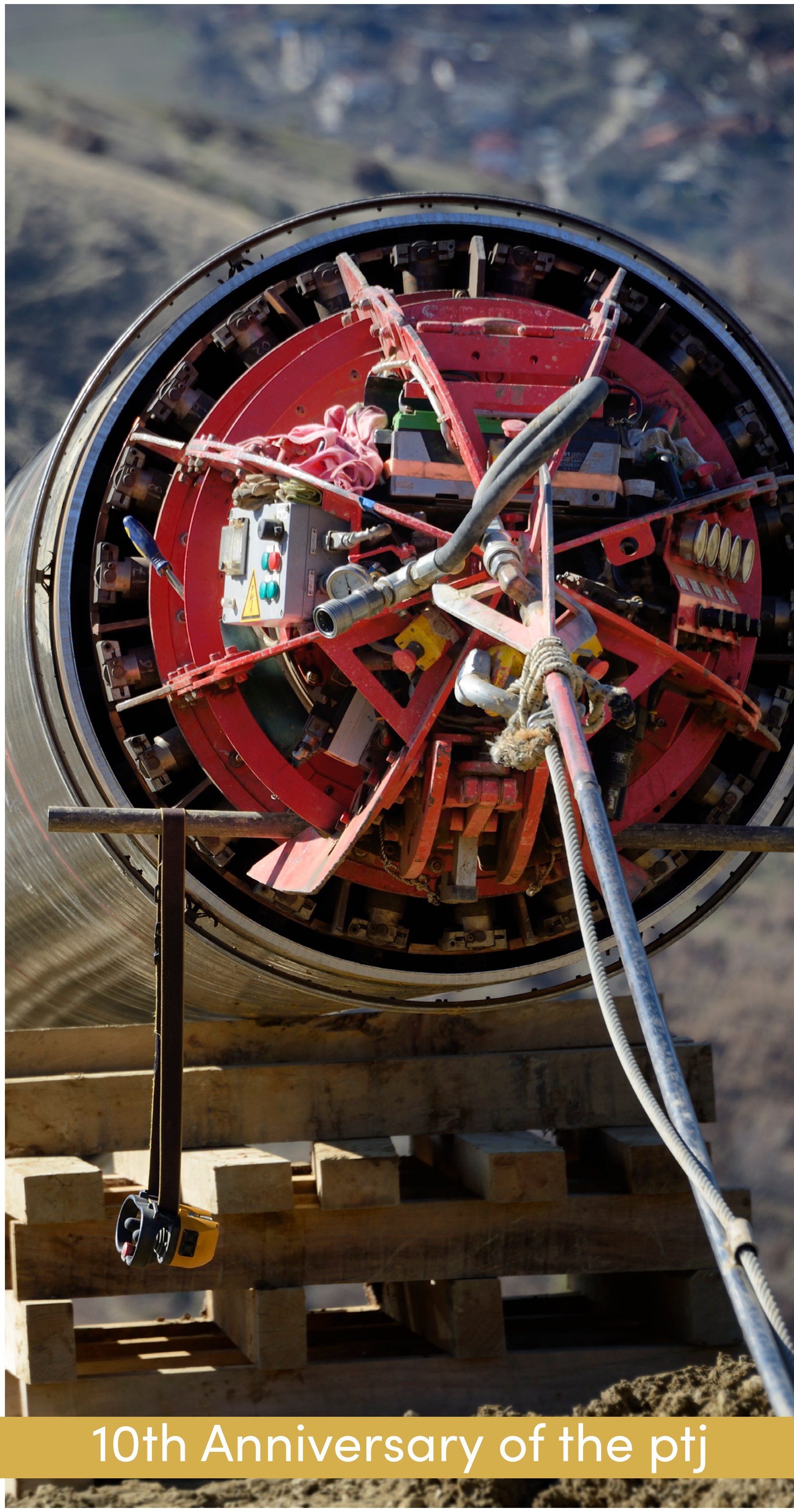
2/2023

ptj Pipeline Technology Journal



Inline Inspection & Integrity Management

Security of Petroleum Pipelines in the Middle East

Innovative Solutions to Address Stabilization Challenges of a 48-Year Old Subsea Pipeline

Integration of multiple Leak Detection Technologies into a single Advanced Leak Detection System

The Influence of Anomaly Dimensions on POX for EMAT-C Crack Detection As Found Dig Results

Low-Cost Airborne Oil Leak and Threat Detection for Pipeline Right-of-Way

10th Anniversary of the ptj

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Greetings to all our esteemed readers,

As managing directors of the EITEP Institute, it is our pleasure to welcome you to our 10th anniversary edition of the Pipeline Technology Journal (ptj). Since its first issue in 2013, our journal has grown into a widely recognized and respected source of information and analysis for pipeline professionals.

Dennis Fandrich
Managing Director

EITEP Institute

As we mark this milestone, we want to express our sincere appreciation to our readers and contributors, as well as to the members of our ptj Editorial Board. Without their support and dedication, we would not have been able to achieve the success we have today.

The mission of the EITEP Institute is to foster exchange of knowledge and ideas and to help advance the field. For ten years now, ptj News with its news portal, social media channels and the newsletter provides up-to-date coverage of pipeline technology and engineering, while the Journal offers in-depth professional articles. Both aim to promote knowledge sharing and advancement in the industry through the dissemination of research and best practices. Furthermore, all technical articles are available on an open-access basis. For this reason, our website has become a valuable resource for pipeline professionals, providing them with a wealth of information on the latest technologies, innovations and best practices in the industry.

Marian Ritter
Managing Director

EITEP Institute

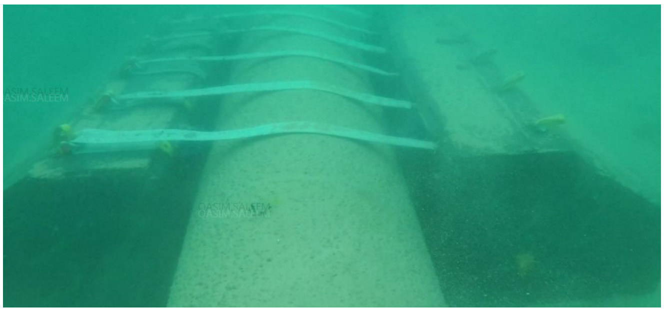
It is not an exaggeration to say that we are proud of the Pipeline Technology Journal, which serves as a testament to the exciting and diverse nature of the pipeline industry. We will continue to cover the latest trends, technologies and regulatory developments and to showcase the innovative work being done by pipeline professionals all around the world.

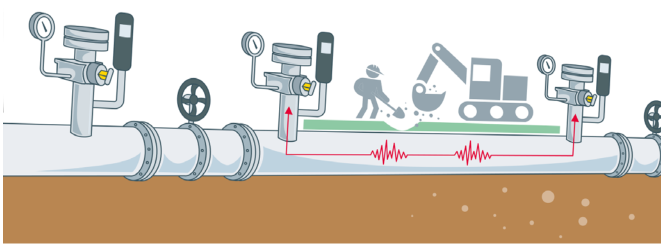
Once again, we would like to thank everyone who has contributed to the success of the Pipeline Technology Journal over the past decade. We look forward to the years to come.

Sincerely,

Dennis Fandrich & Marian Ritter
Managing Directors
EITEP Institute

This Issue's
COMPLETE CONTENT





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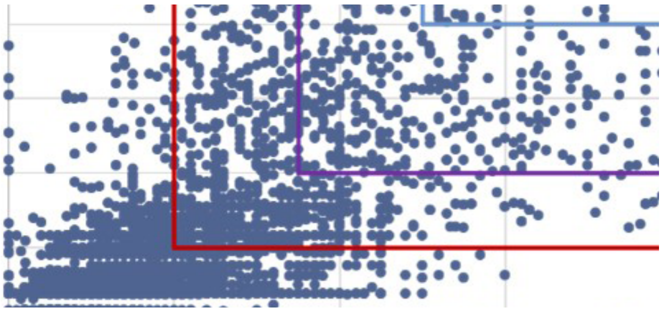


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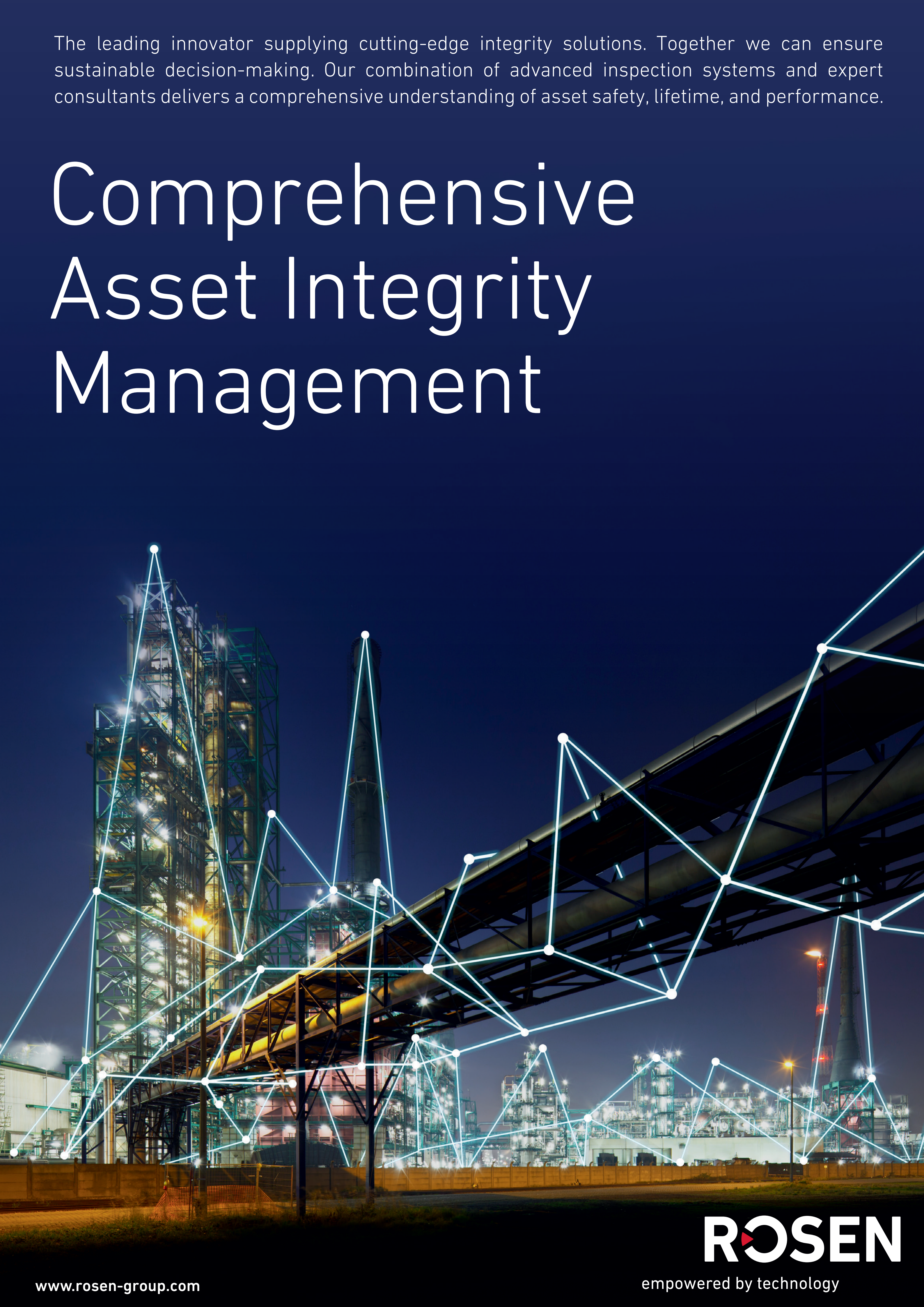
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A message from the

Dear Readers,

Welcome to the latest edition of the Pipeline Technology Journal!

This is the issue with the Focus Theme Pipeline Inspection and Pipeline Integrity. I hope, together with the other members of the editorial board that you find the chosen articles of interest.

Assessing the mechanical integrity of a pipeline is essential. It must be known if defects are present, what size they have and where they are located. This is critical data needed as input for an effective defect assessment, which in turn will provide insights regarding decisions that may have to be taken. This is all part of the process and goal to ensure the best possible availability of a given pipeline for a chosen maximum operating pressure whilst fully complying with applicable regulations.

The current issue is also the one which will be distributed at the upcoming Pipeline Technology Conference in Berlin, the biggest Pipeline Event in Europe. Several sessions of the conference will cover pipeline inspection and integrity. The conference and journal are thus complementing each other, the reason for making this the conference edition.

I would also like to use this opportunity to pick up on a thought communicated in one of the earlier issues of the magazine. In order to make the journal even more interesting and hopefully valuable for our readers we are planning to introduce two new series of articles. In additional to the technical papers already included, we will start to run a series of articles written by well-known industry experts on particular pipeline related topics. The authors will share their experience, insights and opinions.

The first of these will address different aspects of pipeline inspection and integrity. Each article will cover a different topic within the theme. The first article of this series will be included in the next issue of the Pipeline and Technology Journal later this year. The topics covered will range from typical defects in pipelines, internal and external inspection methods, material properties and characteristics all the way to repair and rehabilitation.

A second series we are planning is more educational in nature. The idea is to pick up on a variety of pipeline topics and introduce and explain them to readers which have not been members of our industry for so long. The reason is that we are often approached by delegates of the conference as well as readers of the Journal to provide more background and introductory information on different topics covered in the various sessions of the conference. The conference already provides an opportunity to visit workshops and a range of training sessions complementing the program.

ptj Editorial Board

Now we want to expand this to the Journal itself and add value for our readers. This second series will also start with the next issue of the journal.

My fellow members of the editorial board and I hope that these two new series of articles will find your interest and look forward to your feedback!

Enjoy reading this issue of the ptjJ! If you come to the event in May, enjoy your visit to Berlin and the ptc!

Some members of the editorial board, including myself, will visit the conference and exhibition and we look forward to seeing you there!

Best regards,

Dr. Michael Beller

Chairman of the ptj Editorial Board


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Planning For A North Sea Hydrogen Pipeline Network

Det Norske Veritas, more commonly known as DNV nowadays, has just completed a study asserting that a hydrogen pipeline network in the North Sea would be feasible and doable, highlighting the significant advantages of an offshore hydrogen backbone in the North and Baltic Seas.

Indeed, the North Sea has the potential to become the site of massive offshore hydrogen production from offshore wind and a hydrogen pipeline network. The study says the pipeline network would further enhance connections between northwest European countries.

"The EU expects demand for climate-neutral hydrogen to reach 2,000 terawatt hours (TWh) by 2050, and DNV sees the potential to produce 300 TWh/a of hydrogen using electricity from offshore wind farms in the North Sea by 2050," said Ulrich Benterbusch, Managing Director at Germany's GASCADE, builder and operator of large gas transmission pipelines.

Benterbusch adds that a North Sea hydrogen network would make a significant contribution to reducing dependence on energy imports: "This positive aspect for increasing supply security can hardly be valued highly enough after the experiences of the recent past."

According to the study, an investment of $15.9 billion-$23.3 billion (15–22 billion euros) could build the North Sea hydrogen backbone with pipelines of a total length of 4,200 kilometers (2,610 miles).

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Security of Petroleum Pipelines in the Middle East

DR N. ABI-AAD > PETROLEB

Abstract

Oil pipelines in the Middle East have historically focused on the security of supply and export rather than on the economic benefits of having cheaper oil transport. Looking at the historical record of these pipelines, one could easily conclude that the objective of oil supply security sought by Middle-Eastern producers has not been met through pipelines.

In fact, there is no security of petroleum supply from the Middle East without real political stability in the region. Nevertheless, the turbulent history of the area does not promise future stability.

On the gas side, developers of new gas pipelines have also to take into consideration the new realities in the global gas markets which are now favouring the trade of gas in liquefied form (LNG) rather than through pipelines.

Building a regional gas network between countries of the Middle East should always be kept on top of the policy-makers agenda. Such a network shall increase the gas resources available to regional economies and shall create a strong development drive. In addition, it shall boost intra-regional trade and become an important step towards a long-term political co-operation and economic integration.

1. Introduction

While many situations of instability and conflict in the Middle East remain restricted to the smaller scale, internal or regional crises affecting the security of petroleum supplies from within this region are immediately considered as a threat to international peace and global markets, especially if it is associated with a disruption of petroleum supplies. This behaviour derives from an implicit conviction that Middle Eastern petroleum is to be 'shared' among its producers and consumers, being vitally and strategically important to the latter's economies.

Petroleum has always weighed on the Middle East with its geopolitical and strategic aspects, as the region holds more than 48 per cent of the world's oil reserves and around 40 per cent of those of gas[1] . It is also the region's Achilles' heel: any dispute or conflict there could be is tempted to materialise first by striking the petroleum industry which remains the backbone of many states in the region.

The petroleum industry in the Middle East is indeed highly exposed to both internal instability as well as to external attacks and violence, which can have major consequences on the supply of petroleum. This is especially true for petroleum pipelines in the region, although the situation differs between oil pipelines and those channelling natural gas.

2. Oil Pipelines: An Unsuccessful Track Record

Oil pipelines already established in the Middle East have focused on the security of supply and export rather than on the economic benefits of having cheaper oil transport. In fact, oil pipelines have been

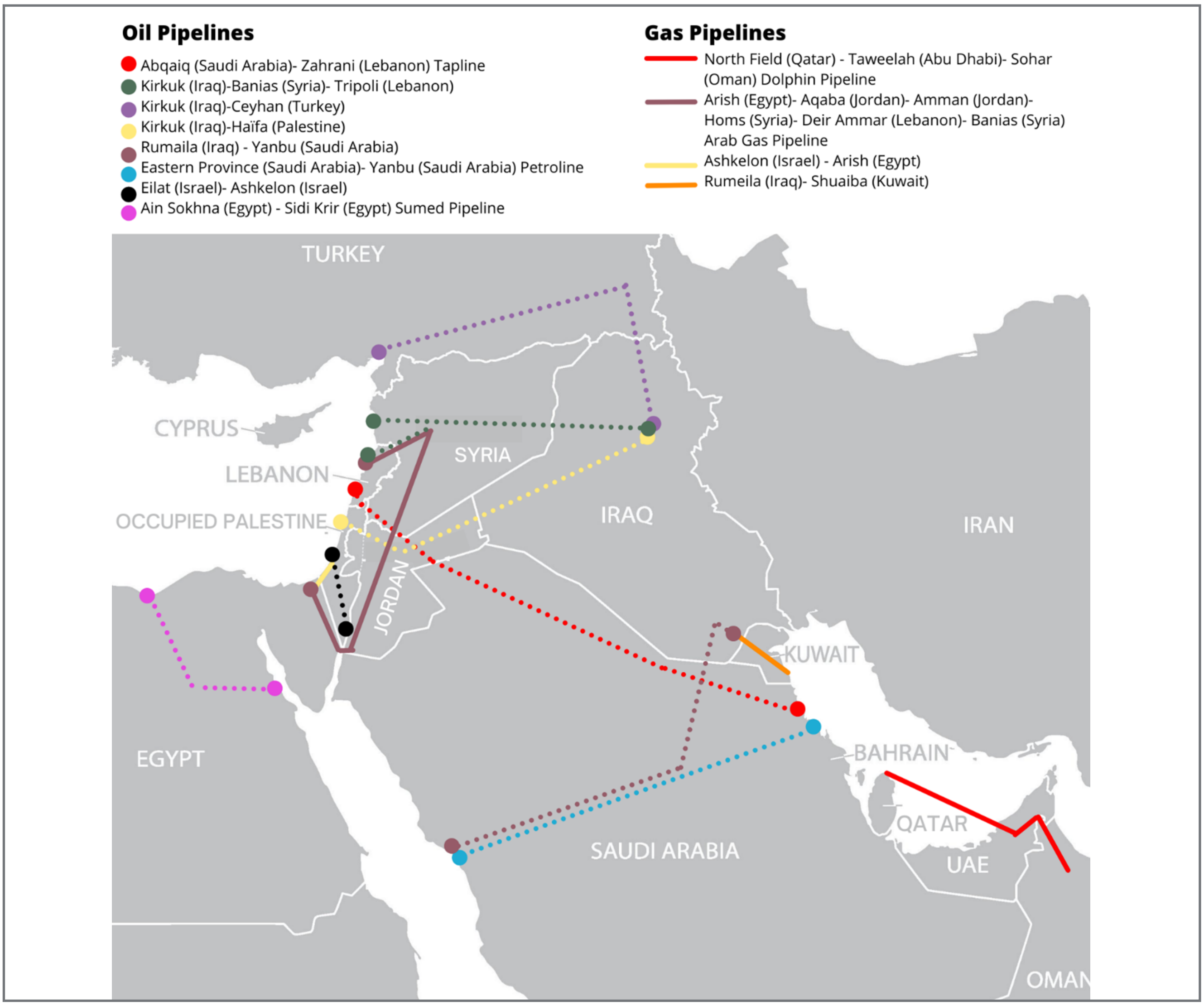

Figure 1: Map of the oil & gas pipelines in the Middle East

expensive to build and operate. In the years just after the World War II, for example, the Arabian American Oil Company (Aramco) had built the Trans-Arabian Pipeline (Tapline) from the Saudi eastern province to Zahrani on the Lebanese coast to avoid the Suez Canal and its transit fees. Yet, Aramco had to innovate in the pipeline's construction to keep it cost-competitive with shipping, and had to overcome fierce competition and related political hostility from Britain and its allies in Jordan and Syria. Later, transit fees imposed by Syria on Tapline's oil undermined the line's economic value.

Nevertheless, the Tapline, as well as Iraqi pipelines through Syria and Lebanon, were priceless immediately after the closure of the Suez Canal in 1967 as it allowed short access of Saudi and Iraqi crude to Mediterranean markets and beyond. With the introduction of supertankers, shipping regained some of its economic advantage, however.

