EPRG-PRCI-APGA
23rd Joint Technical Meeting
Edinburgh, Scotland

6–10 June 2022

EDUCATED GUESSING VERSUS "DEEP FIELD ANALYSIS" - BREAKING MAGNETIC FLUX LEAKAGE BOUNDARIES

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ABSTRACT

Magnetic Flux Leakage (MFL) data have proven to be of high quality and coverage even under difficult or rough In-Line Inspection (ILI) measurement conditions. The high experience level of ILI vendors allows the pipeline industry to accept the heuristic MFL data evaluation principle. Neural networks and artificial intelligence further improve the result probabilities. However, the nature of "educated guessing" remains – even the best assumption is not a definite calculation.

This paper reflects on the methodical-inherent MFL principle of ambiguity and established simplification. This conventional process allows for high performance, but affects result repeatability and the value of run comparison. Moreover, it does not prevent outliers as worst remaining defects. This paper demonstrates substantial alternatives with disruptive new perspectives specifically for complex external corrosion. This novel MFL approach, called "Deep Field Analysis," requires greater calculation efforts, but constitutes a fundamentally new paradigm in MFL technology.

Recently, the industry prepared the ground for more advanced MFL data analysis by improving MFL result data formats. This paper discusses the outlook and potential of new technological analysis developments for these requirements: laser-like metal loss profiles are achievable with MFL-ILI.

DISCLAIMER

1. INTRODUCTION

Reliable and accurate safe pressure prediction for corrosion features is of utmost importance for the safety of pipeline assets. However, MFL simplification tends to introduce conservatism. The established generalization may result in investigating metal loss features too early with additional costs. Nonetheless, even this conservatism in some cases results in erroneous data interpretation due to the ambiguity associated with the MFL data nature. Generalized MFL knowledge databases sometimes may miss complex metal loss structures, often associated with deteriorating coatings. In addition, the principle to go for the most probable shapes may be misleading.

Complex corrosion is not only difficult to interpret, the established ILI geometry conventions simplify the shape but complicate rupture threat assessment or corrosion growth analysis – problematic specifically for critical locations difficult to approach in the field.

These circumstances led to the investigation of possible options to replace the established MFL simplification with calculating the 3D metal loss geometry directly. The MFL methodical characteristics of “indirectness” and “ambiguity” are hurdles to reaching this target and are therefore illustrated below.

2. MFL-EVALUATION ASPECTS

2.1 Interpretation difficulty

The analysis of MFL magnetic field anomalies can be enormously complex. Converting the conventional, axial magnetizer MFL tool inspection data into the metal loss geometry is not only extremely difficult, but virtually impossible. The subsequent section “ambiguity” will elaborate on this aspect, and show that diverse metal loss source geometries can cause nearly identical magnetic disturbance fields.

However, even for thorough approximations, the mathematical complexity is severe and mainly originates from the fact that the entire surrounding is contributing to magnetic flux leakage measurement at a single location. Hence, even for the smallest geometry variation in the model, the entire calculation has to be repeated. This task even today easily exceeds computational resources and performance.

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2.2 Box simplification

For decades, rectangular geometries (referred to as boxes) have been the prevalent approach for simplification of flaw geometries. Metal loss boxes can deliver easy-to-handle parameters, but unfortunately introduce other complications for both accuracy assessment correlations and corrosion growth correlations. With the 2020 Pipeline Operators Forum (POF) data format definitions [1] an important step is made to improve the handling and further development of the MFL geometry output. Now, a 3D data output is prescribed instead of boxes. 3D data are no longer extending the maximum-boxed depth to weakly defined box limits. Hence, interaction and depth profiles can become more realistic and less conservative. Further definitions and tools for accuracy validation and correlation for growth assessments now have a much better development perspective. In addition, an adequate input evolves for the application of the Plausible Profile approach [2]. Besides, the integration of these types of data sets into “virtual pipeline twins” is expected.

