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New Generation of AI Techniques Applied to Third Party Interference and Leakage Detection on Pipelines

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Comparative Assessment of Levelised Cost of Different Hydrogen Transportation Technologies

Circular Economy Concept for Aboveground Storage Tanks - Change In Service

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Pipelines of the Future: The Impact of Digitalization, AI and Cyber Security

Julia Möller
Head of Sales - Chemical Industry
Siemens AG

As vacation season ends and we leave behind blue waters, cold mountain air, and colorful foreign dishes, we also return to a new kind of awareness: sensing with artificial intelligence, detecting cyber threats, and anticipating maintenance.

Digitalization in the pipeline sector enhances asset management and operations. Real-time data analytics and remote monitoring improve safety, efficiency, and streamline operations. This proactive approach reduces downtime, increases profitability, and extends asset lifespan.

However, this digital transformation also exposes the pipeline industry to cyber threats. As connectivity and data exchange become more prevalent, the risk of cyber attacks increases significantly. One of the papers you will find in today's issue will cover hazard based protection of gas infrastructure facilities against cyber-physical attacks.

Protecting sensitive information, infrastructure, and operational systems from unauthorized access and potential disruptions is of paramount importance. To prevent incidents like the attack on the Colonial Pipeline in 2021 extorting the payment of 4.4.mio. USD, robust cybersecurity measures, including encryption, firewalls, and regular vulnerability assessments, are essential to safeguarding the integrity and reliability of digitalized pipelines. Two key risk factors in the whole oil and gas sector are availability and security, cyber threats affect both matters.

The next pages will cover, amongst others, AI techniques for third-party interference and advice on selecting the right leak detection methods to meet legal and operational requirements.

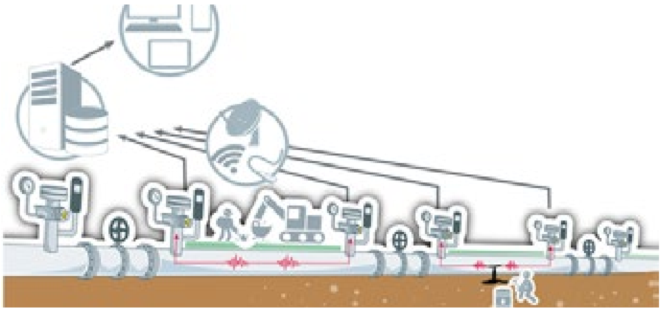
The pipeline sector is on the brink of a digital revolution. Embracing digitalization offers great opportunities, but also introduces cyber risks. By navigating these challenges, the industry can leverage digital technologies while ensuring operational safety.

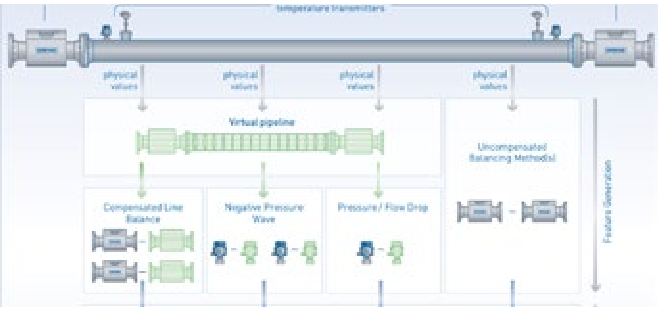
Sincerely Yours,

Julia Möller
Head of Sales – Chemical Industry
Siemens AG

This Issue's

COMPLETE CONTENT

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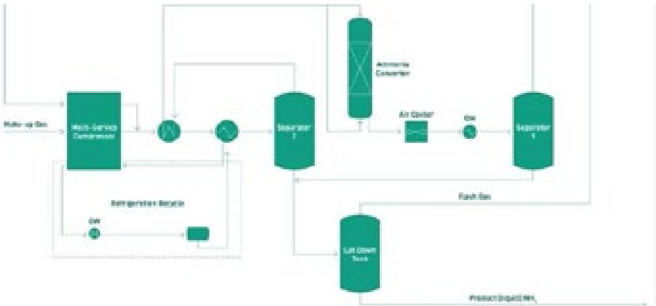

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ptc 2025 Marks 20 Years of Pipeline Innovation and Global Collaboration in Berlin

The Pipeline Technology Conference (ptc) is celebrating its 20th anniversary as "The Global Pipeline Event", set to take place in Berlin from 5 to 8 May 2025. As Europe's premier conference and exhibition for pipeline professionals, ptc 2025 will offer a dynamic, forward-looking program featuring a wide range of training courses, technical sessions, panel discussions, operator round-tables, award ceremonies, and networking events. This milestone event is set to bring together a diverse array of participants from around the world, including delegations from over 100 pipeline operating companies, making it a flagship platform for the global pipeline industry.

The 20th Pipeline Technology Conference will explore key topics at the forefront of the industry, including pipeline research, future fuels like hydrogen and biogas, CO_2 pipelines, digital twins in the pipeline industry, and strategies for managing ageing pipeline infrastructures, including modernization, conversion, and decommissioning. The ptc Conference aims to highlight technological excellence and foster meaningful discussions about the future of the pipeline sector.

Read the full article here:
https://www.pipeline-journal.net/news/ptc-2025-marks-20-years-pipeline-innovation-and-global-collaboration-berlin

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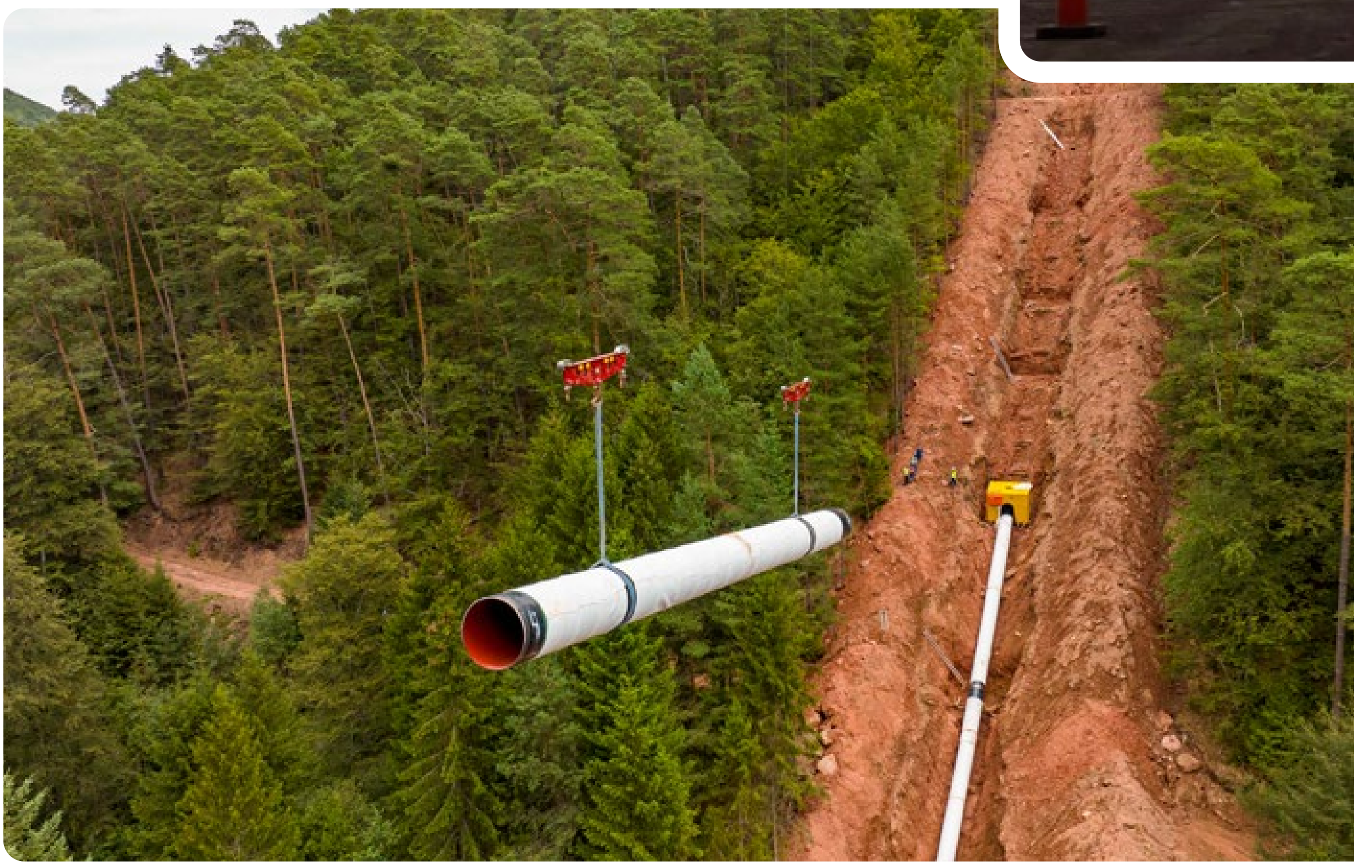