The eight-year Gulf war (1980-88) was a stimulating factor in both Iran and Iraq to plan and implement a number of alternative oil export outlets to replace closed pipelines and damaged terminals. The regional conflict made this diversification attractive to all other Middle Eastern states. Not surprisingly, Iraq, whose meagre Gulf coastline was blocked early in the war and its export outlets through the Mediterranean shut down soon after that, consistently wanted the diversification of its export channels through Turkey and Saudi Arabia.

Although Iran's export security problem has never been as serious as that facing Iraq, sporadic Iraqi air strikes on Iran's Kharg Island in the 1980s gave Tehran some reasons for planning a number of pipelines aiming principally at by-passing the exposed terminal. However, most of the projects were later put on hold as an indirect result of the 1986 Iraqi strikes on the Iranian remote Larak and Sirri terminals that raised serious questions in Iran about the usefulness of pipelines and their security.

For Saudi Arabia, Petroline, its main export pipeline from the eastern province to Yanbu on the Red Sea, was basically built to secure outlets other than on the Gulf, and to lessen the kingdom's dependence on the vulnerable Strait of Hormuz. Yet liftings at the Red Sea must transit the Suez Canal or the Strait of Bab Al-Mandeb, or alternatively be piped through the Sumed pipeline which is linking, within Egypt, the Gulf of Suez to the Mediterranean. A similar role could well be played by the Eilat-Ashkelon pipeline in Israel.

The Eilat–Ashkelon oil pipeline got much publicity lately with the United Arab Emirates (UAE) reportedly agreeing with Israel to channel part of its crude from the Red Sea to the Mediterranean through this line. This pipeline was built in 1968 as a joint-venture between Israel and Iran to transport Iranian crude oil to Europe. However, Iran ceased using the pipeline following the Islamic Revolution of 1979 and the subsequent seizure of the pipeline by Israel. Recently, in May 2021, the pipeline was damaged by a rocket fired from Gaza.

With this in mind, one could easily conclude that the objective of oil supply security sought by Middle-Eastern producers has not been met through pipelines. This is confirmed by an assessment of the historical record of the international oil pipelines (crossing at least one state boundary) in the region until the end of 2022 (Table 1) which reveals that of the 445 years representing the cumulative age of these pipelines, some 168 years of actual pumping, or only 38 per cent, have been recorded. Thus, over their whole lifetime, the international oil pipelines in the Middle East had 277 years, or 62 per cent, of cumulative interrupted pumping.

It is also interesting to note that every international oil pipeline in the region was shut down at least once, and that most of them remain closed until the present time. From the experience of the Middle Eastern, it is becoming clear that the vulnerability of an international pipeline is proportionate to the number of borders that it crosses, which clearly results in internal pipelines having much less problems and difficulties[2].

3. Supply Security or Political Stability?

Many western analysts[3] believe that the security of petroleum supplies from the Middle East has tended to have a circumscribed meaning unrelated to its political context. The two wars involving Iraq in the 1980s and early 1990s showed that oil production and export installations were less vulnerable than was often assumed. The experience of these conflicts suggests that overland oil transportation through pipelines is

Pipeline	*Date of previous and current shut down*	*Reason*	*Actual pumping/ age (year)*
Kirkuk (Iraq)–Haifa (Palestine)	Since 1948	Arab–Israeli conflict	16/91
Kirkuk (Iraq)–Tripoli (Lebanon)	Three days in 1956 June 1972–March 1973 April 1976–December 1981 January and March 1982 Since April 1982	Conflict over Suez Canal Nationalisation of the line by Iraq and Syria Disputes over transit fees Sabotage attacks Iraqi–Syrian antagonism	41/89
Kirkuk (Iraq)–Banias (Syria)	Three days in 1956 June 1972–March 1973 April 1976–February 1979 Since April 1982	Conflict over Suez Canal Nationalisation of the line by Iraq and Syria Disputes over transit fees Iraqi–Syrian antagonism	26/72
Kirkuk (Iraq)–Ceyhan (Turkey) (IT I)	September–November 1980 1990-2003	Iranian air attacks Conflict over Kuwait and UN embargo against Iraq	33/46
Kirkuk (Iraq)–Ceyhan (Turkey) (IT II)	1990-2003	Conflict over Kuwait and UN embargo against Iraq	23/36
Iraqi Pipeline across Saudi Arabia (IPSA)	Since August 1990	Conflict over Kuwait and UN embargo against Iraq	5/38
Abqaiq (Saudi Arabia)–Zahrani (Lebanon) (Tapline)	Three days in 1956 Several days in 1969, 1970, 1971, and 1972 May 1970–January 1971 February 1975–September 1990 Since September 1990	Conflict over Suez Canal Sabotage attacks Disputes over transit fees Economic reasons, only some pumping to Lebanon and Jordan for local use. Meanwhile the line was attacked by Israel in 1981 and 1982 Conflict over Kuwait and deterioration in Saudi–Jordanian relations	24/73
Total			**168/445**

Table 1: Security of International Oil Pipelines in the Middle East (End-2022 Status)

more resilient to attacks than maritime outlets and sea transportation. Then, because of the diversification of the oil transportation system, and with a few additional pipelines, these analysts believe a stage may be reached where oil exports from the Middle East would be considered as 'very safe'.

In fact, only few oil pipelines appear to have been shut down as a result of military hostilities. Pipelines in the region running above ground as well as pumping stations were only intermittently hit by terrorist attacks or air strikes. Both Saudi and Iraqi lines to the Mediterranean have been temporarily cut by terrorist actions and air attacks, while only some sections and pumping stations of the Iraqi export system were damaged as a result of the military conflict with Kuwait.

However, this analysis seems to neglect the main reasons behind the shutdown of many export pipelines in the Middle East, which remain the political conflicts within producing countries or transit states, and the interstate disputes. In fact, most of the pipelines crossing state boundaries have fallen victim to the region's political rivalries and conflicts.

The pipelines built to carry oil from Iraq to the Mediterranean coasts help to prove this point. The line built before World War II to Haifa (now in Occupied Palestine) was closed permanently in 1948 as a result of the first Arab–Israeli conflict, while lines to Lebanon's Tripoli and Syria's Banias repeatedly fell (and are still) victim to Iraqi–Syrian antagonism. Recently, the Iraqi pipelines through Turkey were shut down between 1990 and 2003 in the political aftermath of the conflict over Kuwait, while the Iraqi lines through Saudi Arabia remain permanently closed since then.

As a result, although decades of construction of pipelines have diversified oil export routes in the Middle East and significantly reduced their vulnerability, the threats of political disruption in producing and/or transit countries remain strongly present. This could be, fuelled further by many elements of instability in the region, and could well lead to the closure of many pipelines there.

Nevertheless, considering that producing countries in the Middle East are living with a wealth of hydrocarbon resources, and consequently having to sell them, and that transit fees constitute an important share of the transit countries' revenues, the risk of permanent or sustained interruption of petroleum supplies from the region could well be considered as slight. That is what is called 'the mutual dependency stabilising factor'.

However, the possibility of short-term (weeks, months, or even years) dislocation or interruption of petroleum supplies because of governments in the region losing control over one or more of the endogenous pressures along the area is considered to be high. Arab oil embargoes applied in the aftermath of the 1967 and 1973 conflicts with Israel, the international sanctions against Iraq between 1990 and 2003, and the sanctions on Iran's oil exports since the beginning of the new century have further demonstrated the point.

All this leads to confirm that there is no security of petroleum supply from the Middle East without real political stability in the region. Nevertheless, the turbulent history of the area does not promise future stability: if it is not one country it is another, and if it is not one problematic issue it is another. The end-result for Middle Eastern petroleum pipelines is that most of the closed oil pipelines have remained idle, and that there is no serious plan, with the single exception of an Iraqi-Jordanian oil pipeline, to build new ones.

In addition to securing stability in the exporting, importing and transit countries, many issues have to be addressed for petroleum pipelines to operate properly. There is first the issue of transit fees, especially when a link between two countries passes through the territories of third ones (transit countries). Those fees, in money or nature terms, could well affect the whole economic feasibility of a pipeline network project.

Another important issue related to the transit of natural gas, crude oil or petroleum products through pipeline is connected to the agreements and terms of the World Trade Organization (WTO). In fact, each member of the WTO has to give the owner or operator of any pipeline passing through its territories full and free access to its own domestic market. That right for market access has not always been admitted by all Middle Eastern countries due to various reasons.

4. Gas Pipelines: A Missed Golden Opportunity

Several issues have to be addressed when it comes to gas pipelines in the Middle East[4]. In addition to the critical element of gas price which needs to be competitive on one hand and well determined on the other, ways to handle the swing nature of gas demand in the area should be decided. Indeed, in this part of the world, demand for electric power (and consequently for natural gas) peaks in summer, when all households maximise their air-conditioning uses. There is therefore a huge swing between summer and winter power and gas demand. Options to manage this swing by either creating storage facilities at the upstream producing end, or at the downstream consuming one, should be evaluated together with their impacts on both the capital and operating costs.

There is also the question of "energy independency" which needs to be addressed. Usually, states do not want to depend on neighbouring countries for their fuel supplies. Another related element to be taken into consideration is that most Middle Eastern countries are oil producers and there is a psychological desire among them for self-sufficiency, which promotes a greater willingness to burn more liquid fuels despite their higher relative and opportunity costs and damaging environmental impacts. In fact, many countries there, proud of their large hydrocarbon reserves (including huge associated gas resources, found and eventually produced in association with crude oil), find it difficult to "import" gas (or any other energy sources) from anywhere.

Due to difficulties in dealing with these issues, only few interstate gas pipelines have been built in the Middle East, and most of them have had problems and troubled life. That also led to the failure in building an ambitious regional grid in the region aimed at pumping gas from gas-rich to gas-poor countries or areas, a project which has been "under discussion" since more than 50 years[5].

In fact, only few scattered gas pipelines have been built in the Middle East. The first interstate gas line in the region was built in 1986 linking Iraqi fields to Kuwait. This short-lived pipeline has been closed since the Iraqi invasion of its southern Arab neighbour when it was used to supply water to the Iraqi troops there. Then, following the construction of a small gas link between Oman and the UAE's emirate of Ras Al-Khaimah in the late 1980s, the much larger Dolphin pipeline came on stream in 2007, supplying Qatari gas to the UAE and Oman. Those pipelines were the ultimate result of political compromises and concessions, resulting in generally low prices for the piped gas.

In the East Mediterranean, a gas pipeline linking Egypt and Israel was first used to channel Egyptian gas to Israel, before reversing its flow to supply Israeli gas to Egypt. On a more regional scale, the Arab Gas Pipeline (AGP), built 20 years ago, has been linking Egypt to its Arab neighbours, including Jordan, Syria and Lebanon (through a branch line from Syria), with a plan to connect to the European network in Turkey.

However, the AGP has had serious difficulties since its inauguration. The pipeline's problems have been mainly due to shortage of gas feedstock from Egypt, at a time when its highly-subsidised local gas demand has left very little resources for export, pushing the country to import gas from its Jewish neighbour. These supply difficulties in Egypt have led Jordan to increasingly (although intermittently) rely on imports of liquefied natural gas. In addition, the Syrian civil war has transformed the AGP since 2011 from a regional network to a gas pipeline just linking Egypt to Jordan.

More recently, in September 2021, Cairo announced it would deliver its gas to Lebanon through the AGP as a regional response to Lebanon's ongoing fuel and electricity crisis. However, many challenges have to be faced before getting the first drop of Egyptian gas again in Lebanon, including the availability of sufficient volumes of gas to be exported from Egypt, the prices to be paid for this gas, the transit fees requested by Jordan and Syria, and the security situation in Syria through which a long section of the pipeline passes.

Another blow to the prospects for considering much more gas pipeline schemes in the Middle East came with the development in the region of terminals for importing natural gas in liquefied form (LNG). In fact, Bahrain, Dubai, Jordan and Kuwait are already operating LNG import terminals, while Lebanon, Oman and Saudi Arabia have been seriously considering putting similar facilities in place.

In addition to the problems encountering gas pipelines (transit fees, WTO regulations, political risks, security issues, etc.), the LNG option has been favoured over gas pipelines as a result of many factors, including the competitive costs and prices for building the different parts of its chain (liquefaction plants, transport vessels, and regasification units), the perception that LNG prices shall further decrease in the coming few years, and the increasing use of LNG as a way to diversify energy and gas sources of supply, and to enhance the security of gas supply[6].

To sum up, developers of gas pipelines in the Middle East have to take into consideration the new realities in the global gas markets which are now favouring LNG over piped gas, and the difficulties in dealing with problematic issues encountering gas pipelines in the region. However, policy-makers in the Middle East have to always keep in mind the idea of building a regional gas network on the top of their agenda. In fact, such a network shall increase the gas resources available to the regional economy and shall create a strong development drive. It shall also boost intra-regional trade and act as an important step towards the long-term political co-operation and economic integration.

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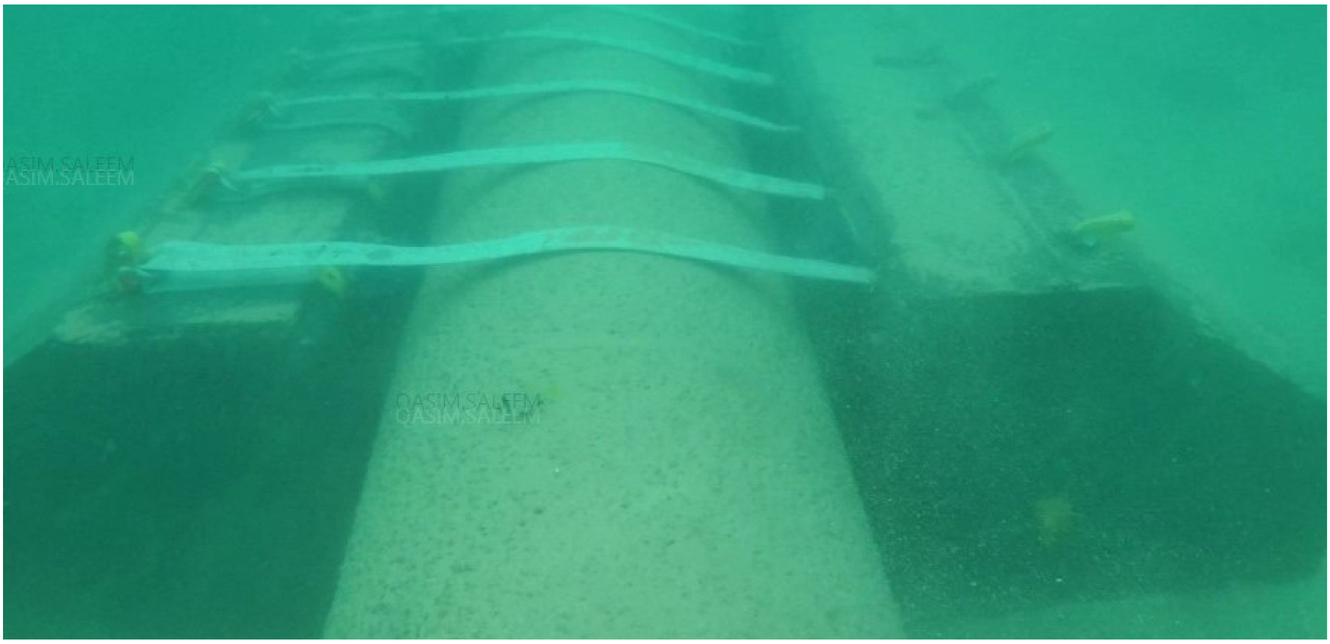

Innovative Solutions to Address Stabilization Challenges of a 48-Year Old Subsea Pipeline

Q. SALEEM, R. AL-SHIBAN, A. AL-SHAMMARI > SAUDI ARAMCO

Abstract

Subsea pipelines are externally concrete coated to provide vertical and lateral stability. The loss of concrete can lead to floatation or lateral movement on the seabed. If seabed is hard/rocky, then lateral rubbing may lead to wall thinning at 6 o'clock and can result in a leak or flattening at the bottom affecting ovality. This paper presents challenges faced during stabilization of an aging pipeline suffering from excessive concrete loss and subsequent lateral movement of 4m. This led to erosion scattered along pipeline length at several locations and flattening at bottom of pipeline. Concrete mattresses were initially used, but due to wall thinning of pipeline sections and significant weight to be compensated, concrete clump weights were subsequently used as an innovative solution. These stabilization measures compensated lost/damaged concrete weight coating by providing sufficient weight to avoid lateral movement, as well as eliminating the risk of pipeline damage in the future.

1. Introduction

Subsea pipelines are externally concrete weight coated to ensure vertical and lateral stability on seabed [1-5]. During operation and especially towards late life and beyond, the concrete coating may be lost, which can lead to subsea pipeline floatation (vertical) or lateral movement on the seabed. If seabed is hard/rocky, then lateral rubbing may lead to wall thinning at 6 o'clock and can result in a leak or flattening at the bottom affecting pipeline ovality. To avoid these serious risks, the lost concrete must be compensated in the form of stabilization weights.

This paper presents the stabilization challenges faced for an aging 48" diameter subsea crude pipeline which was constructed in 1971. The design pressure of the subsea pipeline is 275 psig and maximum water depth along the route is 90ft. The pipeline has a steel wall thickness of 15.9 mm (0.625") and concrete coating thickness of 4" as per design. The pipeline was not designed with permanent scraper launcher and receiver facilities and therefore is non-scrapable. The pipeline condition in terms of internal and external corrosion was a concern considering the age of the pipeline, therefore, an umbilical operated pipeline inspection tool that performs ultrasonic inspection from the inside of a pipeline was employed to perform the in-line inspection. The inspection tool was able to detect and quantify internal and external surface defects. A spool piece was removed from the pipeline on the onshore side to get access to the pipeline and to launch the tool from a vertical position. The in-line inspection (ILI) data outlined the list of internal and external metal loss anomalies as summarised in Table 1.

Metal Loss Depth	Internal Corrosion Anomalies	External Corrosion Anomalies	Total Number of Anomalies
>60%	0	3	3
41-60%	0	10	10
21-40%	0	22	22
10-20%	2	49	51
Total	**2**	**84**	**86**

Table 1: Metal loss features based on ILI data

The maximum external metal loss was 69% and the maximum internal metal loss was 19%. All reported anomalies were analysed by the industry accepted method of ASME B31G "Manual for Determining the Remaining Strength of Corroded Pipelines" [6]. The analysis identified 4 most severe external anomalies with estimated repair factor (ERF) either exceeding or close to 1. As per Company procedures, metal loss defects with ERF equal to or greater than 1 shall be repaired immediately using a suitable repair method. Based on these findings, it was decided to perform field verification of 4 most severe external anomalies.

During field verification, divers reported loss of concrete along the pipeline length, presence of hard rocky seabed and drag marks on the bare pipeline at one location. Furthermore, the same location was identified with bottom flattened length of around 0.3m. The subsequent detailed routine inspection identified pipeline lateral movement of 4m and complete concrete loss along a length of 768m, along with several other locations of concrete weight coat loss. Based on these findings, it was concluded that the lateral rubbing of the pipeline on the hard seabed caused by concrete coat loss led to the damage. The focus of this paper is to address the concrete coat loss and the required mitigation measures to prevent any future damage to the subsea pipeline.

2. Concrete Loss Progression and Consequences

To establish concrete loss history and consequent pipeline lateral movement, all previously available external subsea inspection reports for 48" subsea pipeline were reviewed. The review indicated presence of cracks in concrete weight coating (CWC) in 1999 survey report, however, loss of CWC was first reported in the 2005 survey report with no lateral movement. The 2010 survey showed increased CWC loss still without the presence of any lateral movement. The lateral movement of the pipeline was first reported in 2016 survey data, as shown in Figure 1. The weight coat debris were moved up to 4m away from the pipeline suggesting that it has been pushed away by the pipeline lateral movement.

The 2016 survey also showed significantly increased CWC loss. The 2018 survey revealed insignificant increase in CWC loss in comparison with 2016 data. The progression of CWC loss is summarized in Table 2.

The CWC loss as specified in Table 2 resulted in pipeline rubbing along the hard seabed, which led to erosion

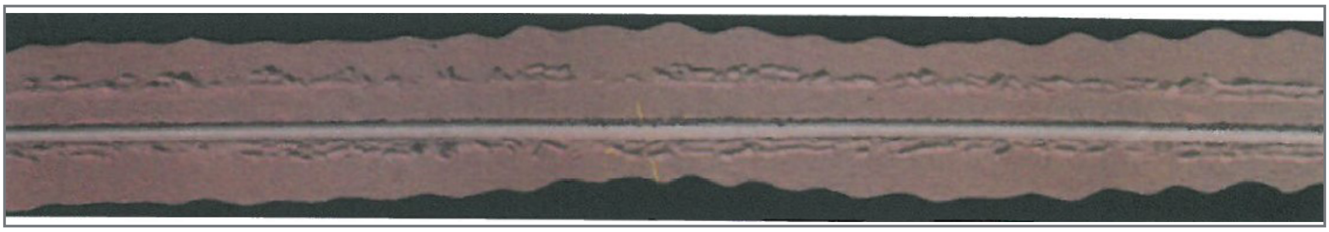

Figure 1: Pipeline lateral movement due to concrete coat loss [8]

along a significant length of the pipeline. The extent of erosion was identified by in-line inspection (ILI) runs carried out in 2014 and 2019. The erosion data based on ILI runs are specified in Table 3.