2.3 Experience-based parameterization and simplification

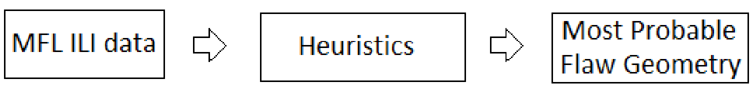

Figure 1. Experience-based translation of MFL data into pipeline geometry

The MFL signal is translated into an anomaly shape using existing knowledge from verifications, pull tests and synthetic data. This process depends on assumptions and conditions, e.g. whether the signal source is a regular shaped corrosion pit. The knowledge from thousands of experiences then contributes beneficially to its sizing. On the other hand, applying this knowledge to a cylindrical machined feature, its depth will be overestimated. A so-called blind performance test can become an exercise about test shape guessing instead of focusing on actual tool and system performance. With the vast experience on expected geometries, this signal analysis process can identify the most probable shape and the accurate depth. This type of translation process is typically referred to as "educated guessing" or "heuristics." Figure 1 sketches this operation.

Figure 2 shows a typical example of the translation result following the established POF conventions. The inherent conservatism introduced by the box generalization is obvious. However, for a few decades now, this has helped to keep the effort for data analysis manageable.

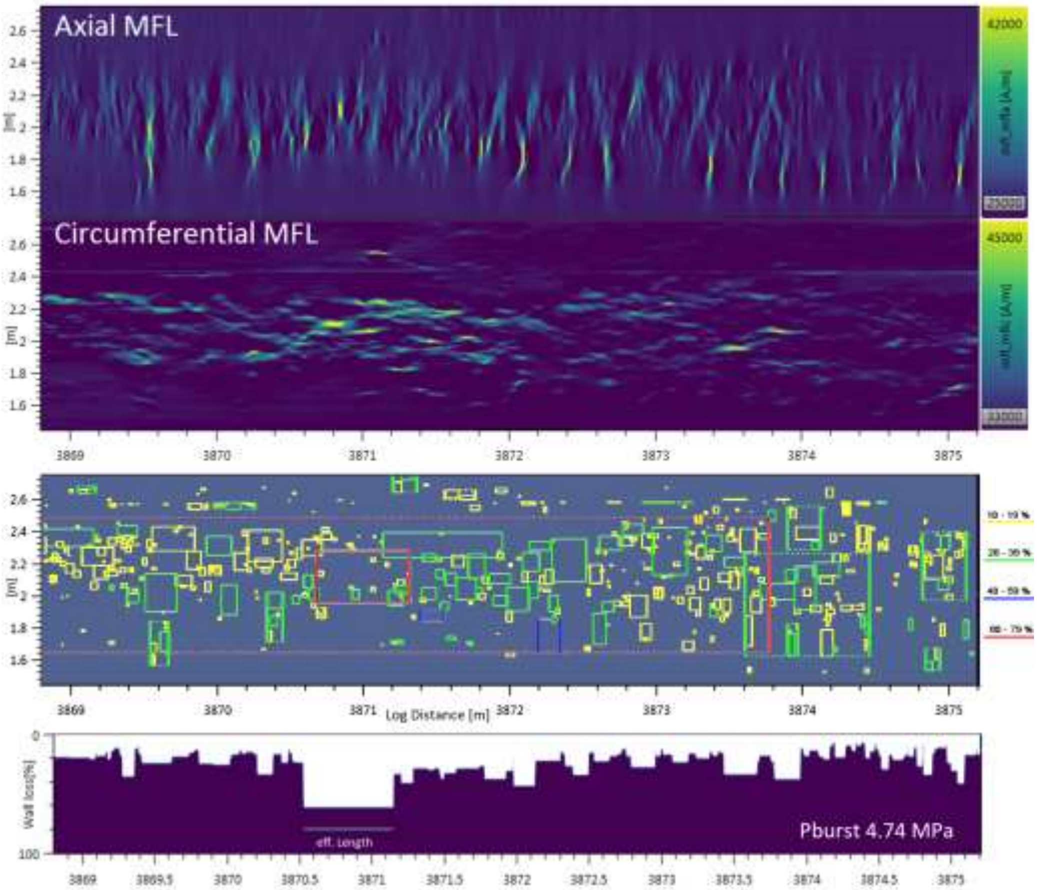

Figure 2. Typical example of an MFL result at heavy external corrosion

2.4 Operator expectations

The ILI metal loss sizing is an essential component in pipeline integrity management. With increasing pipeline age and number of known anomalies, the requirements regarding reliability and level of detail of the respective analysis data is progressively increasing. Apparent discrepancies are often difficult to understand and manage, for which Figure 3 gives an example. Although the results of Figure 2 are entirely compliant and accurate, the deviation to the laser scan field findings of Figure 3 appears suspicious. In addition, the above-mentioned confusion from poorly defined box correlation further complicates the corrosion growth estimation.

