U.S. Department of Transportation (USDOT) Pipeline and Hazardous Materials Safety Administration (PHMSA)
Final Report No. 26-30994-6000754R-Task 6

Evaluation of Analyses for Hydrogen Relevant Threats

Lucinda Smart and Michiel P. Brongers, PE

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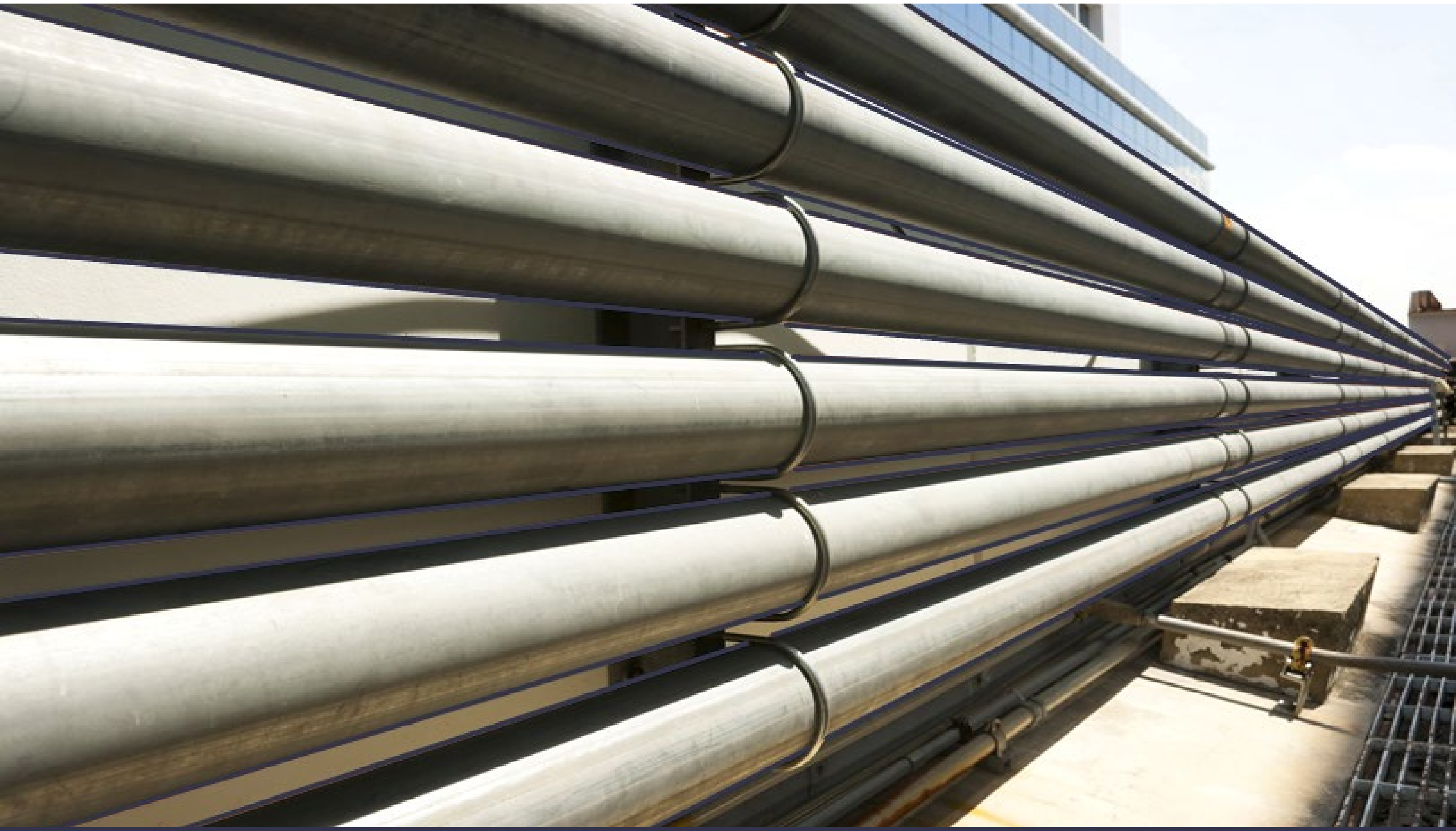

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Evaluation of Analyses for Hydrogen Relevant Threats

to

U.S. Department of Transportation (USDOT) Pipeline and Hazardous Materials Safety Administration (PHMSA)

on

April 10, 2026

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Executive Summary

This report was prepared by Kiefner and Associates, Inc. (Kiefner) as part of the research project titled "Investigate Damage Mechanisms for Hydrogen and Hydrogen/Natural Gas Blends to Determine Inspection Intervals for In-Line Inspection Tools" for the U.S. Department of Transportation (USDOT), Pipeline and Hazardous Materials Safety Administration (PHMSA), under Contract 693JK32310011POTA.

The objective of the Task 6 work was to provide an evaluation of the threat analysis characterization resulting from hydrogen gas service, as informed by the previously funded PHMSA Project #985. Task 6 work involved providing an evaluation of the threat analysis characterization resulting from hydrogen gas service, as informed by the previously funded PHMSA Project #985, to ultimately assess the *threat analysis procedures* compiled in the current project. The evaluation focused on the definition of threats in pipelines transporting hydrogen or hydrogen/natural gas blends, as detected by in-line inspection (ILI) as anomalies.

This evaluation was based on the analysis of previous and ongoing research, publicly available literature, and the evaluation of results from the analyses performed in Tasks 2 and 3 of this project, as well as the discussions included in this report. The recommendations regarding threat analysis for ILI tools are as follows:

- Determine the physical property/properties that the ILI tool aims to detect and size, and relate them to the threats defined in ASME B31.8S.
- Incorporate a standard method of reporting defects by ILI that maps to the threats defined in ASME B31.8S.
- Ensure ILI tool validation is performed with an appropriate field method for the threat requiring evaluation.
- Communicate validation results with the ILI vendor to grow the basis of knowledge, so that the industry can continue to improve over time.

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List of Acronyms and Abbreviations

AMPP	Association for Materials Protection and Prevention
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
CGR	Crack Growth Rate
CSCC	Circumferential Stress Corrosion Cracking
DEF	High-Resolution Deformation
ECA	Engineering Critical Assessment
EMAT	Electro-Magnetic Attenuation Testing
ERW	Electric Resistance Welded
GMA	Geomagnetic Anomaly
GPS	Global Positioning System
GW	Girth Weld
H_2	Hydrogen (molecule)
HAZ	Heat-Affected Zone
HIC	Hydrogen-Induced Cracking
ILI	In-Line Inspection
IM	Integrity Management
IMU	Inertial Measurement Unit
Kiefner	Kiefner and Associates, Inc.
LSW	Long Seam Weld
MFL	Magnetic Flux Leakage
NACE	(formerly) National Association of Corrosion Engineers (now Association for Materials Protection and Prevention (AMPP))
NDE	Non-Destructive Examination
PHMSA	Pipeline and Hazardous Materials Safety Administration
POD	Probability of Detection
POF	Pipeline Operator's Forum
POI	Probability Identification
PRCI	Pipeline Research Council International
RL	Remaining Life
SCC	Stress Corrosion Cracking
SH	Shear-Horizontal
STD	Standard
TDW	T.D. Williamson
USDOT	U.S. Department of Transportation
UT	Ultrasonic Testing
UTCD	Ultrasonic Testing Crack Detection
WT	Wall Thickness
XT	Extended Geometry Tool

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INTRODUCTION

This Task 6 report was prepared by Kiefner and Associates, Inc. (Kiefner) as part of the research project titled "Investigate Damage Mechanisms for Hydrogen (H_2) and Hydrogen/Natural Gas Blends to Determine Inspection Intervals for In-Line Inspection (ILI) Tools" for the U.S. Department of Transportation (USDOT) Pipeline and Hazardous Materials Safety Administration (PHMSA), under Contract 693JK32310011POTA.

In this task, previous research was reviewed to understand the impact of hydrogen on the mechanical integrity threats currently established and defined in ASME B31.8S-2025[1]. In addition to these published threats, the recommendations from prior work during Tasks 2[2] and 3[3] for additional threats were considered. This included the overarching recommendations for pipeline systems, irrespective of the hydrogen threat, as well as threats that only exist in the presence of hydrogen or hydrogen-blended gas, which were incorporated into the evaluation during this task.

One of the key issues to overcome is the use of ILI reports and how they distinguish between defects, anomalies, and threats. Defects can be considered as flaws or weaknesses in the asset, whereas a threat is something that can exploit that defect and cause a failure to occur. When ILI detects an indication, which is identified as a defect such as a dent or metal loss, that reported defect is not necessarily a threat to integrity. An engineering assessment should be done to determine its severity. ASME B31.8S more closely defines the causes of defects, such as external corrosion or manufacturing-related defects, that may pose an integrity threat and can cause a pipe to leak or rupture. This project aims to determine whether the defect identifications, threat characterizations, and threat assessments for hydrogen and hydrogen-blended natural gas pipelines require updates.

When ILI is used to detect anomalies in the pipeline, the data collected by the inspection tool is interpreted and reported to identify the meaning of each ILI indication in terms of a metallurgical feature. The terminology applied by ILI vendors describes the physical appearance or nature of features, e.g., "dent", "metal loss", "crack-like", "girth weld", "lamination", "seam weld indication". It can be challenging to relate those words to the terminology used in ASME B31.8S-2025, which more closely describes the cause of features, e.g., "external corrosion" or "manufacturing-related defect".

When using engineering critical assessment (ECA) procedures for hydrogen or hydrogen-blended gas pipelines, both the physical dimensions and the cause are relevant to select the correct failure mechanism and crack growth rate (CGR) for the calculations. Understanding how threats are characterized provides context and insight into how threat assessment procedures should be carried out.

1 BACKGROUND

1.1 General

The previous research provided a table showing the impact of hydrogen on different threats, ranked as High, Medium, and Low, along with its original results and commentary, in Table 1.[4]

The rows in this table are color-coded to represent high (red), medium (orange), and low (green) impact of hydrogen on the threat.

Based on the research and review of the threats recommended in Tasks 2 and 3, this table has been updated to include additional comments on the effects of hydrogen. The additional line items are provided within each correlating threat category. There is a distinction made for the updates that pertain to Paragraph 2.2 in ASME B31.8S-2025 General Updates and the ASME B31.8S-2025 Hydrogen Updates, all of which are recommended at the time of the report submission and have not yet been integrated or approved in a revised version. However, to anticipate updates to the industry, threats have been updated accordingly in this project review:

- Table 2 for Time-Dependent Threats,
- Table 3 for Resident Threats, and
- Table 4 for Random/Time-Independent Threats.

In these three tables, the rows that have been added to or altered are highlighted to indicate the documents to which the updates pertain. Purple indicates relevance to the recommended updates to Paragraph 2.2 of ASME B31.8S-2025, while blue indicates relevance to the recommended updates to the ASME B31.8S-2025 chapter on hydrogen that is currently under development. These tables provide the foundation for anomaly prioritization in assessing threats influenced by the presence of hydrogen.

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Table 1. Original Integrity Threat Assessment Classification with Hydrogen Consideration from DOT/PHMSA Project 693JK32210013POTA

Category	Integrity Threat	Comment on the Effect of Hydrogen[1]
Time-Dependent	External Corrosion	Not likely an effect on corrosion rate. Decrease in plastic collapse or fracture toughness limit of local thin area. (M)
	Internal Corrosion	Not likely an effect on corrosion rate. Decrease in plastic collapse or fracture toughness limit of local thin area. (M)
	SCC	May be an effect on SCC but decrease in fracture toughness reduces critical flaw size. (M)
Resident	Seam Crack	Decrease in fracture toughness results in smaller tolerable flaw size. Higher fatigue crack growth rate, potential for subcritical crack growth under constant load, particularly during hydrotesting. (H)
	Defective Pipe: *Hardspot*	Decrease in fracture strain and toughness but overall high impact. (H)
	Girth Weld, Fillet Weld, etc.	Decrease in toughness and concentration of hydrogen in HAZ reduces tolerable flaw size. (H)
	Fabrication Weld	Decrease on toughness results in smaller tolerable flaw size. (M)
	Wrinkle Bend/Buckle	Decrease in fracture strain and concentration of hydrogen could result in cracking and failure. (M)
	Stripped Threads, etc.	No Impact (L)
	Gasket O-Ring Failure	No Impact (L)
	Control/Relief Equipment Malfunction	No Impact (L)
	Seal/Pump Packing Failure	Moderate Impact (M)
	Miscellaneous	No Impact (L)
Random/Time Independent	Third Party Damage	Decrease in toughness and fracture strain results in potential for fast fracture. This is likely to manifest sometime later, and not on impact due to high loading rate. (H)
	Previous Damage: Dents/Gouges	Decrease in fracture strain and concentration of hydrogen could result in cracking and failure. (H)
	Vandalism	Low Impact (L)
	Operating Temperature	Low Impact (L)
	High Wind	Decrease in fracture strain, but overall low impact. (L)
	Water-Related	Decrease in fracture strain, but overall low impact. (M)
	Geotechnical	Decrease in fracture strain, but overall low impact. (M)
	Lightning	Low impact. (L)

[1] For this study, the hydrogen within the microstructure originates from the external hydrogen gas. Similar effects would be expected from other hydrogen sources.

