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Safety of Hydrogen Pipelines: Challenges and Solutions

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Pipelines intended for hydrogen transport carry significant risks not only due to corrosion but also crack formation. This is primarily because the "molecule of the energy transition" reduces material strength through embrittlement. Moreover, its greater explosiveness and reactivity compared to methane require specialized safety standards. In-line inspections (ILI) are an essential preventive measure to manage these risks early. As of today, ultrasound-based technologies remain the only precise method to ensure a safe transition to this new resource.

With the transition to climate-friendly energies, hydrogen has become a key focus. However, the safe transport of this highly flammable gas poses considerable technical challenges. In addition to corrosion and manufacturing-related defects (such as inclusions and laminations), crack propagation is a critical safety concern. Managing cracks and detecting them early is vital, as these weak points significantly increase the risk of leaks and explosions.

Existing regulations and standards mandate targeted measures to ensure the safety of pipeline systems used for hydrogen transport. These measures include: specific material property requirements, particularly resistance to brittle fracture; effective pressure management to monitor safe thresholds; and in-line inspection to detect defects early [1, 2].

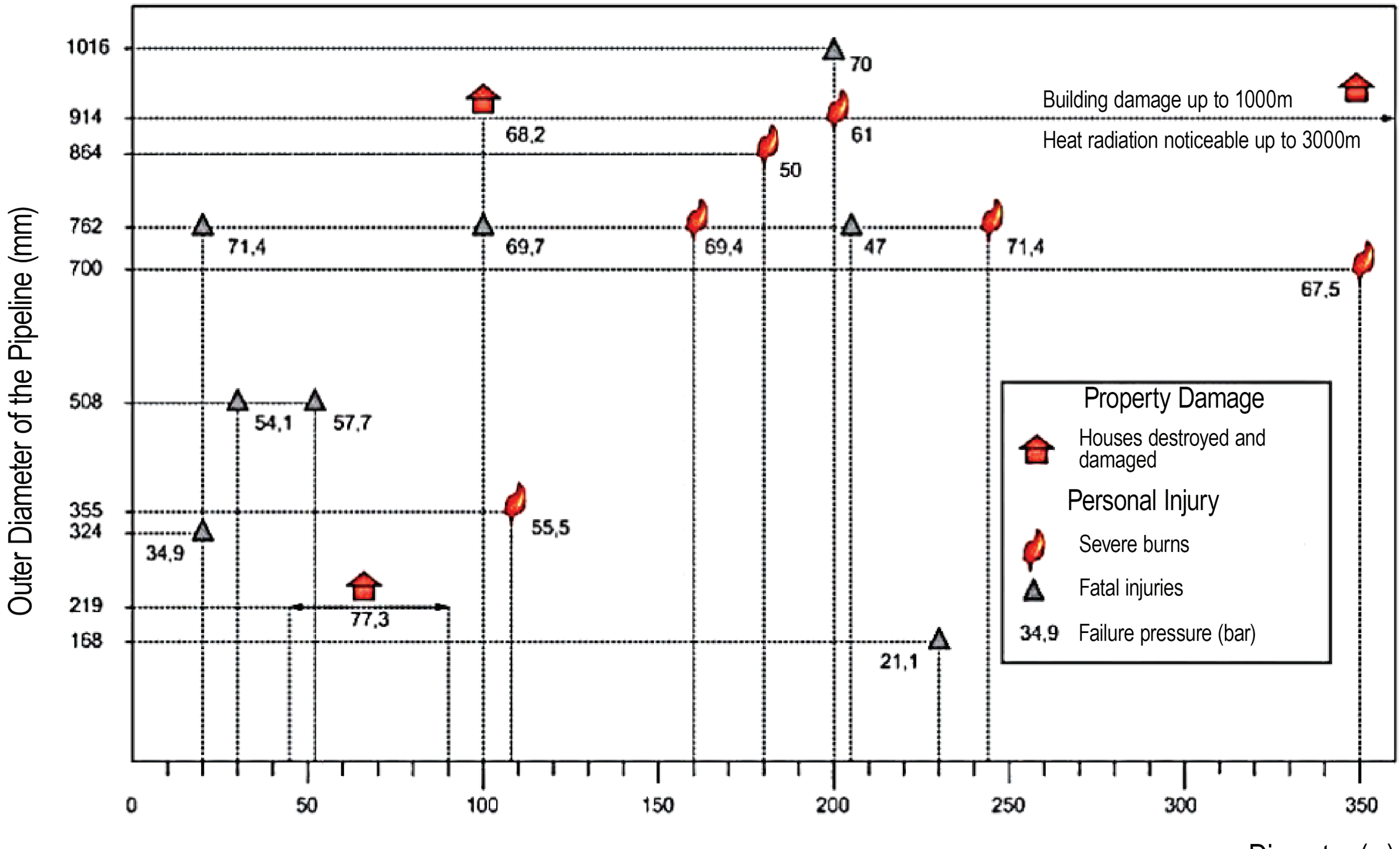

Figure 1: Documented hazard radii of natural gas pipeline failure [3]

Pipeline operators are increasingly adopting technologies that avoid liquid coupling media to prevent residual moisture after inspections, reduce internal corrosion, and minimize logistical effort. However, this strategy carries hidden risks.