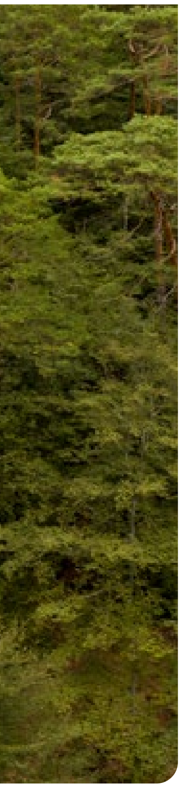

Winner Photo

Argentina/Rio Colorado | The colors of the German flag above the German Rig

Steffen Weinrich

Runner-Up Photo

Network Expansion of the TENP III Natural Gas Pipeline, Germany | Network expansion of TENP III lots 1 – 4 including dismantling of the TENP I natural gas pipeline from the 1970s

Marketing department MAX STREICHER GmbH & Co. KG aA

Interview with YPI Early Achievement Award winner Toon De Bruyne

How does it feel to receive such recognition from your peers in the pipeline industry?

It was a true honor to receive this recognition and to have the opportunity to say a few words on stage during the social gathering at the PTC.

It is pleasant to see that the PTC and YPI want to support young professionals in the industry and motivate them to aim even higher.

Could you tell us about your background and how you became involved in the pipeline industry?

I'm a Belgian Pipeliner and started working in the pipeline industry in 2014 at the Belgian construction company Denys directly when I received my civil engineering degree. I did not know anything about the pipeline industry back then but I had to opportunity to work with several experienced coworkers who learned me everything on the job. I worked on several pipeline construction projects in Belgium, The Netherlands and Germany in different roles as site manager – project engineer and project manager. Since 3 years I'm working as project manager at Pipelink.

I'm now 33 years old, married and have two young children of 2 and 4 years old.

Given your current role as a Projectmanager at Pipelink NV, could you discuss significant milestones that have led you to where you are right now in your career?

- Going to the jobfaire on my university where I got told about Pipelines, unfortunately a world nothing was told about during my school career.
- Following the master in pipeline technology was really important, it gave me a complete vision of the industry next to the construction projects I was working on.
- Working in Belgium-The Netherlands an Germany gave me a new, broader perspective on pipelines in Europe.

Can you share any notable projects or initiatives you've worked on that have had a significant impact on the pipeline industry?

- Pipeliner: first as a board member and currently as chair. Pipeliner is the foundation responsible for the Master in sciences in Pipeline Technology and a more professional course the so called 'Beroepsopleiding'. With Pipeliner we want to help solve the war on talent for the pipeline industry. We will try to give the pipeline industry a place in the programs of the general education and universities.
- Working on facilitating the energy transition at Pipelink

In your experience, what are some of the key challenges that the pipeline industry faces today?

- The Bad atmosphere around pipelines in the general public. It is important that everybody in the industry talks positive about our industry when talking about the job with friends and family.
- The war on talent, in both blue and white collar jobs company's are having difficulties to find the necessary people to achieve the ambitious goals for the energy transition.

- The NIMBY principle and difficulties to get permits for new projects even when they are having a positive impact on the energy transition.

What role do you believe young professionals can play in shaping the future of the pipeline industry?

Creating a positive atmosphere around the industry. Ofcourse we need young professionals to continue the industry itself. But it are the young professionals working on the energy transition who can create a more positive atmosphere around pipelines by mentioning the importance of pipelines in everybody's daily life and the energy transition.

Apart from your professional pursuits, what are some of your hobbies or interests that bring you joy and help you maintain a healthy work-life balance?

Spending time with the family is important for me, my young children put everything in perspective when I come back home.

Besides that I love to do sport, riding my mountainbike or running in nature as a favorite.

Finally, how do you see the future of the pipeline industry evolving, and what role do you envision for yourself in shaping that future??

I would like to see the Pipeline industry being recognized as the 5th transport modality and being recognized for the importance in the daily life of everybody.

I hope a can play a small role in this in my job at Pipelink and at the Pipeliner.

From left to right: Erik Cornelissen (representing the award sponsor ROSEN Group), Toon De Bruyne, Kate Stratogianni (© 2024 Ralph Thiele / EITEP).

Interview with YPI Emerging Young Pipeline Professional Award winner Nikolaos Makrakis

Winning this Award is a significant achievement. Can you share with us how you felt when you received the news and what it means to you?

I remember the day I received the news like it was yesterday!

But first, let me start by sharing a short story. I was anxiously awaiting the award results, so I emailed to ask when they would be announced. Two weeks after the official announcement date, I still hadn't received any updates. Thus, disappointed as I thought I would not win the Award, one morning, I checked the spam folder and came across an email congratulating me for winning the Award. I was completely shocked and overwhelmed by so many emotions. The first thing that came to my mind was pure joy and gratitude. I immediately shared the news with my supervisors and my family, who supported me throughout the process.

Winning this Award means so much to me since it actually confirms that my hard work, dedication, and passion are being recognized by experts. This achievement is a reminder to keep pushing myself towards excellence in everything I do, and never give up on my dreams.

Could you provide an overview of your work or research focus and the potential impact it can have on the pipeline industry?

