In-line inspection tool readiness for hydrogen pipelines

White paper

POF 520

May 2024

Foreword

This document has been reviewed and approved by the Pipeline Operators Forum (POF) and is based on knowledge and experience available from POF members and others at the date of issue. It is stated however, that neither POF nor its member companies (or their representatives) can be held responsible for the fitness for purpose, completeness, accuracy and/or application of this document.

Comments to this white paper and proposals for updates may be submitted to the Administrator at specifications@pipelineoperators.org .

Acknowledgement

POF would like to thank the ILI vendors who answered the questionnaire and participated in the exchange meeting (in alphabetical order): Baker Hughes, NDT Global, Rosen, and T.D. Williamson. Pipecare is acknowledged for answering the questionnaire later. A draft version of this white paper has been sent for review and comments to these in-line inspection vendors. The POF would like to thank the vendors for their constructive feedback.

POF would also like to thank the members of the POF working group on ILI tool readiness for hydrogen lines. A first version was written by Peter van de Camp of Shell, Stefan Klein of Gascade, Charles Fernandez of GRTgaz and Sieger Koops of Gasunie. The other members of the working group reviewed this draft (in alphabetical order of company name): Chris Lewis of BP, Satish Kulkarni of Chevron, Nelson Betancourt of Enagas, Pernille Kildahl of Equinor, Paul Roovers of Fluxys, David Rodrigues de Miranda of Gassco, and Wilson Santamaria of TAP.

Contents

Acronyms:

ATEX	ATmosphères EXplosibles (explosive atmospheres)
ECA	Engineering Critical Assessment
ECT	Eddy Current Testing
EM	Electro Magnetic
EMAT	Electro Magnetic Acoustic Transducer
FMEA	Failure Mode and Effect Analysis
HE	Hydrogen Embrittlement
IECEx	International Electrotechnical Commission Explosive
ILI	In-Line Inspection
IMU	Inertial Measurement Unit
JIP	Joint Industry Project
MAOP	Maximum Allowable Operating Pressure
MFL	Magnetic Flux Leakage
NG	Natural Gas
SCU	Speed Control Unit
TRL	Technology Readiness Level
UT	Ultrasonic Testing
WG	Working Group

1 Background and scope

Hydrogen is becoming increasingly important as part of the energy transition and net-zero emission initiatives. Pipelines are considered a safe and cost-effective method for transporting larger volumes of natural gas over longer distances. There are many opportunities for transferable knowledge and operating experience that could be applicable to hydrogen, replicating the current natural gas supply chain.

It is known that hydrogen affects certain material properties of carbon steel which in turn impacts design and integrity management compared to natural gas. Much work is being done by organisations such as EPRG [1], PRCI EFI [2], and NREL [3] to better understand the impact of hydrogen to pipeline integrity. Although pipeline transport of pressurised gaseous hydrogen is not new and standards do exist, it is expected that this work will lead to updated codes and standards (as issued by bodies such as ASME, CEN, ISO and DNV) to allow safe and cost-effective transport of large volumes of hydrogen with pipelines.

In-Line Inspection (ILI) is an important element of the pipeline integrity management process. It is commonly applied to pipelines containing hydrocarbons and much information is available in the public domain about the capabilities and limitations of the various tools and techniques. However, there are gaps in the understanding when ILI is performed on existing lines to evaluate for hydrogen service and when ILI is performed in gas lines which are either blended with hydrogen or 100 % hydrogen.

POF have set up a working group (WG) on hydrogen pipelines to investigate ILI tool readiness for hydrogen pipeline inspection in 2023. To this end a questionnaire was developed and sent to four globally active ILI vendors, namely Baker Hughes, NDT Global, Rosen and T.D. Williamson. At the back of the last Annual General Meeting of POF in October 2023 in Nice, France, an exchange meeting was held with these ILI vendors to discuss their responses. After the meeting the questionnaire was also sent to ILI vendors that were not present in this meeting. The responses received from ILI vendors, together with information available by the members of the POF working group on tool readiness has been used as input to this white paper. As such, this white paper provides information about the state of tool readiness as of the end of 2023 and gaps presented here are expected to be closed over time. It is the intention of POF to provide an update to this white paper within 3 years after publication of the first version.

The gaps identified by POF can be broadly delineated into four areas:

1. Availability of ILI systems to detect relevant anomalies with sufficient performance.
2. Compatibility of ILI tool materials with a hydrogen environment.
3. Ability to safely launch, run and receive an ILI tool in a hydrogen pipeline.
4. Ability to achieve sufficient ILI data quality from an ILI run in a hydrogen pipeline.

These four areas will be covered in this white paper in subsequent chapters with a summary of all identified gaps in the final chapter. The effect of hydrogen on material properties, definition of inspection requirements, fitness for service and integrity management of hydrogen lines are outside the scope of this document. The term hydrogen pipelines in this paper refers to pipelines containing both pure hydrogen and blends of natural gas and hydrogen.