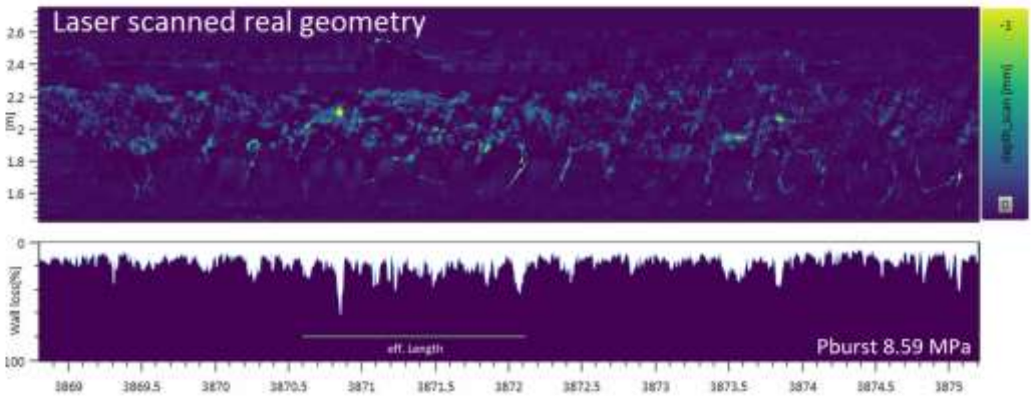

Figure 3. Field findings of laser scan of location of Figure 2.

Figure 4 shows a typical pitfall. The box contains the locations (a) and (b). Its box-wide maximum depth difference of 3% masks the actual significant measured growth of 29% at location (a) [3].

Figure 4. Example of significant flaw growth being masked by box-based assessment [3].

With establishing the new POF data format definitions [1] such situations are intended to be eliminated. Furthermore, the enormous pressure conservatism (Figure 2 vs. 3) will be reduced. Therefore, increasing the level of detail of the MFL results has become desirable. The diverse techniques of artificial intelligence are promising progress in that regard.

2.5 Artificial intelligence versus simplification

The usage of of novel approaches from the field of artificial intelligence (AI) enhance the heuristics. Even more, much larger and better-resolved datasets are nowadays able to facilitate the anticipated judgements [Figure 5]. The methodical progress is largely based on the abundant “ground truth” information stored in knowledge databases of the ILI vendors. It contains hundreds of thousands of anomalies, from pull tests and dig verifications, to synthetic data. This does not only improve the quality, but also the level of detail of the solution, which then can comply with the new POF requirements [1].

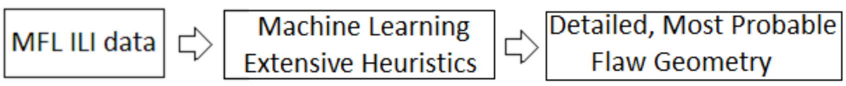

Figure 5. Machine learning based complex flaw analysis

However, it does not change the principle assessment approach. The stored knowledge improves “education” and computing performance enormously, but the heuristic component [Figure 1], the “guessing,” remains.

The achievable level of detail supports the 3D POF [1] or “Plausible Profiles” [2] requirements and substantial solutions like “digital pipeline twins.” However, reliability may suffer from the fundamental fact that not every feature has the most probable signal source geometry as the approach still needs to assume. Moreover, proposing alternative interpretations is, in some instances, not only a matter of measurement-related uncertainty, as shown below under “ambiguity.” In addition, individual aspects of a specific tool, run conditions, or pipeline-specific circumstances can reduce the suitability of generalized ground truth models for AI applications. These effects can accumulate to detrimental bias effects. Additional analyzes, typically making use of in situ verifications, can help to assess and counteract these.