I specialize, both scientifically and professionally, in Structural and Geotechnical Earthquake Engineering and Geoinformatics Engineering. Since 2018, I have been focusing on geohazard assessment and seismic design of energy lifelines, such as cables and high-pressure gas pipelines. Currently, I am a PhD student focusing on Earthquake Engineering and Infrastructure Design, with emphasis on the optimal design of lifelines. My main aim is to improve the design of safe, functional and resilient lifelines and the whole decision-making process of optimal lifeline routing subjected to geohazards, other hazards and multi-hazards. Apart from the scientific contribution to the international literature, I expect my research effort to contribute also to more practical aspects of lifeline geotechnics, seismic design and optimum route selection, thus being highly beneficial for energy companies and the pipeline industry.

Having said that, I would like to thank my PhD supervisor, Dr Yiannis Tsompanakis, Professor in the School of Chemical and Environmental Engineering of the Technical University of Crete, Greece, and Head of Computational Dynamics & Energy (CODEN) Research Group. I really appreciate the trust he has placed in me and his continuous support. With his valuable guidance, the whole group produces high-quality research.

What motivates and inspires you to continue pursuing a career in research and academia?

Pursuing a career in research and academia generously provides the opportunity to engage with complex and challenging problems, think critically, and keep learning and improving my skills and expertise. I am motivated by my curiosity to think and explore hidden things and therefore, to keep delving deeper and deeper into uncovering new knowledge. In addition, I am always passionate about conducting innovative research that not only contributes to the advancement of my research field but also inspires future generations of researchers.

What are the key challenges you have faced in your research journey so far, and how have you managed to overcome them?

I have encountered many challenges throughout my research journey so far. One big hurdle is dealing with certain assumptions that sometimes need to be adopted in numerical simulations with the Finite Element Method and may affect the accuracy and the reliability of the results. Validating the employed numerical methodology through existing experimental data is always essential, but not always feasible, especially for offshore lifelines. Moreover, when using advanced computational techniques, such as Artificial Neural Networks to create prediction models, the fine-tuning and optimization of their configuration need to be treated very carefully to ensure their accuracy and minimize prediction errors.

Finally, the process of optimal lifeline routing requires an enormous amount of geo-data. Although the availability and reliability of geo-data are constantly improving, reliable geo-data is not always available. Consequently, the corresponding deficiencies/uncertainties are addressed through elaborate parametric investigations and stochastic models. Luckily, the experience and know-how of my PhD supervisor and his research group have limited the detrimental impact of these challenges.

As an emerging professional in the pipeline industry, what do you believe are the most pressing issues or trends that need to be addressed? How do you plan to contribute to their resolution?

As an emerging professional in the pipeline industry focusing on the optimal design of lifelines subjected to geohazards, other hazards and multi-hazards, I realized that selecting a safe and cost-effective lifeline route is a complex and challenging issue. On the one hand, completely avoiding hazardous area(s) is sometimes an unfavorable option due to the increase in lifeline's cost and various technical and geopolitical issues. On the other hand, crossing these area(s) may have a high probability of failure, requiring sometimes impractical mitigation measures.

Traditionally, lifeline route selection has been a manual and time-consuming procedure based on the expertise and subjective opinion of the experts. Although modern computational tools have recently been applied, the optimal routing of lifelines in hazardous areas is based on the qualitative assessment of hazards, without assessing the consequent structural distress.

Hence, to ensure the optimal route selection and effectively handle the enormous amount of data required in such complex spatial multi-criteria applications, advanced decision-support tools are essential. The latter need to be capable of quantifying the criticality of the problems (i.e., exceedance of allowable lifeline strains), thus reducing the risk of failure and the life-cycle cost of the lifeline, and minimizing the impact of human errors and bias. Nonetheless, in cases where lifeline re-routing is unfeasible, as well as crossing hazardous areas is unavoidable and leads to non-acceptable lifeline strains, cost-effective and out-of-the-box design concepts should be proposed and applied.

Beyond your technical skills and research expertise, what other qualities or attributes do you think have contributed to your success as an emerging young professional in the pipeline industry?

From my very first steps in the field of pipeline engineering as an undergraduate student, I realized that pipeline engineering under challenging conditions requires a balance between engineering and science. Thus, apart from the research expertise and the relevant technical skills, developing the critical engineering judgment and having a good understanding of the present and future industry trends and problems are crucial. The latter were acquired through real-world experience in pipeline projects and collaborations with industry professionals. These factors have additionally contributed to my success as an emerging young professional in the pipeline industry.

Nevertheless, at this point, I would like to make a special mention to the supervisor of my undergraduate dissertation, Dr Prodromos Psarropoulos, who inspired and encouraged me to get involved in the field of pipeline engineering and provided me with his vast professional and scientific experience in geotechnics and seismic design.

As a PhD Research student, what lessons have you learned throughout your journey that have significantly impacted your personal and professional growth?

As a PhD Research student, I have figured out that success in any field, including a career in research and academia, requires to be fully concentrated and dedicated.

Pursuing a PhD is like a sine wave, with lots of ups and downs. The key is to stay focused and committed even during tough periods; i.e., at the downs of the sine wave, in order to achieve personal excellence and reach your goals. To do this, the most important thing is to take care of your physical, mental, and emotional well-being and keep a balance between work and personal life.

Apart from your professional pursuits, what are some of your hobbies or interests that bring you joy and help you maintain a healthy work-life balance?

Apart from my professional pursuits, I am a health and fitness enthusiast, regularly attending the gym to maintain physical well-being and discipline. In addition, one of my favorite activities is going for long walks and exploring beautiful places. Another thing I really enjoy is reading self-help books for personal growth, aiming to expand my knowledge and keep my mind engaged outside of work-related tasks. Overall, these hobbies help me stay motivated and energized in both my personal and professional life. They provide me with pleasure, relaxation and they constitute an outlet for stress relief, allowing me to step away from the pressures of the workplace and release tension in a healthy way.

From left to right: Erik Cornelissen, Nikolaos Makrakis & Kate Stratogianni (© 2024 Ralph Thiele / EITEP)

Insights

Well-known industry experts share their experience, insights and opinions on pipeline related topics

Bats, Bees, Snakes, Octopuses, and Pigs!

M. KIRKWOOD > T.D. WILLIAMSON

Abstract

In Professor Hopkins' previous ptj Insights, the focus was on pipeline defects. In this ptj Insights, we will focus on anomalies.

The word "anomaly" applies here since we will look at inspection devices that infer as-yet unconfirmed defects. An "anomaly" deviates from what is standard, normal, or expected. The word "defect" is only used when the anomaly has been confirmed as an imperfection.

1. Introduction

Before we go on to anomalies, let me elucidate the title of this editorial. What do animals have in common with pipelines? (Apart from some amusing anecdotal pictures of snakes [1] and crocodiles [2] wrapped around bits of pipe or equipment?) Many wonders of the animal kingdom are gifted with special "powers" by virtue of their evolution.

As an example, bats are great sound navigators, using an ability called echolocation. Bats use their mouths to produce sounds that will bounce off objects and the greater wax moth (Galleria mellonella) has a hypersensitive hearing, which can reach up to 300,000 hertz which it uses to escape from bats. Bees are incredibly hypersensitive that they can also sense the Earth's magnetic field. Snakes not only have a keen smell they also detect the infrared (thermal) radiation emitted by the bodies of their prey animals. Platypuses are not only a mammal that can lay eggs, it has a highly developed sensor that can locate its prey (i.e., small invertebrates) through electroreception.