This document is different from the typical POF standard and recommended practices in the sense that it is not meant to provide guidance on ILI of hydrogen pipelines but instead to better understand the current level of ILI tool readiness for hydrogen pipelines and identify gaps to stimulate developments to close these gaps.

This white paper does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this white paper to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.

2 Availability of ILI technologies to find relevant anomalies

It is important to understand the relevant threats to pipeline integrity as input to selecting an ILI technology and tool to verify the effectiveness of barriers to mitigate these threats. The relevant threats can be identified following a Failure Mode and Effect Analysis (FMEA) and/or reviewing the threats listed in pipeline integrity management standards such as ASME B31.8S [4]. However, for ILI selection it is not sufficient to know what failure modes and/or threats are relevant for a particular pipeline. ILI technologies are generally not sensitive to the failure mode and mechanism, but to the appearance and/or morphology of the resulting anomalies.

Broadly summarised, the following four morphologies/appearances can be distinguished which are detectable with current ILI Non-Destructive Testing (NDT) technologies:

- Volumetric anomalies (e.g. internal and/or external metal loss),
- Planar anomalies (typically perpendicular to the main stress direction), e.g. axial or circumferential cracking,
- Deformation of the pipeline geometry, e.g. dents, axial and bending strain (change in pipeline center line from as the as-built situation),
- Deviation of material properties (e.g. hard spots, pipe grade classification).

Various ILI technologies have been developed that can successfully detect, characterize and size these different anomalies. Much experience has been gained by the industry in using ILI technologies and data for integrity management of hydrocarbon pipelines. Table 1 provides an overview of the ILI technologies that exist for the various threats and their corresponding morphologies. Rows are coloured according to the four morphologies listed above. It is often possible to add multiple technologies to one ILI tool.

Two columns have been added to get an indication about the suitability of the ILI technology for hydrogen lines. The column, second to the right, shows if the technology can be applied in natural gas without the need for liquid batching. The letter ‘D’ indicates that it depends on the actual gas conditions and is mainly determined by pressure, i.e. above a certain pressure full performance specification will be met. It is expected that if a technology cannot be made to work in natural gas it will also not work in hydrogen.

The column to the right gives an indicative assessment if the technology is likely to detect, identify and size critical defects in hydrogen lines, i.e. deemed to have a ‘sufficient performance’. It is realised that this is a subjective assessment and more information on this is given in the next sections.

Degradation /Threat	**Morphology / Appearance**	**ILI technology**	**Applicable to NG[1]**	**Sufficient[2] Performance[3] for H_2 lines?**
Internal and/or external corrosion	metal loss - general and circumferential	Axial MFL	Y	+
Internal and/or external corrosion	metal loss - general and axial	Circumferential MFL	Y	+
Internal and/or external corrosion	metal loss	Liquid coupled UT	N	+
Internal and/orexternal corrosion	metal loss	Gas coupled resonance UT	D	+
HE fatigue	Axial planar anomalies (Int+Ext)	Liquid coupled UT	N	+
HE fatigue	Axial planar anomalies (Int+Ext)	EMAT	Y	o
HE fatigue	Circumferential planar anomalies (Int+Ext)	Liquid coupled UT	N	o
HE fatigue	Axial planar anomalies (Int+Ext)	Gas coupled Lamb waves[4]	D	o
HE fatigue	Surface breaking planar anomalies (Int)	Eddy Current (EC)[4]	Y	o
HE fatigue	Laminations	Liquid coupled UT	N	+
Geohazard	Bending strain	EM Geometry + IMU	Y	+
Geohazard	Axial strain	EC based stress measurement	Y	o
Geohazard	Circumferential planar anomalies (Int+Ext)	Liquid Coupled UT	N	o
Third party damage	Dents	EM Geometry	Y	+
Third party damage	Dents	Liquid coupled UT Geometry	N	+
Third party damage	Gouges	Geometry + MFL[5]	Y[5]	+
Pipe material	Hard spots	EM or low-field MFL	Y	o
Pipe material	Pipe grade	MFL and/or low-field MFL	Y	o

1 Yes/No/Depends as explained in section 2
2 As explained in sections 2.1-2.5 and Table 2
3 Performance assessment: + sufficient for most cases, o sufficient for some but not all cases / unknown, - insufficient for most cases
4 In development
5 Gouges can also be detected by UT and gas coupled UT but with a rating of "N" and "D" respectively

Table 1 Overview of the most common ILI technologies for the four main morphologies considered.

Although hydrogen will be transported as a gas, the inspection requirements may be different for lines to be converted to hydrogen and/or lines already in hydrogen service when compared to natural gas. It is known that hydrogen may affect properties of carbon steel line pipe [5]. The following material properties may be affected:

- Fatigue resistance. It is known, and recent experiments have confirmed, that cracks in carbon steel may grow up to 10 times faster when steel is exposed to a hydrogen environment.
- Fracture toughness. A reduction in the order of 50 % has been observed for carbon steel exposed to a hydrogen environment.
- Ductility. A reduction of up to 50% between ultimate tensile strength (UTS) and fracture has been observed for carbon steel exposed to a hydrogen environment. This may impact fitness for service assessment of metal loss and deformations (dents).