2.6 Individual sizing model refinement

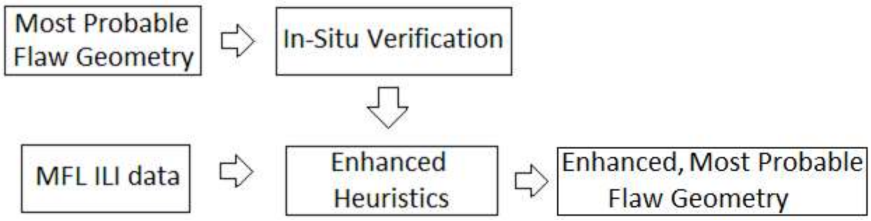

Figure 6. Sizing refinement with individual ground truth complementation

Individual pipelines and tool runs may introduce specific individual characteristics, not fully covered by normalized ground truth data. Therefore, additional information from verifications can help to adapt for bias effects and specific pipeline shape characteristics, as Figure 6 sketches, but the selection and individual weight of contributing locations is critical – typically focused on most critical defects, such preselection may corrupt this process.

The industry has quite some success in adapting sizing models [4], but these corrections do not approach or solve the principal issue of ambiguity.

2.7 MFL ambiguity

A given flaw allows for calculating the MFL magnetic field disturbance directly. This is called the “direct task” or “forward task”, whilst the “inverse task” constitutes by the problem to calculate the defect surface from a given magnetic field. The latter is the key task for MFL ILI However, such a task is known to constitute an “incorrectly formulated problem” [5(1.5.3)], because a unique one-to-one mapping from MFL data to flaw geometry does not exist. Two different non-exotic metal loss flaws, with 29% and 52% relative depth shall exemplary show this in Figure 7.

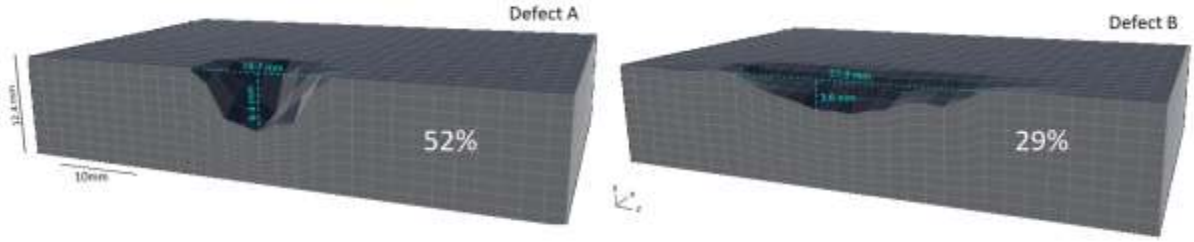

Figure 7. Two symmetric defects cut in the axial mirror axis. Left, nearly spherical 52% deep external metal loss; right, butterfly shaped, circumferential oriented, 29% external

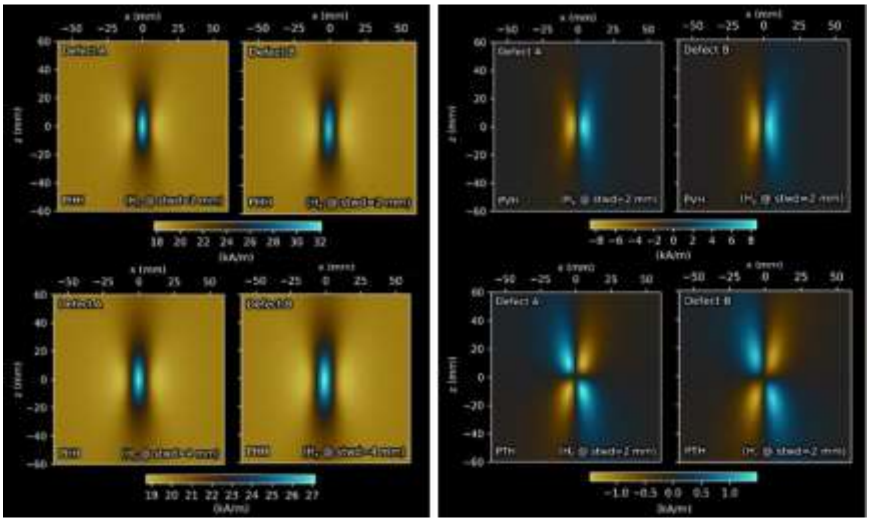

Figure 8. Magnetic field, in all three components, of Figure 7 flaws,
with varying sensor-to-wall-distance (2 & 4 mm) (left)