Corrosion vs. Cracks – Which Poses Greater Danger?

Corrosion has long been a major threat to pipelines. Chemical reactions between metal and the environment lead to material loss and compromise structural integrity. Aggressive substances like hydrogen sulfide (H_2S), carbon dioxide (CO_2), condensation caused by temperature fluctuations, and damaged protective coatings exacerbate this risk. For years, this threat has been mitigated using ILI.

Cracks, however, pose a much greater risk than material loss. Cracks concentrate mechanical stress in small areas, putting the surrounding material under significant strain. This localized stress can lead to rapid crack propagation and, in extreme cases, sudden rupture or explosion. Even small leaks can allow flammable gases to mix with oxygen, creating explosive mixtures. The risk of self-ignition increases due to friction and heat during gas escape, especially under high pressure. Additionally, high gas flow velocities can cause electrostatic charges that may generate sparks and ignite the gas.

In over 30 years of ILI history, no pipeline has been found entirely free of defects. Tragic accidents, such as in San Bruno, California (2010) and Ghislenghien, Belgium (2004), highlight the devastating consequences of cracks in natural gas pipelines, resulting in significant loss of life and property.

The German Federal Institute for Materials Research and Testing (BAM) provides a detailed description of the hazard radii caused by thermal radiation in the event of natural gas pipeline failures [3] (see Figure 1). In some cases, the damage was documented at distances ranging from 350 to 1,000 meters, highlighting the immense danger of such incidents.

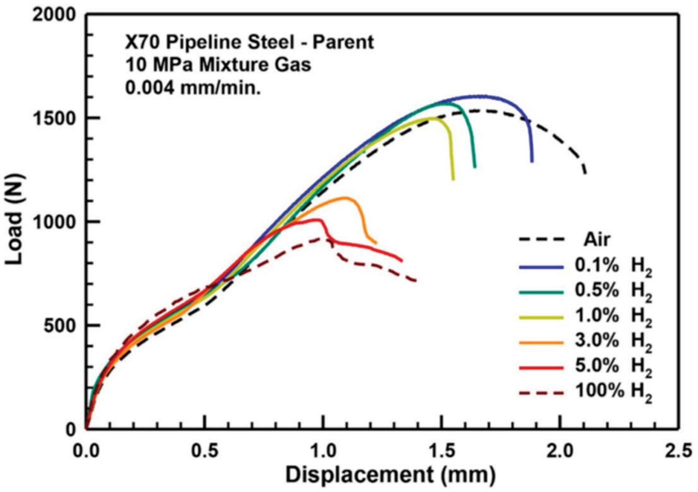

Figure 2: Effect of hydrogen concentration on mechanical properties [6]