There is a lot of research currently ongoing to determine more precisely the effect of hydrogen on pipeline steel properties and integrity threats through joint industry programs. It is expected that these studies will provide more input to future inspection requirements for hydrogen lines.

2.1 Technology capability mapping for use in hydrogen lines

In this chapter a brief review of the various ILI technologies will be given. The applicability for use in hydrogen pipelines together with expected performance will be considered, see Table 1. This is based on the inherent capabilities of the technology only, without considering pigging medium limitations, ILI tool materials compatibility and pigging operational limitations in hydrogen pipelines. These factors will be discussed in the next chapters.

Inspection performance requirements will have to be determined by the pipeline operator. These may depend, among others, on pipeline design, age, history, expected hydrogen operating conditions, etc. Therefore, the first pass assessment given in the column on the right in Table 1 is only indicative and should be re-assessed by the pipeline operator together with the ILI service provider for each specific pipeline to be inspected. More specifically, the term "sufficient" from Table 1 is related to the ability of an ILI technology to successfully detect a defect of critical size, which in turn depends on the factors given in the beginning of this paragraph.

Basically all threats that already exist for pipelines operating in natural gas service are also present for hydrogen service. In addition new threats emerge due to hydrogen affecting material properties. General guidance on technology selection for the various morphologies is given in references [6,7].

2.2 Volumetric metal loss

It is expected that inspection for metal loss may be required for hydrogen pipelines. Susceptibility to external corrosion in hydrogen lines is no different from natural gas lines.

Magnetic Flux Leakage (MFL). With MFL being an electromagnetic inspection technique, it is not affected by the medium, so it will work equally well in hydrogen as in natural gas. Various companies offer this technology with different levels of performance. Tools with a high resolution also have the capability to detect and size pinholes (as per POF definition). It is therefore expected that MFL tools will be able to meet performance requirements for hydrogen pipelines to a similar degree as for natural gas pipelines.

Liquid coupled Ultrasonic Testing (UT). This technology will only work with a liquid couplant. Various companies offer this technology with different levels of performance. It can be used during the repurposing stage before hydrogen is introduced, for instance with water as a couplant if a hydrotest is also required.

Gas coupled resonance UT. This technology works in liquid but also in natural gas if pressure is sufficiently high (~> 50 bar). It is not known yet at what pressure in hydrogen gas this technology will work but it will be higher compared to natural gas. It seems likely that this pressure threshold is beyond typical operating pressures of hydrogen lines. However, this limitation may be overcome if it is possible to run the ILI tool in a long batch of nitrogen gas.

2.3 Planar anomalies

The term planar anomalies ("cracks") summarizes all types of line pipe material separations not exceeding a microscopic volume. The geometry of a planar anomaly can be approximated by its length and maximum depth (or height). Depending on the conditions and anomaly type, the length extension of planar anomalies is typically oriented in either axial or circumferential direction, and the orientation is perpendicular to the pipe wall surface. Laminations are also planar anomalies but with orientation parallel to the pipe wall surface.

Hydrogen Embrittlement (HE) in combination with pressure cycling may lead to fatigue crack growth. Planar anomalies are of particular concern to hydrogen lines. The performance assessment for planar anomalies from the hydrogen embrittlement fatigue threat is based on two assumptions. First, it is assumed that planar anomalies will originate in or near a weld from existing small manufacturing flaws. In general, the detection capability in or near a weld is reduced when compared to the body of the pipe. Second, future hydrogen transmission pipelines will operate with higher stresses (when expressed as % SMYS) and more fatigue loading (due to pressure variations) when compared to currently existing, small diameter hydrogen pipelines. Fatigue is of much less concern to natural gas pipelines where fatigue crack growth rates and typical pressure cycling have a negligible effect on the useful life of a natural gas pipeline. In addition to fatigue crack growth, a reduction in fracture toughness means that planar anomalies that are stable under current operating conditions may no longer by stable once hydrogen is introduced.

Liquid coupled UT crack detection. This technology, using angle beam shear waves, will only work with a liquid couplant. Various companies offer this technology with different levels of performance. It may be deployed during the repurposing stage before hydrogen is introduced, when it is still possible to inspect in water or other suitable liquid. Inspection for planar anomalies in axial direction is the most common application and offers the best sensitivity. Some companies also offer tools for detection of circumferentially oriented planar anomalies, typically with a somewhat lower sensitivity compared to axial anomalies. Planar anomalies parallel to the helical seam weld may not be detected with this technology.

EMAT for crack detection. This technology uses Electro Magnetic Acoustic Transducers (EMAT) to generate ultrasonic waves in the pipe wall without the need for a liquid couplant. It is widely used in natural gas lines mainly to inspect for external stress corrosion cracking. As coupling is achieved by electromagnetics it will work equally well in hydrogen pipelines. EMAT tools are available to detect, identify and size axially oriented planar anomalies. Anomalies in circumferential and/or helical direction will not be detected by these tools. EMAT tools are not as sensitive to seam weld anomalies as high resolution, liquid coupled UT crack detection tools and have limited use in pipelines of greater wall thickness.