Figure 8 demonstrates that these two different source geometries cause virtually identical magnetic field disturbances in the MFL signal [6]. All magnetic field components are related to each other via div(H)=0 and curl(H)=0. More than one component provides not more than redundant information. [7 & 5(5.2.1.6.1)] Even different sensor-to-wall-distances, here 2 and 4 mm, neither allow for a discrimination of the defects nor provide additional information [5(1.5.2.2)]. In other words, given the MFL data shown in figure 8, the geometries of the two flaws (and possibly also of other ones) are perfectly valid answers to the “inverse task”.

Indeed, a similar ambiguity in principle be present for the orthogonal magnetization direction. However, the ambiguity is never present in two perpendicular magnetization directions at the same time. Figure 9 shows that, for the case of a magnetic field that is orthogonally rotated, the MFL signals are notably different. Hence, the incorporation of the orthogonal field direction adds an independent source of information, which is an essential input to finding the unique correct solution [8]. This marks a culture changing advantage.

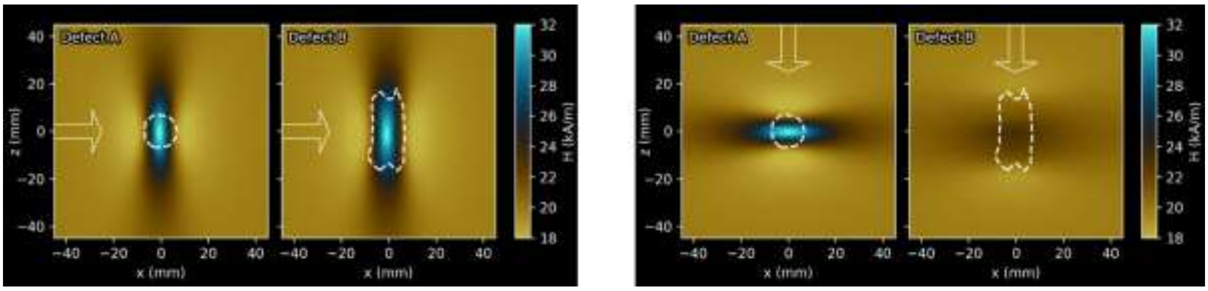

Figure 9. Magnetic field of the main components of the two defects from Figure 7.
Dotted contour = flaw outline. Left/Right: axial/circumferential main component
of axial/circumferential, conventional field (arrow).

2.8 MFL inversion

Although the MFL anomaly does not give the flaw geometry directly, the other way around, directly deriving the MFL anomaly from a predefined source geometry, is possible – in the scheme of Figure 10 marked as “MFL data calculator.”

Consequently, an iterative inversion process is possible, continually improving an internal representation of the flaw geometry until it fits the observation. The fit is deemed successful once the stop criterion is reached, i.e. “negligible observation difference “in Figure 11. The resulting “Calculated Flaw Geometry” is a calculated solution of the pipeline metal loss source geometry. Subsequently, this process is termed “Deep Field Analysis” (DFA). It achieves reliable 3D flaw shapes with overcoming A) model ambiguity by incorporating two independent magnetizing directions and B) mathematical complexity by an iterative approach.