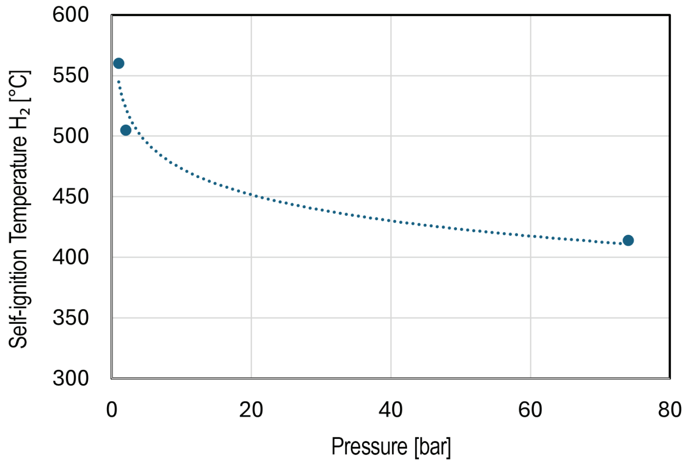

Figure 3: Experimentally determined self-ignition temperature of hydrogen [10]

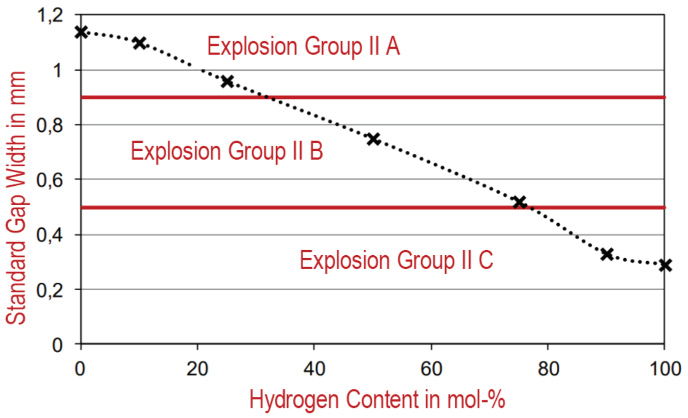

Figure 4: Experimentally determined limit gap widths for hydrogen-methane mixtures [14]

Key Differences Between Hydrogen and Methane

While methane (CH_4), the primary component of natural gas, carries risks due to leaks and the formation of explosive mixtures, hydrogen (H_2) presents additional challenges:

1. **Hydrogen Embrittlement:** Atomic hydrogen can penetrate metals, accumulate at grain boundaries and flaws, and reduce material toughness. Measurements, such as those in the publication "Steel Components in the Hydrogen Economy" [4] and by Chengshuang et al. [5], show that pipeline steel (e.g., X80) experiences a significant drop in fracture elongation, from over 20% without hydrogen exposure to below 5% in hydrogen-rich environments.
2. **Gas Composition:** The influence of different gas compositions on material properties was investigated by Nguyen et al. [6]. The results show the relationship between the applied load and the displacement of the test stamp. The influence of hydrogen becomes visible even at a concentration of 0.1% (Figure 2). As the hydrogen concentration increases, the maximum transmitted loads and deformations tend to decrease and drop significantly when the accumulation reaches 3%. According to the authors, the effect of hydrogen concentration in the gas mixture on mechanical properties is significantly greater than the effect of pressure. Long-term exposure to hydrogen has only a minor impact on the degree of hydrogen embrittlement. The results are consistent with the data provided in sources [7-9].
3. **Ignition Risk:** Hydrogen has a slightly lower self-ignition temperature (~560°C) compared to methane (~595°C) but is more pressure-sensitive. At 70 bar, hydrogen's self-ignition temperature drops to ~415°C [10].
4. **Reactivity:** Hydrogen is far more reactive than methane, with a minimum ignition energy of 0.019 mJ compared to methane's 0.28 mJ. Its wide flammability range (4–75%) in air also makes hydrogen much more prone to forming explosive mixtures than methane (5–15%) [11].
5. **Explosive Force:** Hydrogen explosions generate a pressure rise about 12 times greater than methane [12], earning hydrogen the highest safety classification (IIC) under ATEX regulations [13].
6. **Maximum Experimental Safe Gap (MESG):** The MESG refers to the maximum width of a gap (e.g., a crack in a pipeline) through which a flame cannot propagate under specific gas mixture conditions (Figure 4). For hydrogen, this MESG is only 0.2 mm, as determined by the Federal Institute for Materials Research and Testing [14], which classifies it in the highest hazard category. In contrast, the MESG for methane is 1.14 mm, as reported by Friedmann & Johnston [15].
7. **Reverse Joule-Thomson Effect:** When depressurized, methane cools, while hydrogen heats up, increasing the risk of self-ignition in leaks. Hydrogen can heat by 6–10 K per 100-bar pressure