Magnetic Flux Leakage (MFL). High resolution MFL tools can also detect planar anomalies provided there is a sufficient opening of the fracture surfaces, i.e. it is a "crack-like" anomaly as defined in POF 100 [6]. MFL is not included in table 1 as a technology for the HE fatigue threat as it is assumed that MFL is not sensitive enough for typical HE fatigue cracks. However, testing the performance of MFL tools on actual HE fatigue cracks is required to check if this assumption is valid.

Liquid coupled UT for detection of laminations. This requires a tool with the same set-up as used for metal loss, i.e. normal beam compression waves. It is the only technology available for detection of laminations, and has the same limitations as described above under UT metal loss tools.

New developments. Companies are working to close the gap for crack detection in gas pipelines. Eddy current technologies have the potential to detect and size planar anomalies in any direction (axial, circumferential and helical) that are surface breaking to the inside of the pipe wall. Gas coupled Lamb waves may detect both internal and external planar anomalies. Detection sensitivity of EMAT technology can be improved by using smaller sensors and work is also ongoing to make EMAT suitable for the detection of planar anomalies in the circumferential direction. As these tools are still in development, their actual performance is not known yet.

The assessment for planar anomalies is based on the expected performance for critical defects in or near a weld. The actual critical defects size is determined through an Engineering Critical Assessment (ECA) and will be case (pipeline) specific. For cases that result in large critical defect sizes such as the 3 mm deep by 50 mm long as recommended by EPRG for level 1 [1], all current ILI technologies would score "sufficient". However, in cases where critical defect size is in the order of 1 mm deep by 25 mm long, then only high resolution, liquid coupled UT tools would score "sufficient".

This assessment is based on published performance specifications by the ILI vendors and requires verification if these can be met for tight hydrogen fatigue cracks. Table 2 shows how the general performance assessment can be translated to critical planar anomaly defect sizes and the ability of the various technologies to detect these. More background information is given in Appendix 1. The industry is trying to get a better understanding of ILI crack detection and sizing through programs such as PRCI NDE-4-26 and NDE-4-12.

Symbol	Description	Planar weld anomaly detection sensitivity
+	sufficient for most cases	equal or smaller than 1 mm x 25 mm
o	sufficient for some but not all cases	in the order of 2 mm x 25 mm
-	insufficient for most cases	larger than 3 mm x 50 mm

Table 2 Performance assessment for ILI planar anomaly detection tools.

2.4 Deformation, axial, and bending strain

The requirement to inspect for deformations (e.g. due to third party interference), axial and bending strain (e.g. due to geohazards) is not determined by pipeline contents but by its location. Therefore, requirements to inspect for deformation and strain may also be applicable to hydrogen lines. In addition, the effect on hydrogen on fracture toughness and ductility may lead to stricter inspection requirements compared to natural gas.

Deformation measurement with calipers. Deformation is determined by deflection of calipers which is measured with mechanical and electromechanical methods. This measurement is not affected by pipeline contents, so it works equally well in hydrogen. A wide range of ILI vendors are available that offer this technology in various resolutions. Detection and sizing of metal loss in a dent typically requires a combination of metal loss and deformation sensors in one tool (also known as combo tool).

Deformation measurement with UT. This is an extension or standalone application of the technology that is also used for metal loss inspection. That is, zero-degree UT sensors are used to measure stand-off between sensor and pipe wall. The same remarks apply as given above on metal loss UT tools.

Bending strain with IMU. Inertial Measurement Units (IMU) are relatively small modules that can be added to an ILI tool, most commonly to a geometry tool but also quite often to metal loss tools. The measurement takes place within the module, so it is not affected by pipeline medium. High resolution IMU units are required to measure bending strain.

Axial strain with eddy current technology. Only few vendors offer this service. The measurement is based on eddy current testing (ECT) principles so not affected by the pipeline medium. This is a fairly new technology so there is limited information available about performance and limitations of this technology.

2.5 Deviation of material properties

The requirement to use in-line inspection to determine material properties or deviations from the norm (e.g. hard spots) typically applies to lines that are being repurposed, especially older lines with incomplete records. These inspections will usually take place before hydrogen is introduced into the pipeline. Therefore tool compatibility with hydrogen and/or operational issues when running in hydrogen are less of a concern for these tools.

Hard spots. Hard spots can be more susceptible to crack initiation and thereafter fatigue crack growth. Detection of hard spots is possible with a combination of regular MFL and low field MFL. Some companies are also working on eddy current based technologies for hard spot detection. In all cases the measurement principle is electromagnetic, so not affected by the medium in the pipeline.

Material properties. Mechanical properties such as yield and tensile strength are indirectly related to electromagnetic properties such as permeability. Through experience and calibration the magnetic and/or eddy current response from sensors can be related to mechanical properties. Many vendors with MFL metal loss tools also offer a material properties service. In its basic form, the ILI analysis separates the various joints in bins with similar measured properties such as wall thickness, magnetic signature and pipe manufacturing process.