Year	Length of CWC Loss (m)	Lost Concrete Submerged Weight (Ton)
1971	0	0
1999	0	0
2005	400	339.6
2010	614	521.3
2016	1304	1107.1
2018	1340	1137.7

Table 2: Concrete weight coat loss progression over time

Period	Maximum Erosion (mm)	Minimum Erosion (mm)
2010-2014	8.97	3.34
2010-2019	10.99	3.34

Table 3: External Erosion Based on ILI Data

It is important to note that the comparison between concrete coat loss and erosion data showed a good correlation, confirming the weight coat loss as being the root cause of pipeline damage, including the bottom flattened section, which affected the ovality of the pipeline.

3. Stabilization Measures

If the pipeline length suffering concrete loss is small, concrete mattresses have been traditionally used to provide additional stabilization. If the subsea pipeline suffers an excessive concrete loss scattered along an extended length, such as the 48" subsea pipeline, concrete mattresses may not be a suitable option. Firstly, because they apply weight directly on the pipeline (risk of collapse of the pipeline with wall thinning). Secondly, a very large quantity of mattresses will be required.

As highlighted in section 2, the root cause for the damage that occurred along the 48" pipeline was the concrete weight coat loss. The first set of stabilization measures, in the form of concrete mattresses, was installed along the pipeline in 2015, based on the 2010 survey, the latest data available at that time.

Following the installation of concrete mattresses, the 48" pipeline was repaired using composite repair system at four locations with most severe erosion. The composite repair system was required to be inspected after 2 years to ensure its integrity. The 2017 inspection of repaired locations revealed that a number of previously installed mattresses in 2015 were found to be broken in half, along with pipeline lateral movement of 2.5m (Figure 2).

The mattress damage and lateral movement (2.5m) indicated further concrete loss along the pipeline and was in line with 2016 survey which revealed significant increase in weight coat loss in comparison to previous survey conducted in 2010.

Due to the significantly extended length of pipe with concrete weight coat loss, and the severity of external erosion along the pipeline, concrete mattresses were not considered a suitable option. Consequently, concrete clump weights were introduced as an alternative stabilization method, as their use does not apply any load/stress on the pipeline. This was an important consideration, due to the condition of the pipeline being subjected to rubbing and external metal loss. Further benefits of clump weights include reduced drag forces (as they are positioned close to the pipeline and shield it) and no edge stability issues.

Due to the risk of pipeline damage when in contact with the clump weight, rubber fenders were designed to provide separation between the pipeline and concrete surface of the clump weights (Figure 3). The fenders are manufactured from ethylene-vinyl acetate

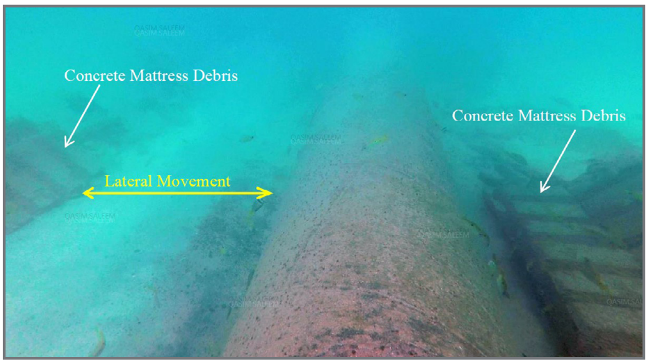

Figure 2: Broken concrete mattress due to persistent lateral movement [7]

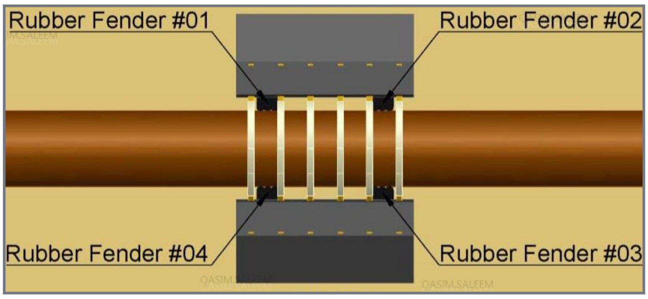

Figure 3: Rubber fenders to avoid pipeline damage [9]

expanded rubber, specifically for the marine environment. Each fender is fitted to the finished clump weights using stainless steel AISI 316 bolts anchored into the clump weight faces.

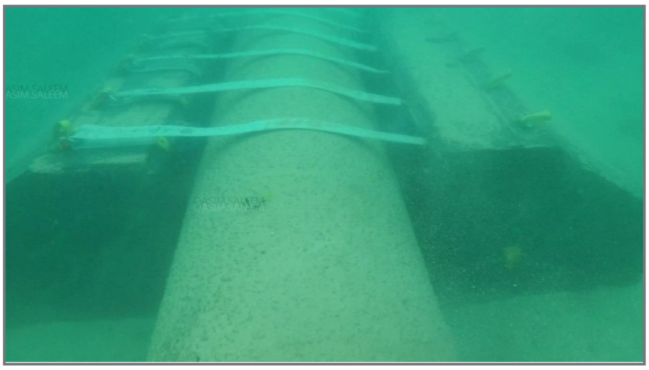

Figure 5: Installed clump weight along the subsea pipeline [7]

In 2017, the concrete clump weights were installed along the 48" pipeline at the locations having concrete coat loss and lateral movement, as shown in Figure 4 and Figure 5. The saddle bags were installed along the 48" pipeline at the locations having concrete coat loss without lateral movement and subsequent erosion.

External subsea inspection was performed in 2018 to check concrete weight coat loss and pipeline lateral movement which confirmed that the pipeline is adequately stabilized with concrete clump weights. These stabilization measures compensated for the lost/damaged concrete weight coating, by providing sufficient weight to avoid lateral movement, as well

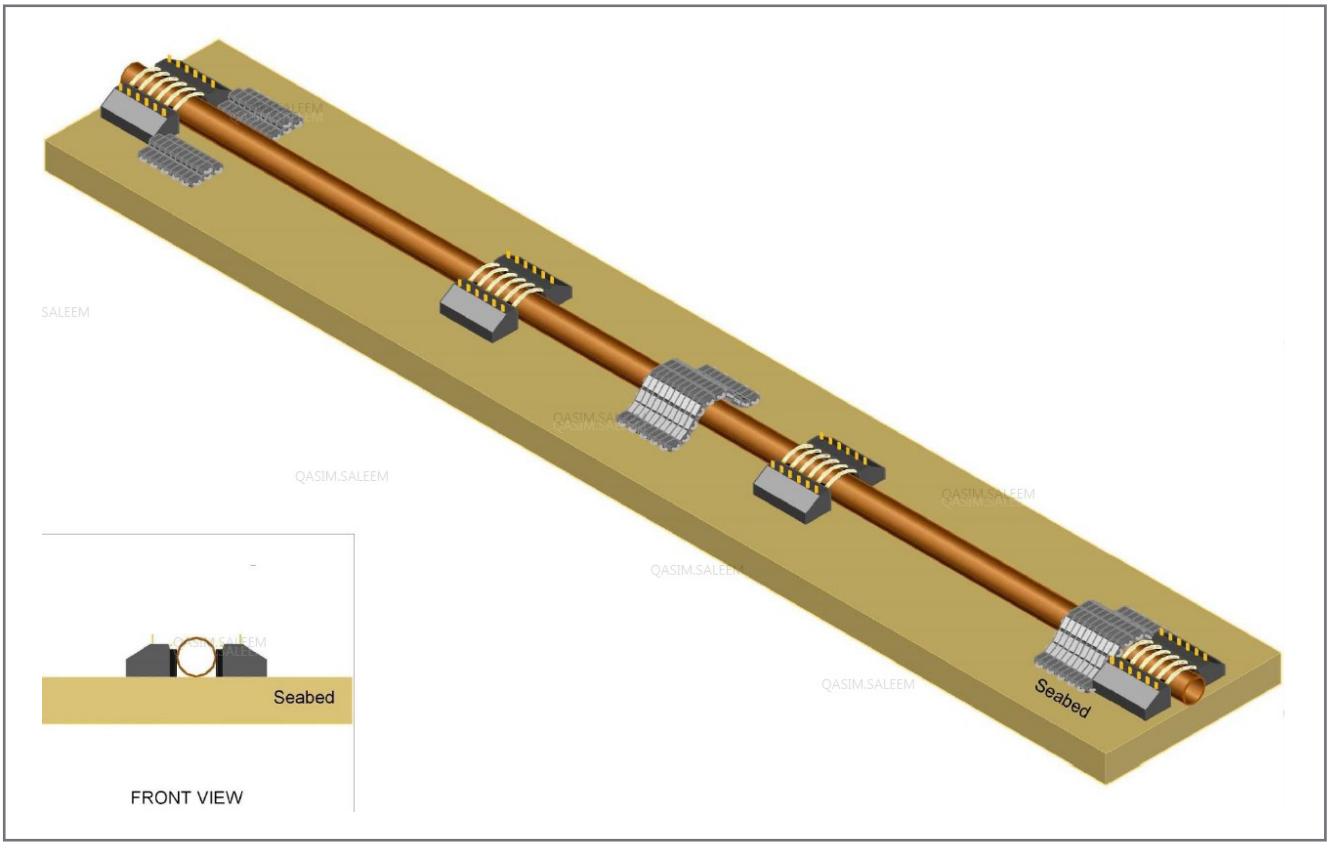

Figure 4: Clump weight and mattresses along subsea pipeline [7]

as eliminating the risk of pipeline damage in future. In line inspection (ILI) run was performed in 2019 to ensure the integrity of the pipeline which indicated slightly higher erosion rate in comparison to 2014 ILI run.

4. Concluding Remarks

The 48" pipeline had a history of significant concrete weight coating (CWC) loss which compromised its on-bottom stability. The loss of CWC resulted in lateral movement against the hard/rocky seabed, which in turn damaged the pipeline, resulting in a bottom flattened section affecting ovality. Concrete mattresses were initially used for stabilization, however, due to pipeline wall thinning and the significant weight to be compensated, concrete clump weights were subsequently used as an innovative solution. This stabilization method was successful to compensate the lost/damaged concrete weight coating, by providing sufficient weight to avoid lateral movement, as well as to eliminate the risk of pipeline damage in future. Furthermore, the external subsea inspection interval for the subsea pipeline was reduced to every 2 years. The use of advanced inspection techniques to monitor concrete coat loss of subsea pipelines is under evaluation to further address the stabilization challenges of aging pipelines.

5. Acknowledgement

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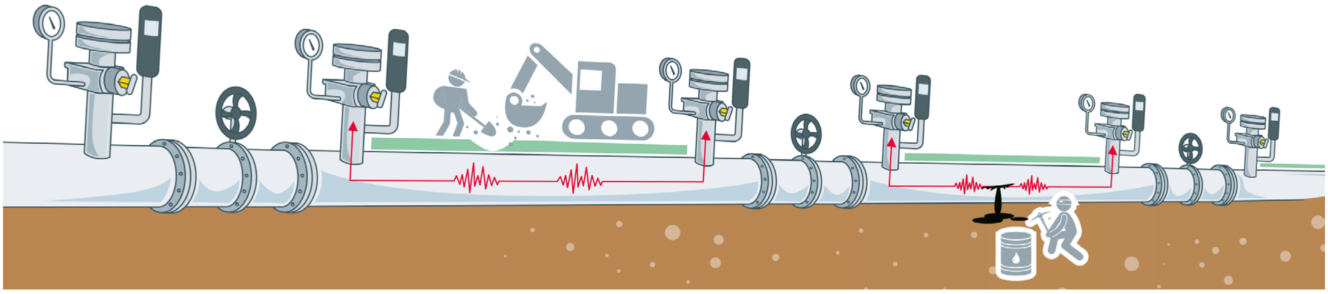

Integration of multiple Leak Detection Technologies into a single Advanced Leak Detection System

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Abstract

This work is centered on the integration of different Leak Detection Technologies into a single platform for a better management of Pipeline Integrity Monitoring issues.

Leak detection methods covered in this paper are based on Advanced-Negative Pressure Wave, Mass-Balance, Acoustic-Noise, and other predictive techniques based on data processing. Each detection technology relies on distinct physical principles, detecting leaks and pipeline interferences originating from various threats (e.g., illegal tapping, third party interference, corrosion, and many other issues).

Such integrated approach has been named Advanced Leak Detection System and is developed over an already existing technological platform based on vibroacoustic sensing, which includes pressure and temperature sensors, accelerometers and flowmeters distributed along the pipeline.

In conclusion, the Advanced Leak Detection System, already deployed on several pipelines over Eni's network, proved to be able to detect various events, leading to a complete and comprehensive Leak Detection Platform.

1. Introduction

The pipeline integrity management challenges vary from corrosion cracks, caused by the most distinct reasons, to illegal tapping. The primary monitoring goal concerns leak detection and localization in real time.

As mentioned, leakages can arise and develop in numerous ways, producing different detectable traces, which demands the creation of a robust leak detection system to detect all kinds of leakages.

Since no single leak detection method is capable to detect every possible leak-originating phenomenon, it is necessary to combine distinct leak detection methods into a single leak detection system or technological platform, known as Advanced Leak Detector.

The Vibroacoustic Technologies considered in this paper, currently used in various scenarios to monitor oil and gas pipelines in real time, are excellent options for system integration, especially when flow measurements are available.

With very few sensors, the system can protect hundreds of kilometers against leaks [1][2][3][4], illegal activities or accidental events [5][6][7]. The system is scalable, easy for retrofitting existent pipelines, non-invasive and cost-effective.

Other strong features include the very low false alarm rate and the ability of the system to reconfigure itself on-the-fly, and therefore, immune to sabotage attempts.

The Vibroacoustic platform includes many integrity management technologies for varied applications, e.g., leak detection, third party interference recognition (i.e., digging, impacts, illegal tapping), PIG tracking, valve status evaluation, failure detection during hydraulic tests and earthquake detection [8][9][10] [11][12] .

The Advanced Leak Detector is capable of integrating efficiently with existing equipment and SCADA/DCS control system; it operates with almost any pipeline diameter, whether in onshore or offshore scenarios, any pressure range, for any fluid.

The Vibroacoustic Technology that integrates the Advanced Leak Detector is also particularly effective when facing modern operative issues for energy transition applications, e.g., Integrity Assessment, Predictive Maintenance and Second Life Asset Reutilization, without need for shutting-down the pipeline.

2. Vibroacoustic Technology

The Vibroacoustic Technology relies on a network of multiple vibroacoustic sensors positioned along a pipeline, connected with any sort of telecommunication system to transfer the data to a central processing server. The sensor blocks are designed to sense the complete elastic-dynamic wave field, and, therefore, vibrations, acoustic pressure and gauge pressure are measured.

All databases, datasets, experiments and analysis of this work were carried out on the Vibroacoustic Framework established by Eni [13][14][15][16].

Given a proper vibroacoustic source, acoustic and elastic waves generated will propagate upstream and downstream at sound speed. The sensor blocks will record the signal while the remote-control unit will transmit data chunks continuously to the processing server. The leak detector core processor runs in the processing server, where advanced digital processing chains, such as non-linear filters, real-time noise estimation and removal, leak detection, and multi-channel localization performed (Figure 1).

The core-processor analyzes pressure waves together with micro-vibrations and sound data: the combined information enables the identification and accurate localization of anomalous noise sources. The signal processing algorithms are highly advanced; the system relies on extremely sensitive sensors capable to detect weak and informative vibrations.

A pipeline is an effective wave-guide system: vibrations propagate through the solid shell while the acoustic pressure field propagates (for kilometers) within the fluid, given pressure of at least 1 bar.

Due to these features, the Vibroacoustic Technology reaches outstanding and superior detection performance levels when compared to a

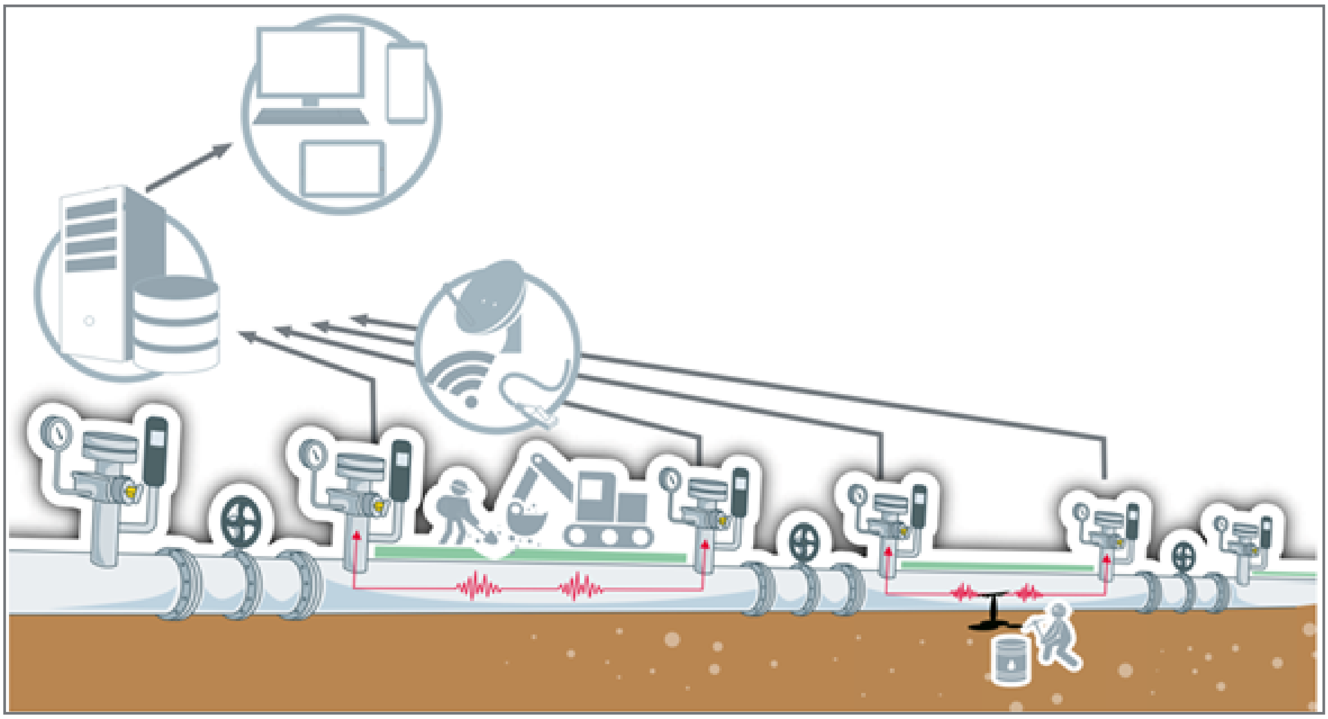

Figure 1 Vibroacoustic hardware schema. Mechanical perturbations (e.g., leakages, impacts, or digging operations) interact with the pipeline, producing a Vibroacoustic wave that propagates along the pipeline. The anomaly reaches the sensors and recordings are sent to a central processing unit.

regular pressure-based system, e.g., systems known as Negative Pressure Wave Systems.

The Vibroacoustic Systems are suitable for retrofitting existing pipelines because the sensor blocks can be installed on existing hydraulic derivations, avoiding hot tapping. The regular sensor block is resistant to harsh environmental conditions, while the Shallow Water sensor block is submersible up to 10 m (e.g., ideal for swampy areas) (Figure 2).

Both sensor block types can be configured to acquire data at different frequencies and with different rationales, depending on which leak detection methods are deployed in any given pipeline.

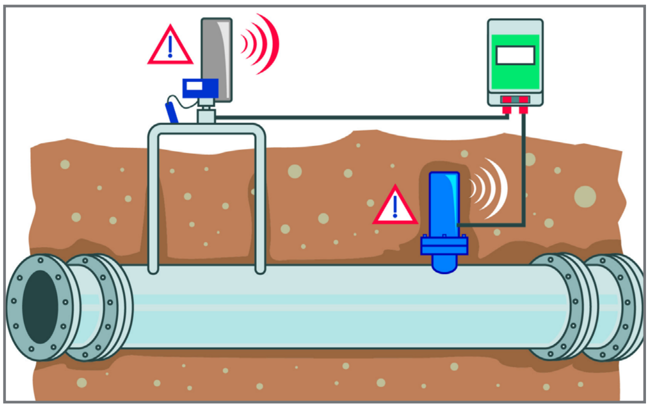

Figure 2: Vibroacoustic sensor blocks: Regular Sensor (upper left, gray) Shallow Water Sensor (bottom right, blue). Acquisition Station (top right, green).

The sensors are ATEX certified (Ex i), suitable even for sour fluids (i.e., mixtures with hydrogen sulphide H_2S).

The sensor blocks are connected to an acquisition unit (Figure 2), placed nearby in the field. This acquisition station is responsible for collecting and transmitting the data in real time to the central processing server. The network data transfer demands less than 20 kbit/s and exploits any available communication channel, as for example LAN, Wi-Fi, ADSL, UMTS or Satellite.

The acquisition units require low power consumption, less than 20W, and can make use of solar panels, fuel cells or directly connected to mains.

In the case of demonstrations or pilot projects, portable sensor blocks are powered by a 12V battery.

2.1 Advanced Negative Pressure Wave - e-vpms® waveleak

The Advanced Negative Pressure Wave method is a highly effective leak detector that can identify and localize in real-time the onset, extinction and variation of a leakage, by exploiting acoustic waves generated by such sudden events.

The data required by the method is collected by sensor blocks, installed tens of kilometers apart along the pipeline.

The acoustic waves generated by the sudden events of onset/variation/extinction of a leak are powerful, impulsive, and propagate in both directions, upstream and downstream, with velocity equal to the sound speed.

The negative pressure waves reach the sensor blocks and are recognized to be associated with each other. Consequently, the Time Difference of Arrival (TDOA) can be utilized.

The TDOA Δt is the arrival time at sensor 2, downstream, minus the arrival time at sensor 1, upstream. If the distance between the sensors is x_{12}, the sound speed c_s, then the distance Δx distance of the leakage position to sensor 1 is

$$\Delta x = \frac{x_{12} - c_s \Delta t}{2}$$

The TDOA method of localization is shown in Figure 3.