Table 2. Update to ASME B31.8S-2025 Table for Time-Dependent Threats

CATEGORY	ROOT CAUSE	INTEGRITY THREAT	COMMENT ON EFFECT OF HYDROGEN[2]
Time Dependent	External Corrosion	External Corrosion	Not likely an effect on corrosion rate. Decrease in plastic collapse or fracture toughness limit of local thin area. (M)
	Internal Corrosion	Internal Corrosion	Not likely an effect on corrosion rate. Decrease in plastic collapse or facture toughness limit of local thin area. (M)
	SCC	SCC	May be an effect on SCC, but decrease in fracture toughness reduces critical flaw size. (M)
	Cracking	Hydrogen-Induced Cracking	Only applicable in hydrogen environment. Does not require external stress to initiate. This threat is self-enhancing - those cracks that have been HIC-initiated cracks will be susceptible to further growth by HEC. (H)
		Fitting and Sharp Transitions	Only applicable in hydrogen environment. Hydrogen preferentially diffuses into areas of elevated tensile stresses and strains. (H)
		Fatigue Cracking	Hydrogen accelerates the fatigue crack growth rate. (H)

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[2] For this study, the hydrogen within the microstructure originates from the external hydrogen gas. Similar effects would be expected from other hydrogen sources.

Table 3. Hydrogen Updates to ASME B31.8S-2025 Table for Resident Threats

CATEGORY	ROOT CAUSE	INTEGRITY THREAT	COMMENT ON EFFECT OF HYDROGEN
Resident	Manufacturing Defects	Seam Crack	Decrease in fracture toughness results in smaller tolerable flaw size. Higher fatigue crack growth rate, potential for subcritical crack growth under constant load, particularly during hydrotesting. (H)
		Defective Pipe: *Hardspot*	Decrease in fracture strain and toughness but overall high impact. (H)
		Defective Pipe Seam: *Low-toughness, Defect in or near ERW seam*	Decrease in toughness in low toughness seam welds. (H)
	Defective Construction or Fabrication	Girth Weld, Fillet Weld, etc. Defect	Decrease in toughness and concentration of hydrogen in HAZ reduces tolerable flaw size. (H)
		Near GW and in-service/repair welds: Arc Burn/Strike on pipe body	Only applicable in hydrogen environment. Locally changed microstructure at an arc burn can create a local hard spot, increasing the risk of cracking. (H)
		At welded sleeves and fittings: *Type B sleeves and Puddle Welds*	Only applicable in hydrogen environment. Impractical to apply PWHT to in-service pipelines, so residual stresses, and elevated hardness may be possible, increasing risks for lines with hydrogen. (H)
		At in-service/repair welds: Hydrogen Stress Cracking	Hydrogen generated during the weld process results in delayed cracking. (H)
		Fabrication Weld	Decrease in toughness can result in smaller tolerable flaw size. (M)
		Wrinkle Bend/Buckle	Decrease in fracture strain and concentration of hydrogen could result in cracking and failure. (M)
		Stripped Threads, etc.	No Impact (L)
	Equipment	Gasket O-Ring Failure	No Impact (L)
		Control/Relief Equipment Malfunction	No Impact (L)
		Disbonded coating caused by hydrogen	Only applicable in hydrogen environment. Hydrogen atoms in the metal recombine with hydrogen molecules in the pipe/coating interface, causing gas to build up and blister, locally disbonding the coating. (H)
		Seal/Pump Packing Failure	Moderate Impact (M)
		Miscellaneous	No Impact (L)

Table 4. Hydrogen Updates to ASME B31.8S-2025 Table for Random/Time Independent Threats

CATEGORY	ROOT CAUSE	INTEGRITY THREAT	COMMENT ON EFFECT OF HYDROGEN
Random/ Time Independent	Mechanical Damage	Third Party Damage	Decrease in toughness and fracture strain results in potential for fast fracture. This is likely to manifest sometime later, and not on impact due to high loading rate. (H)
		Previous Damage: Dents/Gouges	Decrease in fracture strain and concentration of hydrogen could result in cracking and failure. (H)
		Vandalism	Low Impact (L)
	Natural Events	Operating Temperature	Low Impact (L)
		High Wind	Decrease in fracture strain, but overall low impact. (L)
		Water-Related	Decrease in fracture strain, but overall low impact. (M)
		Fire damage	Only applicable in hydrogen environment. Locations that may experience an electrical arc or fire may be more susceptible. (H)
		Geotechnical	Decrease in fracture strain, but overall low impact. (M)
		Lightning	Low impact. (L)

1.2 Industry Established Definitions

The purpose of Task 6 was to evaluate threats. However, when ILI provides a report with potentially actionable data, that data is not presented in terms of threats, but rather in terms of features, indications, or anomalies on the pipeline. Therefore, a brief review of industry-established definitions is provided here to increase understanding and consistency in terminology throughout this report.

The industry has provided similar definitions for terms such as anomaly, defect, feature, flaw, imperfection, and indication across pipeline documents. Consistent terminology ensures safety, clarity, regulatory compliance, and efficient operations. ILI vendors label pipeline anomalies and features using classification standards.[5] Operators then rely on these terms to prioritize and take action based on the inspection results. Inconsistent definitions result in inconsistent data assessments, leading to potentially flawed risk models or unreliable or inefficient integrity assessments.

Table 5 summarizes definitions from applicable codes and standards. In pipeline integrity management (IM), terminology used to describe ILI findings requires precision to ensure clarity in communication and decision-making.

Within a pipeline listing or pipe tally, the column labeled "Feature" typically contains the designation for each item identified by the ILI tool. However, the term "feature" is inherently broad and represents the least specific descriptor for any object detected and reported by ILI technologies. The term indication is conceptually similar, referring to a finding or observation derived from ILI data. Both terms denote the presence of something noteworthy but do not convey its significance or severity.

An anomaly refers to an unverified deviation from expected conditions, such as the uniformity of sound pipe material. This term is particularly relevant when assessing potential threats, as it emphasizes the need for further evaluation prior to regulatory compliance activities or validation digs. Following a detailed assessment, either through in-ditch examination or engineering analysis, an anomaly may be classified as either a defect or an imperfection. A defect represents a condition that requires remediation, whereas an imperfection generally falls within acceptable limits and does not necessitate corrective action.

Although these terms might be used interchangeably in practice, maintaining clear distinctions is important. Documentation typically establishes that all anomalies are features, but not all features are anomalies. Similarly, all defects are anomalies, yet not all anomalies constitute defects. Precision in language is therefore critical for effective communication and accurate threat assessment in pipeline IM.

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Table 5. Industry Established Definitions to Relate ILI Data to ASME B31.8S-2025 Threats

Term	API RP 1160-2019[6]	API STD 1163-2nd Ed.[7]	POF 100-2021[8]
Anomaly	An *unexamined deviation* from the normal sound pipe material, coatings, or welds.	Possible *unexplained deviations* from the norm in sound pipe material, coatings, or welds.	An *unexamined deviation* from the norm in pipe material, coatings, or welds, which may or may not be a defect. See also imperfection, defect, and feature.
Defect	Imperfection of a type or magnitude *exceeding acceptable criteria.*	A physically examined anomaly with dimensions or characteristics that *exceed acceptable limits.*	A physically examined anomaly with dimensions or characteristics that *exceed acceptable limits.*
Feature	Not defined.	Any *physical object detected by an ILI* system.	Any *physical object* detected by an ILI system. Features may be anomalies, components, nearby metallic objects, welds, appurtenances, or some other item.
Flaw	Not defined.	An imperfection that is smaller than the maximum allowable size.	Not defined.
Imperfection	A flaw or other discontinuity noted during inspection *that passes acceptance criteria* during an engineering and inspection analysis.	Flaw or other discontinuity noted during inspection that *passes acceptance criteria* during an engineering and inspection analysis.	An anomaly with characteristics that *do not exceed acceptable limits*
Indication	A *discovery from nondestructive testing (NDT),* inspection technique, or signal from an ILI system.	A *finding from nondestructive testing*, inspection technique, or a signal from an ILI system.	Not defined.

2 OBJECTIVE

The objective of Task 6 work was to provide an evaluation of the threat analysis characterization resulting from hydrogen gas service, as informed by the previously funded PHMSA Project #985, in order to ultimately evaluate the *threat analysis procedures* compiled in the current project. The evaluation focused on the reassessment interval determination for defects in pipelines transporting hydrogen or hydrogen/natural gas blends, as detected by ILI.

3 CLASSIFYING THREATS TO EVALUATE

3.1 In-Line Inspection Capabilities

Pipeline operators employ a range of methods to evaluate, inspect, and monitor the hundreds of thousands of miles of transmission pipelines in operation worldwide. Such activities include right-of-way surveys, cathodic protection surveys, leak detection programs, excavations to look for pipe corrosion or protective coating failures, hydrostatic tests, and the use of ILI tools that travel through the pipe.

ILI tools are highly sophisticated instruments that vary in technology and complexity according to their intended use and manufacturer, providing insight into and understanding of the pipe wall from “inside the pipe”. An ILI tool consists of a mechanical core comprised of an arrangement of conforming cups and sensors that enable the ILI tool to be conveyed along with the product flow or gas or liquid injected into the pipeline (flow conveyed). Attached to, or an integral part of the ILI tool core are nondestructive examination (NDE) modules (ultrasonic testing [UT], magnetic flux leakage [MFL], or mechanical geometry sensors), data and positional memory, and a self-contained power supply.

ILI vendors continue to enhance the technology modules, often utilizing multiple NDE modules within a single tool configuration. Each individual technology has capabilities and limitations for detecting and identifying anomalies or features on the pipeline, and applying a multi-data set approach provides more insight into the true condition of the pipeline.

This section of the report starts with a review of the current state-of-the-art ILI multidata set tools, which are designed with the purpose of correlating these data streams to provide insight into not only the anomalies reported, but also the threats that can be interpreted by the integrity engineer based on the output of the ILI tools. The capabilities and limitations of each technology are then described in more detail.

3.1.1 General

Historically, ILI tools were developed to identify volumetric metal loss. The first MFL technology was patented in 1963 and had coverage for only the bottom quarter of a pipe. Full circumference tools were developed a few years later. UT tools were introduced in the 1980s, and transverse MFL tools were first used in the late 1990s. Most of the history of ILI tools involves the detection of volumetric metal loss and deformations. Only within the last few decades has ILI advanced to detecting and sizing features such as cracks, hard spots, and other features of significance to the pipeline's integrity.

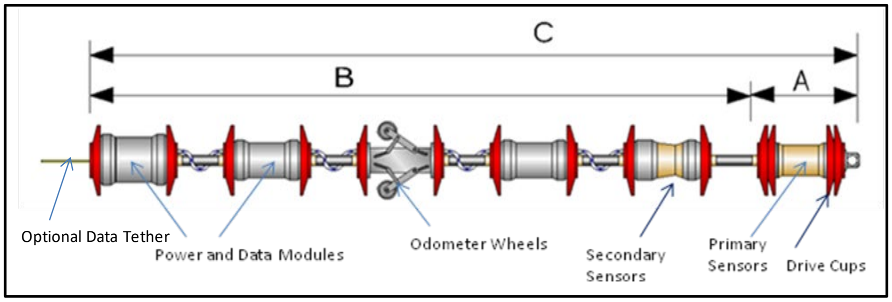

Figure 1. Design Elements of an ILI Tool

ILI technological advancements are driven by the need to detect the minimum defect size that could lead to a failure. When anomalies initiate through a particular mechanism, whether that is due to a resident manufacturing defect or caused by an external source after the pipe is operational, they must be detectable.

If the size of the anomaly is below the threshold at which an inspection technology can detect it, it essentially does not exist because there is currently no way to know it is there. If the defect has the potential to grow to a detectable size, then this is an anomaly that can be addressed through assessment methods and IM decisions as part of an overall process and procedure for maintaining the pipeline's integrity.

3.1.2 Magnetic Flux Leakage Technology

3.1.2.1 Detection of Metal Loss from Corrosion and Mechanical Damage

The most widely used technology within pipelines is MFL, one of the oldest methods for evaluating the integrity of pipeline materials. Figure 4 is a schematic showing the generation of the magnetic flux field and the change caused by the presence of a volumetric metal loss defect. As shown in the figure, the MFL method involves inducing a magnetic field in the pipe wall and observing any flux leakage resulting from a defect.

A defect, such as local reduced wall thickness (WT) or a volume with different magnetic properties, like an inclusion, can cause a deviation in the magnetic field. The magnetic field is induced either by permanent magnets or electromagnets, the former being more widely used because they do not require an electrical power supply.

MFL is an indirect measurement method, in that the amount of wall loss or defect size must be inferred from the change in magnetic field disruption. There is no need for couplant between the MFL sensor and the pipe wall. Therefore, MFL-based ILI tools are ideal for inspecting gas pipeline systems. Resolution can vary significantly depending on design features for MFL sensor technologies. Common sensor arrangements can provide high levels of metal loss discrimination with claimed sizing performance of ±10% WT 90% of the time. The industry has been well-served by sensor configurations that capture only axial and radial flux vectors, and these have been the basis for the industry-standard performance specification of ±10% wt, 80% of the time. The inner and outer location capability for metal loss depends on additional, secondary sensors that provide the historical discriminator between high-resolution MFL technologies.