Both inspection services are relatively new, so there is limited information available about performance and limitations of this technology. PRCI projects NDE-4-23 and MAT-7-2A aim to shed more light on the physics of these technologies and the performance of commercially available ILI tools.

Recently, Non-Destructive Testing (NDT) technologies have been developed for localized or in-situ measurement of hardness, strength, ductility and fracture toughness.

3 Compatibility of ILI tool materials with hydrogen

Hydrogen does not only affect material properties of pipeline's carbon steel, but it may also affect the properties of materials being used for ILI tools. This implies that a hydrogen compatible ILI tool requires careful material selection of its various components including, but not limited to, sealants, high strength steel, rubber, cable jackets, magnets, ceramics, spacers, cups, sensors, etc.

ILI tool readiness for hydrogen service has been discussed with ILI vendors. POF requested these vendors to express this in terms of a technology readiness level (TRL). The TRL concept originates from space industry and is defined in the ISO 16290 standard [8]. It is now adopted by other industries and the European Union has generalized the descriptions [9]. There are nine TRLs, ranging from level 1 'Basic principles observed' to level 9 'Actual system proven in operational environment', see Table 3.

TRL	Description
1	Basic principles observed
2	Technology concept formulated
3	Experimental proof of concept
4	Technology validated in laboratory
5	Technology validated in relevant environment
6	Technology demonstrated in relevant environment
7	System prototype demonstration in operational environment
8	System complete and qualified
9	Actual system proven in operational environment

Table 3 Technology Readiness levels (TRL) according to [9]

The TRL ratings of the various ILI technologies that POF summarized from ILI vendor responses are given in Table 4 for the base case of running in natural gas (NG) and when running in a 100 % hydrogen environment (H_2). In many cases the TRL ratings in hydrogen cover a range as responses from the ILI vendors differed. Technologies that require a liquid couplant to acquire data have not been assigned a TRL. When running in liquid the readiness of these technologies is TRL 9. However, they can only be applied to an in-service NG or H_2 line in a batching operation or when the line is taken out of service and filled with a suitable liquid.

Degradation / Threat	Morphology / Appearance	ILI technology	TRL[1] for NG	TRL[1] for H_2
Internal and/or external corrosion	Metal loss - general and circumferential	Axial MFL	9	6-9
Internal and/or external corrosion	Metal loss - general and axial	Circumferential MFL	9	2-6
Internal and/or external corrosion	Metal loss	Liquid coupled UT	n/a	n/a
Internal and/orexternal corrosion	Metal loss	Gas coupled resonance UT	9	2
HE fatigue	Axial planar anomalies (Int+Ext)	Liquid coupled UT	n/a	n/a
HE fatigue	Axial planar anomalies (Int+Ext)	EMAT	9	2-6
HE fatigue	Circumferential planar anomalies (Int+Ext)	Liquid coupled UT	n/a	n/a
HE fatigue	Axial planar anomalies (Int+Ext)	Gas coupled Lamb waves	7	2
HE fatigue	Surface breaking planar anomalies (Int)	Eddy Current (EC)	4	2
HE fatigue	Laminations	Liquid coupled UT	n/a	n/a
Geohazard	Bending strain	EM Geometry + IMU	9	3-7
Geohazard	Axial strain	EC based stress measurement	9	2-3
Geohazard	Circumferential planar anomalies (Int+Ext)	Liquid coupled UT	n/a	n/a
Third party damage	Dents	EM Geometry	9	3-7
Third party damage	Dents	Liquid coupled UT Geo	n/a	n/a
Third party damage	Gouges	Geometry+ MFL	9	3-7
Pipe material	Hard spots	EM or low-field MFL	9	3-7
Pipe material	Pipe grade	MFL and/or low-field MFL	9	3-7

1 TRL levels as per table 3; n/a is not applicable.

Table 4 TRL [9] of various technologies for natural gas (NG) and hydrogen (H_2)

Based on input and discussions with ILI vendors the following remarks can be made:

- Magnets, as used in MFL and EMAT tools, require protection (sealing) otherwise they will disintegrate when exposed to hydrogen gas. ILI vendors have identified solutions for this issue.
- Hydrogen embrittlement is not considered a concern for most high strength steel ILI components as they do not experience high fatigue loading during a run. A possible exception might be the couplings between the modules.
- Ingress of hydrogen into the pressure vessels that house electronics is an issue as it may affect proper working of these components. Failure may not occur immediately but could lead to a shorter mean time between failure (MTBF) of these components.
- Pure hydrogen gas is considered to be a “dry” pigging medium which may lead to high cup wear.
- Experiences from using ILI tools in other difficult environments such as sour gas (with high levels of H_2S) and dry media such as ethylene has helped ILI vendors with material selection.
- There is already some experience with running ILI tools (mostly MFL) in lines with hydrogen, both in mixtures (NG +H_2) and 100% H_2. Though in many cases these were small diameter, short pipelines with low pressure.
- TRL levels for running in hydrogen are mostly low. ILI vendors state that they have identified the required tool modifications for use in hydrogen but are awaiting market pull to start building these tools.