This detection method is independent of the leaked volume and on the leak duration, being highly sensitive to the least outflow rate, alarms are documented to be issued even in absence of outflow.

This top-class performance leak detector is able to identify leakages down to 0.1" hole diameter, with sensor blocks installed every 20-25 kilometers.

2.2 RTTM Compensated Mass-Balance - e-vpms® massleak

Mass-Balance is an internal leak detection method that exploits the mass conservation law in the monitored segments. The sensors installed along the pipeline collect pressure, temperature, flow rate, flow velocity and sound speed data that are used by the software algorithms to analyze if the inlet corresponds to the outlet flow.

The pipeline is monitored by Mass Balance Sections (MBS) that correspond to control volumes [17]. MBS is characterized by flowmeters or by closed valves at the segment extremities.

When a leak occurs, the Mass-Balance software detects an imbalance between the mass inflow and outflow rates; if the mass variation inside the MBS is balanced there is no loss of the transported fluid.

The mass inflow rate ($\dot{m}_{in}$) and mass outflow rate ($\dot{m}_{out}$) are computed at the inlet and outlet of the MBS, respectively. The mass contained inside the MBS is called mass packing rate, $\dot{m}_{MPR}$. The mass conservation states that the mass packing rate in the MBS is equal to the difference of the inflow and outflow rates.

$$\dot{m}_{in} - \dot{m}_{out} = \dot{m}_{MPR}$$

The mass packing rate m_{MPR} can be computed from density ρ_i and cross-section area A_i profiles along the MBS, discretized at steps Δx is given by the time derivative of the fluid mass in the MBS. The density and

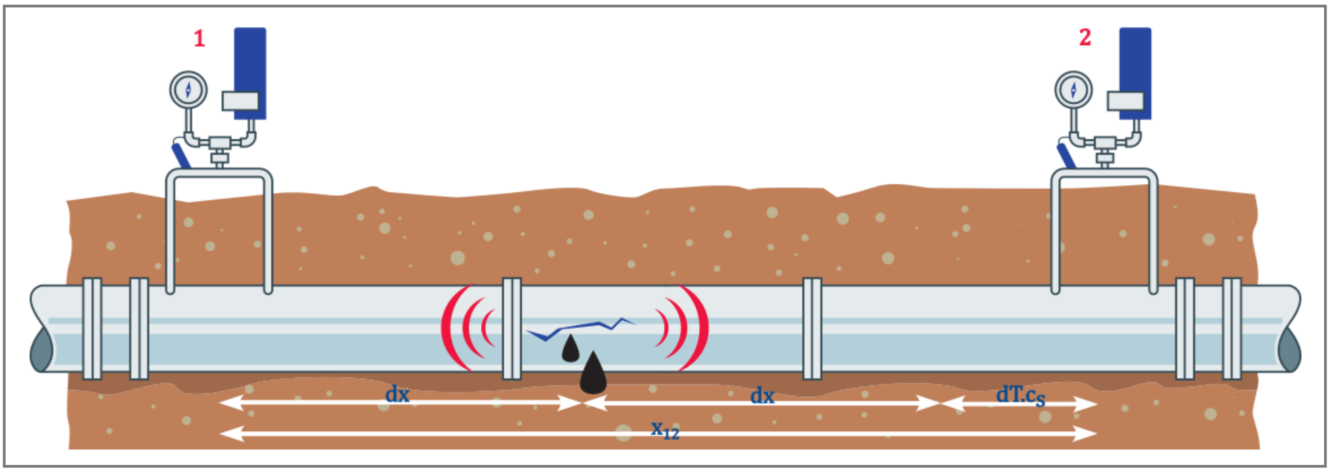

Figure 3 TDOA method of localization

cross-section area profiles are the output of the RTTM (Real Time Transient Model), the mathematical model of the fluid-dynamics in the pipe.

$$m_{MPR} = \sum_i \rho_i A_i \Delta x$$

Therefore, the leak mass rate ṁleak is given by the equation below.

$$\dot{m}_{leak} = \dot{m}_{in} - \dot{m}_{out} - \dot{m}_{MPR}$$

If a leakage is ongoing, the mass packing rate will be negative and the mass outflow rate will be lower than the mass inflow rate. The imbalance corresponds to the amount of leaked mass. This method is **called RTTM-compensated mass balance leak detection system**.

The flow rates are measured using clamp-on flowmeters placed in the extremities of the section to be monitored. Clamp-on flowmeters are non-invasive, easily installed.

The RTTM computes the fluid mass in real time to compensate mass variations and improve the leak detection, provided that the pipeline is in transferring condition.

The localization is limited to the identification of the MBS.

The sensitivity of the RTTM depends on the accuracy of flowmeters.

The detection sensitivity does not depend on the leak onset or extinction, but on the outflow rate and the duration of the spill.

2.3 Acoustic Noise Leak Detection - e-vpms® noiseleak

The Acoustic Noise method exploits the stationary noise created by the leakage to detect and localize it.

The stationary noise created by the fluid jet will travel along the pipeline until it reaches the vibroacoustic sensors.By correlating the signal collected by adjacent vibroacoustic sensors it is possible to confirm if the noise source corresponds to a continuous leak.

The correlation peak threshold is set by analyzing data from test campaigns.

The noise source, i.e., the leakage, is localized by using the time difference of arrival (TDOA), which is the delay of the correlation peak. It is the same localization method used by the Advanced Negative Pressure Leak Detector described in the chapter above.

The detection sensitivity does not depend on the leak onset or extinction, but on the outflow rate and the duration of the spill.

2.4 Data Driven Leak Detection - e-vpms® smartleak

The e-vpms® smartleak is based on machine learning algorithms. Long term analysis of the data collected by the e-vpms® sensors reveals slow variation of the fluid transportation parameters, which are associated to ageing pipes, formation of pipe deposits, fluid changes, seasonal fluctuations, pump failure and pipe failure.

The basic principle is to examine the e-vpms® vibroacoustic data, in order to “learn” their safe range of variation and to build a discrete set of operational status. Then, e-vpms® data are analyzed in real time to automatically identify the operational status and/or to highlight the presence of system anomalies, e.g., leakages.

3. Advanced Leak Detection

Given that each e-vpms® leak detection method exploits a different physical principle, requires different input measurements, and yields different output quantities, all e-vpms® leak detectors are independent from each other but can be deployed on the same pipeline for enhanced protection.

Table 1 provides a detailed description of the main aspects of each e-vpms® leak detector.

The integration of leak detection methods at core-level offers a higher level of protection since it combines outputs from different core-processors to create new information regarding the event identified. The integration is possible when the detection systems are deployed on the same technological platform.

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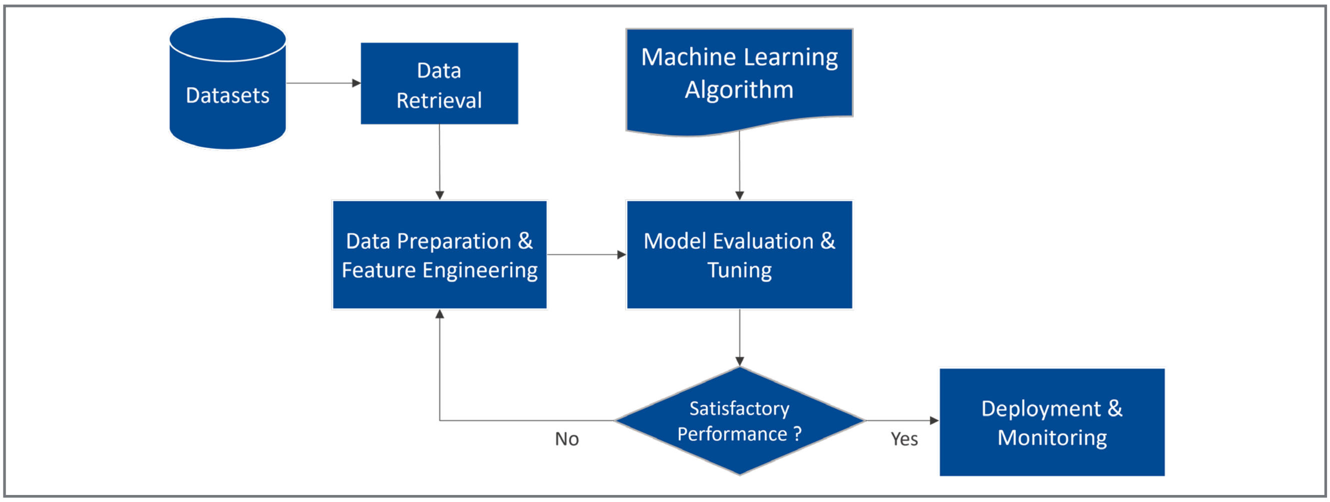

Figure 4 Flowchart of a data driven leak detector

	e-vpms® waveleak	e-vpms® massleak	e-vpms® noiseleak	e-vpms® smartleak
Detection	Detection of Acoustic transients of a leakage	Detection of mass flow difference	Detection of jet acoustic noise of a leakage	Data driven detection of noise signature produced by a leakage
Detected Event	Onset, extinction, and flow-variation of a leakage	Long-lasting leakages (existing or creeping)	Long-lasting leakages (existing or creeping)	Long-lasting leakages (existing or creeping)
Sensors Required	- Sensor Blocks	- Flowmeters - Sensor Blocks	- Sensor Blocks	- Flowmeters - Sensor Blocks
Pipeline Status	- Transferring - Shut-in	- Transferring	- Transferring - Shut-in	- Transferring - Shut-in
Output	- Accurate leakage location - Magnitude, number, and duration of acoustic transients	- Outflow rate - Outflow mass - Profiles of pressure, velocity and temperature	- Accurate leakage location - Magnitude of jet noise	Pipeline status (Adjustable according to specific application): - Leak - Flow Regulation - Fluid transportation - Shut-in - Anomalies

Table 1: Description of different leak detection methods

Also, to improve the accuracy of the results, part of the integration consists of cross-checking the quantities computed by different methods.

The last step of the integration is to collect alarms that are linked to the same leakage event, independently of their type. This is achieved by using a time-space proximity indicator. At this step, depending on which alarms were issued, it is possible to obtain novel information about the leakage, i.e., data that is not available in the initial alarms.

4. Success Cases

The success cases presented here are a collection of several test campaign results, performed on three different pipelines in Italy. The characteristics of each pipeline and the detection systems deployed are available in Table 2.

The Advanced Leak Detection System installed is made of all leak detection sub-systems installed in the pipeline.

Pipeline	e-vpms® leak detectors deployed				Length	Diameter	Fluid
	waveleak	massleak	noiseleak	smartleak	[km]	[in]	
Pipeline #1	x	x	x		40	10	Jet Fuel
Pipeline #2	x	x	x		16	12	Jet Fuel
Pipeline #3	x	x		x	10	4-8	Process water

Table 2: Pipelines characteristics and e-vpms® leak detectors deployed

Pipeline	Test ID	Pipeline Condition	Hole Diameter [in]	Pressure @ Spill Site [bar]	Spilled Mass [kg]	e-vpms® waveleak	e-vpms® massleak	e-vpms® noiseleak	e-vpms® smartleak
#1	1	Pumping	0.10	5.9	85.4	-	-	✓	N/A
#1	2	Pumping	0.16	5.9	200.4	-	-	✓	N/A
#1	3	Pumping	0.20	5.9	333.1	✓	✓	✓	N/A
#1	4	Pumping	0.25	5.9	502.9	✓	✓	✓	N/A
#1	5	Shut-in	0.10	9.2 - 8.0	99.2	✓	N/A	✓	N/A
#1	6	Shut-in	0.16	7.5 - 5.4	202.7	✓	N/A	✓	N/A
#1	7	Shut-in	0.20	5.2 - 3.9	187.3	✓	N/A	✓	N/A
#1	8	Shut-in	0.25	3.8 - 2.3	219.4	✓	N/A	✓	N/A
#2	9	Pumping	0.1	5.9	76.2	-	-	-	N/A
#2	10	Pumping	0.16	5.9	184.2	-	-	-	N/A
#2	11	Pumping	0.20	5.9	286.8	✓	✓	-	N/A
#2	12	Pumping	0.25	5.9	362.3	✓	✓	-	N/A
#2	13	Shut-in	0.1	5.6	74	✓	N/A	-	N/A
#2	14	Shut-in	0.16	5.3	163.6	✓	N/A	-	N/A
#2	15	Shut-in	0.20	5	224.1	✓	N/A	✓	N/A
#2	16	Shut-in	0.25	4.8	273.5	✓	N/A	✓	N/A
#3	17	Pumping	0.1	150	750	✓	✓	N/A	✓
#3	18	Pumping	0.16	150	800	✓	✓	N/A	✓
#3	19	Pumping	0.20	150	1100	✓	✓	N/A	✓
#3	20	Pumping	0.25	150	1100	✓	✓	N/A	✓

N/A: Not Applicable

Table 3: Test log and alarms issued individually by each Leak Detection System

A sequence of several spill tests was performed to simulate corrosion/wearing phenomena and fraudulent product theft on all three pipelines in pumping and shut-in conditions. The alarms issued by every e-vpms® leak detector were used to determine the performance.

The spills were performed with the goal of triggering alarms of all leak detection systems at once for every test. The test procedure employed a calibrated electro-valve that allows slow opening in combination with quick manual closing of the outflow valve.

The slow openings replicate the corrosion/wearing phenomena in the pipeline; the fast closing represents a sudden movement, typical of product theft or pipe ruptures.

The total opening time (several minutes) was long enough to allow the detection systems to identify the events. The tests were designed to trigger as many alarms as possible.

The product spilled during each test was weighed for comparison with the estimated leaked amount. The test log and the alarms issued individually by each Leak Detection System are reported in Table 3.

The previous table shows the individual performance of each detection system and the necessity to create an Advanced Leak Detector to manage the several alarms that can be issued during a spillage event.

Once an alarm is issued, it is communicated through e-mail, SMS, and Graphic User Interface. The Advanced Leak Detector will group different e-vpms® alarms issued by different core processors within a configurable time range. Once the alarms issued for a given event are identified by the Advanced Leak Detector, the information available (i.e., the output quantities) is grouped, and, depending on the availability, new outputs can be created.

The Key Performance Indicators used to evaluate the test results are:

- Sensitivity
- Response time: the difference between the timestamp where the leak is detected and the instant of the alarm delivery by e-mail
- Localization precision, which is the standard deviation of the localization position
- Propagation distance, i.e., the distance of the farthest station able to detect the event

		e-vpms® leak detector			
		waveleak	massleak	noiseleak	smartleak
KPI	Sensitivity* [in] Minimum detectable hole size	0.2″ / 0.1″	0.2″ / N/A	0.1″ / 0.1″	0.1″ / N/A
	Response time [min]	7	8	12	45
	Localization precision [m]	25	Distance between flowmeters	25	Distance between sensors
	Propagation distance [km]	>40	>40	≈5	>40
* The sensitivity is given for pumping (top left) and shut-in conditions (bottom right)					

Table 4: Leak Detection Technology KPIs

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5. Discussion and Conclusions

The successful cases show the reliable performance of the e-vpms® technology whether as individual leak detection systems or integrated as an Advanced Leak Detection system.

The same flowmeters and sensor blocks, i.e., the same hardware, installed along the pipeline collect the data to be used by all detection systems.

Even though the tests were designed to trigger all alarms at once, spills occur with varied features, and, depending on the background noise levels, the performance on each pipeline might vary.

Therefore, if one of the leak detectors does not detect a spill, another leak detector does, in such a way that every spill performed is detected by, at least, one leak detector.

The Advanced Negative Pressure leak detector identifies sudden onset, flow variation and extinction of a leak with high sensitivity and robustness, whether the pipeline is pumping or shut-in. The localization is accurate even with large sensor spacing along the pipeline.

The Mass Balance leak detector identifies existing or creeping leaks, provided that the outflow volume and rate are sufficiently high. The pipeline must be in pumping condition and the localization is limited to the control volume.

The Acoustic Noise leak detector also identifies existing or creeping leaks but performs better in shut-in condition in some pipelines. The localization is accurate, but the method requires smaller sensor spacing if compared to the Advanced Negative Pressure leak detector.

The data driven machine learning leak detector also identifies existing or creeping leaks when the pipeline is in pumping condition. It requires a training stage with representative datasets of recordings by e-vpms® sensors and flowmeters before it is deployed. Localization is limited to the distance between sensors used for the modelling.

The improvement of a technology that combines the leak detection systems, i.e., the Advanced Leak Detector, is therefore due to the complementarity of the capabilities, requirements and output quantities of each method.

The core-level integration of the leak detection methods is possible when there is a common technological platform among the leak detectors: to improve the accuracy of the results, the quantities calculated by one method can be cross-checked with those computed or measured by another method.

The Advanced Leak Detector system identifies when alarms that are associated to the same physical event are issued by different leak detectors, and the output quantities of the different systems are integrated to produce novel information about the leak, that was not available in the original single alarms.

In conclusion, a technological platform of integrated leak detection systems represents the current leading edge of pipeline integrity monitoring.

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A technological platform of integrated leak detection systems represents the current leading edge of pipeline integrity monitoring.

This work is centered on the integration of different Leak Detection Technologies into a single platform for a better management of Pipeline Integrity Monitoring issues.

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The Influence of Anomaly Dimensions on POX for EMAT-C Crack Detection based on As Found Dig Results

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Abstract

In the context of repurposing of natural gas transmission pipelines to Hydrogen service the sensitivity of inspection systems with a focus on POX is frequently discussed. Often an increase of crack growth rate da/dN and a reduction in pipe steel toughness require a reduction of minimum remaining anomaly dimensions, in order to satisfy economically acceptable re-inspection intervals. However, the influence of anomaly dimensions on inline inspection performance represents a key metric for decision on a suitable approach. The combination of POD and POI within the term POX and the product of the previously mentioned elements represents an accepted metric for the assessment of performance for an inline inspection system (ILI). The foundation is an arbitrarily chosen reflector that sets a certain minimum performance for both POD and POI. However, it primarily represents means to compare different inline inspection systems, but is at the same time not suitable to evaluate the complex interaction between different reflector dimensions and the sensitivity of a chosen inspection system related to these. This is one of the reasons, why the most commonly applied standard for inline inspection, API 1163, implies the validation of inspection performance with use of dig-ups based on the reported results. In addition, a performance specification can be derived exclusively based on a dig-campaign, if no performance specification to compare the dig-results to is available at forehand.

Previous publications as well as physics foundations of NDE show, that an increase in anomaly dimensions typically yields a higher sensitivity of the underlying inspection system. These effects can be seen dominantly, if a receiver operator characteristic (ROC), is used to compare different classifiers of an inspection system. Here, a classifier for a larger reflector enables a lower false negative rate than a classifier for a smaller anomaly. This can be immediately linked to the POX as product of POD times POI.

This paper provides access to an in-depth assessment of POX based on the results of excavation data base for the most recent years. The interaction between POX and different reflector dimensions are discussed.

1. Intorduction

The upcoming conversion of natural gas pipeline systems to the operation of hydrogen, either pure or in blends, requires renewal of a baseline assessment of anomalies present in the specific pipeline. As crack-like indications show larger growth and the toughness is known to decrease in presence of hydrogen compared to natural gas as shown by Sandia National Laboratories and others [1], the minimum detectable anomaly dimensions are of primary interest when the conversion of the pipeline network is assessed. The pipelines, which are considered in the first phase for conversion to hydrogen service [2], are primarily higher toughness pipelines that are not considered as vintage. Overall, it is not assumed that these are prone to cracking in general. It can be assumed, that inline inspection will often be applied to verify the absence of crack-like indications in these cases or to show that no anomaly above the acceptance limits applied in the pipe mill are present.

In other cases for pipelines converted in the second phase pipelines will be considered, that are expected to have also cracks, which have grown since the start of the operation of the pipeline. Here, cracks will be detected and by repair/removal of these the population of remaining cracks will be reduced to an acceptable dimension limit. The stress intensity factor of each anomaly represents the driving force for its growth rate and is strongly depending on the depth and width. In addition, smaller anomaly dimensions will immediately enable extension of re-inspection intervals. For that reason, minimum possible anomaly dimensions are desirable from a fracture point of view inherently leading to increased remaining life.

Based on fundamental physics the probability of detection (POD) and probability of identification (POI) are related to and varying with the anomaly dimensions [3]. The larger an anomaly the higher the probabilities for both, detection and identification. However, this situation represents a dilemma for the planning of re-inspection intervals and overall integrity assessment for the cracking threat in general, but as well for the repurposing of natural gas pipelines to Hydrogen. The larger the anomaly the higher the likelihood for high POD and POI values. However, larger anomalies have smaller re-inspection intervals.

2. Effect of Hydrogen

If pipelines are to be practically repurposed then it is necessary to quantify the effects of hydrogen on fatigue crack growth rate and fracture toughness, and relate these to a tolerable defect size. Exactly what these effects and relationships are is still a subject of much research in the industry, a recent literature survey performed on behalf of EPRG reported decreases in fracture toughness of 35-70% compared to the in-air value, and increases in FCGR of ~10x, although there was a wide range of scatter in data available.

The scatter reported appears to be due to a number of factors, both due to the materials and microstructure tested and the particular test protocols (partial pressure of hydrogen, test geometry, loading rate etc.) used. The industry generally is performing a lot of work currently to try to quantify these issues, for example as part of the DVGW SyWestH2 project , however as yet there is no firm consensus.