reduction [16, 17].

8. **Catalysts:** Nickel, iron oxide, platinum, and palladium act as catalysts, reducing ignition temperatures for both methane and hydrogen. Hydrogen is particularly reactive, with catalytic surfaces enabling self-ignition at 70°C, whereas methane's ignition temperature only drops to 400–450°C in similar conditions [18, 19].
9. **Electrostatic Discharge:** According to the *Linde Safety Data Sheet on Hydrogen Handling* [20], rust particles carried by high-velocity hydrogen streams can generate sparks through electrostatic discharge or upon impact, igniting the gas.

These characteristics make hydrogen inherently more dangerous than methane, requiring strict safety measures for handling and transport.

Examples and Lessons from Hydrogen Accidents

A striking example of the dangers associated with hydrogen and the risk of explosions is provided by the Minerva Database [21], a comprehensive collection of incidents and accidents involving hydrogen. The database documents over 700 incidents, resulting in more than 150 fatalities. These alarming figures highlight how severe the consequences of inadequate safety measures or technical deficiencies can be. Hydrogen is a key element of the energy transition, but its safe handling requires the consistent implementation of safety measures.

The investigation of the incident revealed that material fatigue, insufficient inspection measures, and the specific chemical properties of hydrogen were key factors in the explosion. In particular, hydrogen's ability to penetrate metals and weaken their structure (hydrogen embrittlement) played a crucial role. Such incidents have led to increased efforts worldwide to improve safety standards and develop new technologies for the safe operation of infrastructure.

It is evident that even minor material defects, which may not be considered critical in natural gas pipelines, can pose a risk in hydrogen pipelines. The described mechanisms and their impact on the lifespan and safety of steel pipelines emphasize the importance of modern ILI methods. These techniques enable the early detection of cracks and material damage before they reach a critical size. When the tolerances of ILI tools become larger, there is an increased risk that critical defects may be overlooked or inaccurately assessed. This directly affects the remaining service life of a pipeline. Standards such as ASME B31.12 [22] and DVGW G 463 [23] require, in such cases, either shorter inspection intervals, more conservative fracture mechanics assessments, or a reduction in permissible operating time to minimize safety risks.

Table 1: Strengths and Limitations of Different Inspection Technologies

Feature	EMAT	Lamb Wave	UT Amplitude-Based (Batch)	UT Crack-Tip Detection (Batch)
Data Source	Field results*	Test results	Field results	Field results
Reporting Threshold (length)	40 - 50 mm	40 - 50 mm	25 mm	25 mm
Reporting Threshold (depth)	2.0 mm / 15% WT	~1.0 mm	1.0 mm	1.0 mm
POD (Probability of Detection)	>90% [26]	90% [26]	60% [25]	>95% [25]
POI (Probability of Identification)	<20% [26] after verified excavations	>85% [26]	90%	>90% [25]
POS (Probability of Sizing)	~55% [26] for ±1.1 mm @ 80% confidence	>85% [26] ** for ±1.0 mm @ 80% confidence	90% [25] for ±1.7 mm @ 80% confidence	90% [25] for ±1.0 mm @ 80% confidence
Maximum Crack Inclination	±10°	Not specified ***	±10°	±45°
Length Measurement Accuracy	±20 mm	±10 mm	±10 mm	±10 mm
Inspection Intervals	3–6 years due to limited measurement accuracy & tolerances [26]	5–10 years possible	5–10 years possible	5–10 years
False Positive Rate	High	Low to medium	Low	Low
False Negative Rate	Average	Low to medium	Medium	Low
Suitability for Crack Detection	Good for SCC but lower accuracy in POS and POI	Insufficient data	Good for cracks at weld seams	Excellent for cracks, especially at weld seams
Circumferential Crack Detection	Not specified	Not specified	Specified	Specified