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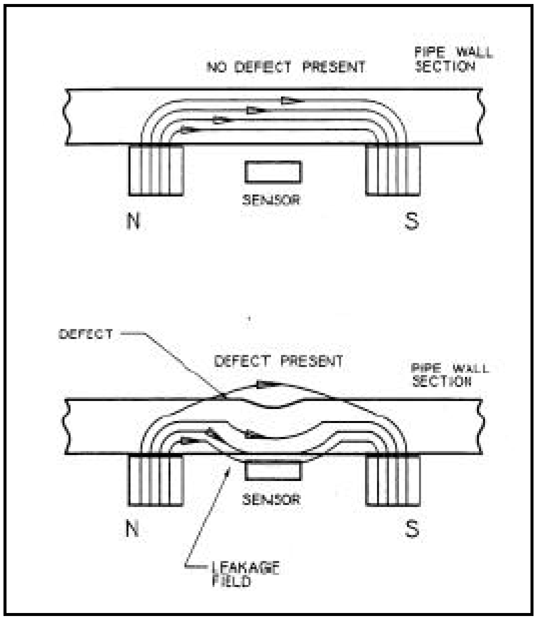

Figure 2. Schematic Showing the Generation of Magnetic Flux Gield and the Change Caused by the Presence of a Defect Such As Metal Loss Corrosion

MFL is designed to detect volumetric metal loss. Whether the metal loss is due to internal or external corrosion, or a gouge caused by third-party damage, MFL can accurately identify those locations. This can then support the review for locations such as initiation sites for hydrogen-induced cracking (HIC), under cyclic loading conditions, or in the presence of residual stresses.

Regions with general wall thinning reduce the pipe's load-bearing capacity and can amplify the effects of hydrogen degradation. MFL is not sufficiently capable of detecting this type of wall thinning, since the physics require a large enough change in the magnetic field to detect a metal loss, rather than a gradual thinning of WT, which can go undetectable by MFL tools. In this case, UT straight beam ILI tools should be applied to directly measure the WT to evaluate the effect of the wall thinning on the pressure-carrying capacity of the pipe.

One consideration for the application of UT versus MFL sensors is the vintage of the pipe to be inspected, which relates to the frequency and severity of mid-wall laminations. The presence of laminations for UT can result in echo loss, which can adversely affect the probability of detection (POD) for metal loss.

3.1.2.2 Identification of Dents and Gouges

Mechanical damage, such as dents and gouges, is a key contributor to crack initiation in hydrogen environments. These features introduce localized plastic deformation and stress concentrations that may act as nucleation points for HIC. While MFL does not directly characterize the geometry of a dent, it can detect metal loss associated with gouges and dent gouging, prompting further assessment with high-resolution geometry tools or UT for crack detection.

3.1.2.3 Hard Spots and Magnetic Anomalies

Hard spots are localized regions of increased hardness, often caused by manufacturing inconsistencies, that are more susceptible to hydrogen embrittlement. These areas often produce distinct magnetic responses in MFL data due to differences in permeability and magnetic hysteresis behavior.

The application of a residual or low-field MFL tool allows the detection of these changes in the microstructure of the pipe material. The tool cannot quantify hardness but instead reports on changes in localized areas that require further evaluation through data analysis and calibration. Additionally, advanced tools and machine learning techniques are becoming increasingly capable of identifying such areas as potential integrity threats. Residual or low-field MFL tools should be used in conjunction with a comprehensive validation program to continue capturing the confirmed locations of hard spots.

3.1.2.4 Indirect Support for Crack Detection

Crack and crack-like anomalies require a certain minimum crack opening to be detected by MFL, typically at least 0.1 mm (0.004 inches). Therefore, MFL is not a standalone technology to identify cracking anomalies. However, MFL can indirectly support crack management programs by identifying features that are statistically correlated with crack formation, such as seam weld corrosion, dent gouging, or areas with multiple interacting threats. These findings can inform decisions to deploy more sensitive crack detection technologies, such as ultrasonic testing crack detection (UTCD) or electromagnetic attenuation testing (EMAT).

Although MFL technology is not inherently designed for crack detection, it plays a valuable role in identifying conditions that may lead to hydrogen-related failures. Its strengths in detecting volumetric metal loss, mechanical damage, and localized hard spots provide important indirect indicators of potential hydrogen vulnerability.

3.1.2.5 Challenges and Considerations

The primary limitation of MFL in hydrogen-related IM is its inability to directly detect tight or planar cracks, which are typical for hydrogen damage. Additionally, MFL resolution may be limited in older tools or in pipes with thinner WT.

Another consideration is the observed incompatibility of the materials used in permanent magnets with hydrogen gas. The solid-gas interaction is so aggressive that ILI vendors have encountered magnets that were completely wasted away by the end of a run.[9] A remedy to this problem is to encapsulate the magnets in another, non-corrosive metal, such as stainless steel, to avoid direct gas contact.

Tool validation must include a representative range of defects, including those that mimic hydrogen-induced damage, to ensure consistent performance. Operators should also use MFL data in conjunction with other inspection methods and operational data (e.g., pressure cycling, hydrogen concentration) for a comprehensive integrity assessment.

While MFL ILI is not optimal as a crack detection tool, its proven capabilities in detecting metal loss, mechanical damage, and magnetic anomalies make it a vital component in integrity programs for hydrogen-blended natural gas pipelines. The technology provides early warning of regions susceptible to HIC and supports prioritization of follow-up inspections using crack-sensitive technologies. Continued development in signal processing, data fusion, and integration with material property data will further enhance MFL's relevance in hydrogen pipeline systems.

3.1.3 Ultrasonic Inspection Technology

Ultrasonic ILI technologies are widely used for detecting and characterizing defects in pipeline systems, particularly those involving metal loss and cracks. These tools function by transmitting high-frequency sound waves into the pipe wall and measuring the reflected signals from internal and external surfaces or discontinuities, shown in Figure 3. As it is a direct measurement method, ultrasonic inspection is an optimal technology for detecting and sizing planar flaws, including those caused or enhanced by hydrogen exposure.

Ultrasonic ILI tools are especially suitable for detecting the types of flaws that hydrogen can initiate or accelerate. These include fatigue cracks, environmental cracking, weld defects, and hard spot cracking. UTCD tools operate by measuring both the time-of-flight and amplitude of ultrasonic signals, enabling them to characterize the length, depth, and orientation of flaws.

Similar performance limits for detection apply to NDE technologies used on the outside of the pipe, as well as to inside pipe applications deployed using ILI tools. Differentiators between individual technologies for a given application include the number of sensors within a tool, data resolution, data storage, runtime, and the sensitivity of the NDE technology to the cleanliness of the pipe bore. For metal loss or wall thinning, the reporting accuracy for depth measurement is ±0.20 mm (±0.008 inches) for UT, and the highest possible resolution is 0.06 mm (0.002 inches). The threshold for depth measurement for metal loss is generally set at 1.0 mm (0.039 inches) (approximately 15% WT), but lower thresholds to 10% WT are possible.

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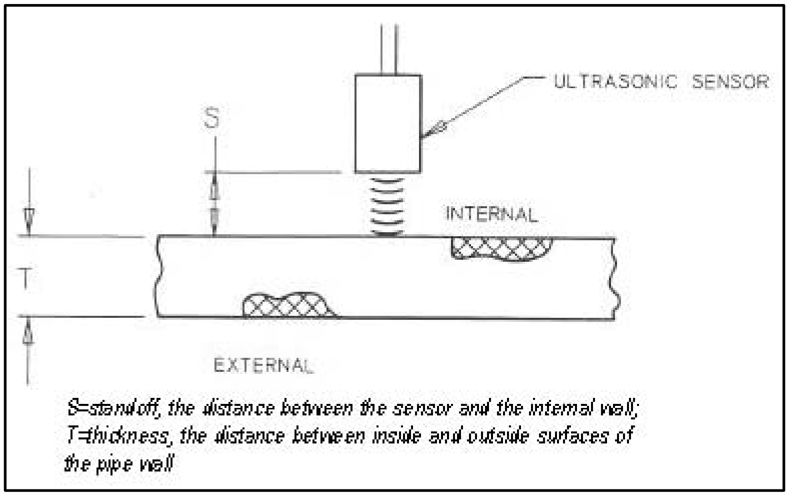

Figure 3. Schematic Showing Ultrasonic Straight Beam Scanning Set Up, with Stand-Off of Sensors and Wall Thickness Identified

Ultrasonic sensor technology requires a couplant to be used between the transducer and the metal surface. Therefore, piping systems must be filled with a single-phase fluid, such as water, oil, or refined products, for inspection purposes. The system performance is limited by beam size, wavelength, and travel speed.

Ultrasonic thickness measurement is limited by its characteristic limits of detection for small diameter flaws, which are typically limited to one-half wavelength, where the wavelength is the ultrasonic velocity divided by the ultrasonic transducer frequency. Various transducer frequencies, ranging from 2 to 10 MHz, are routinely applied, with high frequencies providing the ability to detect smaller diameter features. However, resultant sizing sensitivity (accuracy) considering beam divergence must be taken into account. For thickness gauging techniques, a thickness accuracy of as high as ±1 micron or ±0.0001 inches (+/- 0.01 mm) is the technology limit.[10]

3.1.3.1 Detection of Axial and Circumferential Cracks

Angle beam transducers allow a refracted shear wave to come in from the side, as shown in Figure 4, which allows for improved detection of flaws in and around welded areas. This technique can then be refined to perform crack tip diffraction, to determine the length of a crack originating from a surface, as shown in Figure 5.[11]

Further technological enhancements, including automated scanning techniques and process refinements specific to pipeline cylindrical applications, enable UT to be a highly effective tool for determining crack depth and location. The resulting sizing accuracies for typical UTCD tools are as follows: detection of cracks with a minimum length of 20 mm (0.79 inches) and a depth of 1.0 mm (0.04 inches) in the base material and at welds, and 2.0 mm (0.08 inches) depth in welds. Most tools are sensitive enough to detect flaws with a depth of only 0.5 mm (0.02 inches).[12]

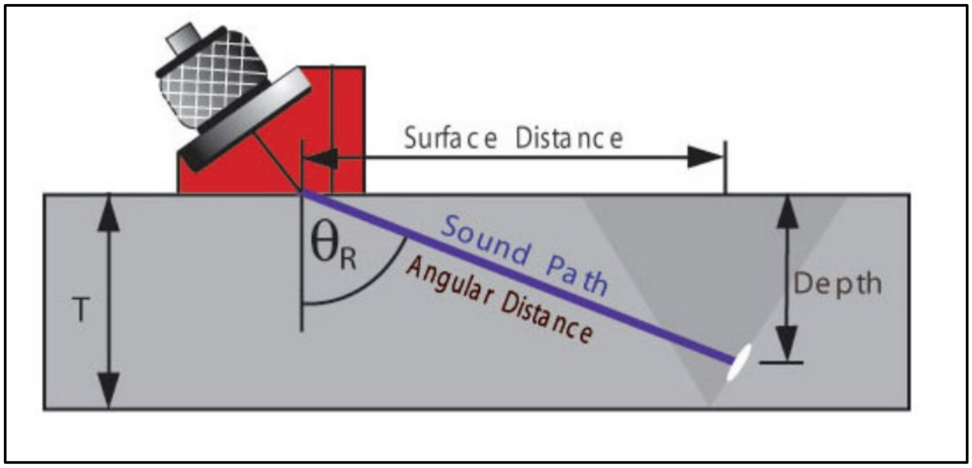

Figure 4. Diagram of Angle Beam Transducer with Angle of Refraction Considered

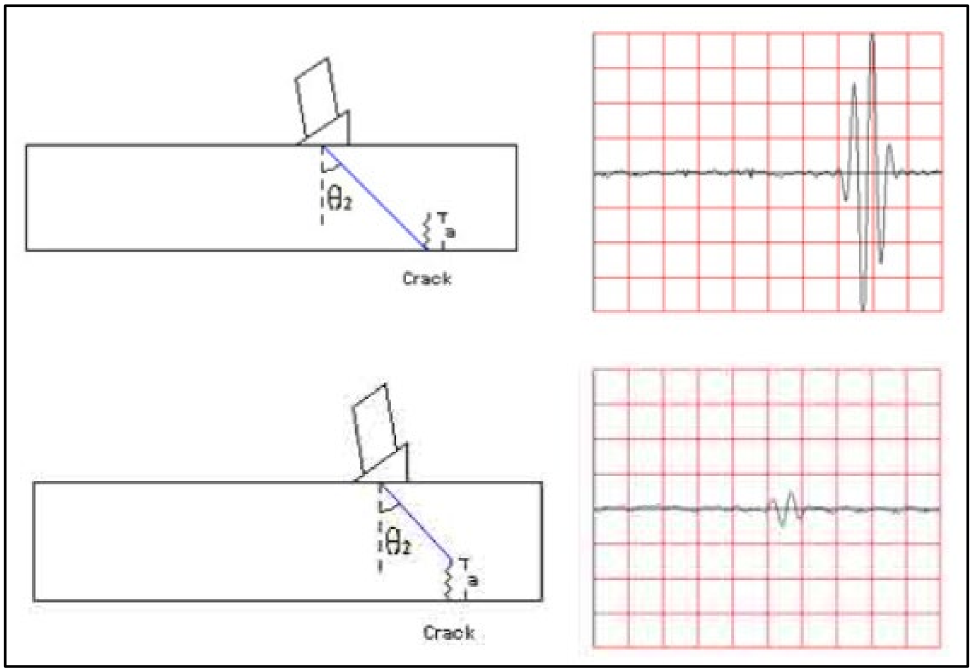

Figure 5. Angle Beams Applied to Crack Tip Diffraction Techniques to Determine the Position and Size of a Crack

HIC often manifests along the axial direction, particularly near seam welds, but can also occur circumferentially at girth welds, or off-axis under wrapped coatings or at spiral welds. UT tools equipped with angled beam sensors can effectively detect these types of cracks by scanning the WT from multiple orientations. This is especially useful in detecting cracks that originate from or propagate along a longitudinal electric resistance weld (ERW) seam or spiral weld.