To quantify the effects of reducing fracture toughness and increasing fatigue crack growth rate EPRG funded some further work looking at methods of assessing damage, including cracks . In this work two idealized pipelines were assessed, one large diameter transmission type and one small diameter distribution type. For each pipeline, 2 separate idealized materials were assessed with a median hydrogen "knock-down" effect of 50% on the fracture toughness. One "modern" high in-air toughness and one "vintage" low in-air toughness, an example of the tolerable axial crack size for the large diameter pipeline is shown in Figure 1

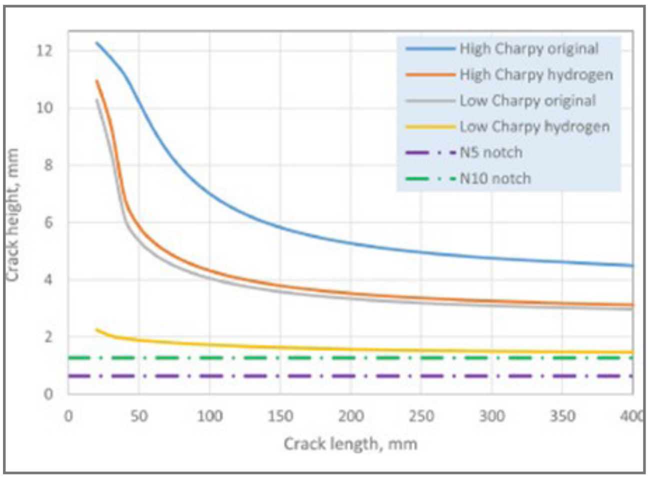

Figure 1: Tolerable axial crack sizes for an example large diameter pipeline

As can be seen hydrogen has a significant effect on the tolerable defect size for an existing low toughness material, while having less of an effect on higher toughness material, in essence this is because the existing low toughness material was closer to failing by fracture than the high toughness material, hence any further decrease in toughness has a large effect. Further, the EPRG work calculated fatigue lives for the different pipelines using FCGR rates in accordance with BS7910 (to represent in-air) and ASME B31.12 (to represent hydrogen). In these cases the predicted fatigue lives in hydrogen varied between 2% and 57% of those in air, depending on the exact conditions assumed.

Although only illustrative, the EPRG work cited above is a clear example of the way in which hydrogen can have a significant effect on the criticality of cracks, potentially reducing both the critical flaw size and the predicted fatigue life. In such cases, and accurate understanding of any actual cracks present within a pipeline becomes critical.

In this context, the interaction of anomaly dimensions and probabilities for detection, identification and sizing is assessed in the following based on an example of EMAT-C crack detection service.

3. Performance Metrics of Inline Inspection Technical Systems

A further reduction in critical anomaly dimensions is desirable for the conversion of natural gas pipelines to hydrogen service. The remaining anomaly dimensions are of primary interest for planning of re-inspection intervals – ideally with no reduction in performance for the probabilities of detection, identification and sizing. The definitions for POD and POI and as well POX according to API 1163 are applied [4] as shown in the following.

$$\text{POD (reported anomalies)} \approx \frac{\text{True Positives (within specifications)}}{\text{True Positives (within specifications)} + \text{False Negatives (within specifications)}}$$

$$\text{POI(detectable anomalies)} \approx \frac{\text{Correct Identifications (A)}}{\text{Correct Identifications (A)} + \text{Incorrect Identifications (B)}}$$

For the purpose of this paper the values of probability of detection POD, probability of identification POI and probability of correct sizing POS within the given tolerance values are combined to a single value for the assessment in the following

$$POX = POD \times POI = f(\text{anomaly depth}, \text{anomaly length})$$

With additional consideration of POS, the value of POXS is derived.

$$POXS = POD \times POI \times POS = f(\text{anomaly depth}, \text{anomaly length})$$

In different situations the usage of either POX or POXS might be favorable depending on the overall purpose of the assessment. If detectability of an anomaly is assessed the value of POX shall be used. If for a specific integrity assessment in addition the sizing accuracy need to be taken into consideration the value of POXS is better suited as it allows to assess the probability of the correct detection and identification with additional consideration of probability of correct sizing. Current standards applied for the re-purposing of natural gas pipelines to Hydrogen service are not considering specifically the probabilistic aspect of inline inspection. Nonetheless, the aforementioned values are investigated as it is assumed that the current performance metrics shown throughout the industry for crack assessment with inline inspection are broadly accepted. Thus, it is assumed, that in specific cases the probabilities shall not be lower than those published as standard performance for inline inspection systems.

The POX need to be assessed as a function of anomaly dimensions representing a driving factor for decisions in the context of conversion of natural gas pipelines to hydrogen, but as well for integrity assessment in general and irrespective of the transported product. As an example, for the assessment in this paper the dig up verification database established for EMAT crack detection is used. The entries of this data base are based on the ILI call-outs as reported and the corresponding dig-up results as found. The results of the ILI data signal search process prior to classification and sizing were not available in this type of assessment, solely the reported and thus classified anomalies are considered in this study. A discrimination of POD and POI is not feasible. Consequently, the POX is considered as a single value based on the formulae in section 2, which in itself represents the product of POD times POI.

4. EMAT Crack Detection

EMAT crack inspection represents a broadly accepted technical system for the assessment of cracks in gas and liquid pipelines. Guided horizontal shear waves, which are emitted and detected by electro-magnetic acoustic transducers, represent the technical foundation of the inspection device. The excited acoustic wave travels through the pipe wall. If an anomaly is hit, a portion of the acoustic wave is reflected and detected by a receiver, while the remaining acoustic energy is detected as transmission signal by another opposite receiver. The overall principle is described elsewhere [5-7]. The technology is subject to continuous improvement related to the essential variables and the included sizing system components according to API 1163 [4].

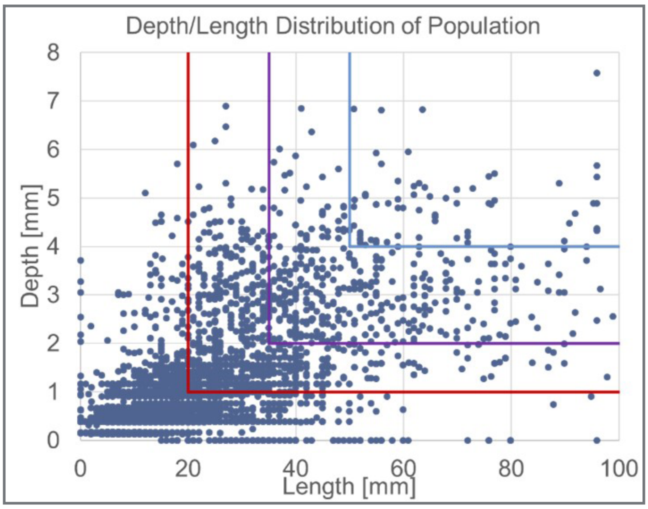

Figure 2: Anomaly Population showing anomalies with Depth over Length. 22,055 Anomlaies are included in the assessment.

The anomalies in this population, Figure 2, are primarily related to wall thicknesses ranging up to 10 mm, see Table 1. At many anomaly location the tool velocity was within the limits of the applicable essential variables, however, the majority of anomalies assessed had experienced tool velocities beyond the limits of the essential variables, see Figure 3. Furthermore, it was not discriminated, if a certain anomaly is in the vicinity of seam or girth weld areas or not. As the aim of this paper is to assess the overall statistical and physical behavior of the inline inspection system as function of anomaly dimensions, a further differentiation related to the factors mentioned above, were not assessed in further detail.

WT range[mm]	5.5 - 6.5	6.5 - 7.5	7.5 - 8.5	8.5 - 9.5	9.5 - 10.5	10.5 - 11.5	11.5 - 12.5	12.5 - 13.5	13.5 - 14.5
Number of anomalies in WT range [#]	3279	1207	14370	549	92	66	0	18	1

Table 1: Number of Anomalies in different Wall Thickness Ranges of the population applied, for some Data Points no information was available during this assessment.

5. Methodology of the Statistical Performance Assessment

5.1 Determination of POX

The overall population used for this paper consisted of 22,055 anomalies revealed in dig-ups. These have been found while digging based on EMAT call-outs. In each excavation the target joint and in many cases the additional upstream and downstream joints were exposed, the coating was removed and the pipe surface was sandblasted. Subsequently 360º MPI (magnetic particle imaging) was conducted on each of the exposed joints. This procedure allowed to identify false negatives in a consistent overall setup, which is a precondition for the assessment of POD. Other in-the-ditch practices, which are limited to the close vicinity of the reported anomaly location will not allow to establish a solid and unbiased assessment of POD. Thus, in this study only data sets have been used that were found with full exposure of the full target joint.

As mentioned already the anomalies verified in excavations and reported based on correct detection and identification of anomalies within the EMAT-C data set represent a valid detection and identification, if correctly validated in the field. Thus, these values represent the POX value.

For the length of the anomaly, the full interlinking cluster length as found with MPI was used. For the depth sizing three different NDE techniques were applied depending on availability. On a standard basis an initial estimation of crack depth was conducted based on the MPI finding – of course with a relatively high uncertainty. In case deeper anomalies were found, the full joint had been replaced and the deeper anomalies underwent lab tests either with grinding, freeze breaks or phased-array UT (PAUT). Some of the anomalies underwent additional x-raying. In any of the cases the as found depth was applied to assign a specific anomaly to a size category as shown in Table 2. Table 3 summarizes the anomaly numbers found within one specific size class and below class 1.

The size categories have been reviewed with regard to performance without considering the overlap of the size categories, with the focus to have an exclusive assessment of the respective influence of anomaly dimensions. This means, that explicitly the limits of the next anomaly size class being larger than the considered one were used as an upper limit of the anomaly sizes. Only those anomalies within a specific size category and being smaller than the next one being larger were considered. As an example, in size category 1 only anomalies larger than 1 mm depth or 10 % nwt (nominal wall thickness) and longer than 20 mm in length and smaller

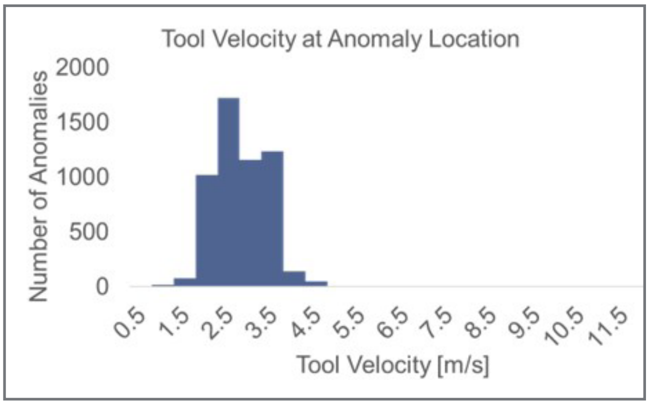

Figure 3: Historgram of Tool Velocity Distribution at Anomaly Location for those anomlies equal to or larger than Category 1

Category	Min. Depth			Min. Length
1	≥ 1 mm	or	10 % nwt	≥ 20 mm
2	≥ 2 mm	or	20 % nwt	≥ 35 mm
3	≥ 4 mm	or	40 % nwt	≥ 50 mm

Table 2: Categorization of Anomaly Dimensions

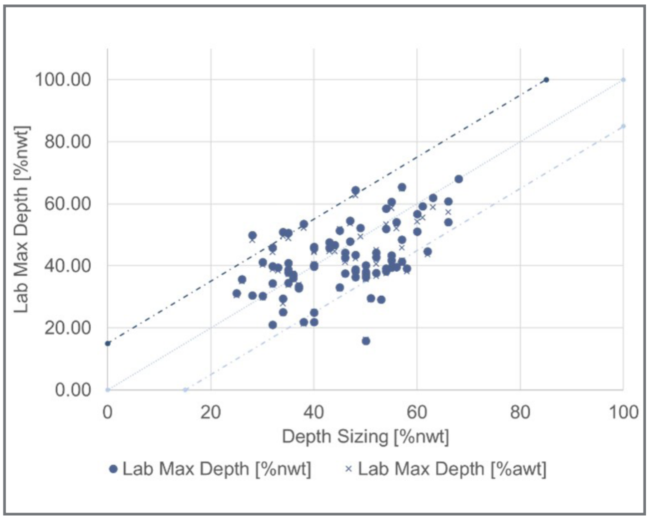

Figure 4: Depth Sizing results based an a Sub-Population related to X-Ray CT sized SCC Colonies. NWT – Nominal Wall Thickness, AWT – Apparent Wall Thickness.

Category	< 1	1	2	3
Number of anomalies in Size Class [#]	19,099	1551	1173	232

Table 3: Anomalies within one specific size class

than 2 mm or 20 % nwt and 35 mm length are included to determine the performance in category 1.

5.2 Determination of Probability of Sizing

The overall approach applied for the determination of POX was not suitable to assess the probability of correct sizing. The depth accuracies of the NDE in-the-ditch sizing methodologies applied were not sufficiently accurate [8, 9] in order to allow a reasonable assessment of sizing accuracies of the EMAT. This is related to the finding, that to a large extent phased-array UT with unknown accuracy and depth estimations based on MPI were conducted, only. These results are not considered sufficiently accurate to yield a reliable foundation for the determination of sizing performance. However, in previous work the validation of the current machine learning based sizing model was carried out with a detailed assessment of sizing performance based on real run data and X-ray Computer Tomography (XCT) validated results based on coupons taken from the excavation site. Because of the limited size of the overall population, it was not meaningful to assess sizing performance as function of anomaly dimensions. Consequently, no differentiation of sizing performance with regard to the influence of anomaly size on sizing performance was made. The derived overall performance for the full population was applied for each size class. The results are based on 212 individual crack colonies chosen and applied for validation of the algorithm as they were the only ones available with validation results based on highly accurate x-ray CT evaluation and matching to EMAT-C data sets.

The unity plot of this sizing can be seen in figure 3. A depth sizing accuracy of 82 % was demonstrated on run data, i.e. a probability of correct sizing of POS = 82 % based on real run data captured with multiple different inline inspection tools and under various different run conditions was achieved.

6. POX and POXS as Function of Anomaly Dimensions

Category	POX	POXS
1	94.52 %	77.51 %
2	97.95 %	80.32 %
3	98.01 %	80.37 %

Table 4: Categorization of Anomaly Dimensions

	Isolated radial cracks with longitudinal orientation		Colonies (e.g. SCC colonies)
	In pipe body	In longitudinal weld area	In pipe body
Minimum length	40 mm (1.57")		
Minimum depth at POD 90 %	1 mm (0.04") or 0.20t [1]	2 mm (0.08") or 0.30t[1]	1 mm (0.04") or 0.20t [1]
Depth sizing at 80 % certainty	for t < 10mm (t < 0.39"): ±0.15t for t ≥ 10mm (t ≥ 0.39"): ±0.20t		
Length sizing accuracy at 80 % certainty	±20 mm (±0.79")		
Width sizing accuracy at 80 % certainty	n/a	n/a	±30 mm (±1.18")
Orientation to pipe axis	±10°		
Inclination to pipe surface	40 – 90°		

[1] Whichever value is greater (mm or percentage of wallthickness (t))

Table 5: Standard performance of EMAT-C, Standard POI is 80%

Within each size category shown in table 2 the performance values for POX and POXS are determined. The results are summarized in Table 4.

Performance Metric	$POX_{standardspec}$	$POXS_{standardspec}$
Value	72 %	57.6 %

Table 6: POX and POXS derived for standard performance specification

On a high level, it was assumed that anomaly dimensions have an effect on the overall system performance of an inline inspection technical system. This overall behavior is visible in the results shown. POX and POXS can be derived from the published performance specification (Table 5) as well, see Table 6. Here, the POI of 80 % is declared, which is defined in the performance specification for the identification of crack-like anomalies.

Comparing the values for the standard performance as shown in Table 4 and Table 6, it becomes apparent, that in average for all anomalies assessed, a better performance was achieved than shown in the standard performance specification related to the applicable essential variables. This finding need to be considered in the context of the standard workflow of API 1163.

7. API 1163 Standard Workflow

The widely used standard for system qualification of inline inspection systems describes all aspects related to the performance and quality management to ensure that targeted performance can be achieved and as well is being validated. In the context of the aim of this paper two of the mentioned aspects and chapters are of primary relevance, see Figure 5.

- Performance specification (API 1163 chapter 6)
- Validate performance (API 1163 chapter 8)

In chapter 6 of API 1163 the requirements towards derivation and validation of the performance specification are described. Chapter 8 gives access to three levels of validation of the performance in a dig-up campaign, based on different confidence levels and boundary conditions. This validation levels described are explicitly related to the performance achieved in a single specific service or small number of services in the framework of comparable essential variables, which represent a small subset of the overall range of essential variables defined in the performance specification. Thus, it is obvious, that different performance values might be achieved between the two cases:

- Performance applicable to the full range of essential variables
- Performance achieved in a specific pipeline under boundary conditions representing a small sub-set of the range of essential variables valid for the full performance specification

On an average basis, the performance achieved in the analysis shown in Table 4 is superior to the published performance specification, see Table 5 and 6. There are multiple explanation for this finding. In general, the limitation of specific essential variables can yield better performance as not the full range of essential variables need to be covered. In this specific case, all anomalies considered featured relatively low wall thickness as no comparable results were available with the same approach of full exposure of the target joint in higher wall thicknesses. In summary, the performance metrics in terms of POD, POI, and POS summarized in single values as POX and POXS are derived exemplarily for these standard reflector dimensions and a specific subset of essential variables. In essence, the values determined for POX and POXS are applicable for the conditions shown in Table 1 and Figure 2, i.e. wall thicknesses ranging from 5.5 to 11.5 mm and tool velocities up to 3.5 m/s. Based on the fact, that no differentiation was made between pipe body and seam weld, it need to be assumed, that it may only be considered for pipe body.

In effect, the difference between these two performance values applicable in the cases can be related back to the API 1163 workflow. In the step – Select ILI System – the published performance specification is used as a foundation and as means to have a measure to compare different inline inspection systems and to allow the decision of the most suitable inspection system. It is self-evident, that a general approach is necessary in this step. Reference anomaly dimensions are applied in this step to derive applicable and comparable performance values related to POD, POI, and POS. As the statistical efforts described in section 5 and general principles of physics suggest, this does not mean, that the performance values reached for this reference anomaly will be equivalent for all other anomaly dimensions above or below these dimensions. The workflow step of API 1163 of – Validate Performance – describes in contrast the validation of as run performance for a specific and limited range in the set of essential variables and for a specific run or integrity campaign in similar pipelines. It is based on three levels to be applied in different cases.

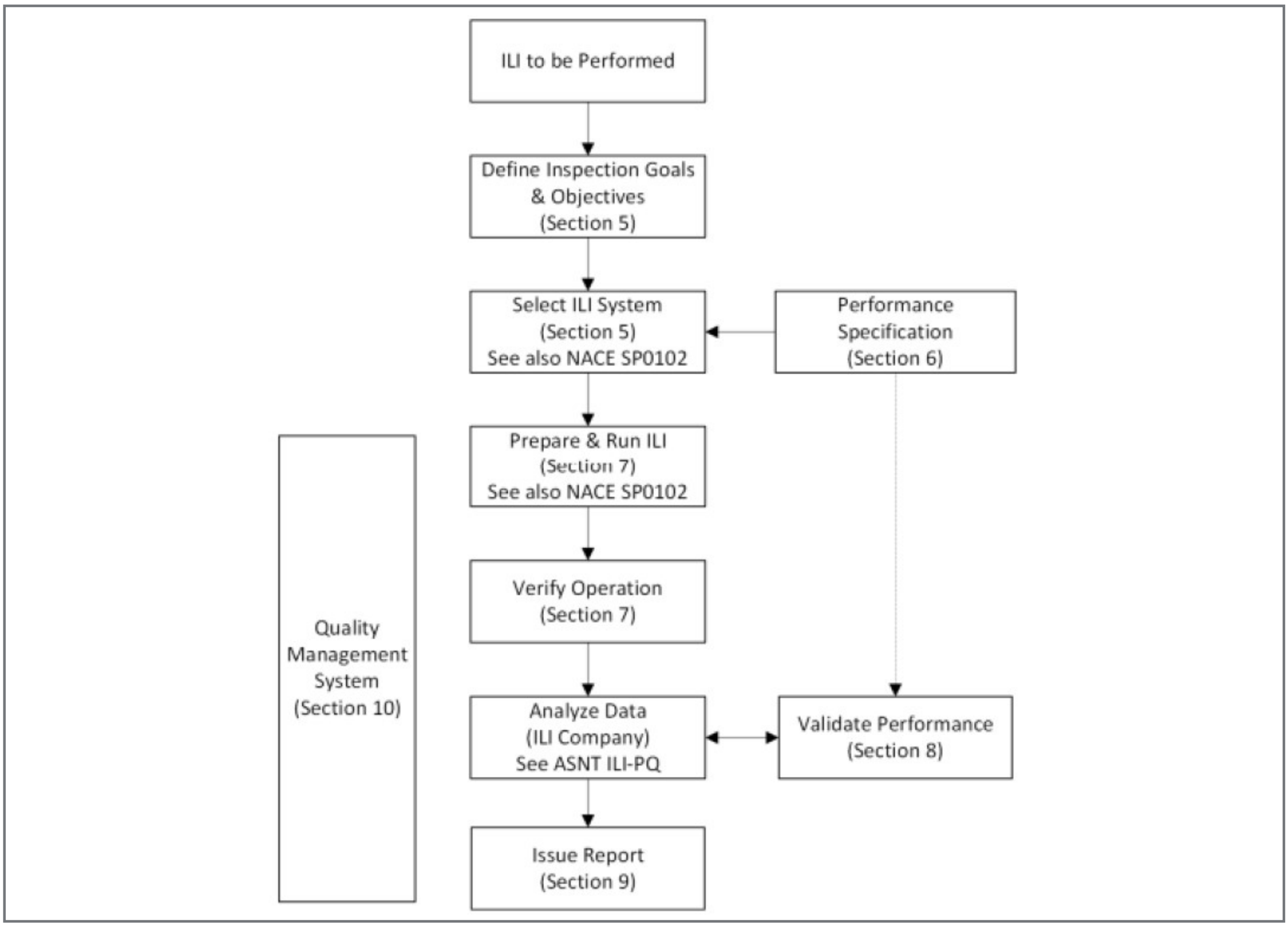

Figure 5: API 1163 Standard Workflow [4]

Level I: Validation for low risk pipelines without significant anomalies and if dig-up results are consistent with previous experience under similar boundary conditions. Applied visually with use of unity plots or similar representation of as called/as found comparison

Level II: Validation in pipelines with threat that has already been managed successfully with respective inspection system in the past. Positive validation with use of hypothesis test based on as-called/as-found comparison versus the published performance specification. Instead of determining the performance of the ILI system directly, its aim is to assess, if the as run performance meets or is worse than the published performance specification

Level III: Application of statistical methods based on larger excavation populations with the aim to derive estimate directly the performance of the ILI system. Prior knowledge of the performance specification is not required. This approach may be applied as well in cases, where an inspection system is applied where the boundary conditions during inspection are outside of the range of the essential variables.