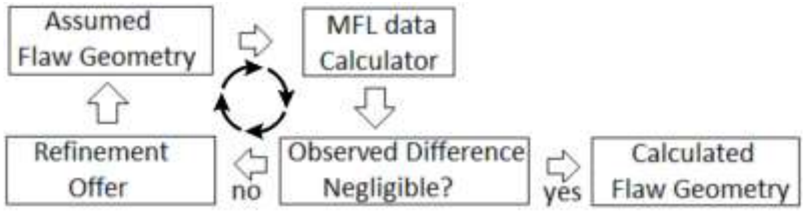

Figure 10. MFL iterative inversion calculation process

Within the “Virtual–Dig Up” (VDU) service, DFA is being utilized for the calculation of flaw geometries. This process can run standalone or with combined MFL field directions many thousand times. Figure 11 [8] shows the calculation results of a location affected by complex external corrosion. The left-hand image shows the result for conventional, standalone axial MFL (MFL-A), the right-hand image shows the corresponding result from a combination with circumferential MFL (MFL-C).

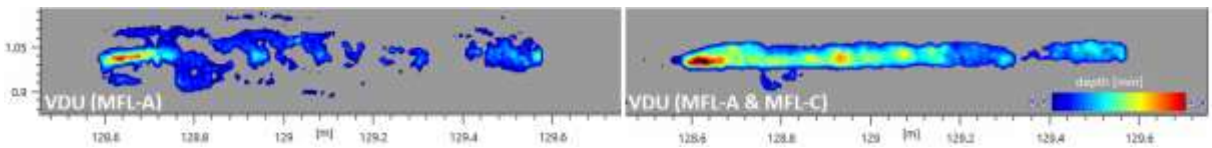

Figure 11. VDU calculation – Left: axial magnetizer standalone, right: combined with circumferential magnetizer.

Both calculation results are theoretically valid models, when considering the axial MFL ILI data only. Even more, the fields of the two geometries are in notable conformance for all three components. Out of the two results, however, the combined solution is not only mathematically correct. It represents even the only possible geometry, based on the MFL ILI data available from the circumferentially magnetizing tool (MFL-C). Consequently, it validates well against the laser scan (Figure 12).

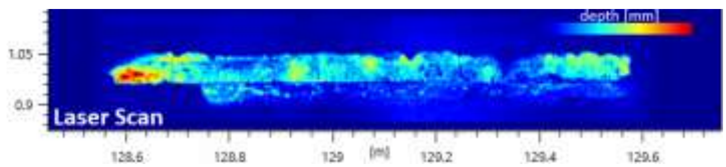

Figure 12. Laser scan of the flaw geometry measured by ILI MFL-A and MFL-C for Figure 11

The corresponding RSTRENG (ASME B31G 2012) burst pressure calculation of the laser scan (Figure 12) is 8.4MPa. The remaining deficits of the correct mathematical solution of standalone MFL-A (Figure 11 left) deviates with 9.0MPa, whilst the MFL-A and MFL-C combination (Figure 11 right) is only slightly over-conservative with 8.2MPa.

3. INTEGRATION OF MAGNETIC FIELD DIRECTIONS AND INVERSION

The inversion of MFL data with the DFA process used in the VDU application opens a new paradigm to MFL. The VDU MFL result quality is independent from the quality of neural networks ground truth or experience based data pools and sizing models. In addition, the experience of evaluators is not required to approach complex corrosion with VDU, only computation operations need to be managed.

To achieve a fundamentally unambiguous solution, ILI measurements in both field directions are required. Their quality remains the dominant precondition. Standalone inversions of MFL-A or MFL-C are possible options. Hence, ground truth and assumptions may still influence standalone MFL-A, tending to under- and MFL-C to over-conservative profiles typically.

The integration of MFL-A and MFL-C for established simplification approaches generally requires vast efforts. This is, however, not the case for DFA, because the combined inversion provides a robust integration on the fly.