There are more "super animals" such as elephants, which have 2,000 scent receptors in their trunks. (By comparison, humans only have 400.) Catfish have up to 175,000 taste sensors, while humans only have around 10,000. Spiders have a hypersensitivity to touch thanks to many hairs (known as trichobothria) on their legs. This lets them detect and trace the origin of a vibration created by an object or animal. Cavefish are nearly blind, but they have acute hearing down to 1 kHz. Finally, the mantis shrimp have 16 types of photoreceptors (light detectors) that can detect visible and ultraviolet (UV) light and are the only known animals to see the circularly polarized light [3] [4].

So, what about the link to pigs? In this paper, we discuss "smart pigs," although not the porcine variety. (They, too, have a keen sense of high-frequency hearing and are well known for their sense of smell — if the reader ever wants to find truffles.) Smart pigs, or in-line inspection (ILI) tools, also have sensors which can then be chosen to suit the threat or defect. I will come back to sensors.

2. In-line Inspection

The first ILI tool was a very simple beast that used a rudimentary measurement system of displacement transducers and a moving disc that electronically recorded traces on a roll of paper. The tool, called the "Kaliper," was developed in the late 1960's by T.D. Williamson (TDW) [5]. It measured the changes in internal bore and highlighted issues such as transitions, fittings, and dents - Figure 1.

As technology developed, Tuboscope and British Gas invented the first magnetics tools [6]. These magnetic flux leakage (MFL) tools have been in service for many years and are vital to the integrity of pipelines. Ultrasonics were also developed for wall loss applications in mainly liquid pipelines then further adapted to look for cracks. Electromagnetic acoustic transducers (EMAT) were developed for crack detection in gas pipelines.

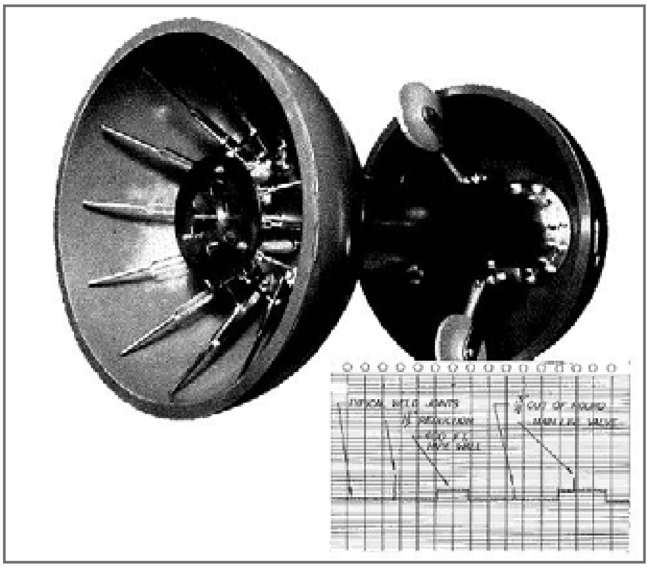

Figure 1: Kaliper (circa 1970)

Many sensors were developed and long used for the detection of anomalies before ILI tools were even conceived. In the early development of railway trains, skilled people called "wheel tappers" were employed to hit the running gear of locomotive and rolling stock to listen for cracks - Figure 2. If there were no cracks, the wheels would "ring true" which is a saying derived for testing something to find if it was substandard or damaged e.g. gold coins, bells etc. This coarse acoustic approach generated a signal of around 500-1,000 hertz (Hz) detectable by the human ear. Ultrasonic ILI tools operate between 400 kHz and 25 MHz.

These tools served a valuable purpose, but each could

Figure 2: Wheel Tapper [4]

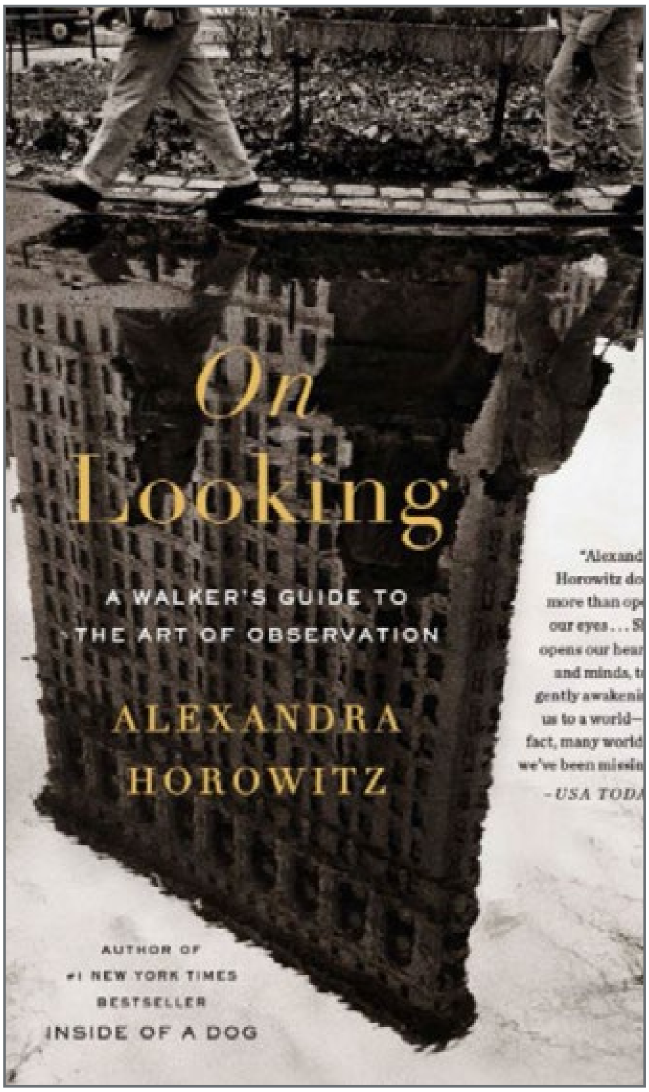

Figure 3: On Looking: A Walkers Guide to the art of Observation - Horowitz [8]

only detect one or two types of defects. They remained blind to other anomalies and had not mastered the "art of looking".

In 2019, my colleagues and I wrote a paper for ptc entitled "The Art of Looking: An In-Line Inspection Perspective," [7] which was inspired by Alexandra Horowitz [8], a specialist in cognitive science who researched the question: What is like to be a dog? In her book "On Looking: A Walkers Guide to the Art of Observation," she explores seeing without seeing through 11 walks with different subject matter experts in her native New York - Figure 3. She uses the eyes of these experts to see different things given their "selective enhancement," or seeing what is important and discarding peripheral data. Each of the "walkers" enhances what they see with their specialist's eye.

For example, a geologist sees more than 60 types of rock on the face and interior of the American Museum of Natural History. It would take a geologist to see the schist, gneiss, quartz and garnet in a building -- but what has he missed with this focused expertise? Possibly the Pantone colours of the window frames, the architectural signs of Greek revival, art deco, and even brutalism?