The results shown in section 5 show evidence, that it is beneficial to assess the performance according to the workflow described. The assessment described in this paper could be seen as a Level III assessment for a limited range of essential variables applied. The overall concept of performance specifications is based on standard anomaly dimensions as reference conditions to allow comparison of different inline inspection systems to each other and allow the operator to choose the best-suited solution for a specific demand or threat. This does not mean that below and above these reflector dimensions or outside the defined essential variables, the performance is equal to the performance specification or in-existent. For a specific inspection campaign the determination of as-run performance based on reliable NDE results in-the-ditch is a crucial element for the overall process described in API 1163 in the context of collaboration between service provider and operator. In specific situations the performance achieved for a specific sub-set of the range of essential variables can be above the published performance specification, this was demonstrated based on the example of EMAT-C within the framework of this paper.

8. CONCLUSION

In the specific case of repurposing of a natural gas pipeline to Hydrogen service the requirement may arise that different anomaly dimensions than those referenced in the published performance specification for an inline inspection technology might be required. In the case of Hydrogen related repurposing this might be due to the need of adaptation of the material properties to the new medium type, e.g. crack growth rate da/dN. These anomaly dimensions are not immediately accessible via the published performance specification. However, these can be determined with valid field validation results, if certain boundary conditions are applied, e.g. full 360 degree MPI for the full target joint in a consistent manner. Thus, this paper demonstrates the relevance of NDE results from dig-ups for validation of both, the as run performance for a specific run, but as well the validation of performance specification. While initially a large amount of anomalies were applied as input, due to the consideration of size classes, availability of NDE results, restriction of essential variables, the applicable number of anomalies is rapidly decreasing. Thus, it is of utmost importance to have a focus on gathering NDE results with highest possible number and reliable NDE results whenever feasible. In addition, if applied for as run performance of a specific inspection campaign, it can yield a better performance to be used as foundation for the integrity assessment compared to the standard performance specification. Based on this field practice, it is possible to review the performance metrics for anomaly dimensions other than those mentioned in the published performance specifications.

Hydrogen can have significant effects on both critical crack size and predicted fatigue life. If a pipeline is to be practically and economically repurposed, an accurate understanding and quantification of any existing cracks is key. Once this data is available, it can be used within engineering assessments to make evidence-based decisions on re-purposing feasibility and future operating conditions. Without this data there are risks of either unnecessary over-conservatism jeopardizing the feasibility of a project, or non-conservatism potentially leading to failure.

The dependency of POX and POXS as function of the anomaly dimensions is assessed exemplarily for

EMAT-C crack detection. Increasing performance for larger anomaly dimensions was demonstrated. To date, the applicable standards applied for conduction of repurposing of natural gas pipelines to Hydrogen transportation are not based on probabilistic approaches, consequently the differences between POX and similar values cannot be applied in the integrity assessment directly. Nonetheless, it was shown that similar or better performance metrics may be achieved for smaller anomaly dimensions, when a subset of the range of essential variables is considered, if compared to the industry-accepted standard performance metrics.

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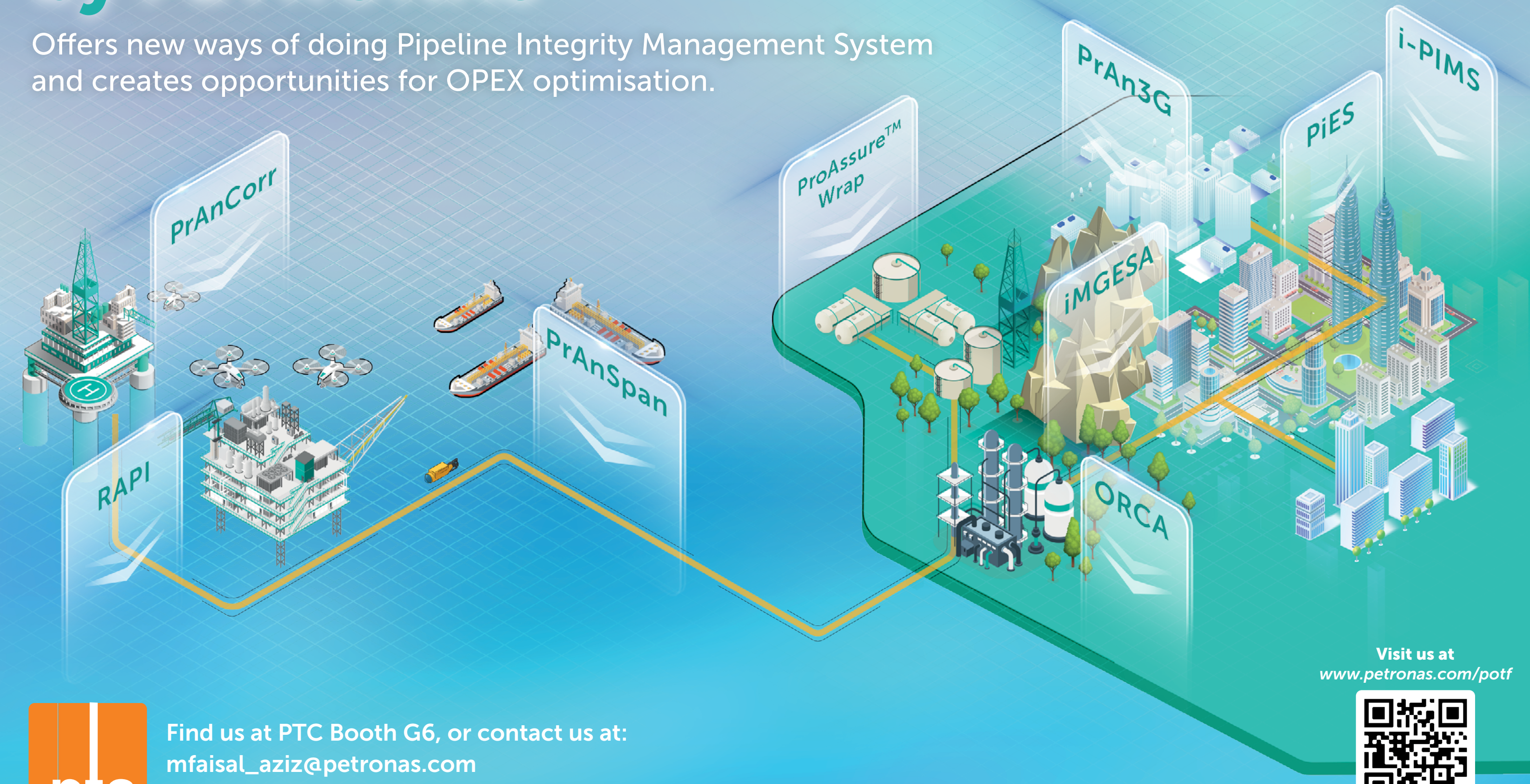

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WHICH OF THESE IS THE ONLY PIG SIGNALLER IN THE WORLD CERTIFIED IIC FOR HYDROGEN?

ANSWER: ALL OF THEM!

GROUP

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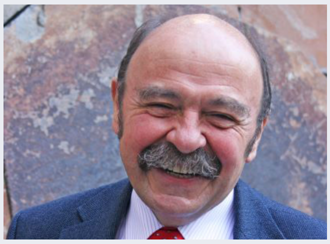

For readers who may not be so familiar with that name: John Tiratsoo was an eminent member and pillar of our industry. He is perhaps best known as the former editor of Pipelines International magazine and the Journal of Pipeline Engineering. John was also co-founder and co-organizer of the Pipeline Pigging and Integrity Management conference and exhibition (PPIM). He made major contributions to our industry and has been a driving force in the professional sharing of information.

The following paper by Eric Bergeron, Alexandre Thibeault and Ray Philipenko was chosen by the PPIM organizer, Clarion, and made available for reprint in this edition of the PTJ as a commemorative tribute to John Tiratsoo. The paper was presented at the recent 35th PPIM held in Houston February 6-10, 2023. Special thanks to BJ Lowe and Ben Stroman of Clarion for making this possible.

Low-Cost Airborne Oil Leak and Threat Detection for Pipeline Right-of-Way

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Abstract

For years, pipeline operators have relied on human observers flying at low altitude to perform visual inspection of their ROW, without any automatic documentation or detection system. This paper presents the first real-life results of a test campaign performed by Flyscan Systems, integrating detection algorithms developed by Enbridge, over ROWs of 7 operators in 7 US states and 2 Canadian provinces. Capabilities tested includes crude oil and refined product leak detection, real-time detection, location, and reporting of threats in the ROW, as well as generation of high-definition imaging, vegetation analysis and digital surface ground mapping. Statistics and real-life examples will be presented, including real unplanned threats as well as simulated and hidden leaks and encroachment

1. What is the Flyscan Systems solution The Test System Setup

Flyscan Systems attested a multi-aspect pipeline ROW monitoring solution for hydrocarbons leak and high priority threat detection solution. It also included an online data and notification distribution platform for monitoring of operator's assets providing real-time insights for intervention.

The certified hardware (for airworthiness) system was mounted on a Cessna 172 which is the most widely used vehicle for pipeline inspections and is operated at low cost. The system is fully compatible from the C172K to the C172P models. It is also compatible and tested on the Robinson R44 helicopter and is in the process of being mounted on the Cessna 182 and 206 models. The system has received all required airworthiness certification (STC – Supplemental Type Certificate) from Transport Canada. It is also designed to be operated by a single pilot-operator. It will self-locate, self-calibrate, process the data in real time automatically and manage data acquisition. Once landed, the operator must connect to the software to upload the data onto the cloud. The detailed post processing, data enhancing, and report generation processes will then automatically start. All the threats and leak statistics and reports are delivered on the customer portal.

The Figure 1 showcases the hardware system and main components.

Figure 2 shows some examples of the data portal and generated notifications taken from the demonstration campaign.

1.1 Hyperspectral liquid leak detection solution

Hydrocarbons leaks are detected by computing the spectral absorption of the target illuminated by the sunlight. This is a widely used remote sensing technique using hyperspectral cameras that can map the intensity of the reflected light at each wavelength. Hydrocarbons has a specific signature that the system can detect.

The camera is operated in the Short-Wave Infra-Red (SWIR) spectrum from 0.97µm to 2.5 µm. This is highly advantageous because the sun naturally provides a high illumination intensity, and its natural spectrum is very well known.

Currently, the instrument is the HySpex Mjolnir S-620 with a spectral resolution of 5.1 nm and a framerate of 100 Hz. The main spectral features of interest are located at around 1.7 and 2.3 µm as is shown in the figure below that is illustrating the measured spectrum of a hydrocarbon spill in water.

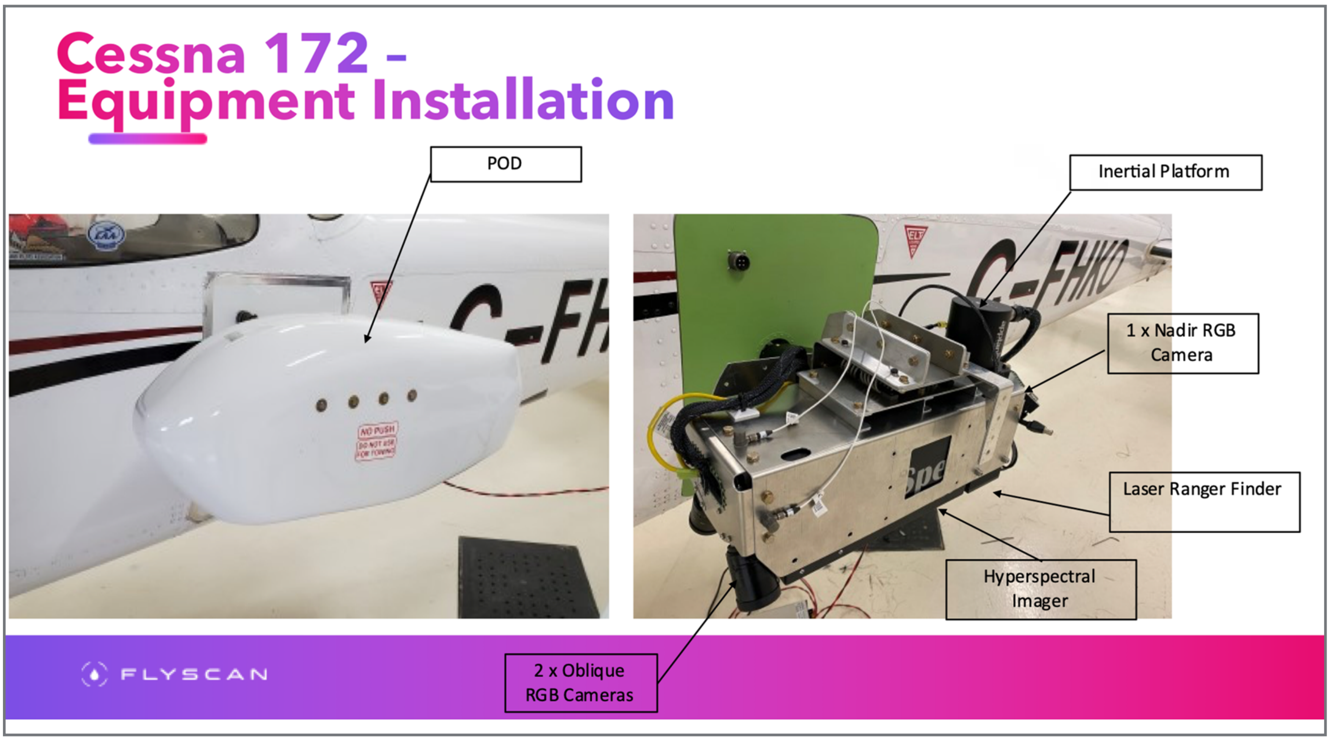

Figure 1: Cessna 172 side-mounted "pod" with hardware components

Figure 2: Phone notification on the left and client portal threat management platform on the right.

The algorithms that are used for this system are proprietary and combine multiple different methods. This article presents the combined results using widely known radiance-based methods. Newly developed capabilities are not presented here.

1.2 Spectral Angle Mapper (SAM)

SAM requires a target spectrum and calculates the spectral angle for all other spectra in the

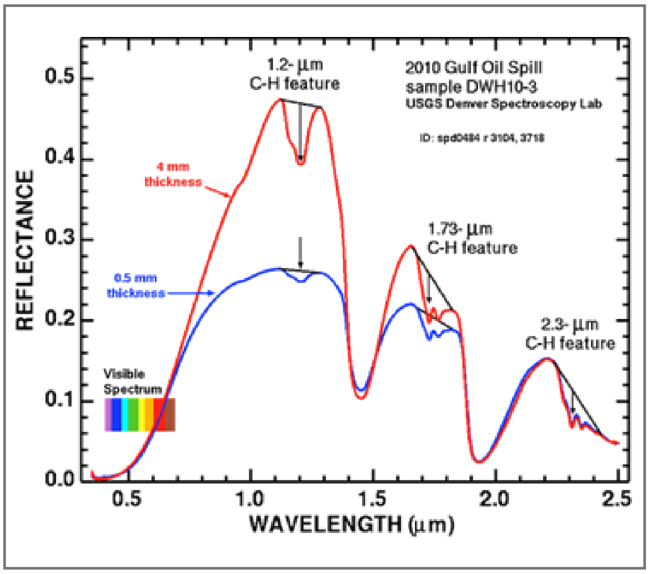

Figure 3: Hydrocarbons spectral features

image. The larger this angle is, the less similar are the target spectrum and the spectral signature. Ideally, both spectra are identical, which means a SAM of 1. A threshold value can be

applied to the result for better visualization. The SAM is a classifier that can easily be motivated

from a geometric perspective. Considering each spectral signature as a vector in *bb*-dimensional space, where *bb* is the number of spectral bands of the hyperspectral data set, two spectra are identical, when the angle between them is zero. Thus, the SAM between a spectral

signature $\boldsymbol{xx} \in \mathrm{R}bb$ and a target reference $\boldsymbol{tt} \in \mathrm{R}bb$, can be calculated as follows:

$$SAM(\boldsymbol{x},\boldsymbol{t}) = \frac{\pi}{2} - acos\left(\frac{\boldsymbol{x}^T\boldsymbol{t}}{\|\boldsymbol{x}\|_2\,\|\boldsymbol{t}\|_2}\right)$$

This is done for all $\boldsymbol{xx}$ in the data set, and the result shows values in [0,1], where 0 stands for orthogonal spectra with no similarity to the reference and 1 stand for a perfect match. The SAM is a quick way to find similar spectra in a scene, but it struggles with noise in the data as it doesn't incorporate a directional bias, e.g., by using the image statistics. After the classification, an additional threshold can be applied to improve the visualization.

1.3 Adaptative Coherence Estimator (ACE)

The Adaptive Coherence Estimator (ACE) requires the same input information as the SAM.

Similarly, a scalar product is calculated between the reference spectrum and all spectra in the scene. The main difference is that the vector multiplication is weighted with the inverse covariance matrix of the mean adjusted data set. The formula is

$$ACE(\boldsymbol{x}, \boldsymbol{t}) = \frac{(\tilde{\boldsymbol{x}}^T \Sigma^{-1} \tilde{\boldsymbol{t}})^2}{(\tilde{\boldsymbol{x}}^T \Sigma^{-1} \tilde{\boldsymbol{x}})(\tilde{\boldsymbol{t}}^T \Sigma^{-1} \tilde{\boldsymbol{t}})}$$

As a result, the spectra can be more easily discriminated compared to the SAM. Additionally, the detection of spectra that occur so rarely that they do not significantly influence the image statistics is improved. These are ideal prerequisites for use in a realistic scenario in which even small puddles of hydrocarbons are to be detected.

1.4 Reed-Xiaoli anomaly detector (RX)

The last method tested is the Reed-Xiaoli (RX) Anomaly Detector. This requires neither target nor background spectra and delivers a high signal in areas that stand out from the general image statistics. Again, the inverse covariance matrix of the mean adjusted data set is used to determine outliers for its statistics. The calculation is as follows:

$$RX(\boldsymbol{x}) = |\tilde{\boldsymbol{x}}^T \Sigma^{-1} \tilde{\boldsymbol{x}}|$$

Due to the expected rarity of hydrocarbons leaks in pipelines, this was considered a valuable approach. This approach was demonstrated to work well for isolated targets.

1.5 Combined approach

The best results were achieved by a combination of these approaches and other remote sensing techniques. Current capabilities already exceed the showcased results in this article.

1.6 High priority threat detection

The threat detection system combines robust machine learning trained algorithms working on visual spectrum (RGB) images. It uses the model to detect and classify every significant object in the images. The high image quality further improves the performance. The models have been trained by Enbridge and Flyscan and the performance examples for threat detection are excellent and presented in Figure 4.

The model is a YoloV5. YOLO an acronym for 'You only look once', is an object detection algorithm that divides images into a grid system. It is one of the most used object detection algorithms because it has a high speed and accuracy.

The training, test and validation datasets have been acquired on a variety of scene configurations in all seasons. The images are cropped from bigger images of 4096x3000 into 640x640 pixels. Over 100 thousand images have been used and a library of more than 1 million images is available to further improve the model performance. Figure 4 is an example of pictures used to train and validate the model. It contains a mix of synthetic and real images. The types of equipment and threat categorization models have been developed with partners from the hydrocarbons and gas industry who are well aware of what is high value and what is not. Human validation demonstrated that the model is performing according to expectations.

2. What are the Characteristics of the tested platform

Liquid pipeline operators have a typical regulatory obligation to perform visual inspections of their ROWs every 2 weeks (in North America). This is traditionally done by plane, which counts as visual inspection, flying at relatively low altitude (between 300 to 1000 feet). Human observation without instrumentation cannot easily find small traces of hydrocarbons at the surface, especially transparent liquids like diesel or gasoline, and human observers get tired in general after 20 minutes of focused inspection (that's why luggage screeners at airports are rotated every 20 minutes). Pilots flying for hours, avoiding obstacles and managing radio traffic, can hardly have a consistent observation of the ROW during the entire flight.

Figure 4: Training and validation images

2.1 Operations

The system is designed to provide operators with capabilities to monitor their ROW assets in detecting hydrocarbons spills when their magnitudes are smaller and to avoid larger repairs costing much more in remediation costs and environmental damage. Detecting leaks while they are small often results in less down time due to repair and clean-up operations. Small sized leaks are known to evolve into more major leaks, which can be avoided using prevention and by acting in a timely manner. All of this has been demonstrated to be possible using the hyperspectral hydrocarbons leak detection system.

2.2 ESG compliance reporting

As environmental regulations become more and more important, investors now select their assets taking account of ESG compliance. Performing regular hydrocarbons leak surveys with high sensitivity sensors enables maintaining a clean social image for the operators while remaining ESG compliant and demonstrating concrete actions to reduce environmental impacts will give operators a new tool to gather data year over year for their environmental reports and statistics on the number of detected leaks.