3.1.3.2 Inspection of Welds and Heat-Affected Zones

Weld areas and their adjacent heat-affected zones (HAZs) are known to exhibit increased susceptibility to hydrogen embrittlement due to localized hardening, residual stress concentrations, and potential weld defects such as lack of fusion or undercut. Ultrasonic ILI tools can provide high-resolution inspections around welds, identifying anomalies like toe cracks, cold welds, porosity, or low-toughness seams that may serve as initiation points for HIC.

3.1.3.3 Hard Spot and Inclusion-Related Cracking

Hard spots and non-metallic inclusions in the pipe body can cause local stress concentrations that act as nucleation sites for HIC. UT tools offer minimal to no capability of distinguishing such material inconsistencies.

3.1.3.4 Quantitative Crack Sizing and Orientation

One of the primary advantages of UTCD tools is their ability to quantify the size of a crack with sufficient resolution to support engineering assessments based on fracture mechanics. Tools can detect cracks as small as 1 mm (0.04 inches) in depth and provide accurate orientation data, such as differentiating between axial, circumferential, or oblique cracks. This quantitative data is essential for determining the criticality of defects in hydrogen service, where reduced fracture toughness may significantly lower the tolerable flaw size.

3.1.3.5 Challenges and Considerations

Implementing ultrasonic inspection in gas pipelines introduces some operational challenges, particularly because traditional UT requires a liquid couplant. To overcome this in gas environments, operators may use temporary batching with water, foam-based couplants, or gel-filled inspection tools. Additionally, the presence of hydrogen in the gas stream may affect acoustic properties, requiring careful calibration. Tool validation must be performed using realistic defect replicas under hydrogen-influenced material conditions to ensure reliable performance.

3.1.4 Electromagnetic Acoustic Transducer Technology

EMAT technology is an ultrasonic inspection method that generates sound waves directly within the material using electromagnetic principles, rather than relying on a liquid couplant, as in conventional ultrasonics. The process involves two key components: a magnet and a coil. The magnet creates a static magnetic field in the material, while the coil induces an alternating current that generates a dynamic magnetic field. This interaction generates Lorentz forces or magnetostrictive effects in the material, resulting in localized vibrations that form ultrasonic waves. These waves propagate through the material and reflect off discontinuities such as cracks, inclusions, or weld flaws. The same EMAT sensor then detects the returning signals, which are analyzed to characterize defects.

Because EMAT does not require physical contact or couplant, it is highly effective for inspecting coated or oxidized surfaces and can operate in harsh environments, including high temperatures. It can generate specific wave modes, such as shear horizontal (SH) or guided waves, that are particularly sensitive to crack orientation and depth. This makes EMAT well-suited for detecting stress corrosion cracking (SCC), HIC, and other anomalies in pipelines. Its ability to work through coatings and debris, combined with precise control over wave mode selection, provides a significant advantage for ILI of pipelines transitioning to hydrogen service.

3.1.4.1 Detection of Axial and Circumferential Cracks

Recent advances in EMAT technology have significantly enhanced the detection of both axial and circumferential cracking in hydrogen service pipelines. The latest EMAT Ultra configuration from ROSEN and colleagues, tailored for hydrogen pipeline inspections, employs a dual-sound path (clockwise/counter-clockwise) and doubled sensor coverage, achieving a reported 95 % POD for cracks with critical dimensions that may prove to exceed current industry standards.[13,14]

In hydrogen environments, high diffusivity and embrittlement tendencies in steels amplify crack initiation and propagation, particularly in axial orientations due to the pipe's hoop stress and cyclic pressure loading, and as circumferential cracks due to axial bending loads and residual stresses around girth welds. SH guided-wave modes generated by EMAT are highly sensitive to crack orientations and depths, making them especially effective for these threat profiles. The non-contact nature of EMAT enables reliable inspections through coatings and internal debris, an essential capability for the varied field conditions of natural gas pipelines transitioning to hydrogen.

3.1.4.2 Inspection of Welds and Heat-Affected Zones

Welds and HAZs in pipelines repurposed for hydrogen present microstructural heterogeneity and elevated residual stresses, making them susceptible to HIC. A comprehensive study conducted by NIST in 2025 evaluated fracture toughness across welds, HAZs, and base material in environments ranging from air to high-pressure hydrogen.[15] The findings revealed that hydrogen significantly degrades toughness in both weld metal and HAZ regions, underscoring the necessity for targeted inspection strategies.

EMAT's ability to generate ultrasonic waves without a liquid couplant enables effective in-line detection of weld flaws, such as lack of fusion, porosity, and hot cracks, even in the presence of coatings or residues. Furthermore, EMAT can detect subtle changes in the acoustic response caused by microstructural transformations induced by hydrogen exposure, enabling both flaw detection and material condition assessment with a single modality.

3.1.4.3 Hard Spot and Inclusion-Related Cracking

Hard spots and non-metallic inclusions pose critical threat areas in hydrogen-service pipelines by acting as stress concentrators and focal zones for HIC. These defects, which may include manganese sulfide, oxide inclusions, or carburization zones, exacerbate local hydrogen embrittlement under stress. EMAT is adept at identifying such features due to their differing acoustic impedance compared to the surrounding steel matrix. As detailed in the EMAT product literature from T.D. Williamson (TDW), the SpirALL® EMAT system is able to detect both surface-breaking and mid-wall laminar anomalies, including hard inclusions, while maintaining high signal fidelity in gas environments.[16] This capability is particularly valuable in hydrogen pipelines, where even minor inclusions can accelerate crack initiation and propagation rates, thereby impacting overall structural integrity.

3.1.4.4 Quantitative Crack Sizing and Orientation

Precise sizing and orientation measurements of cracks are essential for informing IM decisions, particularly given the accelerated crack growth rates encountered in hydrogen environments. EMAT's use of guided-wave modes facilitates quantitative assessment: multi-channel, dual-path systems allow inferring crack depth, length, and orientation through signal attenuation, time-of-flight, and mode conversion characteristics.

The EMAT-C Ultra tool, as detailed in a 2025 Pipeline Pigging & Integrity Management (PPIM) Conference paper, doubles the standard sensor coverage, enabling higher-resolution results and improved overall coverage of the pipeline.[17] It applies both clockwise and counterclockwise sound paths to enable redundant data acquisition and enhance sizing accuracy. Data from these systems support probabilistic failure models and pipeline re-rating decisions, which are critical in hydrogen-service pipelines where conventional fracture toughness is reduced. This quantitative insight helps operators optimize hydrotest regimes, excavation scheduling, and fitness-for-service evaluations.

3.1.4.5 Challenges and Considerations

While EMAT offers distinct advantages, the technology faces several challenges when applied in hydrogen pipeline service. EMAT-generated signals typically exhibit lower amplitude than conventional ultrasonics, requiring advanced filtering and amplification techniques to improve the signal-to-noise ratio without introducing artifacts.

Hydrogen also affects material properties, such as grain boundary cohesion and attenuation behavior, which can alter wave propagation characteristics and complicate the interpretation of defect signals. Calibration baselines established using air-service steels may not directly translate to hydrogen-exposed pipeline sections.

Validation of EMAT sizing and detection accuracy will also need representative test specimens containing hydrogen-exposed defects, which are currently limited. Finally, integrating EMAT modules into compact ILI platforms necessitates careful consideration of tool geometry, flow dynamics, and power management to ensure operational reliability over long pipeline lengths transitioning to hydrogen service.

3.1.5 Deformation Technologies

Caliper tools, also known as geometry or deformation pigs, employ mechanical arms to capture the internal diameter profile of pipelines with high precision. These mechanical probes continuously record diameter variations, identifying anomalies such as dents, ovalities, buckles, and weld features. Providers deliver 3D mapping capabilities, detecting deviations such as bulges, buckling, and ovality across pipeline diameters from 4 inches to 52 inches.

High-resolution variants employ multiple circumferential calipers to ensure full coverage and minimize lift-off, thereby improving detection accuracy for even minor deformations. The geometric data derived from caliper inspections is critical for assessing risks related to hydrogen-induced material changes. In hydrogen-service pipelines, internal pressurization and phase transformations can result in subtle strain and diameter reduction. High-resolution caliper measurements allow for precise quantification of this mechanical deformation. By providing benchmarks before and after hydrogen exposure, caliper-derived geometric profiles aid in corrosion management, strain tracking, and validation of fitness-for-service assessments.

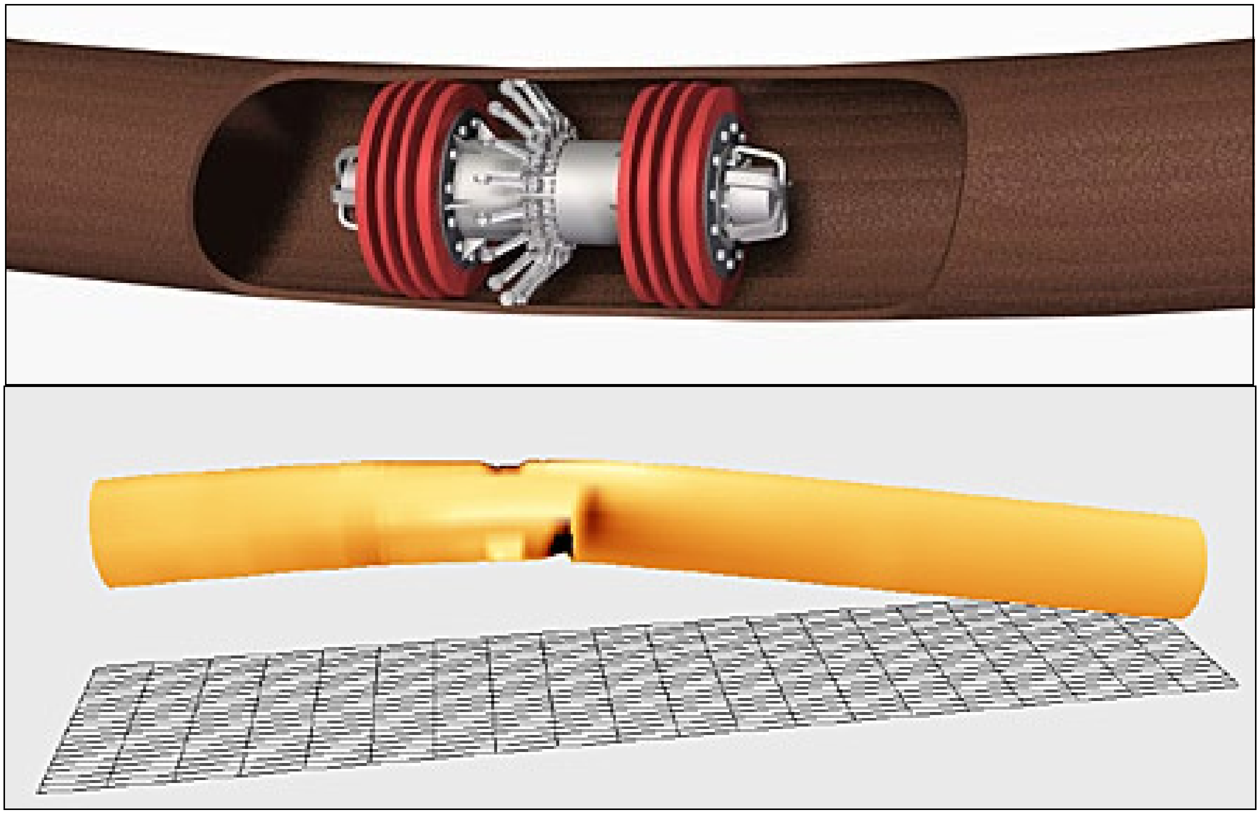

Figure 6. Illustration of Caliper ILI Tool and the Types of Applicable Mechanical Damage Defects

High-resolution deformation (DEF) tools advance pipeline integrity assessment by detecting minute changes in internal geometry down to a fraction of a percent of nominal pipe diameter. TDW's DEF system achieves ±0.5 % accuracy in dent depth and ±0.15 % in expansions by utilizing circumferential sensor arrays that ride directly on the pipe wall. These tools identify local features, such as buckle expansions, re-rounding, wrinkle bends, and welded seam anomalies, providing essential context for mechanical damage analysis.

When employed in pipelines exposed to hydrogen, DEF tools can detect the subtle, progressive deformation patterns associated with phase changes, hydrogen-enhanced creep, or fatigue strain. These data provide operators with actionable insights to guide dig prioritization and long-term assessment strategies. Moreover, when integrated with multi-dataset inspection platforms that combine MFL and inertial measurements, DEF tools enable holistic evaluation of hydrogen-related anomalies and ensure pipeline IM keeps pace with emerging risk profiles.