The need for many senses makes animals better equipped to find things such as food, shelter, companionship, etc. The same analogy can be made in the world of pipeline inspection. Because the bat's great echolation lets it operate in the dark, its sense of sight is not so good, and it tends to hunt at night. Similarly, while ultrasonic ILI tools are great in liquids or within a slug, they don't do well in gas or even liquefied gas. As the saying goes, "horses for courses."

A while back, there was a lot of talk around how sensors were getting smarter, computers faster, batteries longer lasting and everything getting so much smaller that it could be possible to put several sensors on a single tool to look for every perceivable defect type and measure it. The concept of the colloquially termed "Swiss Army" tool [9] was bandied around the industry [10].

Was it developed? Well, nearly! The limiting factor tends to be volume. The smaller the diameter, the longer the tool — which becomes a practical limitation based on what launch and receive traps are on the pipeline. Sure, bigger tools have more volume for ILI stuff (batteries, CPU, storage, etc). However, the external real estate for sensor deployment becomes the limit for ILI tools to traverse pipeline features such as bends, bore restrictions and other paraphernalia. The articulation needed requires careful design of modules that fit together like a train.

Currently, there is a huge array of sensor types available in some form on an ILI platform. Some of these include:

- Calliper
- Magnetic flux leakage (MFL) or axial MFL (A-MFL)
- Transverse field inspection (TFI) or circumferential MFL (C-MFL)
- Helical or spiral MFL (SMFL)
- Low field MFL (LFM)
- Inside diameter, outside diameter (IDOD) sensors
- Eddy current (EC)
- Ranging ultrasonics
- Ultrasonic wall measurement (UTWM)
- Ultrasonic crack detection (UTCD)
- Electromagnetic transducer (EMAT)
- Phased array ultrasonics (PAUT)
- Acoustic resonance (ART)
- Inertial measurement unit (IMU)
- Axial strain measurement (AXISS)
- Cathodic protection current measurement (CPCM)
- Optical systems

All these sensors are necessary but putting them all on one Swiss Army tool will be impossible. As some sensors type have dual capability and no one pipeline is the same, the "mission" of a tool can be tuned to find the desired anomaly. Several ILI providers can now run tools with multiple sensors so our understanding of pipeline threats can be better understood.

An example of the combination of sensors was the old British Gas MFL tool. The design used permanent magnets to saturate the pipe wall and coils to measure any flux leaking because of metal loss. A secondary, unmagnetized array of sensors measured the proximity of the magnetized pipe to another coil. This was then used to identify if the metal loss anomaly was close to the sensor (inside the pipe) or far away (outside of the pipe). This was referred to as IDOD discrimination. As a by-product of this combination of sensors, it was possible to see hard spots [10].

There are now several combination or "combo" tools available to pipeline operators. The one tool with the most sensor types is probably the multiple dataset or MDS Pro tool.

The TDW MDS platform (Figure 4) comprises several complementary technologies, including:

- High resolution deformation (DEF): Provides a measurement of the changes of the inner pipeline bore.

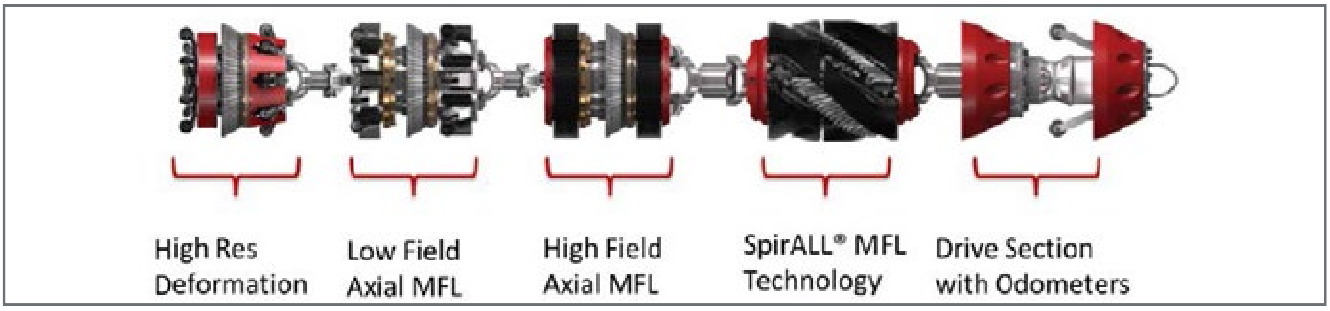

Table 1: Superiority of coextruded Tapes

- High field axial magnetic flux leakage (MFL): Detects volumetric metal loss, mill anomalies, and extra metal and has a strength in detecting wide features.

- Low field axial magnetic flux leakage (LFM): LFM identifies magnetic permeability changes in the steel microstructure due to mechanical working and/or heating /cooling.

- Helical/spiral magnetic flux leakage SMFL): Provides inspection of the longitudinal pipe axis, including weld seams, and detection of other longitudinally oriented anomalies.

- XYZ mapping: Provides high resolution pipe centre-line trajectory.

In Professor Horowitz's - on looking world, this would be like walking a city block with five uniquely skilled subject matter experts!

As I mentioned, some sensors overlap and some complement. For a picture of how the MDS tool can be deployed against a set of specified anomalies [11], we can draw a rather complex Venn diagram [12] - Figure 5.

As this tool is based on the physics of magnetism (A-MFL, S-MFL and LFM), the type of weld and pipe body defects are mainly focused on those that have volume. Although some cracking presents itself magnetically, close fitting cracks need another technology such as UTCD or EMAT.

Trying to cram all this technology onto one tool, as Keith Grimes of British Gas posited, "invariably raises the question as to who would genuinely wish to hire such a complex beast." As Grimes states quite categorically, there is a cost implication -- not just in running the tool, but also for on-costs such as data analysis, the risk of damage and refurbishment and the unthinkable of getting stuck or damaged beyond repair.

3. Case Study

As an example, here are a series of images taken from an MDS run.

Figure 7 through Figure 11 show an example of the MDS datasets.

Starting with Figure 6, the high resolution caliper (or DEF) highlights significant indentation presenting