* Based on 90 inspections
** Possibly UCL according to data in Figure 8 in [26]
*** [26] states that sharp-edged corrosion does not produce evaluable signals. Inclined cracks follow a similar reflection pattern.

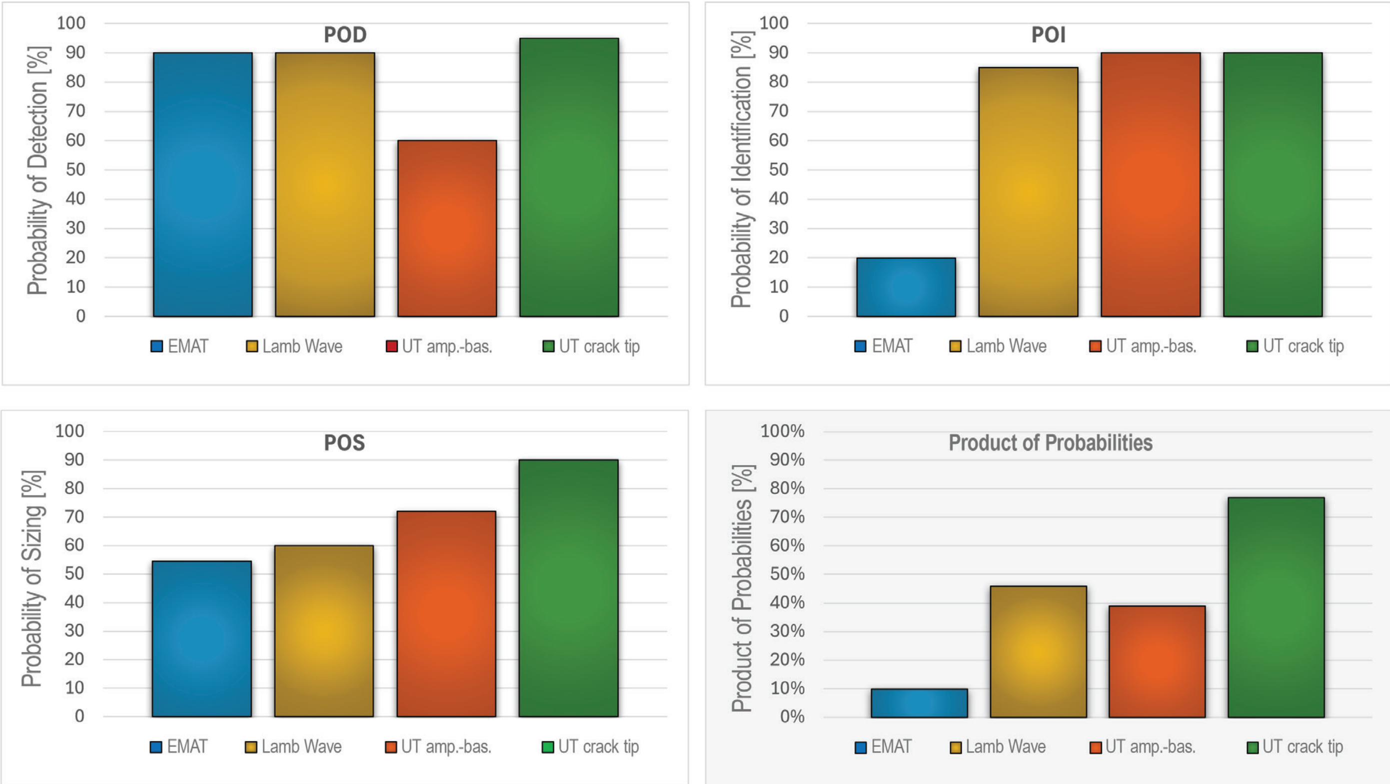

Figure 5: POD, POI, POS, and product of probabilities per test technology

Technologies for Crack Inspection

Pressure testing of pipelines poses a risk of pressure reversal, where small cracks or material weaknesses grow under high test pressure but fail suddenly during normal operation. In contrast, ILI with inspection tools (pigs) provides a safer and more precise monitoring method. It detects material defects early without subjecting the pipeline to extreme pressure. Key technologies include:

- **Electromagnetic Acoustic Transducer (EMAT):** Detects axial stress cracks, coating defects, and corrosion using electromagnetic waves.
- **Acoustic Resonance Technology:** Uses Lamb waves for detecting axial cracks.
- **Axial Magnetic Flux Leakage (Axial MFL):** Identifies material loss or corrosion through magnetic field disruptions.
- **Ultrasonic Crack Detection (UT-CD):** Employs ultrasonic waves in liquid to detect axial and circumferential cracks but requires clean inner surfaces for effective coupling.

Each technology has its strengths and limitations, making the choice dependent on the expected damage types and pipeline conditions.

Strengths and Weaknesses of ILI Technologies

