 9. Over all categories, the generalised tolerance model had tighter tolerances than POF for 84% of features. The improvement was particularly pronounced on pinholes (>95% showed improvement) and slots/grooves.

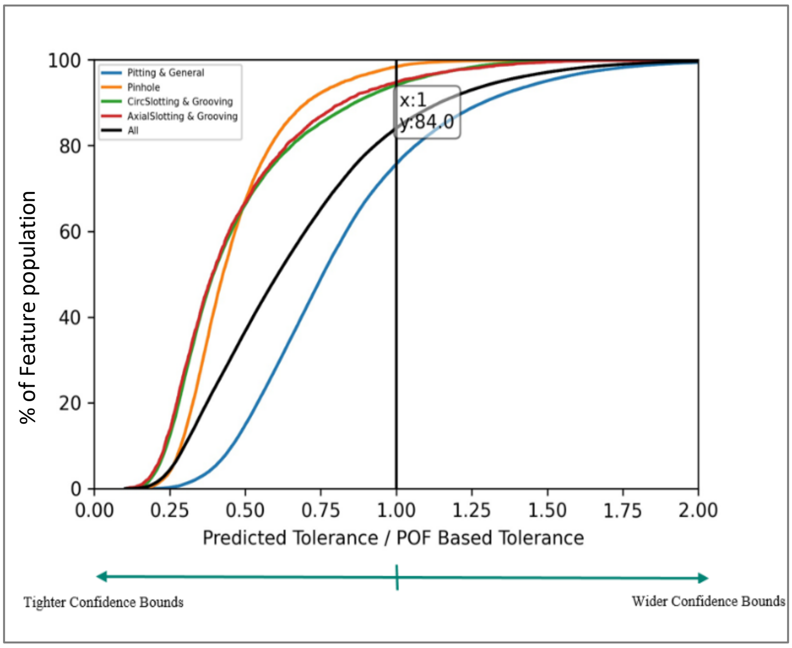

Figure 9: Relative change in tolerance vs. POF

Conclusions:

POF tolerances based on length and width categories made sense in an era where accurate truth data were not readily available. Advances in dig technology, data storage and analytics and integrity management programs have led to both the ability to refine these models and an environment in which such refinements have a material impact on the effective management of the safety of pipelines.

The initial, defect-specific tolerance models gave good results against the POF tolerances on the individual lines they were developed on, and this performance fed through to similarly positive results when the practical implications were evaluated on a tolerance-based pipeline integrity management plan.

Baker Hughes was then able to develop a generalised tolerance model which retained the strong performance against POF tolerances but had broad applicability, without further training, to corrosion defects in all Baker Hughes tool diameters. Overall, 84% of tolerances were improved upon with results particularly favourable in the pinhole and slotting/grooving categories.

It is Baker Hughes' belief that defect-specific tolerances offer pipeline operators a more accurate view on the risks in their lines and, for those conducting integrity management programs which account for defect tolerances, a more effective risk-based method to target spending.