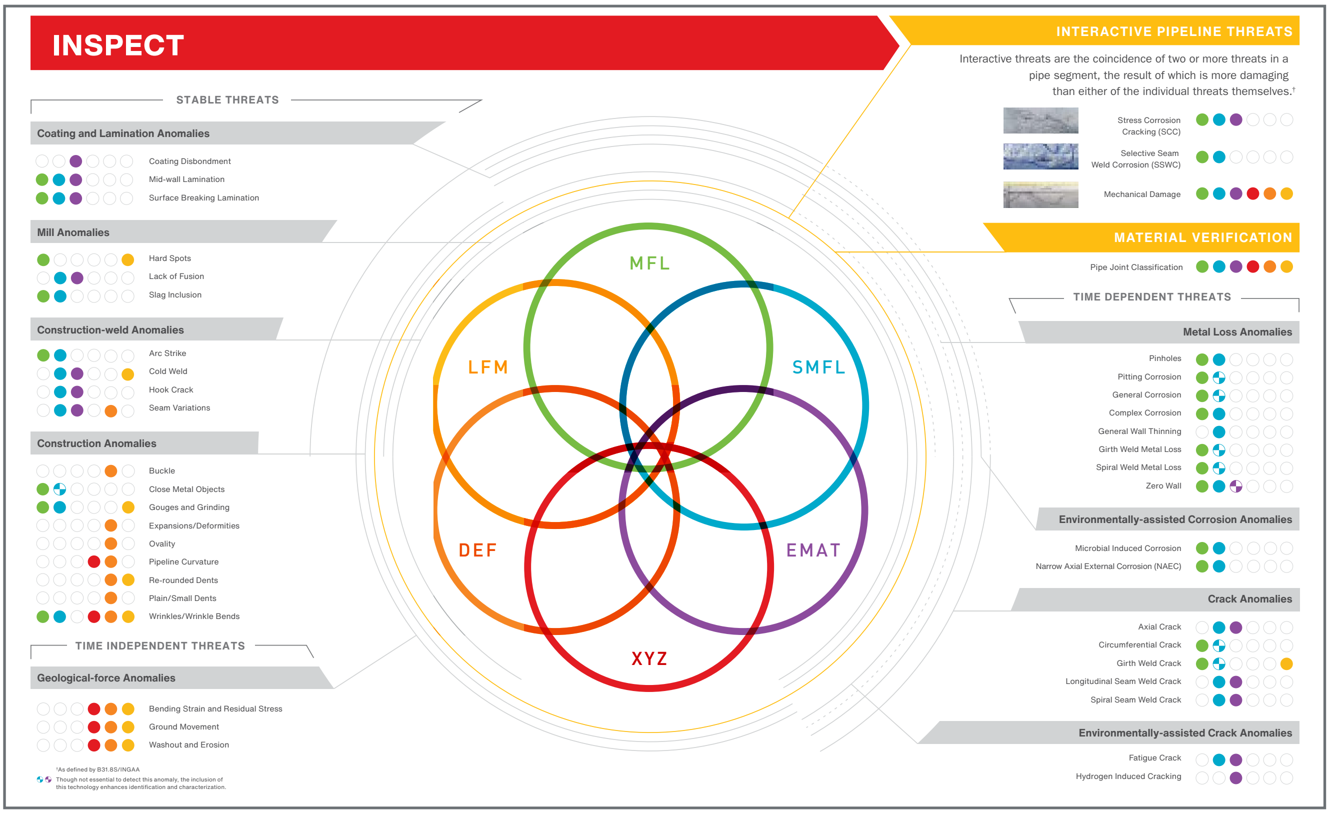

Figure 5: Venn Diagram for ILI Against Defects Defined in POF [11]

itself as non-axially orientated. In keeping with the animal theme, the shape resembles a "tadpole."

In the axial MFL (Figure 7), we can see significant metal loss. At this stage it's difficult to establish if this is corrosion or a gouge.

However, adding the SMFL (Figure 8) indicates that the anomaly is reasonably long and at some angle to the axis of the pipe. Again, it is shaped like a tadpole.

In the LFM (Figure 9), there is a distinct change in the material state because of strain hardening the pipe material. That indicates this is not corrosion but a gouge.

Using the data from the inertial measurement unit (IMU), the location of the anomaly is confirmed to be the backyard of a residence (Figure 10).

Combining all the datasets provided us with five views of the anomaly, which excavation confirmed was a dent with gouging, probably caused when the posts for a small garden building were installed and struck the pipe wall (Figure 11).

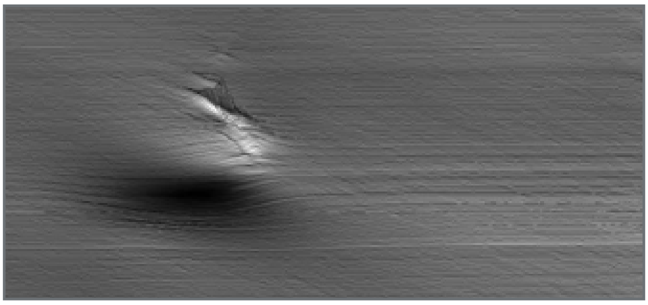

Figure 8: Spiral MFL – showing that the metal loss extends axially and circumstantially.

Figure 10: Location – this highlight not only the proximity of the anomaly and risk but also alludes to the possible cause.

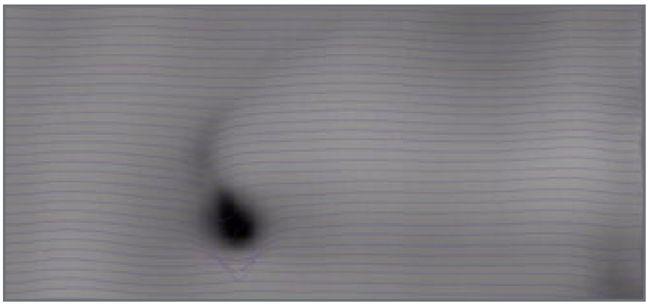

Figure 6: Geometry – highlighting there is a significant geometric change in the form of a dent

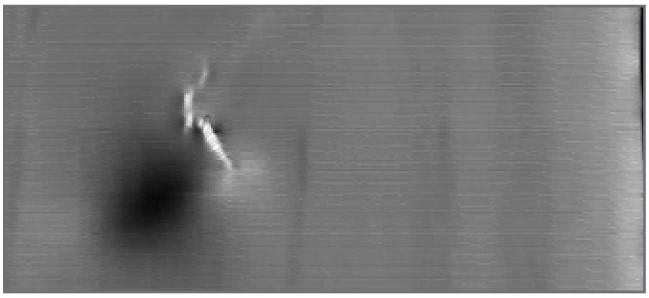

Figure 7: Axial MFL – showing significant metal loss.

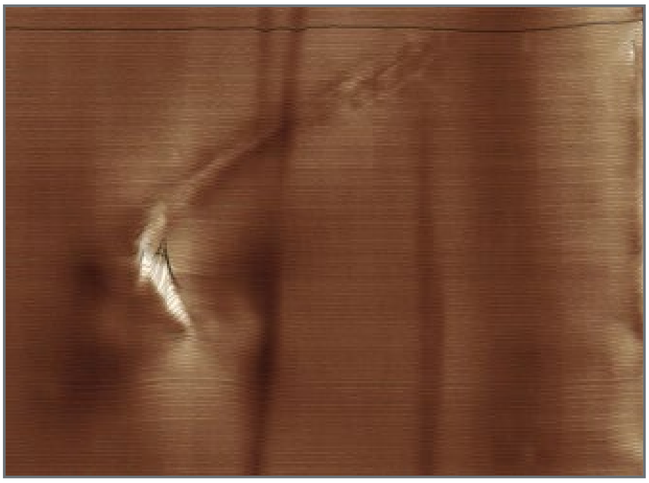

Figure 9: Low field MFL – showing that there is significant material changes around the metal loss (from MFL and SMFL) as well as the dent.