4 Ability to safely launch, run and receive ILI tools

Hydrogen has a lower density, wider explosion limits and smaller ignition energy in air when compared to natural gas. This affects the health and safety risk to people when launching, running and receiving ILI tools in hydrogen lines. In addition, there is also the risk of excessive tool speed excursions that may damage the pipeline with potential consequences to people working nearby.

One of the ways to mitigate the health and safety risk of launching and receiving tools in pipelines containing a flammable and potential explosive environment, is to require the ILI tool to be certified against a safety standard. The ATEX and IECEx schemes are commonly accepted. Many ILI tools used by pipeline operators are certified according to IEC 60076-0 [10] equipment group II-A (typical gasses:

natural gas, propane, toluene) or II-B (typical gasses: coal gas, ethylene) but are not certified for hydrogen gas which would require an equipment group II-C certification, see ISO/IEC 80079-20-1 [11] Table B.1. This issue is well understood by the ILI vendors, and it is known how tools should be modified to obtain a ATEX class II-C certification. However, this takes time and money and likely requires more market pull before it is undertaken by the ILI vendors.

Some other remarks on safety from the interaction with the ILI vendors are summarised below:

- Tool launch and receive procedures require more attention due to the higher risk of explosion of hydrogen compared to natural gas. Purging pig traps with nitrogen is seen as an important mitigation measure.
- Tool speed excursions are more likely in hydrogen due to its low density. Care should be taken to avoid speed excursions before the receive trap and sharp bends as it may have safety implications. Speed excursion may also affect data quality, more on this in the next chapter.
- Hydrogen ingress into ILI pressure vessels may introduce a new safety risk. Special attention is required when working on the tool after a pig run.

The issue of safely running a tool in a hydrogen or hydrogen mixture pipeline is also addressed in PRCI-EFI project JEFI-06-03. A process hazard analysis (PHA) was performed resulting in 44 recommendations for consideration [12].

5 Ability to get good quality data from an ILI run in hydrogen

Several factors play in a role in the ability to achieve a successful ILI run in a hydrogen pipeline. First, the tool itself must be compatible for use in hydrogen as discussed in section 3 of this paper. Second, it is about preventing run behaviour of the ILI tool that will result in degraded and/or loss of data which will be covered in this section.

ILI tool dynamics and allowable maximum tool speed are essential variables of the performance specification for all ILI tools. Depending on technology design details, the acceptable maximum tool speed varies throughout the ILI industry. Assuming present tool design, the risk of getting degraded or loss of ILI data due to speed excursions is increased for pressurized hydrogen compared to natural gas conditions.

5.1 Operating and pipeline parameters

Hydrogen has a much lower density than natural gas which affects ILI tool dynamics and run behaviour [13, 14]. ILI vendors and operating companies have a good understanding of the required pipeline operating conditions to achieve a tool speed profile over the line length with no or very limited speed excursions in natural gas. However, these required conditions will be significantly different for hydrogen pipelines.

In addition to pipeline operating conditions such as pressure, gas velocity and flow control, the pipeline design also influences the susceptibility of the ILI tool for speed excursions. High curvature bends and changes of the internal diameter at wall thickness changes or valves may trigger speed excursions. The pipeline elevation profile and inspection section length are other factors that affect tool speed profile.

5.2 Adverse effects of high tool speed

Speed excursions are more likely to happen with high friction tools such as those having MFL or EMAT technology. A study that was executed on behalf of the POF [14] showed that ILI tools in hydrogen pipelines can reach a much higher peak velocity and will exceed a certain velocity threshold over a longer distance compared to natural gas. For hydrogen natural gas blends of up to 30 % hydrogen, the modelling results showed very little difference in run behaviour compared to pure natural gas with equal pressure and gas velocity.

A high tool velocity during an ILI inspection run could affect data quality in two ways.

1. ILI tool data acquisition systems have an upper limit on axial sampling frequency during a run. If the tool speed exceeds a certain limit, the required axial sampling to maintain tool detection and sizing performance cannot be achieved anymore. This limitation applies to all ILI technologies, although the actual speed limit will be different for the various tools and technologies due to different electronics.
2. The measurement principle itself may be affected by the tool speed. This specifically applies to the MFL technology where eddy currents that are generated by the moving magnets inside the pipeline, can distort the pipe wall magnetization. MFL requires a uniform magnetization of the pipe wall in the radial direction at the position of the MFL sensors. At elevated tool speeds, the pipe magnetization becomes non-uniform with a higher magnetization level at the inner pipe surface and lower level at the outer pipe surface [15]. This can lead to loss of sensitivity for external anomalies and less accurate sizing for internal anomalies. The situation for EMAT technology may be different but from tool data sheets it is clear that EMAT tools have a lower allowable maximum tool speed than MFL tools.