2.3 Threat detection

Regular, automated, and precise documentation of threats in the ROW was identified as a high-priority feature by the operators who participated in this POC exercise. Machine Learning capabilities provide a high level of detail for threat detection and classification. This enables operators to prioritize interventions and be aware of potential threats like excavation equipment on their ROWs. The most important part is to classify the objects that are detected in a way that is most useful to the operators, for example construction equipment. The categories of objects the model is currently trained on and can detect as Threat are the following:

1. **Commercial trucks:** Semi-trailers, hauling
2. **Mechanical Equipment:** Crane, dump truck, Scraper, front Loader, excavator, cement mixer, ground grader, trencher, bulldozer, vacuum excavation truck/trailer, agricultural equipment
3. **Movable:** Anything with wheels that you would tow
4. **Oversized Passenger Vehicles:** motorhomes, limousines, bus
5. **Personal Property**
6. **Recreational Off-Road Vehicles:** ATVs (quad), motorcycles, snowmobiles

7. **Regular Passenger Vehicles:** Cars, pickup, SUVs, vans, ...

8. **Structure:** Semi-containers, large gas/hydrocarbons/water tanks

2.4 Tested Characteristics

The Flyscan solution was installed as an integrated system on a typical plane used for visual inspection, the Cessna 172. The system was tested to detect and document high-resolution imaging, potential threats and hydrocarbons spills using hyperspectral capabilities.

The main characteristics were

- Fully automatic, plug and play, minimal operation needed, in order to be operator by a single pilot/observer.
- Low cost and can be deployed at large scale
- Improve consistent threat identification and documentation
- Enable sensitive hydrocarbons spill detections and documentation
- No additional work methods are needed: Just install the system on existing surveillance planes
- Much more sensitive than space-based solutions due to the lower altitude of acquisition and higher resolution
- Detect leaks while they are small, minimizing shutdowns and associated remediation costs
- Build ESG and operational performance statistics: document and follow progress weekly, monthly, or annually.

3. Airborne hyperspectral hydrocarbons leak detection and automated threat detection demonstration campaign

In 2021, Flyscan in collaboration with its partner and client ecosystem, performed a capability demonstration campaign. A number of pipeline operators wanted

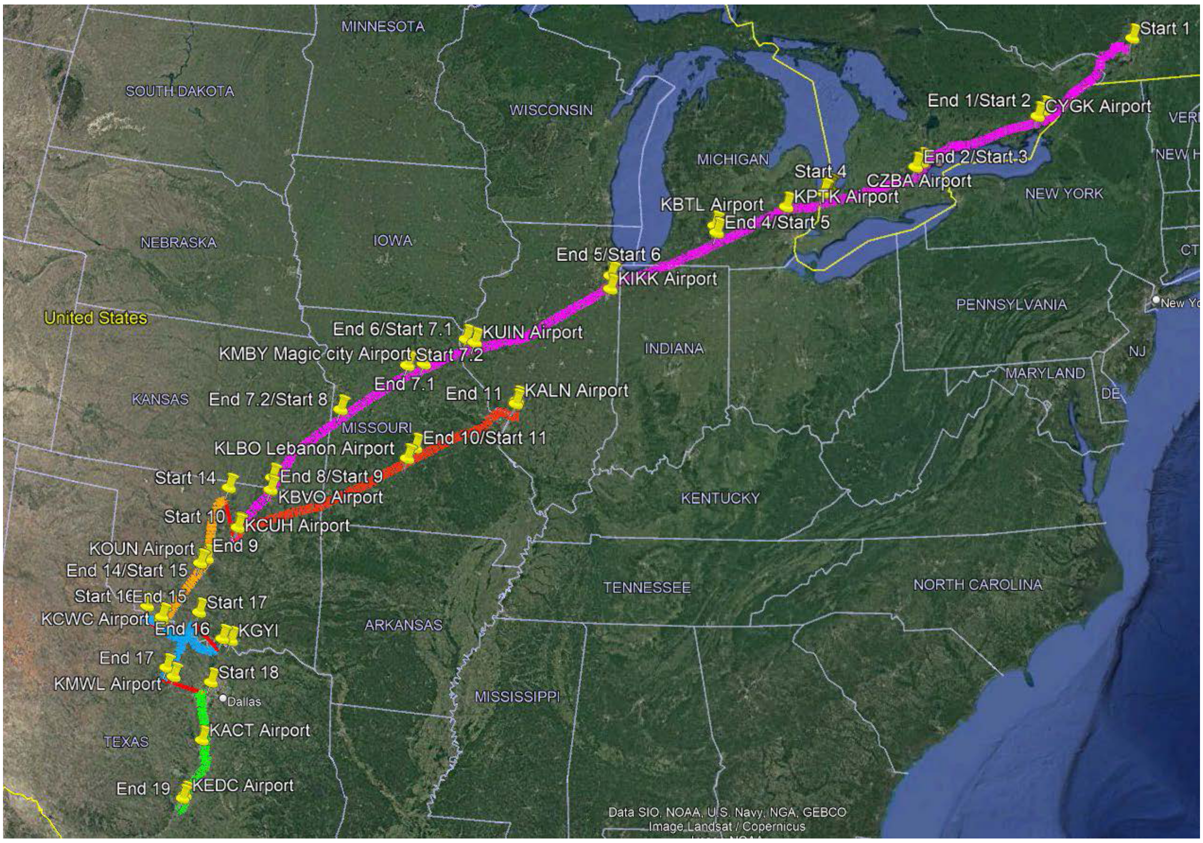

Figure 5: Mission route

Flyscan to demonstrate their Threat Detection and Leak Detection capabilities on their assets. Pipeline operators were asked to share sections of their pipeline network that could be surveyed for this mission. Using the collective information of the five initial participants a route spanning from Montreal, Quebec to Austin, Texas was created. Participating operators included Enbridge, Marathon Pipeline, Kinder Morgan and ARB Midstream.

To be able to carry out this event the following items were necessary:

- Transport Canada STC (July 8th)
- Airworthiness certificate
- Approval of maintenance schedule
- FAA permission to operate in the US and to cross the border, work permits etc.

Final approvals were granted, the planning was completed before departing on Friday, July 29th for the first mission, Enbridge Line 9, Montreal to Sarnia. The final mission was:

- 7 operators (including Marathon Pipeline, ARB Midstream and Kinder Morgan)
- 21 flight legs (2missions merged and 2 added)
- 3177 miles of pipeline surveyed

3.1 Hyperspectral hydrocarbons leak detection

For this part of the mission, 4 operators participated. The objectives were to demonstrate detection capabilities using the hyperspectral system down to a 1m2 spill size.

Operators were asked to provide know targets for demonstration. In figure 7, metal pans were filled with hydrocarbons, water and one was empty for control and to demonstrate that the instrument triggers only on hydrocarbons. It was important to demonstrate that the system does not trigger because of the high reflectivity of the metal pans. In Figure 7 and 8, hydrocarbons were mixed with hydrocarbons and vegetation representing a more typical scene. The site called High Vegetation Area 1 is presented in the left image of Figure 9. All sites were thoroughly cleaned and decontaminated after the tests.

3.2 Results

The results were positive demonstrating that with good weather conditions, the system can detect small

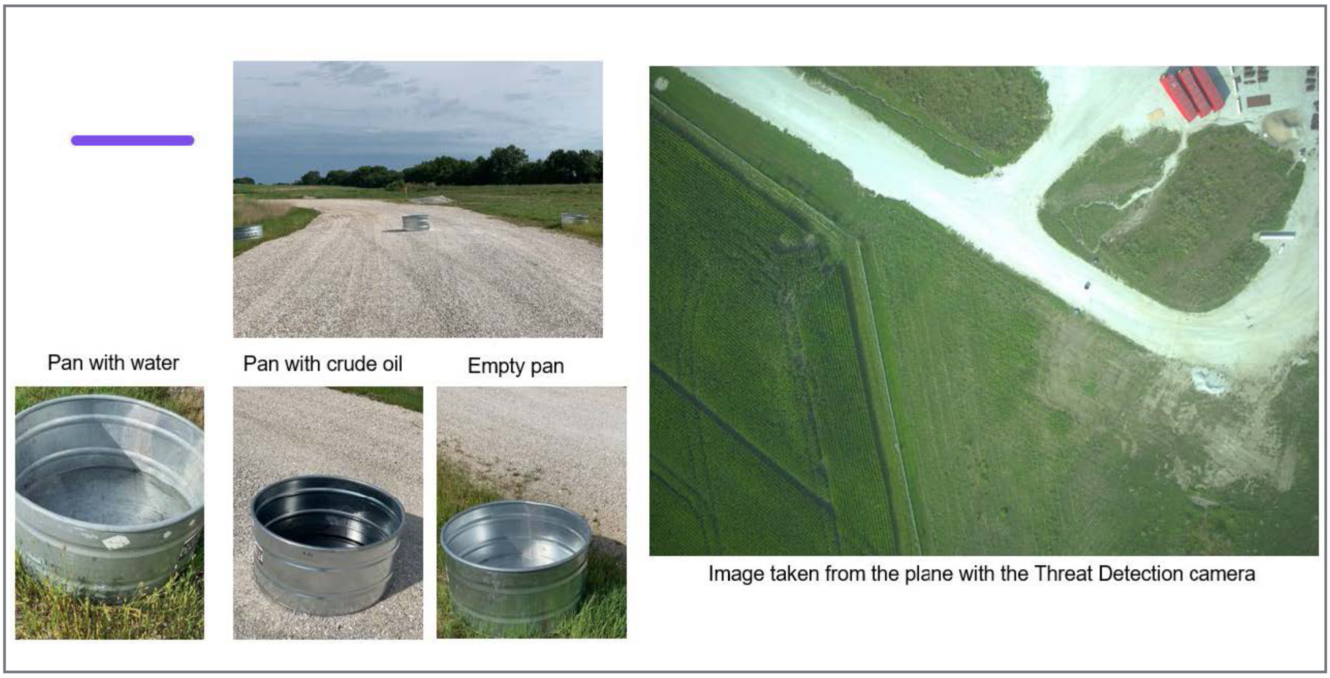

Figure 6: Testing site with hydrocarbons in pans

Figure7: Testing site with hydrocarbons mixed in soil and vegetation. The High Vegetation Area 1 is shown on the right image

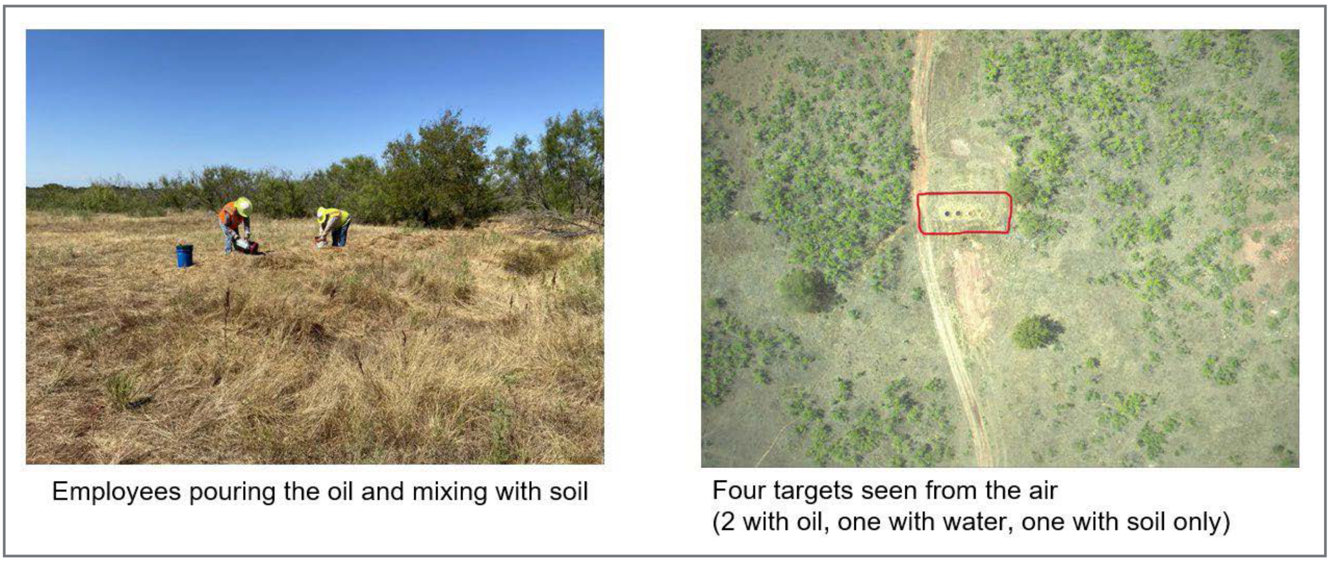

Figure 8: Second testing site with hydrocarbons mixed in soil and vegetation

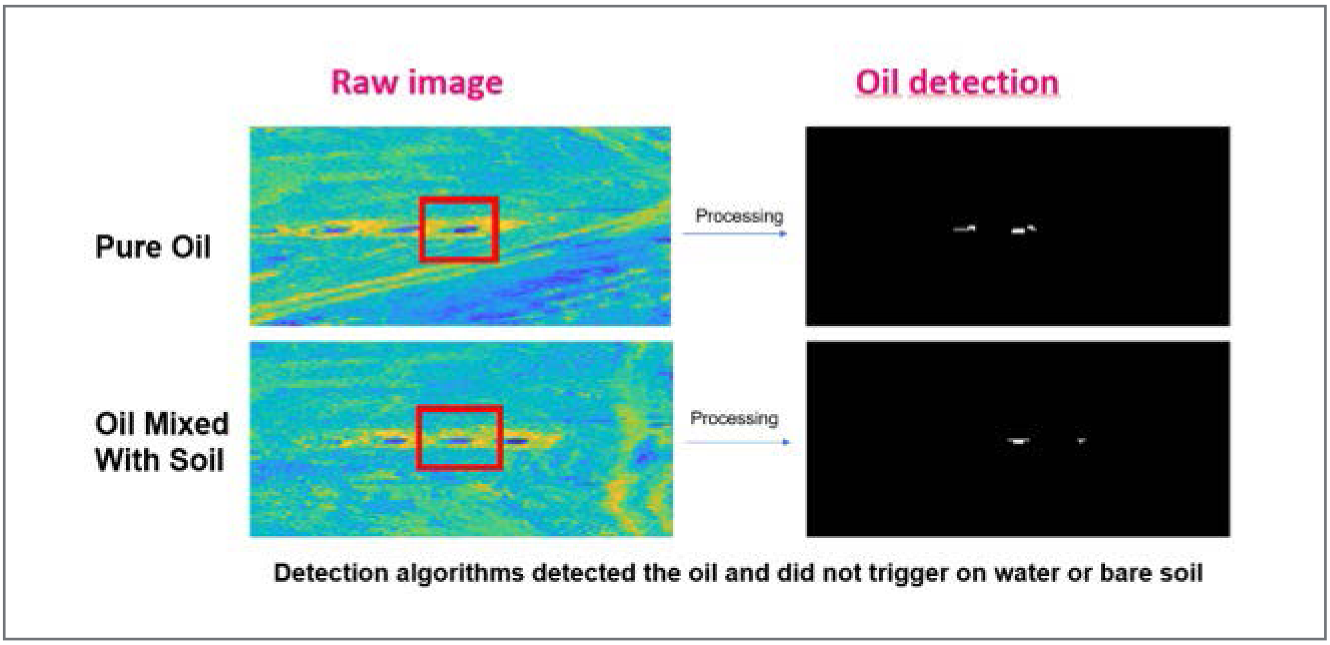

Figure 9: Texas first testing site with hydrocarbons mixed in soil vegetation detection results of raw and final images

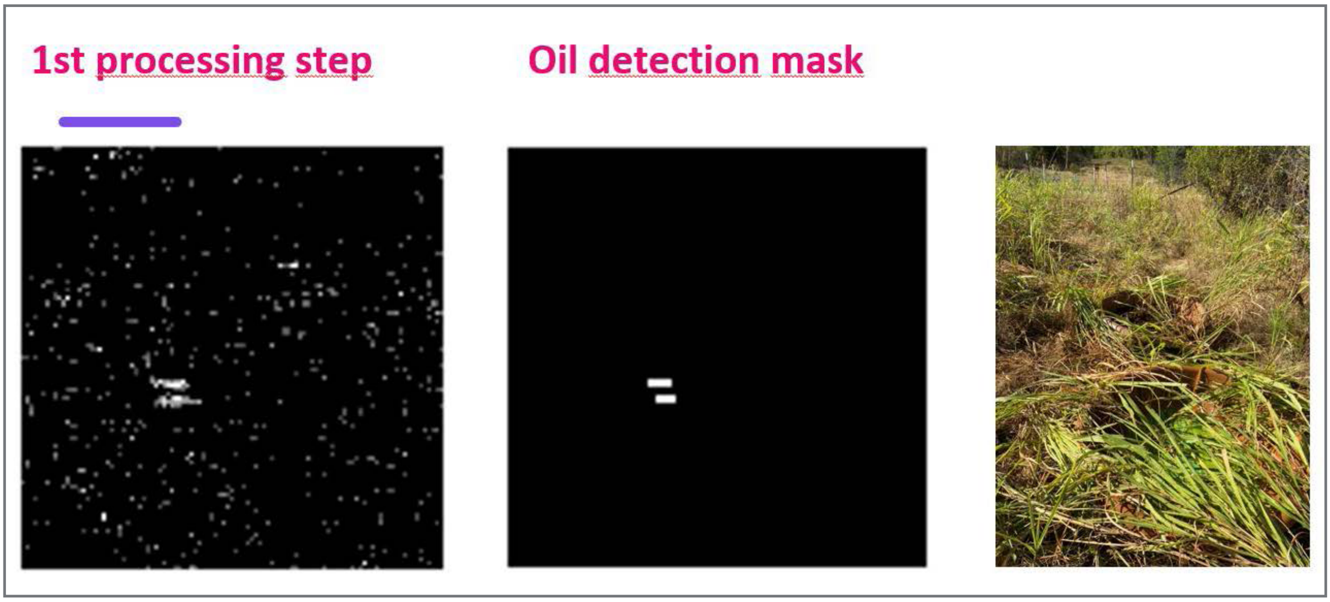

Figure 10:Testing site with hydrocarbons mixed in soil with vegetation hiding the containers. Detection results of the first and last processing steps

quantities of hydrocarbons in pans and mixed with hydrocarbons and vegetation on targets down to 1m2. In summary all the known targets were successfully detected showcasing the sensitivity of the solution, except one location where vegetation covered was too thick and the amount of oil mixed with soil was insufficient for saturation.

InFigure 9, the 4 targets (hydrocarbons, water, hydrocarbons with soil and pure hydrocarbons) are showcased side by side as seen from the plane. The raw image shows that the reflectivity is indeed affected even without hydrocarbons due to the ground being worked. After applying all the processing steps, the pure and mixed hydrocarbons targets are successfully detected while the other targets are discarded.

In Figure 10 below, the first processing step result is shown. This is the result after taking account of the spectral data. Noise can be seen but also the hydrocarbons targets are beginning to appear. This is only the first step, and it is critical to apply the next advanced algorithms to differentiate between the noise and the signal as well as to focus on the spectral features of interest. The final image is also shown, and the 2 distinct hydrocarbons mixed with vegetation targets are clearly detected.

Figure 11 shows another testing site where hydrocarbons (diesel) is mixed with soil and vegetation. Once again, the first pre-processing step result is shown and this time the results right before applying the hydrocarbons detection algorithms are also shown. Adaptative thresholds can easily identify the hydrocarbons targets

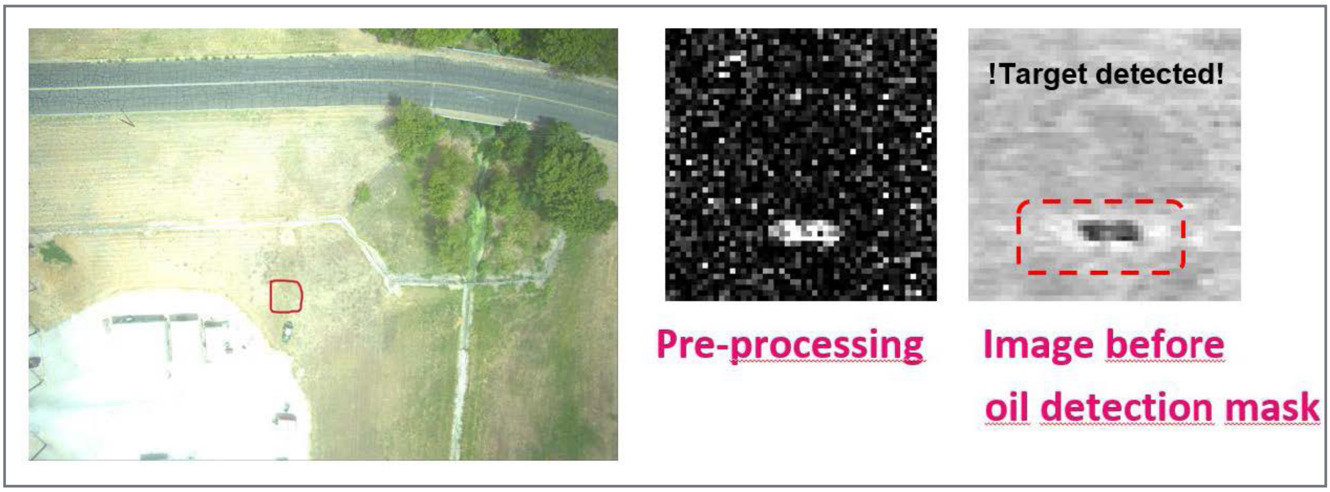

Figure 11: Testing site with diesel mixed in soil with vegetation detection results of the preprocessing and just before applying the hydrocarbons detection algorithm

starting from these results and so once again the hydrocarbons target is successfully detected.