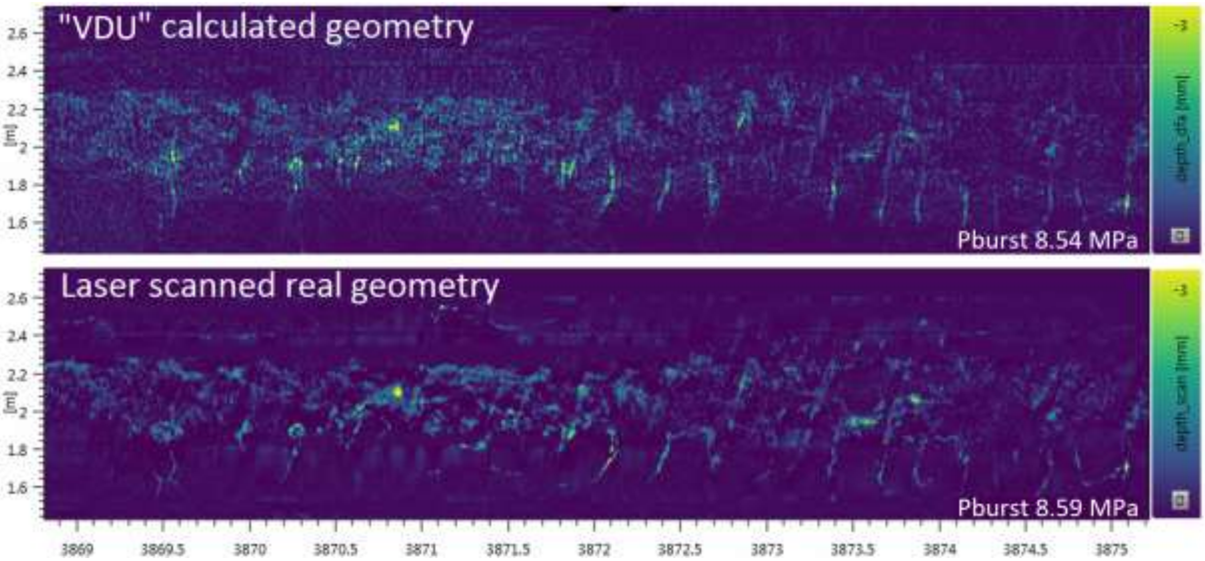

Figure 13. VDU calculation result from MFL-A and -C data (Fig. 2) vs. laser scan results (Fig. 3)

Furthermore, the increased calculation efforts of MFL-A and MFL-C reduce the calculation speed. However, the enhanced target orientation and prevention of wrong (or implausible) flaw model realizations accelerates the assessment on the long run.

The VDU result (Figure 13) for the Figure 2 and 3 complex corrosion location demonstrates the DFA potential to achieve the real complex metal loss shape by integrating MFL-A and MFL-C.

4. CONCLUSIONS

Converting conventional standalone MFL inspection data into metal loss geometries is impossible. Increasing knowledge and artificial intelligence further improve the result probability and principal potential of the heuristic approach. The pipeline industry still accepts the empirically founded MFL data evaluation principle. In present time, the best assumption is still not a definite calculation, and the prevalent approach for standalone MFL remains "educated guessing."

The individual adjustment of sizing models can be successful, but is labor intense and the selection and individual weight of contributing locations is critical. Sizing model revisions do not principally change the ambiguity. Ambiguity means, the wrong shape assumption may cause depth deviations significantly higher than specified.

Industry demands of repeatability, reduced conservatism and level of detail increase. Three-dimensional metal loss geometry data are required to meet these demands. MFL inversion is able to deliver mathematically correct 3D solutions. The integration of MFL-A, MFL-C and inversion (DFA, VDU) ensures the uniquely correct 3D flaw geometry. Laser-like metal loss profiles are achievable with MFL-ILI.

The sensitivity of the 3D model on local measurement aspects makes the result parameters comparable to those of ultrasonic testing (UT), i.e. MFL accuracy specifications can follow those UT formalism definitions of the POF 2021 ILI Specifications [9] in the future.

5. REFERENCES (in order of appearance)

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6. ABBREVIATIONS

3D	Three-dimensional		
AI	Artificial intelligence	Pburst	Predicted Burst Pressure
API	American Petroleum Institute	PHH	MFL Axial Component
DFA	Deep Field Analysis	PTH	MFL Circ.Component
H	Magnetic Field Strength	PVH	MFL Radial Component
ILI	In-line Inspection	POF	Pipeline Operators Forum
MFL	Magnetic Flux Leakage	RSTRENG	Remaining Strength
MFL-A	MFL axial magnetizing direction	STWD	Sensor to Wall Distance
MFL-C	MFL circ. magnetizing direction	VDU	Virtual–Dig Up