Inertial measurement units (IMUs) are increasingly integrated into ILI platforms to provide precise 3D mapping and pipeline positioning capabilities, especially when global positioning system (GPS) measurements are not feasible, such as in subsea or buried environments. IMU systems typically combine tactical-grade gyroscopes and accelerometers, recording at high sample rates (200–400 Hz) to track the tool's trajectory and changes in altitude.

IMU-enhanced pig tools, such as IPOZ's LDS4 and NDT Global's IMU modules, deliver sub-meter spatial accuracy by processing raw inertial data to correct for drift and environmental effects. The relationship between IMU and geometry data significantly enhances defect localization accuracy, enhancing position-based diagnostics for dents, weld flaws, or buckles.

In hydrogen-service pipelines, where precise geo-referencing supports strain mapping, terrain movement monitoring, and defect correlation across repeated runs, IMU data is indispensable. By enabling accurate alignment of defect locations over time, IMU-derived spatial mapping underpins advanced IM and requalification workflows necessary for safe hydrogen operation.

3.1.5.1 Detection of Metal Loss from Corrosion and Mechanical Damage

While DEF tools are not designed for direct metal loss detection, they play a complementary role in identifying geometric distortions that often accompany corrosion or mechanical damage. For example, localized wall thinning can lead to ovality or expansion under pressure, which high-resolution caliper tools can detect with sub-millimeter accuracy. When integrated with MFL or ultrasonic modules, deformation data enhances interpretation by correlating shape changes with corrosion patterns. In hydrogen-service pipelines, where embrittlement and localized corrosion may accelerate deformation, these tools provide early indicators of structural compromise.

3.1.5.2 Identification of Dents and Gouges

Caliper and DEF tools excel at detecting dents, gouges, and wrinkles, all of which are features that significantly increase the risk of crack initiation in hydrogen environments. Mechanical dents introduce stress concentration zones, and when combined with hydrogen embrittlement, these areas become critical points of failure. Advanced DEF tools utilize circumferential sensor arrays to measure dent depth, shape, and interaction with weld seams, achieving accuracy within ±0.5% of the nominal diameter. This precision supports strain-based assessments and prioritization of repairs before hydrogen-induced degradation accelerates the growth of cracks.

3.1.5.3 Hard Spots and Magnetic Anomalies

Although DEF tools do not directly detect metallurgical hard spots, they can identify geometric distortions associated with localized hardness variations, such as bulging or re-rounding. When paired with magnetic anomaly detection systems, operators can correlate deformation signatures with potential hard spots or inclusions. This integration is particularly relevant for hydrogen pipelines, where hard spots act as initiation sites for HIC. Combining deformation and magnetic data enables a more holistic integrity assessment.

3.1.5.4 Crack Detection and Sizing

Deformation technologies are not primary crack detection tools. However, they provide critical context for crack susceptibility. Dents, wrinkles, and ovalities identified by caliper or DEF tools often coincide with areas of high strain, where cracks are most likely to initiate and propagate under hydrogen exposure. By mapping these geometric anomalies and integrating them with EMAT or UTCD data, operators can prioritize inspections and excavations in regions of compounded risk.

3.1.5.5 Challenges and Considerations

Deploying DEF tools in hydrogen-service pipelines introduces unique challenges. First, hydrogen-induced changes in steel microstructure can alter deformation behavior, making historical benchmarks less reliable. Second, interpreting deformation data requires careful consideration of pressure cycling and thermal effects, which may differ in hydrogen blends compared to regular natural gas. Third, tool passage in pipelines with tight bends or restrictions demands a robust design to prevent lift-off and ensure accurate measurements. Finally, integrating deformation data with other inspection modalities, such as EMAT for cracks and MFL for corrosion, requires advanced data fusion techniques to deliver actionable insights for hydrogen IM. Caliper, DEF, and IMU tools provide valuable information to distinguish between simply coinciding and potentially detrimental interacting defects.

3.1.6 Specialized Multi-Data Set Tool Technologies

ILI vendors are constantly working to solve the problems the industry is currently facing, and this often involves working with multiple sets of data to arrive at a more informed final answer regarding what the tool has detected in isolation. By understanding the principles of metallography and material science, combining data sets gives insight into the material properties of the pipe. The volumetric and/or planar defects detected by various ILI technologies can be assessed to gain a more accurate understanding of the pipeline's true condition. Particularly when hydrogen is involved, the need for thorough information to interpret the data received and reported by ILI is crucial to provide insight into the potential threats of interest.

3.1.6.1 Novitech: Micron CD-360™ Crack Detection

As a technical advisory panel (TAP) member and co-sponsor on this project, Novitech has provided information about its Micron CD-360™ Crack Detection ILI tool.[18] This tool utilizes several streams of ILI-based NDE technologies to identify anomalies for assessment. Novitech staff have published several research papers to support the development of their tools for detecting and sizing anomalies of interest, particularly those highly impacted by the introduction of hydrogen, such as cracking.[19]

An example of how Novitech uses its data to get better tool performance for the threats that may impact lines with hydrogen or blended hydrogen is shown in Figure 7. Off-axis cracking has historically been difficult to detect and size due to its unique geometric nature. There is minimal validation data to confirm the defect information and feed it back into the tool for improved algorithm processing.[20] Novitech has combined the use of their circumferential MFL (CMFL), axial MFL (AMFL), Geometry, Residual Field, and Internal Depth Detection – Stress Measurement™ (IDD-SM™) data.

There is a minimum crack tip opening required for the MFL technology to detect the defect. Due to the physical limitations of MFL, this is to be expected. However, combining the data from multiple sources of technologies ultimately allows improved identification of the defect type.

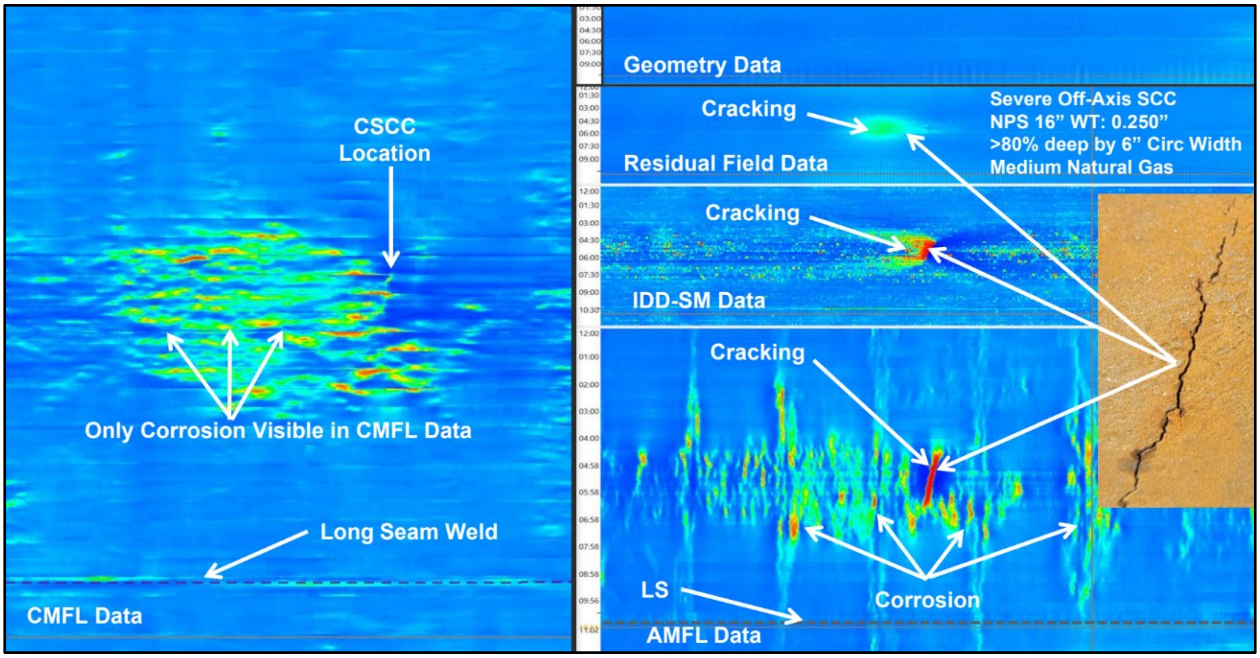

Figure 7. Signals of Data Provided by Novitech of Off-Axis Cracking Indication

Novitech is not the only ILI vendor to provide these services. TDW, Rosen, and others are introducing additional capabilities to integrate and optimize their combination tools and technologies, providing the most thorough evaluation of the current state of the pipe.

3.1.6.2 T.D. Williamson (TDW): MDS™ Pro Multi-Dataset ILI

The MDS™ Pro platform from TDW is an advanced ILI solution designed to address a wide range of pipeline integrity threats, including those associated with hydrogen service. This tool is shown in Figure 8 with five modules on it, integrating multiple technologies, Ultra-Resolution Axial MFL, SpirALL® MFL, Low-Field MFL (LFM), DEF, and XYZ mapping, into a single inspection run. This approach enables improved detection of corrosion, mechanical damage, and geometric anomalies, while also supporting material verification and bending strain analysis.

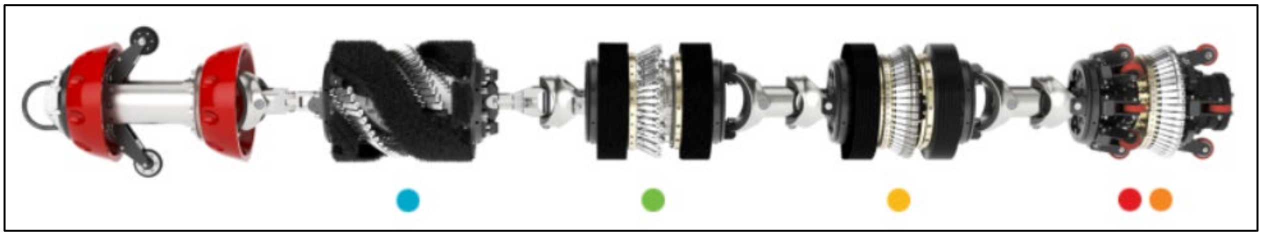

Figure 8. TDW's MDS™ Pro with Ultra Res MFL Technology Tool Configuration

This tool configuration has the ability to detect crack-like anomalies, such as fatigue cracks, SCC, and HIC, when paired with EMAT technology. TDW is also able to provide capability in identifying and characterizing circumferential SCC (CSCC).[21] These threats are particularly critical in hydrogen environments, where embrittlement can compromise pipeline integrity.

High-density sensor arrays, combined with multiple MFL technologies, enable the precise sizing of pinholes, complex corrosion patterns, and interacting defects, such as dents with corrosion. Additionally, material property mapping and pipe joint classification features help operators verify pipeline materials and manage integrity programs with greater confidence.

3.1.6.3 Rosen Multi-Technology Inspection Solutions

Rosen does not offer a specific hybrid tool, as Novitech and TDW have established, but they recognize the need to integrate multiple technologies to achieve similar conclusions and outputs for pipeline integrity assessments using ILI.

Rosen has developed a modular ILI platform[22] that integrates multiple technologies, such as MFL, UT, EMAT, geometry measurement, and inertial mapping, into a single inspection run. This multidata set approach enables operators to capture comprehensive integrity data, including metal loss, deformation, and variations in material properties, while minimizing operational downtime.[23] By combining these data sets, Rosen's system supports advanced integrity assessments and improves detection accuracy for interacting threats, such as dents with corrosion or gouges.

Rosen's EMAT Ultra technology is specifically designed for hydrogen service. EMAT Ultra uses dual sound-path scanning and expanded sensor coverage, achieving a 95% POD for critical cracks.[24] This capability is essential for identifying HIC and SCC, which are primary concerns in hydrogen environments due to embrittlement mechanisms. The RoCD EMAT-C Ultra service further enhances resolution, detecting axial and longitudinal cracks as small as 20×2 mm, while maintaining POD and probability of identification (POI) rates that exceed industry benchmarks. These features make Rosen's tools highly suitable for pipelines transitioning to hydrogen or operating under mixed-energy conditions.

3.2 Integrity Threat Assessment Classification

3.2.1 Pipeline Operators Forum ILI Hydrogen Readiness Research

Based on this review and the associated updates, the threats are known and understood. However, classifying threats based on ILI data can be challenging, as not every threat is managed by ILI. Furthermore, the detection limitations of readily available ILI technologies may not be sufficient to accurately address the threat.

The Pipeline Operator's Forum (POF) document POF 520, In-Line Inspection Tool Readiness for Hydrogen Pipeline,[25] offers guidance on the degradation, or threat, and how it is perceived by the ILI tool. POF 520 defines the nomenclature by the morphology or appearance of the defect that can be reported by a particular ILI technology, see Table 6. Mapping the POF-defined threat morphologies detected by ILI back to the hydrogen-related threats identified as of high significance from Task 2,[26] shows that not all threats can be sufficiently captured by ILI for gas pipelines.