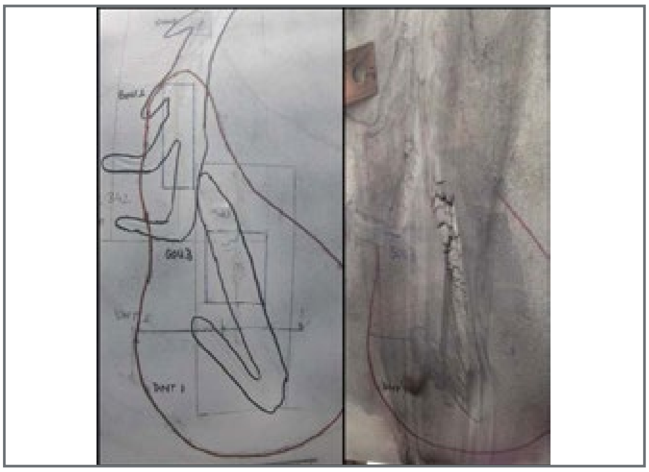

Figure 11: Actual damage – a severe dent and gouge combination most probably because of a small construction in a residential back yard.

In this case, we would have excavated the defect purely on the strength of just one or two of the data sets. However, additional data sets do help us determine whether the dent was larger upon impact, whether the metal loss is a gouge, and the material hardening because of the impact and metal flow. These datasets all align and allow us to make this call, which is a massive step forward from the simple Kaliper tool of the 1970s. However, I left one super animal until last: Octopuses boast a sophisticated array of senses. They possess keen vision, sensitive touch facilitated by suckers on their arms, discerning taste, and a sharp sense of smell. Furthermore, their ability to detect alterations in light polarization enhances their camouflage and communication strategies. Remarkably, octopuses exhibit an advanced sense of proprioception, enabling them to perceive the positions of their limbs without visual cues. Recent studies propose the presence of a distributed nervous system within their bodies, suggesting a unique form of intelligence or awareness that enriches their understanding of the environment. Octopuses have been around for 296 million years (Carboniferous period); ILI development only spans some 50 years, so we have a long way to get as good as an octopus!

4. Final comments

There are many ILI tool types now available. Thus, most defects can be detected, sized, and characterized to a given specification. Using the wrong tool because it is convenient reminds me of the idiom “buy cheap, buy twice.” In the pipeline world, there are wider implications of getting it wrong. When considering inspection needs, operators need to consider the balance of costs and return on investment as well as the need to meet regulatory rulings.

In choosing the right tool or tools, I refer back to the analogy of “horses for courses.” In this simple idiom, there are thoroughbreds bred to run fast for short periods (racing) horses bred for elegance and gymnastics (dressage), for getting over fences and hedges (show jumping), and for running fast with amazing stamina (endurance), to name a few. I will certainly not enter any of my champion dressage Friesians in the next Grand National or Kentucky Derby. So, make sure you assess the threats you are looking for and select the right tool or tools for the job.

“VLIP VAN GRIETJE N” – RIP

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Hazard Based Protection of Gas Infrastructure Facilities against Cyber-Physical Attacks

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Abstract

The rapid growth in digitalization and automation results in industrial plants increasingly interconnected through IT (Information Technology) and OT (Operational Technology) networks. While this interconnectedness offers significant operational advantages, it also makes plants vulnerable to cyber-physical attacks. Such attacks can lead to major accidents like fires or explosions. Currently, scenarios resulting from cyber-physical attacks are inadequately considered in process hazard analyses, such as HAZOP studies. To protect plants against these threats, a comprehensive combined safety and security analysis is required. Therefore, the novel Safety-Cyber-Security-Evaluation (sCSE) methodology is presented, which builds upon existing HAZOP studies. The sCSE methodology identifies potential safety-relevant scenarios resulting from cyber-physical attacks, determines potential attack vectors, and derives appropriate security countermeasures. Finally, the security countermeasures are prioritized for implementation.

1. Introduction

Digitalization and automation lead to increasingly integrated plants with both internal and external networks. Isolated networks, which are not connected to other IT and OT systems, are becoming rare. This growing connectivity facilitates the analysis of process data, enhancing the efficiency of plants and enabling predictive maintenance (Patel & Patel, 2016). Gas pipelines can be operated cost-effectively from a distance through network integration and remote access capabilities (Zaidi, 2024). While the increasing automation and networking of plants offers operational advantages, the plants are becoming more vulnerable to cyberattacks. Such attacks against gas pipelines are motivated by political or financial motives and pose a significant threat to critical infrastructure (Kovacevic & Nikolic, 2015). On one hand, cyberattacks can significantly reduce the availability of plants and thus cause considerable financial losses; on the other hand, cyberattacks can affect the safety of the plant and thus cause major accidents.

Cyber-physical attacks can create new scenarios that are currently inadequately considered in process hazard analyses such as HAZOP studies. For instance, cyber-physical attacks can restrict the availability of one or more safety instrumented systems. The possibility of severe accidents due to cyberattacks is well-known and addressed in various regulations, such as DIN EN 61511, KAS 51, and NA 163. However, even these guidelines lack uniform methods for conducting risk analyses and selecting appropriate security countermeasures against cyberattacks. It is urgently necessary to integrate safety-relevant scenarios resulting from cyber-physical attacks into hazard and impact analyses. Integrated concepts from the areas of "safety and security" have been shown to be essential to achieve a comprehensive risk assessment of plants (Tantawy, Abdelwahed, Erradi, & Shaban, 2020).

2. Safety-Relevant Scenarios

To identify potential safety-relevant scenarios resulting from cyberattacks, the Safety-Cyber-Security-Evaluation (sCSE) methodology was developed at the CSE Center of Safety Excellence (Biernath, Dürrwang, Schmidt, & Denecke, 2022). The sCSE methodology identifies these scenarios based on existing HAZOP studies by converting the columns of traditional HAZOP studies into a matrix format. This conversion results in matrices that map the dependencies between Nodes (N), Deviations (D), Causes (Ca), Consequences (C), and Safety Countermeasures (SaC), as illustrated in Figure 1.