7. ADDENDUM

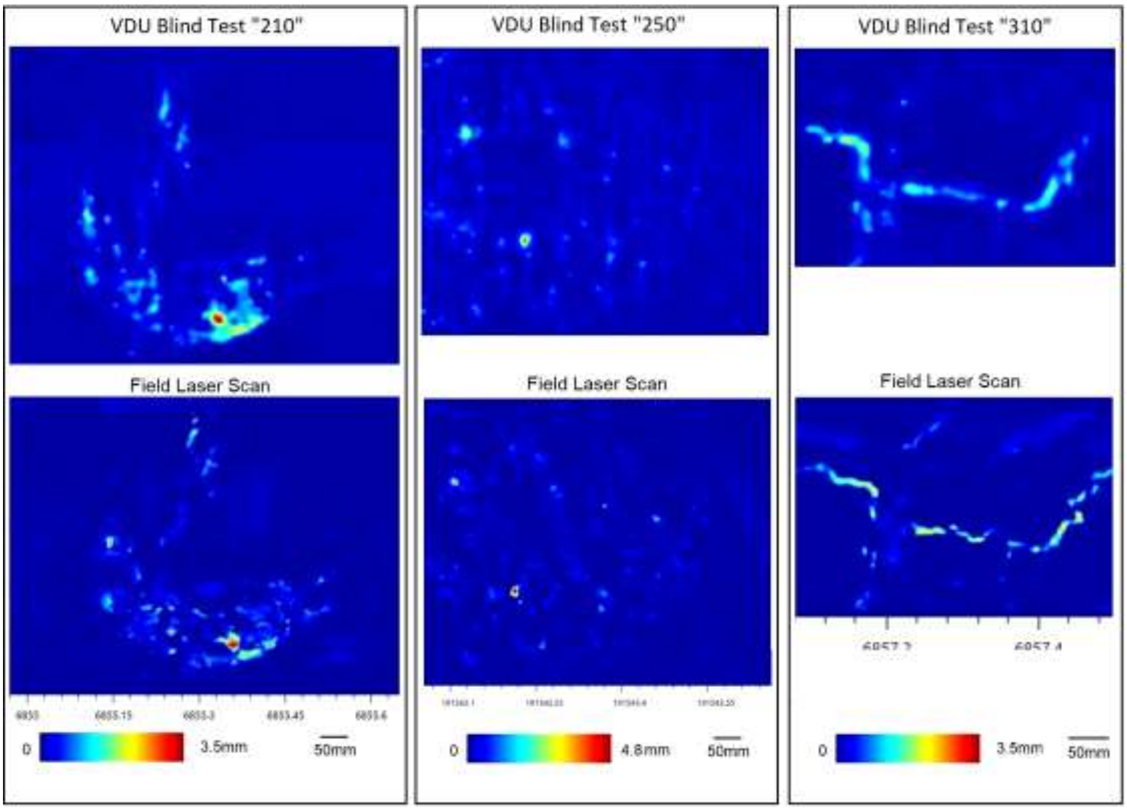

Figure 14. 3D maps of a VDU blind test vs. high-resolution laser scan maps

Blind Test Location	VDU depth [%t]	VDU P burst [MPa]	laser depth [%t]	laser P burst [MPa]
210	34	8.30	38	8.24
250	47	8.47	51	8.63
310	25	8.41	26	8.38

Figure 15. Feature depth and burst pressure of Figure 14 VDU blind test

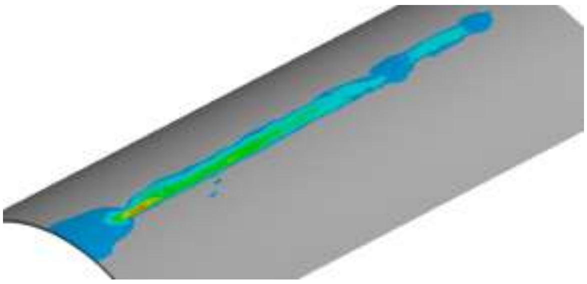

Figure 16. von Mises stress calculation Figure 11 right