Table 6. POF 520; ILI Tool Readiness for Hydrogen Pipeline Threat Assessment

Degradation/ Threat	Morphology/ Appearance	ILI Technology	Applicable to NG	Sufficient Performance for H_2 Lines
Internal and/or External Corrosion	Metal Loss - general and circumferential	Axial MFL	Yes	Sufficient for most cases
Internal and/or External Corrosion	Metal Loss - general and axial	Circumferential MFL	Yes	Sufficient for most cases
Internal and/or External Corrosion	Metal Loss	Liquid coupled UT	No	Sufficient for most cases
Internal and/or External Corrosion	Metal Loss	Gas coupled resonance UT	Depends	Sufficient for most cases
HE Fatigue	Axial planar anomalies (Int+Ext)	Liquid coupled UT	No	Sufficient for most cases
HE Fatigue	Axial planar anomalies (Int+Ext)	EMAT	Yes	Sufficient for some but not all cases / unknown
HE Fatigue	Circumferential planar anomalies (Int+Ext)	Liquid coupled UT	No	Sufficient for some but not all cases / unknown
HE Fatigue	Axial planar anomalies (Int+Ext)	Gas coupled Lamb waves (in development)	Depends	Sufficient for some but not all cases / unknown
HE Fatigue	Surface breaking planar anomalies (Int)	Eddy Current (EC) (in development)	Yes	Sufficient for some but not all cases / unknown
HE Fatigue	Laminations	Liquid coupled UT	No	Sufficient for most cases
Geohazard	Bending strain	EM Geometry + IMU	Yes	Sufficient for most cases
Geohazard	Axial strain	EC based Stress measurement	Yes	Sufficient for some but not all cases / unknown
Geohazard	Circumferential planar anomalies (Int+Ext)	Liquid coupled UT	No	Sufficient for some but not all cases / unknown
Third Party Damage	Dents	EM Geometry	Yes	Sufficient for most cases
Third Party Damage	Dents	Liquid coupled UT Geometry	No	Sufficient for most cases
Third Party Damage	Gouges	Geometry + MFL	Yes	Sufficient for most cases
Pipe Material	Hard spots	EM or low-field MFL	Yes	Sufficient for some but not all cases / unknown
Pipe Material	Pipe grade	MFL and/or low-field MFL	Yes	Sufficient for some but not all cases / unknown

3.2.2 NACE SP0102-2017 Table 1 Tool Technology Guidance

NACE SP0102-2017[27] is intended to serve as a guide, providing operators with a starting point to understand what ILI technologies can detect and size. NACE SP0102-2017 Table 1 (full table provided in APPENDIX A – NACE SP0102-2017 Table 1) provides an overview of types of ILI tools that may be appropriate for certain anomaly types. The table is currently organized by the type of anomaly that the tool can detect, including metal loss, cracking, and deformation.

The following list identifies the technologies that can both detect and size anomalies without special setup requirements, as outlined in NACE SP0102-2017, Table 1. There are several limitations that must be understood when applying ILI technologies, particularly the fact that many ILI tools require specific setups and modifications to capture the anomalies of interest.

NACE SP0102-2017 Table 1: Types of ILI Tools and Inspection Purposes

- (1) Metal Loss Tools
  - (1) Axial MFL
    - (1) Metal Loss: External Corrosion
    - (2) Metal Loss: Internal Corrosion
    - (3) Weld Anomalies: Girth Weld Anomaly (voids, etc.)
  - (2) Ultrasonic Compression Wave
    - (1) Metal Loss: External Corrosion
    - (2) Metal Loss: Internal Corrosion
    - (3) Crack-Like Anomalies: Narrow Axial External Corrosion
    - (4) Weld Anomalies: Girth Weld Anomaly (voids, etc.)
    - (5) Misc. Components: Thermite Welds
    - (6) Misc. Damage: Laminations
    - (7) Misc. Damage: Inclusions
- (2) Crack Detection Tools
  - (1) Liquid Coupled
    - (1) Crack-Like Anomalies: Narrow Axial External Corrosion
    - (2) Crack-Like Anomalies: SCC
    - (3) Crack-Like Anomalies: Fatigue Cracks
    - (4) Crack-Like Anomalies: Long Seam Cracks, etc. (toe cracks, hook cracks, incomplete fusion, preferential seam corrosion)
    - (5) Weld Anomalies: Lack of fusion in Long-Seam Weld (LSW)
  - (2) EMAT
    - (1) Crack-Like Anomalies: Narrow Axial External Corrosion
    - (2) Crack-Like Anomalies: SCC
    - (3) Crack-Like Anomalies: Fatigue Cracks
    - (4) Crack-Like Anomalies: Long Seam Cracks, etc. (toe cracks, hook cracks, incomplete fusion, preferential seam corrosion)
    - (5) Weld Anomalies: Lack of fusion in LSW
  - (3) Transverse MFL
    - (1) Metal Loss: External Corrosion
    - (2) Metal Loss: Internal Corrosion

(3) Weld Anomalies: Girth Weld Anomaly (voids, etc.)

(3) Deformation Tools

(1) Deformation: Sharp Dents

(2) Deformation: Flat Dents

(3) Deformation: Buckles

(4) Deformation: Wrinkles, Ripples

(5) Deformation: Ovalities

3.2.3 Threat Assessment Classification Integration

Making a clear distinction between anomalies, threats, and defects is critically important in ILI assessments. This section explores these concepts by examining the relationship between these terms and their application in industry standards from various perspectives. It then extends the discussion for hydrogen-specific threats.

ASME B31.8S-2025 considers integrity from the viewpoint of identifying threats, but not all threats are named. This threat list in this standard is more than 25 years old and is due for an update to be more comprehensive. Furthermore, hydrogen-specific threats are currently not included. Currently, a Hydrogen Task Group of the ASME B31.8 Operations and Maintenance Committee is working to update ASME B31.8 and B31.8S for hydrogen applications.

NACE SP0102-2017 discusses which ILI technologies can detect and size different anomaly techniques; however, this standard is approximately eight years old. ILI technologies have continued to evolve, and new and diverse ILI capabilities are now available. The next revision, NACE SP0102-202X, is expected to discuss which anomalies can be detected and sized by different ILI technologies. This is very different, because the revised standard will be centered around the tools rather than around the anomalies.

3.2.3.1 Integrity Threats Versus Detectable Anomalies

What is missing in NACE SP0102-2017, Table 1, is tracking anomalies back to the associated threat as defined within ASME B31.8S-2025. Currently, the AMPP Committee SC-10 "Asset Integrity Management", responsible for NACE SP0102, is working on the next revision (NACE SP0102-202X). As part of that revision, Table 1 is also undergoing an industry review to update it with technologies relevant to the types of anomalies it can detect and size.

The proposed updates (still in committee) include a revision to identify the technology applied and address the specific configuration of that technology. That can then be used to determine the type of anomaly that the ILI technology can either size or detect, rather than stating the generic anomalies addressed and then listing the technology under that category.

To address the lack of threat identification, the portion of the table that shows the anomaly and associated "Imperfection/Defect/Feature" has been edited for this project to include the associated threat from ASME B31.8S-2025 and color-coded to assess the impact of hydrogen on that threat, see Table 7.

Table 7. NACE SP0102-202X Anomaly Versus Imperfection/Defect/Feature and Associated ASME B31.8S-2025 Threat

Anomaly Type	Integrity Threats per ASME B31.8S-2025 and Additional Proposed Threats per Task 2 of Current Study	Imperfection/Defect/Feature
Metal Loss	Time Dependent: External Corrosion	External Corrosion
Metal Loss	Time Dependent: External Corrosion	Narrow Axial External Corrosion [1]
Metal Loss	Time Dependent: Internal Corrosion	Internal Corrosion
Metal Loss	Time Dependent: Internal Corrosion	Narrow Axial Internal Corrosion [1]
Metal Loss	Random/Time Independent: Previous Damage (Gouge)	Gouging
Crack-Like	Time Dependent: SCC	Axial Stress Corrosion Cracking (SCC)
Crack-Like	Time Dependent: SCC	Non-Axial or Circumferential Stress Corrosion Cracking (SCC)
Crack-Like	Time Dependent: Fatigue Cracking	Axial Cracks (Fatigue, HIC)
Crack-Like	Time Dependent: Fatigue Cracking	Non-Axial Cracks (Fatigue, HIC)
Weld Anomalies	Resident: Manufacturing Defect (Seam Crack)	Long Seam Manufacturing Anomalies (toe cracks, hook cracks, lack of fusion)
Weld Anomalies	Time Dependent: External Corrosion	Selective Seam Weld Corrosion (SSWC)
Weld Anomalies	Resident: Defective Construction (Girth Weld Anomalies)	Girth Weld Anomaly (voids, etc.)
Deformation	Random/Time Independent: Mechanical Damage (Previous Damage: Dents/Gouges)	Dents
Deformation	Resident: Defective Construction (Wrinkle Bend/Buckle)	Buckles, Wrinkles, Ripples
Deformation	*Not a threat in B31.8S-2025 – affects evaluation of other defects*	Ovalities
Misc. Components	Time Dependent: Cracking (Fitting and Sharp Transitions) [2]	In-Line Valves and Fittings
Misc. Components	*Not a threat defined in B31.8S-2025*	Casings
Misc. Components	*Not a threat defined in B31.8S-2025*	Eccentric / Shorted Casings
Misc. Components	Resident: Defective Construction or Fabrication (Wrinkle Bend)	Bends
Misc. Components	Resident: Defective Construction or Fabrication (Fabrication Welds)	Branch Appurtenances / Tees / Hot Taps
Misc. Components	*Not a threat defined in B31.8S-2025*	Close Metal Objects
Misc. Components	*Not a threat defined in B31.8S-2025*	Pipeline Coordinates
Previous Repairs	Resident: Defective Fabrication or Construction (At welded sleeves and fittings) [2]	Type A Sleeve
Previous Repairs	Resident: Defective Fabrication or Construction (At welded sleeves and fittings) [2]	Type B Sleeve
Previous Repairs	*Not a threat defined in B31.8S-2025*	Composite Sleeve
Previous Repairs	*Not a threat defined in B31.8S-2025*	Compression Sleeves
Previous Repairs	Resident: Defective Fabrication or Construction (At welded sleeves and fittings) [2]	Patches / Half Soles
Previous Repairs	*Not a threat defined in B31.8S-2025*	Recoat
Misc. Damage	*Not a threat defined in B31.8S-2025*	Laminations
Misc. Damage	*Not a threat defined in B31.8S-2025*	Inclusions
Misc. Damage	*Not a threat defined in B31.8S-2025*	Cold Work
Misc. Damage	Resident: Manufacturing Defects (Hardspot)	Hard Spots
Misc. Damage	*Not a threat defined in B31.8S-2025*	Grind Marks
Misc. Damage	Random/Time Independent: Natural Events (Geotechnical)	Strain
Misc. Damage	*Not a threat defined in B31.8S-2025*	Scabs / Slivers / Blisters
Misc. Damage	Resident: Equipment (Disbonded coating caused by hydrogen)	External Coating Disbondment

[1] No definition for maximum dimension of corrosion opening
[2] Only applicable in hydrogen environment

The following list presents the proposed modifications to the NACE SP0102-2017 Table 1 categories, which are currently being discussed in the AMPP SC-10 committee. The major change will be that the anomalies will be organized primarily by general tool technology and secondarily by the configuration of the technology. Please note that any proposed changes are not finalized and approved until the balloting process is complete.

Proposed NACE SP0102-202X Table 1: Types of ILI Tools and Inspection Purposes

(1) Magnetic Flux Leakage / Electromagnetic
- (1) Axial MFL
- (2) Non-Axial MFL (Transverse / Circumferential / Helical)
- (3) Residual or Low Field MFL
- (4) Electromagnetic (EM)

(2) Ultrasonic
- (1) Ultrasonic Compression Wave Normal Beam (UT)
- (2) Ultrasonic Shear Wave Angle Beam (UTCD)
- (3) Electromagnetic Acoustic Transducer (EMAT)

(3) Geometry
- (1) Caliper
- (2) High Resolution Deformation
- (3) IMU

3.2.3.2 Hydrogen-related integrity threats

The current study evaluates the tools that can capture the threats that are highly impacted by the presence of hydrogen. Therefore, the content of the above-described tables was further organized to isolate the hydrogen-related threats for each ILI technology in Tables 8, 9, and 10.

Table 8 shows the threats highly impacted by the presence of hydrogen and the associated ability of the most commonly implemented technology, MFL, to detect or size them. Different types of MFL tools include: Axial MFL, Non-Axial MFL, and Residual or Low-Field MFL. *Note that none of these MFL types can detect and size cracks or crack-like anomalies without some sort of caveat associated.* Those caveats are listed below and provided in Table 8 by letter designations:

(B) If tools are equipped for detection of mechanical damage, otherwise, detection and sizing of metal loss component only.

(C) Detection and sizing of metal loss component only.

(E) Reduced POD for tight cracks, a minimum opening of the crack-like feature is required for detection.

(G) Reduced POD and sizing capabilities depending upon size and shape.

(K) If tool is designed for hard spot detection.

(P) When high field axial MFL is used in conjunction with axial residual or low field.

(Q) Can detect restrained versus unrestrained.

(R) Residual and low-field magnetization can be used to differentiate between type A and type B sleeves.

Table 9 shows the threats highly impacted by the presence of hydrogen and the associated ability of ultrasonic technology to detect or size them. Different types of UT tools include the Ultrasonic Compression Wave Normal Beam, the Ultrasonic Shear Wave Angle Beam (UTCD), and the EMAT.