Reber and Beller's study "Evaluation of UT Crack Sizing" [24] highlights the strengths and limitations of axial MFL and ultrasonic inspections. While axial MFL is effective for detecting elongated corrosion, it struggles with non-volumetric cracks. The study emphasizes the need for combining multiple inspection methods to address the full spectrum of pipeline defects. As the technology is unambiguously not ideal for crack detection, it was excluded from Table 1 and Figure 5.

Ultrasonic crack inspection is noted as the most precise method for detecting and sizing cracks, especially small ones, ensuring pipeline safety and reliability in hydrogen transport.

Performance Evaluation of ILI Tools

The performance evaluation of ILI tools compared to their specified capabilities is a critical factor for the integrity and safety of pipelines. However, in practice, significant discrepancies often arise between these specifications and actual results, particularly in the detection and sizing of cracks. These discrepancies pose risks, as they lead to increased tolerances, deviations from field results, and additional costs due to data-verification excavations.

Studies such as "Innovative and Accurate Time-Based Crack Sizing ILI Tool for Greater Pipeline Reliability" by Krynicki et al. (ExxonMobil, Dexon Technology) [25] emphasize the need for more precise and reliable crack-sizing tools to improve confidence in ILI results. The study highlights the differences between the performance of older, amplitude-based ILI tools and the newer generation of ILI systems, which determine crack depth by measuring crack tips. Similarly, research by Hubert et