The POF 100 standard practice [6] contains guidance on acceptable data loss. The acceptable limit for accumulated data loss is less or equal to 0.5 % of the pipeline length. It is doubtful if this criterion can be met for MFL or EMAT inspections in hydrogen pipelines, especially for those that are repurposed from natural gas. Current pipeline design and construction codes can put stricter limitations to allowable stress in hydrogen pipelines resulting in a lower maximum allowable operating pressure (MAOP) of a repurposed pipeline compared to natural gas pipelines. A lower operating pressure leads to a higher potential for speed excursions. Another complicating factor is that gas velocity in hydrogen lines is expected to be higher than in natural gas lines due to the lower energy density (per volume) of hydrogen.

5.3 Potential ways to mitigate speed excursions

The following considerations are noted related to speed excursions from the interaction with the ILI vendors:

- ILI vendors have experience in mitigating speed excursions in natural gas pipelines. ILI tools can be modified to reduce friction. They have also developed guidance on the window of pipeline operating conditions in natural gas where the effect of speed excursions is limited. This guidance does not exist yet for hydrogen lines, but it is expected that the hydrogen operating window will be more confined and thus more difficult to achieve in practice. With input from the pipeline operator, ILI vendors can provide pipeline specific tool velocity simulations to assess and potentially mitigate the risk of speed excursions.
- Speed control units (SCUs) potentially offer solutions for lines with a high gas velocity. Experience is largely built up for natural gas pipelines. SCUs have space constraints and are therefore available for larger diameters only. It is still unknown how SCUs will perform in hydrogen lines. Some ILI vendors are working on active braking systems to help control tool velocity, however there is no or limited field experience yet with this technology.

- Running the ILI tool in a batch of nitrogen (even without sealing pigs) is a way to mitigate or potentially prevent, speed excursions [14]. This would also have a positive effect on the tool material compatibility issues (chapter 3) and the ability to safely launch and receive an ILI tool in hydrogen pipelines (chapter 4). Details of such an operation would still need to be worked out and it may not be practical for many hydrogen pipelines.
- As mentioned before, hydrogen is a dry pigging medium. Generally pigging vendors have solutions for dry environments to limit cup wear. Excessive cup wear may lead to stalled or even stuck pigs. ILI tools have been successfully run in hydrogen, but these were mostly small diameter, short lines. ILI vendors still have to demonstrate that these solutions also work in large diameter, long distance hydrogen pipelines.

6 Overview of gaps in ILI tool readiness for hydrogen lines

This section contains an overview of challenges/gaps identified in the four areas covered in the previous chapters. The gaps are shown in the table below.

1. Gaps in availability of ILI technologies with sufficient performance for hydrogen pipelines	
1.1	It is not known if resonance UT for metal loss could work in hydrogen pipelines at typical operating pressures.
1.2	No ILI technology exists to inspect for planar anomalies parallel to the helical seam weld direction. Neither for technologies that require a liquid as couplant nor for technologies that can run in gas service.
1.3	No ILI technology currently exists to inspect for planar circumferential anomalies in gas service.
1.4	It is not clear if existing crack detection technologies are sensitive enough to detect and size tight fatigue crack as may be expected in hydrogen lines with fatigue loading.
1.5	The performance of new technologies (e.g. eddy current, gas coupled Lamb waves) for crack detection in gas service is not known as these are still in development (service not commercially available yet) and require further validation.
1.6	Limited, publicly available, performance validation information about ILI tools that measure pipeline axial strain.
1.7	Limited, publicly available, performance validation information about ILI tools that can detect hard spots.
1.8	Limited, publicly available, performance validation information about ILI tools that can identify changes in material properties (e.g. yield and/or tensile strength) at joint level.
2. Gaps in compatibility of ILI tool materials with hydrogen	
2.1	ILI tools need be redesigned or modified for use in hydrogen pipelines. Current TRL levels of various tools and technologies for hydrogen pipelines are still low.
2.2	There is some experience running ILI tools in hydrogen (mostly MFL) but mainly in small diameter, short distance pipelines. There is a lack of experience in running

	these tools in larger diameter, high pressure, longer distance transmission pipelines relevant for the energy transition.
2.3	ILI vendors have identified solutions to potential material compatibility issues when running in hydrogen. However, some issues require more testing with longer exposure to hydrogen to ensure effectiveness of the solution.
3. Gaps in ability to safely launch, run and receive ILI tools in hydrogen pipelines	
3.1	Current tools are not ATEX certified at the required level for use in hydrogen pipelines (i.e. ATEX II-C)
3.2	Work has been done to better understand process safety risks and corresponding mitigating measures when launching, running and receiving ILI tool in hydrogen pipelines. However, there is still limited experience how to best implement these measures in practice.
3.3	Hydrogen ingress into ILI pressure vessels may introduce a new safety risk when working on the tool after a run. This risk is not fully understood yet and effective mitigation measures need to be developed and implemented.
4. 4. Gaps in ability to get good quality data from an ILI run in a hydrogen pipeline	
4.1	The low density of hydrogen can result in excessive speed excursions for high friction tools from technologies such as MFL and EMAT. In areas with high tool speed, data degradation/loss can occur.
4.2	ILI vendors have developed guidance for natural gas lines under which operating conditions (pressure, gas velocity, flow control) speed excursions can be minimised. Such guidance is not available yet for hydrogen lines.
4.3	Speed control units and/or active braking systems might be used to limit speed excursions. It is not known yet how effective these systems can be in typical hydrogen pipeline conditions.
4.4	Running an ILI tool in a batch of nitrogen could be an option to mitigate speed excursions. More work is required to develop this approach in more detail and to assess its practicality for the various hydrogen pipeline configurations.
4.5	Hydrogen is a “dry” pigging medium which could lead to high cup wear and might result in a stalled or stuck pig. ILI vendors have experience with other dry pigging media, but it is not known yet if these solutions also work in long hydrogen pipelines.