Note that ultrasonics are not typically capable of operating in a gas-coupled environment; instead, they require a liquid couplant, which limits the use of UT tools in hydrogen blend lines.

Research suggests running UT tools prior to introducing hydrogen into the line would be advisable. EMAT offers a unique advantage in that it can be run without requiring a liquid couplant. Therefore, EMAT may be the most advantageous technology to apply to lines with hydrogen or hydrogen blends. The caveats of the technologies are listed below, as provided in Table 9 by letter designations:

> *(C) Detection and sizing of metal loss component only.*
>
> *(F) Using modified sensor carrier with transducers rotated by 90 degrees.*
>
> *(G) Reduced POD and sizing capabilities depending upon size and shape.*

Table 10 shows the threats highly impacted by the presence of hydrogen and the associated ability of geometry tools to detect and size. Obviously, these tools are designed for dent detection and sizing, so that is the primary threat that will be captured. However, there is also a benefit in detecting Type B sleeves and patches, or half soles. The caveats of the technologies are listed below, as provided in the table by letter designations:

> *(B) If tools are equipped for detection of mechanical damage, otherwise, detection and sizing of metal loss component only.*
>
> *(C) Detection and sizing of metal loss component only.*
>
> *(E) Reduced POD for tight cracks, a minimum opening of the crack-like feature is required for detection.*
>
> *(G) Reduced POD and sizing capabilities depending upon size and shape.*
>
> *(K) If tool is designed for hard spot detection.*
>
> *(P) When high field axial MFL is used in conjunction with axial residual or low field.*
>
> *(Q) Can detect restrained versus unrestrained.*
>
> *(R) Residual and low-field magnetization can be used to differentiate between type A and type B sleeves.*

A review of the technologies most applicable to gas pipeline accessibility and configuration for hydrogen implementation, in relation to the highest threats, was conducted to provide recommendations. Ultrasonic compression wave normal beam and shear wave angle beam tools were not considered due to the complexity of application for the majority of gas product pipelines. The resulting recommendations for the most applicable and secondary technologies are shown in Table 11. EMAT provides significant benefits to the overall application for detecting and sizing axially oriented cracking, as well as for detecting external coating disbondment. Using a combination of Axial, Non-Axial, and Residual or Low-Field MFL tools provides the most comprehensive approach for evaluating gas pipelines for the threats most impacted by the presence of hydrogen. However, there are limitations to the detection capabilities of MFL for cracking anomalies. As an operator selecting tool technologies, it will be important to validate and verify the tool performance to ensure the POD and accuracy of identification are sufficient to respond to any defects, particularly those that are time-dependent, prior to the potential time to failure for the anomaly of interest.

Table 8. NACE SP0102-2017 Table 1 with Proposed Revisions – for Threats Highly Affected by Hydrogen, for MFL ILI Tools

Associated Threat Defined in ASME B31.8S	Imperfection/Defect/Feature	Axial MFL	Non-Axial MFL	Residual or Low Field MFL
Random/Time Independent: Previous Damage (Gouge)	Gouging	Detection (B), Sizing (B)	Detection (B), Sizing (B)	Detection (B), Sizing (B)
Time Dependent: SCC	Axial Stress Corrosion Cracking (SCC)	No Detection	Limited Detection, Sizing (E)	No Detection
Time Dependent: SCC	Non-Axial or Circumferential Stress Corrosion Cracking (SCC)	Detection (P), Limited Sizing (E)	No Detection	Detection (P)
Time Dependent: Fatigue Cracking	Axial Cracks (Fatigue, HIC)	No Detection	Limited Detection, Sizing (E)	Limited Detection, Sizing (E)
Time Dependent: Fatigue Cracking	Non-Axial Cracks (Fatigue, HIC)	Detection (P), Limited Sizing (E)	No Detection	Detection (P)
Resident: Manufacturing Defects (Seam Crack)	Long Seam Manufacturing Anomalies (toe cracks, hook cracks, lack of fusion	No Detection	Limited Detection, Sizing (E)	No Detection
Resident: Defective Construction (Girth Weld Anomalies)	Girth Weld Anomaly (voids, etc.)	Detection, Sizing (C)	Detection, Sizing (C)	Detection
Random/Time Independent: Mechanical Damage (Previous Damage: Dents/Gouges)	Dents	Detection (G)	Detection (G)	Detection (Q)
Resident: Defective Fabrication or Construction (At welded sleeves and fittings)	Type A Sleeve	Detection	Detection	Detection (R)
Resident: Defective Fabrication or Construction (At welded sleeves and fittings)	Type B Sleeve	Detection	Detection	Detection (R)
Resident: Defective Fabrication or Construction (At welded sleeves and fittings)	Patches / Half Soles	Detection	Detection	Detection
Resident: Manufacturing Defects (Hardspot)	Hard Spots	Detection (K)	Detection (K)	Detection
Resident: Equipment (Disbonded coating caused by hydrogen)	External Coating Disbondment	No Detection	No Detection	No Detection

Table 9. NACE SP0102-2017 Table 1 with Proposed Revisions – for Threats Highly Affected by Hydrogen, for Ultrasonic ILI Tools

Associated Threat Defined in ASME B31.8S	Imperfection/Defect/Feature	Ultrasonic Compression Wave Normal Beam	Ultrasonic Shear Wave Angle Beam (UTCD)	Electromagnetic Acoustic Transducer (EMAT)
Random/Time Independent: Previous Damage (Gouge)	Gouging	Detection (C), Sizing (C)	No Detection	No Detection
Time Dependent: SCC	Axial Stress Corrosion Cracking (SCC)	No Detection	Detection, Sizing	Detection, Sizing
Time Dependent: SCC	Non-Axial or Circumferential Stress Corrosion Cracking (SCC)	No Detection	No Detection	No Detection
Time Dependent: Fatigue Cracking	Axial Cracks (Fatigue, HIC)	No Detection	Detection, Sizing	Detection, Sizing
Time Dependent: Fatigue Cracking	Non-Axial Cracks (Fatigue, HIC)	No Detection	No Detection	No Detection
Resident: Manufacturing Defects (Seam Crack)	Long Seam Manufacturing Anomalies (toe cracks, hook cracks, lack of fusion	No Detection	Detection, Sizing	Detection, Sizing
Resident: Defective Construction (Girth Weld Anomalies)	Girth Weld Anomaly (voids, etc.)	Detection, Sizing (C)	Detection, Sizing (F)	No Detection
Random/Time Independent: Mechanical Damage (Previous Damage: Dents/Gouges)	Dents	Detection (G)	No Detection	No Detection
Resident: Defective Fabrication or Construction (At welded sleeves and fittings)	Type A Sleeve	No Detection	No Detection	No Detection
Resident: Defective Fabrication or Construction (At welded sleeves and fittings)	Type B Sleeve	Detection	Detection	Detection
Resident: Defective Fabrication or Construction (At welded sleeves and fittings)	Patches / Half Soles	Detection	Detection	Detection
Resident: Manufacturing Defects (Hardspot)	Hard Spots	No Detection	No Detection	No Detection
Resident: Equipment (Disbonded coating caused by hydrogen)	External Coating Disbondment	No Detection	No Detection	Detection, Sizing

Table 10. NACE SP0102-2017 Table 1 with Proposed Revisions – for Threats Highly Affected by Hydrogen, for Geometry ILI Tools

Associated Threat Defined in ASME B31.8S	Imperfection/Defect/Feature	Caliper	High Resolution Deformation	IMU
Random/Time Independent: Previous Damage (Gouge)	Gouging	No Detection	No Detection	No Detection
Time Dependent: SCC	Axial Stress Corrosion Cracking (SCC)	No Detection	No Detection	No Detection
Time Dependent: SCC	Non-Axial or Circumferential Stress Corrosion Cracking (SCC)	No Detection	No Detection	No Detection
Time Dependent: Fatigue Cracking	Axial Cracks (Fatigue, HIC)	No Detection	No Detection	No Detection
Time Dependent: Fatigue Cracking	Non-Axial Cracks (Fatigue, HIC)	No Detection	No Detection	No Detection
Resident: Manufacturing Defects (Seam Crack)	Long Seam Manufacturing Anomalies (toe cracks, hook cracks, lack of fusion	No Detection	No Detection	No Detection
Resident: Defective Construction (Girth Weld Anomalies)	Girth Weld Anomaly (voids, etc.)	No Detection	No Detection	No Detection
Random/Time Independent: Mechanical Damage (Previous Damage: Dents/Gouges)	Dents	Detection, Sizing	Detection, Sizing	Limited Detection
Resident: Defective Fabrication or Construction (At welded sleeves and fittings)	Type A Sleeve	No Detection	No Detection	No Detection
Resident: Defective Fabrication or Construction (At welded sleeves and fittings)	Type B Sleeve	Detection	Detection	No Detection
Resident: Defective Fabrication or Construction (At welded sleeves and fittings)	Patches / Half Soles	Detection	Detection	No Detection
Resident: Manufacturing Defects (Hardspot)	Hard Spots	No Detection	No Detection	No Detection
Resident: Equipment (Disbonded coating caused by hydrogen)	External Coating Disbondment	No Detection	No Detection	No Detection

Table 11. Recommended ILI Technologies for Highly Impacted Hydrogen Threats Based on NACE SP0102 Guidance

Associated Threat Defined ASME B31.8S	Imperfection/Defect/Feature	Most Applicable Technology for Gas Lines	Capability	Secondary Technology for Gas Lines	Capability
Random/Time Independent: Previous Damage (Gouge)	Gouging	Axial, Non-Axial, Residual or Low Field MFL	Detection (B), Sizing (B)	Ultrasonic Compression Wave Normal Beam	Detection (C), Sizing (C)
Time Dependent: SCC	Axial Stress Corrosion Cracking (SCC)	EMAT	Detection, Sizing	Non-Axial MFL	Limited Detection, Sizing (E)
Time Dependent: SCC	Non-Axial or Circumferential Stress Corrosion Cracking (SCC)	Axial MFL	Detection (P), Limited Sizing (E)	Residual or Low Field MFL	Detection (P)
Time Dependent: Fatigue Cracking	Axial Cracks (Fatigue, HIC)	EMAT	Detection, Sizing	Non-Axial, Residual or Low Field MFL	Limited Detection, Sizing (E)
Time Dependent: Fatigue Cracking	Non-Axial Cracks (Fatigue, HIC)	Axial MFL	Detection (P), Limited Sizing (E)	Residual or Low Field MFL	Detection (P)
Resident: Manufacturing Defects (Seam Crack)	Long Seam Manufacturing Anomalies (toe cracks, hook cracks, lack of fusion	EMAT	Detection, Sizing	Non-Axial MFL	Limited Detection, Sizing (E)
Resident: Defective Construction (Girth Weld Anomalies)	Girth Weld Anomaly (voids, etc.)	Axial, Non-Axial, Residual or Low Field MFL	Detection, Sizing (C)	Residual or Low Field MFL	Detection
Random/Time Independent: Mechanical Damage (Previous Damage: Dents/Gouges)	Dents	Caliper, High Res Deformation	Detection, Sizing	Caliper or High Res Deformation	Detection (G)
Resident: Defective Fabrication or Construction (At welded sleeves and fittings)	Type A Sleeve	Axial, Non-Axial, Residual or Low Field MFL	Detection		
Resident: Defective Fabrication or Construction (At welded sleeves and fittings)	Type B Sleeve	Axial, Non-Axial, Residual or Low Field MFL, Caliper, or High Res Deformation	Detection	EMAT	Detection
Resident: Defective Fabrication or Construction (At welded sleeves and fittings)	Patches / Half Soles	Axial, Non-Axial, Residual or Low Field MFL, Caliper, or High Res Deformation	Detection	EMAT	Detection
Resident: Manufacturing Defects (Hardspot)	Hard Spots	Residual or Low Field MFL	Detection	Axial or Non-Axial MFL	Detection (K)
Resident: Equipment (Disbonded coating caused by hydrogen)	External Coating Disbondment	EMAT	Detection, Sizing		

3.3 Probability of Identification

3.3.1 Industry Guidance: API 1163 3rd Edition (2021)

API 1163-2021 "In-Line Inspection Systems Qualification" [28] provides a guideline for understanding the performance of an ILI tool, regardless of the technology applied and the pipeline in which it is run. In addition to providing insight into the sizing and detection methods for determining the characteristics of anomalies, this document calls for determining the POI. Identification of a feature is paramount to understanding the delineation of the characterization, because the type of assessment method and mitigation decisions for that anomaly hinge upon that characterization.

An ILI tool performance specification will define the system's capabilities and its ability to detect, locate, identify, size, and characterize anomalies. The example for Characterizing Cracking POIs from Section 6.2.4 of API 1163 3rd Edition is reproduced in Table 12 in this report. The validation process for all ILI tools should include a review of the POI to ensure proper assessment methods are applied for remediation and mitigation.

Note that the 3rd edition of API 1163 is not incorporated by reference into the regulatory requirements 49 CFR 192. Currently, the 2nd edition issued in 2013 is the latest version required by regulation to be used, but the majority of the content and the emphasis on POI remain for understanding the anomalies reported by ILI.