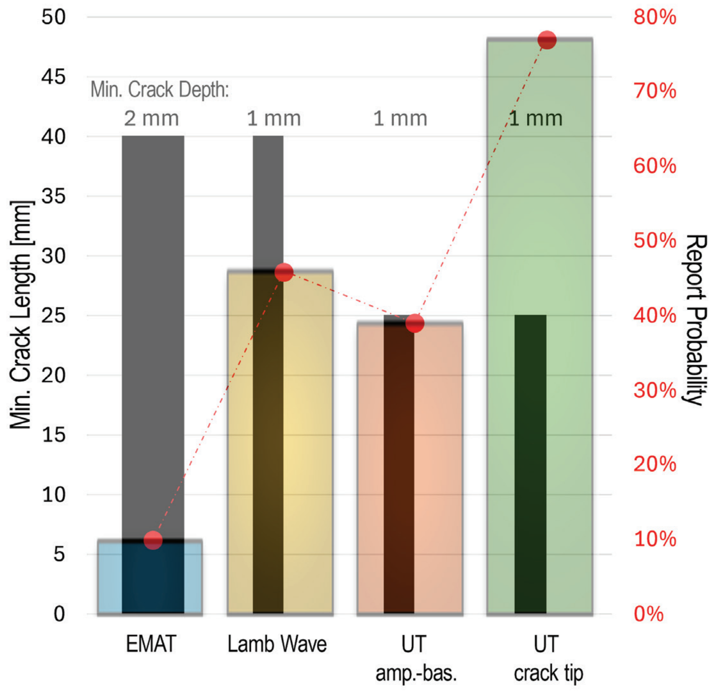

Figure 6: Crack size and report probability

al. [26] underscores the necessity of technological advancements in crack detection and classification to reduce discrepancies between specifications and field performance.

When comparing ultrasonic crack inspection in batch mode with EMAT and Lamb Wave technologies, it becomes evident that ultrasonic testing can detect significantly smaller cracks. Another advantage of conventional ultrasound is its reliable detection and precise measurement of circumferential cracks, which, to date, can only be addressed effectively by this technology. Alternative inspection methods, such as EMAT or Lamb Waves, face limitations in this context.

A key consideration is the radial inclination of defects. For inclinations greater than 10°, only ultrasonic tools with very high sensor coverage, combined with crack-tip detection (TOFD), can deliver satisfactory results (see Table 1).

Analyses from [25] and [26], based on extensive field data, reveal significant deviations from specifications in EMAT reports and amplitude-based ultrasonic sizing. These discrepancies affect both accuracy and consistency, highlighting potential challenges in the reliability of these methods.

What Does This Mean for Report Quality?

In pipeline inspections, report quality is assessed based on three key probabilities (see Figure 5):

- **Probability of Detection (POD):** How likely is it that a defect will be detected?
- **Probability of Identification (POI):** How accurately can the defect be classified (e.g., corrosion, crack)?
- **Probability of Sizing (POS):** How precisely can the depth or size of the defect be measured? For better comparability across all technologies, POS is standardized to ±1.0 mm at 80% confidence.

The product of these probabilities determines the overall likelihood that a defect is accurately captured in the report. Maximizing this probability is essential to enhance the reliability of inspections and ensure effective repair planning.

Ultrasonic crack inspection, particularly with TOFD, consistently demonstrates superior precision and reliability in addressing even the smallest cracks, making it a key technology for ensuring pipeline safety.

Considering Crack Size in Reliability Assessments

When evaluating the reliability of crack inspections in pipelines, it is insufficient to consider only the probabilities for detection (POD), identification (POI), and sizing (POS). These probabilities must also be related to the actual size of the crack, as smaller cracks are typically harder to detect. To accurately represent the overall probability, the probability product must be linked to the crack dimensions. This can be visualized through graphical representations, with crack size illustrated as black bars (Figure 6).

Ultrasonic crack inspections based on crack-tip signal measurement are unmatched in practice. This method allows for the detection and precise measurement of even the smallest cracks with high accuracy.

The combination of high sensitivity and precision makes ultrasonic crack inspection the best option for reliably identifying and sizing small cracks. Correlating probabilities with crack size clearly demonstrates that this method is currently unparalleled in minimizing safety risks and avoiding unnecessary excavations.

Conclusion

The transition to hydrogen as an energy carrier presents a significant challenge for existing infrastructure, especially for pipelines originally designed for natural gas. It is essential to inspect these pipelines not only for corrosion but also for cracks before transporting hydrogen. This ensures that all relevant safety aspects of the pipeline infrastructure are addressed. Limiting inspections to corrosion would be negligent—cracks must become a central focus.

At present, ultrasonic technology remains irreplaceable for this purpose. Pipeline operators should increasingly consider the use of liquid batches to ensure comprehensive and reliable inspections, ultimately safeguarding the infrastructure for hydrogen transport.

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