This white paper and the table above summarize the work of POF on ILI tool readiness for hydrogen lines. It is important to note that these are gaps as identified in October 2023. The ILI industry is constantly developing and improving so it is possible that some gaps have been (partially) closed and TRLs have increased since then. It is the intention of POF to provide an update of this work within the next 3 years.

Detailed guidance on how gaps can or should be closed is out of the scope of the POF work. The main action party to close these gaps are different for each gap, with the main parties being:

- ILI vendors. Many of the tool/technology specific gaps will have to be closed by them.

- Hydrogen pipeline operators. The main responsibility for safe operation of the ILI run rests with the operator. They will also need to work together with the ILI vendors about priorities and required timing for the various ILI technology development steps.
- Joint Industry Programs. Certain gaps about insufficient information about technology performance might be best closed through a JIP where operators and ILI vendors work together to determine performance using realistic test pipes under realistic test conditions.

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Appendix 1: Planar anomaly sensitivity

Planar anomalies are of particular concern to hydrogen pipelines as these may become injurious due to enhanced fatigue crack growth rates from pressure cycling. The actual critical defect size can be determined through an Engineering Critical Assessment (ECA). This white paper does not purport to address acceptable defect sizes or the considerations and assumptions to be undertaken in conducting an ECA for hydrogen service. Notwithstanding this a range of defect sizes has been considered that may be typical starting defect sizes coming from an ECA. More detailed information on inputs and approaches for an ECA are given in the EPRG guidelines [1].

To get some idea how the required performance of ILI tool for planar anomalies is related to critical flaw sizes, three inputs will be considered.

Flaws from line pipe manufacturing. Seam welds are inspected in the pipe mills for planar anomalies. Initially with radiography but since the 1990s increasingly with ultrasonic testing (UT). The API-5L standard specifies an internal and external N5 or N10 notch (depending on the welding process) in longitudinal direction as reference indicators. An N5 notch has a depth of 5% of the wall thickness and maximum length of 50 mm. An N10 notch has the same length but a depth of 10% of the wall thickness. If the inspection in the pipe mill has been performed correctly, the seam welds should not contain any flaws larger than the reference indicator. For instance for a 0.5” = 12.7 mm wall thickness this means a maximum depth of 0.64 mm and 1.27 mm for N5 or N10 notch respectively.

Detection threshold of ILI crack detection tools. Some basic information about crack detection capabilities of the various inline inspection tools is available from published performance specifications by the ILI vendors. For a certain technology they may differ per ILI vendor but roughly the following thresholds are applicable for inspection of long seam welds:

- EMAT: 2 mm depth by 50 mm long,
- Standard liquid coupled UT: 2 mm depth by 25 mm long,
- High resolution liquid coupled UT: 1 mm depth by 15 mm long.

Using these specifications and comparing it to the performance assessment for planar anomalies given in Table 2, it becomes clear why EMAT and standard liquid coupled UT are assessed as “sufficient for some but not all cases” and high-resolution liquid coupled UT is assessed as “sufficient for most cases” in Table 1. It should also be noted that all current ILI crack detection tools would score sufficient for the case where the critical defect size in a seam weld is equal to the EPRG level 1 size of 3 mm deep by 50 mm long [1].

The situation is different for the inspection of girth welds. Of the three technologies listed above, only the standard liquid coupled UT technology is available for the inspection planar anomalies in circumferential direction.

Typical starting defect size for ECA. There are various considerations that can be made in determining the starting defect size for an engineering critical assessment (ECA). It can be based on expected defect size, inspection capabilities and safe defect size. There is guidance on how to determine starting defect size for in the EPRG white paper [1]. In the absence of more detailed inspection and manufacturing information, EPRG recommends a standard workmanship defect of 3 mm deep and 50 mm long. More stringent values with round numbers of 1 or 2 mm depth and 25 mm long are also used frequently.

The above information is summarised in Figure 1 below. Flaws right and above the ILI lines should be detectable by these tools. Flaws right and above the N5 lines should not be present in the line pipe seam weld just after manufacturing. Whether ILI tools are sensitive enough depends on the starting defect size required to demonstrate a practical fatigue life of the pipeline under typical operating conditions. The figure shows that current tools are likely to be sensitive enough for the more relaxed starting defect size of 3 mm x 50 mm. However, more sensitive tools are needed for cases when smaller, ECA based, starting defect sizes are required.

Figure 1 Seam weld flaw acceptance compared to detectability with ILI crack detection (CD) tools.