Table 12. Reproduction of API 1163 3rd Edition Table 4--Example of Characterizing Cracking POIs

Table 4—Example of Characterizing Cracking POIs

Type	Qualifiers and Limitations	Crack Depth	POI
Isolated crack	In body of pipe	1 mm	90 %
	Adjacent long seam	1.5 mm	80 %
	Adjacent girth weld	3 mm	70 %
Crack colony	In body of pipe	1.2 mm	90 %
	Adjacent long seam	1.8 mm	80 %
	Adjacent girth weld	2.75 mm	70 %

NOTE POI can be a function of crack depth, length, and other factors.

3.3.2 ILI Reporting Review

To evaluate the reported data supplied by ILI vendors from various technologies and to various operators, Kiefner evaluated 11 different reports. The technologies supplied included UT-C, UT-A, MFL-A, Residual MFL, Caliper, XT, and IMU tools.

The results shown in Table 13 classify 49 different naming conventions for the feature/anomaly/events reported by ILI. Ideally, these naming conventions should be standardized, perhaps through the guidance provided in API 1163-2021 or the recommendations for updates to the next revision of NACE SP0102, for various types of features and anomalies. However, in practice, this is challenging because each pipeline is unique, and the circumstances under which the tool is run will vary. This provides varying levels of confidence in detecting and identifying the features.

The ILI vendor is also likely providing as much insight into the anomaly as is possible, either at the request of the Operator or based on their internal protocols, such as is the case with the "Deformation – Field Bend Related", rather than simply identifying a deformation, but associating it with relevant locating information.

Table 13. Example List of Features and Anomalies Reported by 11 Unique ILI Reports

ANOMALY	Fitting	Metal Loss
ATTACHMENT	Girth weld anomaly	Metal Loss Cluster
cluster	GMA (GW SW)	Metal Loss Group
Crack Field	GMA	metal loss-girth weld anomaly
crack field anomaly	Hard spot anomaly (BHN)	metal loss-manufacturing anomaly
Crack Like	*INT MFG	Metal Object
crack like anomaly	Int ML	Mfg. Indication - Mill Defect
Deformation - Dent	Interior Metal Loss	Mill anomaly
Deformation - Dent - Repaired	Interior Metal Loss - Axial Slotting	Multiple Exterior Metal Loss - Pitting
Deformation - Field-Bend Related	Interior Metal Loss - Circ Grooving	Multiple Interior Metal Loss
deformation anomaly-dent	Interior Metal Loss - Mill Related	Multiple Interior Metal Loss - Mill Related
Dent	Interior Metal Loss - Pitting	Multiple Interior Metal Loss - Pitting
dent-detected w/ metal loss	linear girth weld anomaly	Notch Like
*EXT MFG	Linear Long Seam Anomaly	notch like anomaly
Ext ML	manufacturing anomaly	seam weld anomaly-corrosion
Exterior Metal Loss	Manufacturing Indication	Possible buckle/wrinkle
Exterior Metal Loss - Axial Slotting	Material property deviation	
Exterior Metal Loss - Pitting	Hard spot anomaly (BHN)	

Ultimately, the goal is to understand the data reported by ILI and trace it back to the integrity threats defined in ASME B31.8S-2025. There are already lists of defect types provided in NACE SP0102-2017 and API 1163-2021, so these should be used for reporting ILI indications and ensuring that the features are traced to their associated threats in ASME B31.8S-2025.

There is also the issue of coincident versus interacting anomalies to consider. ILI reports will provide the data to predict whether anomalies are coincident but will not necessarily provide an understanding of whether these anomalies are interacting. Interacting anomalies require an evaluation to understand the potential for elevated risk to the threat of failure. This is a separate discussion beyond simply identifying the anomalies and their associated threats, as the method of assessment may differ when anomalies interact. From prior research, additional insights can be incorporated to understand the likelihood that threats could interact and elevate the risk to the pipeline.[29] The concept of interacting threats should be considered as it relates to the impact of hydrogen.

4 DISCUSSION

The primary difficulties with assessing the threats using ILI include:

- There exists no single ILI technology to detect and size all threats that are highly affected by hydrogen.
    - An obvious difficulty for the industry when evaluating pipelines for threats associated with hydrogen blending or full hydrogen pipelines is that the anomalies of interest cannot be identified by a combo of axial MFL and DEF tools, as is typically deployed for IM using ILI tools.
    - Kiefner recommends careful consideration of a combination of axial, non-axial, low-field MFL tools, and DEF tools to be implemented as necessary to detect anomalies and address the impact of hydrogen on the pipeline system.
    - For new or newly converted hydrogen or hydrogen blend pipelines, there is also a potential for the implementation of a baseline ultrasonic ILI tool to be run prior to the introduction of hydrogen gas in the pipeline. This may be necessary to establish a foundation for identifying defects in the pipeline and evaluating remaining life (RL) intervals and anomalies that require monitoring during future inspections.
- There is inconsistent use of verbiage from reported ILI anomalies to defined ASME B31.8S threats.
    - Operators and ILI vendors alike have preferred verbiage for ILI reports that does not necessarily align with the threats defined in ASME B31.8S.
- There is a poor or unknown understanding of POD and POI for the anomalies of most concern in hydrogen pipelines.
    - This is further exacerbated by the previous issue of an individual ILI technology's inability to capture a full breadth of understanding of an anomaly.

5 CONCLUSIONS

This evaluation was based on the analysis of previous and ongoing research, publicly available literature, and the evaluation of results from the analyses performed in Tasks 1 and 2 of this project, as well as the discussions included in this report.

5.1 Recommendations

The recommendations regarding threat analysis for ILI tools are as follows:

- Determine the physical property/properties that the ILI tool aims to detect and size, and relate them to the threats defined in ASME B31.8S.
- Incorporate a standard method of reporting defects by ILI that maps to the threats defined in ASME B31.8S.

- Ensure ILI tool validation is performed with an appropriate field method for the threat requiring evaluation.
- Communicate validation results with the ILI vendor to grow the basis of knowledge, so that the industry can continue to improve over time.

5.2 Future Research

Additional research will continue to be essential in establishing the understanding of threats and how to evaluate them from the perspective of ILI. Research should focus on the experimental validation of ILI tools under hydrogen exposure, to ensure current probabilities of detection and identification continue to reflect industry expectations. This is a requirement as technology continues to evolve and expand its capabilities through the integration of multiple data streams, assisting in the overall understanding of the actual threat to the pipeline.

The development of probabilistic models for reinspection intervals and the optimization of established frameworks for anomaly classification. The work in this project, which involved associating threats defined within ASME B31.8S with anomalies as provided by NACE SP0102, was manually correlated using industry subject matter expertise. However, utilizing machine learning tools can help prioritize a matrix of technology selection moving forward.

Additional work is needed to standardize reporting terminology and establish performance benchmarks for hydrogen pipeline IM.

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6 APPENDIX A – NACE SP0102-2017 TABLE 1

Anomaly	Imperfection/ Defect/ Feature	Metal Loss Tools		Crack Detection Tools			Deformation Tools
		Axial MFL	Ultrasonic Compression Wave (A)	Ultrasonic		Transverse MFL	
				Liquid coupled (A)	EMAT		
Metal Loss	External Corrosion	Detection, Sizing	Detection, Sizing	No Detection	No Detection	Detection, Sizing	No Detection
Metal Loss	Internal Corrosion	Detection, Sizing	Detection, Sizing	No Detection	No Detection	Detection, Sizing	Detection (D), Sizing (D)
Metal Loss	Gouging	Detection (B), Sizing (B)	Detection (C), Sizing (C)	No Detection	No Detection	Detection (B), Sizing (B)	No Detection
Crack-Like Anomalies	Narrow Axial External Corrosion	Detection	Detection, Sizing	Detection, Sizing	Detection, Sizing	Detection, Sizing	No Detection
Crack-Like Anomalies	Stress Corrosion Cracking (SCC)	No Detection	No Detection	Detection, Sizing	Detection, Sizing	Limited Detection (E), Sizing (E)	No Detection
Crack-Like Anomalies	Fatigue Cracks	No Detection	No Detection	Detection, Sizing	Detection, Sizing	Limited Detection (E), Sizing (E)	No Detection
Crack-Like Anomalies	Long Seam Cracks, etc. (toe cracks, hook cracks, incomplete fusion, preferential seam corrosion)	No Detection	No Detection	Detection, Sizing	Detection, Sizing	Limited Detection (E), Sizing	No Detection
Crack-Like Anomalies	Circumferential Cracks	Limited Detection (E), Sizing	No Detection	Limited Detection (F), Sizing (F)	No Detection	No Detection	No Detection
Crack-Like Anomalies	Hydrogen-Induced Cracking (HIC)	No Detection	Detection, Sizing	No Detection	No Detection	No Detection	No Detection
Weld Anomalies	Lack of fusion in Long-Seam Weld (LSW)	No Detection	No Detection	Detection, Sizing	Detection, Sizing	Detection (E), Sizing (E)	No Detection
Weld Anomalies	Lack of fusion in GW	Detection (E), Sizing	No Detection	Detection (F), Sizing (F)	No Detection	No Detection	No Detection
Weld Anomalies	Girth Weld Anomaly (voids, etc.)	Detection, Sizing	Detection, Sizing	Detection (F), Sizing (F)	No Detection	No Detection	No Detection
Deformation	Sharp Dents	Detection (G)	Detection (G)	No Detection	No Detection	Detection (G)	Detection, Sizing
Deformation	Flat Dents	Detection (G)	Detection (G)	No Detection	No Detection	Detection (G)	Detection, Sizing
Deformation	Buckles	Detection (G)	Detection (G)	No Detection	No Detection	Limited Detection (G)	Detection, Sizing
Deformation	Wrinkles, Ripples	Detection (G)	Detection (G)	No Detection	No Detection	Limited Detection (G)	Detection, Sizing
Deformation	Ovalities	No Detection	No Detection	No Detection	No Detection	No Detection	Detection, Sizing
Misc. Components	In-Line Valves and Fittings	Detection	Detection	Detection	Detection	Detection	Detection

Anomaly	Imperfection/ Defect/ Feature	Metal Loss Tools		Crack Detection Tools			Deformation Tools
		Axial MFL	Ultrasonic Compression Wave (A)	Ultrasonic		Transverse MFL	
				Liquid coupled (A)	EMAT		
Misc. Components	Casings (Concentric)	Detection	No Detection	No Detection	No Detection	Detection	No Detection
Misc. Components	Casings (Eccentric)	Detection	No Detection	No Detection	No Detection	Detection	No Detection
Misc. Components	Bends	Limited Detection	Limited Detection	Limited Detection	No Detection	Limited Detection	Detection (H), Sizing (H)
Misc. Components	Branch Appurtenances/Hot Taps	Detection	Detection	Detection	Detection	Detection	Detection
Misc. Components	Close Metal Object	Detection	No Detection	No Detection	No Detection	Detection	No Detection
Misc. Components	Thermite Welds	No Detection	Detection, Sizing	No Detection	No Detection	No Detection	No Detection
Misc. Components	Pipeline Coordinates	No Detection (I)	No Detection (I)	No Detection (I)	No Detection (I)	No Detection (I)	No Detection (I)
Misc. Damage	Laminations	No Detection	Detection, Sizing	No Detection	No Detection	No Detection	No Detection
Misc. Damage	Inclusions	Limited Detection	Detection, Sizing	Limited Detection	Limited Detection	Limited Detection	No Detection
Misc. Damage	Cold Work	Detection (B)	No Detection	No Detection	No Detection	No Detection (B)	No Detection
Misc. Damage	Hard Spots	Detection (K)	No Detection	No Detection	No Detection	No Detection	No Detection
Misc. Damage	Grind Marks	Limited Detection (L)	Detection (L)	Detection (L)	Detection (L)	Limited Detection (L)(C)	No Detection
Misc. Damage	Strain	No Detection	No Detection	No Detection	No Detection	No Detection	Detection (M)
Misc. Damage	Scabs/Slivers/Blisters	Limited Detection (L)	Detection	Limited Detection (L)	No Detection	Limited Detection (L)	Limited Detection (N)
Misc. Damage	External Coating Disbondment	No Detection	No Detection (O)	No Detection	Detection, Sizing	No Detection	No Detection

(A) ILI technologies that can be used only in liquid environments, i.e. liquid pipelines or in gas pipelines with a liquid couplant. (Wall thickness measurement applications based on EMATs do not require liquid coupling.)
(B) If tools equipped for detection of mechanical damage, otherwise detection and sizing of metal loss component only.
(C) Detection and sizing of metal loss component only.
(D) Tool resolution is typically not adequate for detection and sizing of internal metal loss.
(E) Reduced POD for tight cracks, a minimum opening of the crack-like feature is required for detection.
(F) Using modified sensor carrier with transducers rotated by 90°.
(G) Reduced POD and sizing capabilities depending upon size and shape.
(H) If tool is equipped for bend measurement.
(I) Unless tool is equipped with mapping capabilities.
(J) Composite sleeve without ferrous markers is not detectable.
(K) If tool is designed for hard spot detection.
(L) Depending on the orientation and shape of the anomaly.
(M) Local strain can be deduced from deformation measurements; large scale strain can be detected only if the tool is equipped with mapping capabilities.
(N) Only those protruding to the interior of the pipe.
(O) Technology could potentially be used for detecting changes in coating bonding.

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