In summary, all the known hydrocarbons targets have been successfully detected except for one site called the High vegetation Area 1. Flyscan demonstrated the capability of the system to document small hydrocarbons spills over the entire ROW infrastructure. The High Vegetation Area 1 site non detection can be explained by the fact that there was to too much vegetation and not enough hydrocarbons present as shown on the left image of Figure 7. More work is on-going to improve the performance, reduce the false alarm rate and improve sensitivity.

3.3 Automated threat detection

For the threat detection capability demonstration, the system used regular industrial-grade visual light cameras, and rack mounts of computer in the back of the plane. Machine learning detection algorithms, developed by Enbridge's Technology and Innovation Lab, were used. The system can differentiate between trucks or heavy machinery for example. These threats were automatically detected and classified by the trained machine learning algorithms in real time, generating SMS and email notifications which are sent to the clients on the ground for review and response. After the campaign, a detailed report was provided to the participating customers about the potential threats on their assets.

In summary, the threat detection system capability demonstration campaign was a success. Operators were positive on the capability to receive these real-time reports of heavy machinery on their assets. Customer feedback clearly shows that the product features tested were a useful new toolset and a great fit for

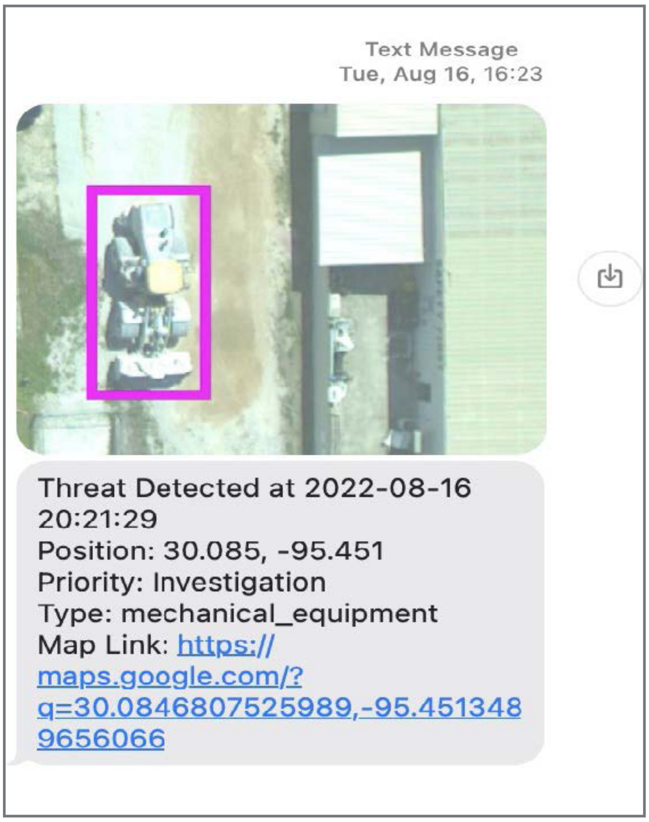

Figure 12: A real-time notification of a threat sent to an operator in Texas

POC mission stats			Number of detections									
Leg	Miles surveyed	Survey time	Identified potential threats	Commercial truck	Mechanical equipment	Movable	Oversized passenger vehicle	Personal property	Regular passenger vehicle	Structure	Total
Mission #1	188	2h 4m 29s	0	167	53	409	22	332	1842	302	3127
Mission #2	205	2h 9m 37s	5	75	72	344	15	90	2249	165	3010
Mission #3	127	1h 20m 20s	0	14	11	86	2	40	232	114	499
Mission #4	157	1h 2m 37s	3	59	103	421	9	70	722	325	1709
Mission #5	160	1h 32m 54s	3	82	51	297	15	63	1031	249	1788
Mission #6	216	2h 21m 55s	2	10	15	122	0	5	103	53	308
Mission #7.1	87	1h 11m 22s	0	13	16	52	0	4	53	65	203
Mission #7.2	111	1h 5m 25s	0	5	15	52	0	0	84	33	189
Mission #8	139	1h	0	10	43	88	0	3	72	40	256
Mission #9	91	1h	0	7	21	31	0	1	59	24	143
Mission #10	276	2h 35m 43s	12	28	96	458	2	61	605	297	1547
Mission #11	167	1h 43m 19s	12	75	88	443	10	204	1838	419	3077
Mission #12	167	1h 5m 10s	2	6	24	90	0	11	110	61	302
Mission #13	276	1h 51m 29s	15	15	78	268	1	37	346	170	915
Mission #14	97	1h 50m 21s	5	46	51	364	5	100	1417	171	2154
Mission #17	217	1h 21m 9s	5	4	7	38	0	2	64	27	142
Mission #18	174	1h 34m 54s	8	26	51	199	0	7	283	102	668
Mission #19	118	1h 4m 58s	5	69	57	223	5	12	464	113	943
Mission #20	118	1h 9m 44s	7	22	31	95	7	38	166	35	394
Mission #21	29	10m 8s	1	35	5	115	5	214	1507	51	1932
Mission #22	48	27m	9	83	59	301	5	136	1779	180	2543
Total	**3177**	**35hrs 35mins**	**94**	**851**	**947**	**4496**	**103**	**1430**	**15026**	**2996**	**25849**

Figure 13:Threat detection mission results and statistics

their needs and that the performance was something never demonstrated in the industry.

A test campaign is currently being performed by Enbridge to benchmark the automated algorithms vs the regular air patrol pilots. Tests were delayed multiple times by bad weather in the Rockies and Mid-West and we are not able to present results in this paper

4. Flyscan Systems solution Road map

Flyscan is continuously working on research and development to add more detection functionalities. Here is presented the roadmap for the Flyscan solutions:

Methane (CH4) leak detection: The system is very much capable of adding this very important gas to its detection capability. Algorithms and processes are being adjusted to offer operators an additional leak detection service. A test campaign to demonstrate capability is under planning.

Hydrocarbons spill sensitivity and reliability: New machine learning and physics-based algorithms are being developed to improve the sensitivity of the system and robustness to false alarms. Robustness is one of the most important criteria. More traditional retrieval and atmospheric modelling techniques are also giving improved results.

Disturbed soil, markers management, urban development and risk analysis and vegetation analysis: Using the same hardware, Flyscan is also developing new machine learning solutions.

For example, monitoring the pipeline markers and ensuring their integrity. Broken, missing or displaced ones can be easily replaced. This feature would replace a process done manually by employees walking the ROW

Vegetation analysis is also being developed to help operators plan their interventions on the field based on growth and potential threat. Using the hyperspectral data, species classification and health monitoring capabilities are also being developed which can indicate presence of hydrocarbons in the soil.

Signs of disturbed soils or construction are also being monitored and Flyscan is developing the system to be able to classify the worked soils and find evidence of construction and recent excavation activity.

Operators must also perform risk analysis of their assets that can change for example when urban, residential, or commercial areas are expanding near the ROWs. This analysis can be performed using machine learning and image analysis to classify and track development around ROW's all using the same hardware. High consequence areas will be monitored.

Geohazard assessment: Using the combination of LiDAR, hyperspectral and visible images, Flyscan, in partnership with multiple operators, is developing capabilities to assess ground movements and geohazard assessment using high precision 3D point clouds. This is very useful to identify for example potential landslides or movement that would disturb the installations.

5. Conclusion

In summary, Flyscan demonstrated its automated threat detection and documentation capabilities as well as its liquid hydrocarbons leak and spill detection system performance. The simulated hydrocarbons spill targets have been detected and multiple threats have been identified and geo-referenced.

Hydrocarbons spills of 1m2 have been successfully identified on various types of soils and mixed vegetation showcasing the performance of the spectral classifier algorithms.

3170 miles of ROW were surveyed in multiple types of vegetation and backgrounds. Over 26,000 objects were automatically detected, geo-referenced and documented in reports. Multiple threat categories such as mechanical equipment or vehicles have also been classified and reported in real-time to operators, for a total of 94 high value potential threats.

The test campaign was a success and generated a lot of interest from operators who are now moving to integrate these systems to their operations.

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Ask the Experts

Inline Inspection & Integrity Management

Q1) How does repurposing existing pipelines for hydrogen use impact their integrity?

One of the main challenges when repurposing existing pipelines for hydrogen use is the lower BTU energy content of hydrogen, which means that a larger volume of hydrogen needs to be transported to maintain the same downstream energy delivery. This can result in higher pressures exceeding the pipeline's maximum allowable operating pressure (MAOP). Furthermore, hydrogen atoms can permeate the pipeline material and cause embrittlement, leading to increased fatigue crack growth rates that can be several orders of magnitude higher.

As a result, pipeline operators must carefully assess their existing pipeline networks, line, and station components for their compatibility with hydrogen. Ensuring the safe transport of hydrogen through existing pipeline networks also requires a proactive and comprehensive approach to pipeline integrity management that considers the unique characteristics of hydrogen and the risks associated with transporting it.

Q2) How can we better assess the risks associated with ageing pipelines and develop effective mitigation strategies?

A comprehensive approach is required to better assess the risks associated with ageing pipelines and develop effective mitigation strategies. This involves data collection and analysis to identify potential hazards and assess the likelihood and consequences of failure. Based on the risk assessment results, appropriate mitigation strategies should be developed and implemented, such as regular inspection and maintenance, repair or replacement of damaged pipeline sections, and the use of advanced technologies to monitor the pipeline's health. Ongoing monitoring and review of the pipeline and its associated risks are also crucial to ensure the effectiveness of mitigation strategies.

Q3) Can LNG pipelines (Unloading/loading jetty to LNG Tanks) be Inspected by ILI tools? Has it been done previously?

In theory, there are no fundamental constraints that would prevent the inspection of LNG pipelines using in-line inspection (ILI) tools. Depending on factors such as pipeline size and flow rates, magnetic flux leakage (MFL) technology may be used to inspect the pipeline. Alternatively, a robotic crawler could be employed, although this option can be more costly. One key challenge would be pressurizing and depressurizing the pipeline traps during the inspection process, as this could result in a phase change and temperature change. To mitigate any potential issues, operators could implement appropriate processes and procedures around the traps to ensure safe and effective inspection.

Q4) Which Inline Inspection can detect girth weld anomalies with actual sizing in gas pipelines?

Magnetic flux leakage (MFL) and ultrasonic testing (UT) are two potential methods that could be employed for detecting and sizing pipeline defects. One of the advantages of MFL is that it does not require a liquid coupling medium, as opposed to UT. However, MFL tools are generally limited to detecting and sizing metal loss defects, and their accuracy may be impacted by factors such as pipeline diameter, wall thickness, and the presence of coatings or liners. UT, on the other hand, will require the introduction of a liquid such as gel to run effectively. UT can provide a higher probability of detection (POD) of anomalies and does not require a physical sensor to run on the pipeline. However, there is a risk of liftoff and mechanical removal of sensors due to pipe issues, which can impact results. The type of defect that can be detected and the accuracy of sizing and detection will vary depending on the specific tool used.

It is also important to note that the accuracy and reliability of the inspection results will depend on the specific tool used, the experience of the operator, and the interpretation of the results. To ensure the safe and reliable operation of pipelines, it is crucial to conduct regular inspections using appropriate NDT techniques and follow up with appropriate maintenance and repair activities.

Q5) What are the latest developments for ILI of hydrogen pipelines?

The development of intelligent pigging or in-line inspection (ILI) technology for hydrogen pipelines is ongoing. Currently, ILI tools designed for natural gas pipelines are being tested for use with hydrogen pipelines, with modifications made to address the unique characteristics of hydrogen.

Regarding the ILI of hydrogen pipelines, there are some concerns due to the harsh environment in which they operate. However, some ILI tool vendors are working on updated MFL tools with magnets that can endure the hydrogen environment. Additionally, NDT experts are developing sensors that can operate in harsh chemical environments, which could potentially be used for hydrogen pipelines. Additionally, research is being conducted to determine the optimal operating pressures and temperatures for hydrogen pipelines to minimize the risk of pipeline failures.

Q6) How can ILI be performed in pipelines used for the storage of CO2?

Performing inline inspection (ILI) in pipelines used for the storage of CO2 is possible, but it is important to consider the physical and chemical properties of CO2. The high-pressure operation of CO2 pipelines limits the options for ILI, and the pipelines may have heavier than normal wall thickness.

However, magnetic flux leakage (MFL) technology can be used, and ART Scan, an acoustic resonance technology initially developed for offshore applications, can also work well in high-pressure and heavy-wall pipelines.

It is crucial to ensure that the ILI tool does not introduce any additional risks or hazards into the pipeline system, such as temporary pressure or temperature increases that could lead to pipeline failure. Pipeline operators must carefully evaluate and select the appropriate ILI technology and procedures to ensure the safe and effective inspection of CO2 pipelines.

Find more of your questions answered here: www.pipeline-journal.net/news/ask-experts

Alex Woll, Pipeline Risk Team Lead, DNV
Alex Woll worked as a risk and integrity engineer with major gas and liquid operators before joining as part of the Pipeline Risk Team. He has substantial experience implementing different risk model types and forming different IMP approaches around risk and PMMs as they fit into the larger integrity program. Alex's day-to-day is focused on driving risk modelling innovation to better support integrity decision making.

Ben Allen, Principal Consultant Digital Solutions, DNV
Ben works in DNV Digital Solutions and is responsible for assisting operators with our risk and integrity software, and risk modeling. Ben has 20+ years in software, with the last 12 predominantly in the oil and gas industry. Ben has consulted and led large implementations integrating risk and asset management with GIS throughout North America, as well as providing ILI solutions and associated engineering services.

Troy Weyant, Product Manager - Pipeline Product Line, DNV
Troy joined DNV in 1994 and is currently responsible for the risk & integrity management software strategy and roadmap to meet the needs of the global integrity management market. Before this role, Troy held the position of Principal Integrity Solutions Consultant responsible for the implementation of projects based upon DNV's Asset Integrity Management suite of products. He has also been responsible for the development of DNV's MAOP management solution and has served as a Synergi Pipeline technical lead for large integrity and GIS implementation projects in the US and abroad.

With each issue of the journal, the "Ask the Experts" section focuses on a new topic of particular relevance to the pipeline industry. People from the international pipeline community are invited to send in their questions which will afterwards be answered publicly by selected experts from the respective field.

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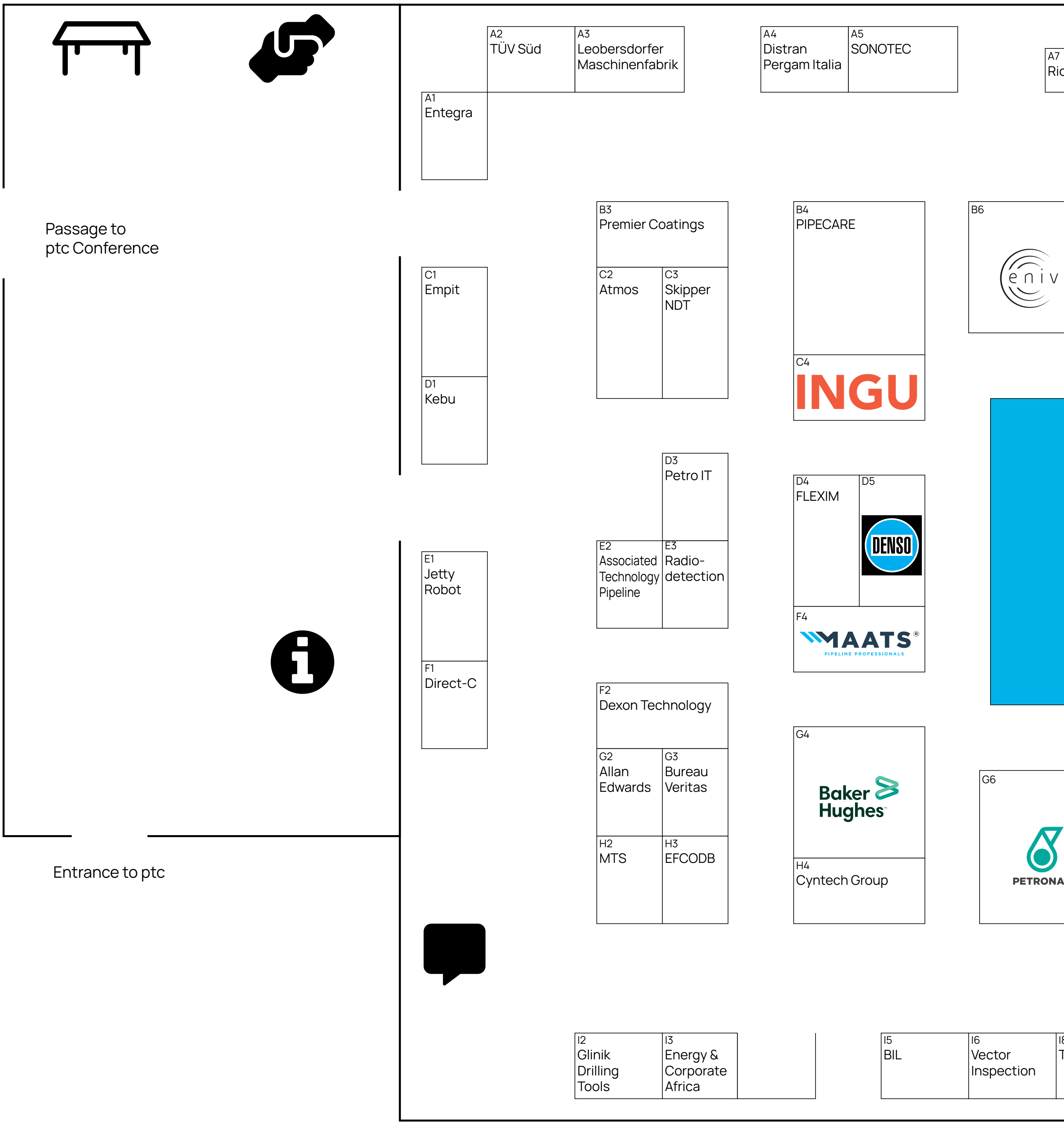

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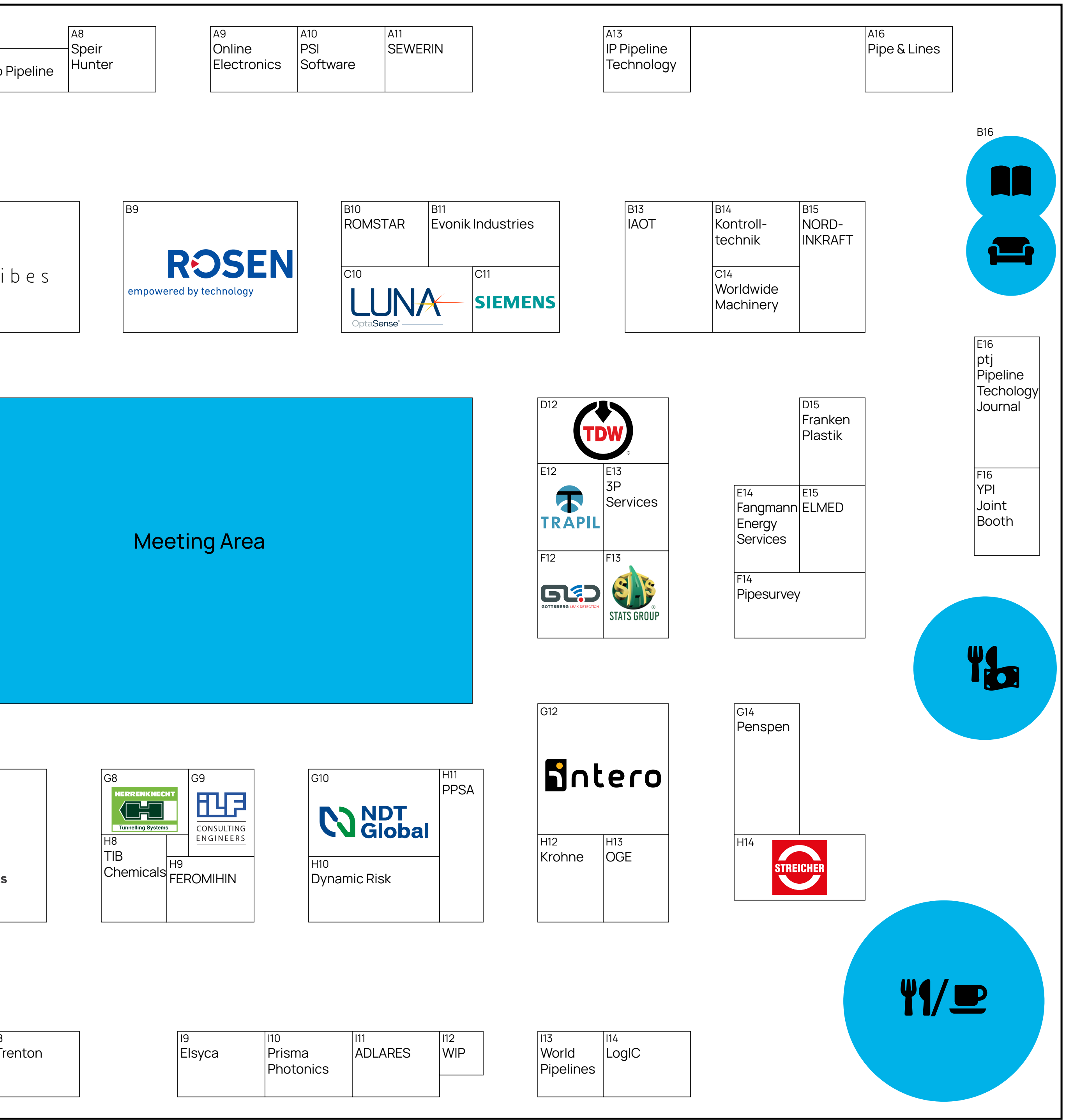

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