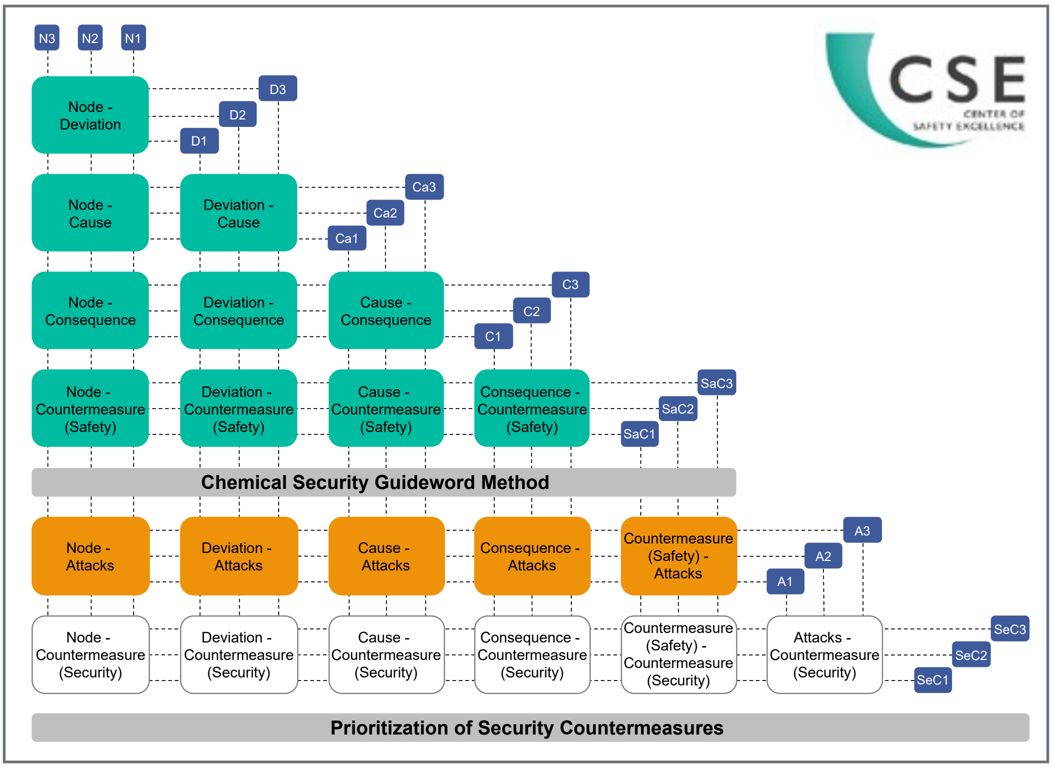

Figure 1: Concept of the sCSE-Methodology: (1) Transformation of the HAZOP study into the green matrices to derive potential scenarios resulting from cyberattacks; (2) Applying the CSGM to derive potential attack vectors; (3) Integration of the attack vectors into the matrix notion (orange matrices); (4) Derivation of appropriate security countermeasures (white matrices); (5) Prioritization of security countermeasures.

By converting the HAZOP study into a matrix format, the following scenarios resulting from a cyber-physical attack can be identified: (1) Attacks on safety instrumented systems, leading to the non-performance of one or more safety instrumented systems. (2) Simultaneous triggering of various safety scenarios that are covered by the same safety countermeasure. Safety countermeasures are sized under the assumption of a single primary failure and can be overloaded by the simultaneous triggering of multiple safety scenarios. (3) Simultaneous triggering of multiple non-safety-relevant scenarios that, in combination, can cause a safety-relevant scenario and may not be covered by adequate safety countermeasures. (4) Attacks on the availability of essential functions according to IEC-TR63069. Since the matrices are directly based on the columns of the HAZOP table, the conversion can be automated.

3. Identification of Potential Cyber Threats

In the next step, the potential cyber threats that trigger the safety-relevant scenarios are identified. Through this analysis, vulnerabilities and their potential impact on the physical process are determined at component level. To identify possible security threats, the Chemical Security Guideword method (CSGM) is used, which is derived from the STRIDE framework (Khan, McLaughlin, Laverty, & Sezer, 2017). Guidewords, that represent potential cyber threats, are applied to the components of the OT network. The following guidewords are used:

- Delay: Unavailability of information due to a delay of data on a communication channel
- Denial of Service: Blocking of a critical service which leads to an unavailability of the service
- Trigger: An unauthenticated execution or activation of a software function on the target component
- Manipulation: Malicious modification of existing information to change the behaviour of the target component
- Resequencing: Maliciously manipulated bus device modifies the safety message sequence

After applying the guidewords (i.e. cyber threats) onto the OT components, possible vulnerabilities are determined that are exploited by the threats. An example for the Chemical Security Guideword Method is shown in Figure 2. In the shown example, the guideword “Manipulation” is applied to a temperature transmitter with a Bluetooth interface, whereby the communication via the Bluetooth interface is manipulated due to a Man-in-the-Middle attack. For example, the vulnerability CVE-2023-24023 according to the NVD (National Vulnerability Database) can be exploited for this purpose.

This process determines potential attack vectors (A), which are then converted into the matrix format in the third step of the sCSE-Methodology, as shown in the orange matrices in Figure 1. The matrices highlight possible attack vectors against components. Additionally, the orange matrices can help to determine if an attack vector can simultaneously trigger multiple safety-relevant scenarios, potentially overloading safety countermeasures. The attack vectors can be generically created for various standard components, allowing this step to be largely automated.

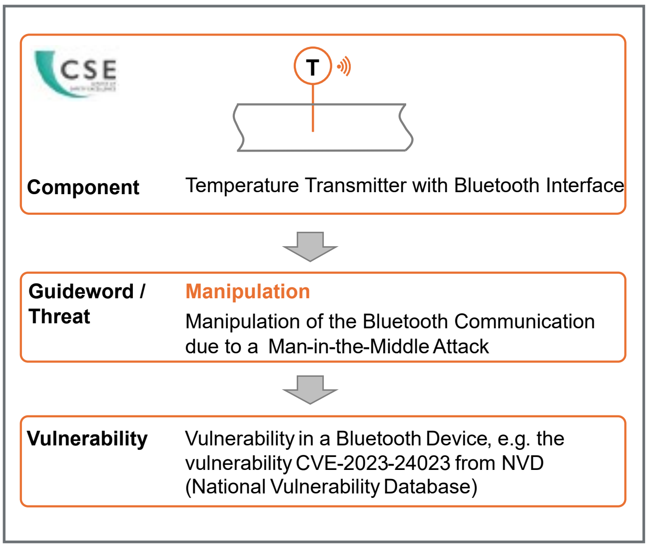

Figure 2: Applying the CSGM to a temperature transmitter with a Bluetooth interface.

4. Prevention of Vulnerability Exploitation

To prevent the exploitation of vulnerabilities by cyber threats, appropriate security countermeasures must be implemented. Potential security countermeasures are derived from IEC 62443, the BSI IT-Grundschutz Compendium, and other regulations. Both IEC 62443 and the BSI IT-Grundschutz Compendium define different levels of protection for each security countermeasures. The selection of an appropriate level of protection is based on the risk associated with the respective safety scenarios. The matrix schema is extended by the security countermeasures (SeC). Based on the matrix format, potential interactions between the safety countermeasures from the HAZOP study and the security countermeasures against cyberattacks are evaluated. The countermeasures can reinforce each other, be independent, or in conflict with each other.

5. Prioritizing Implementation

In the final step, the security countermeasures against cyberattacks are prioritized for implementation. The following criteria are used for prioritizing the security countermeasures: (1) Prioritization based on the risk associated with the scenarios as identified in the HAZOP study. (2) Prioritization of security countermeasures using an assessment of the vulnerability exploited by the attack vectors. (3) Prioritization based on the relevance of the components. (4) The number of components protected by the security countermeasures. Prioritization enables the operator to implement the most urgent countermeasures in a timely manner.

6. Conclusion

The Safety-Cyber-Security-Evaluation (sCSE) methodology, developed at the CSE Center of Safety Excellence, offers an innovative and automated approach to extend existing process hazard analyses by a security risk analysis. The sCSE method is based on existing HAZOP studies, which are automatically expanded to include safety-relevant scenarios resulting from cyberattacks. Potential attack vectors are systematically identified using a guideword method. The methodology then derives appropriate security countermeasures against the possible attack vectors and prioritizes them to facilitate implementation for the operator.

The sCSE method forms the foundation for further innovative research projects. Based on the sCSE method, the most critical OT components can be identified. These components are then to be transferred into a digital twin to conduct virtual penetration tests. Through these virtual penetration tests, the effectiveness of security countermeasures can be tested without endanger the availability or safety of the plant. This project has started at CSE.

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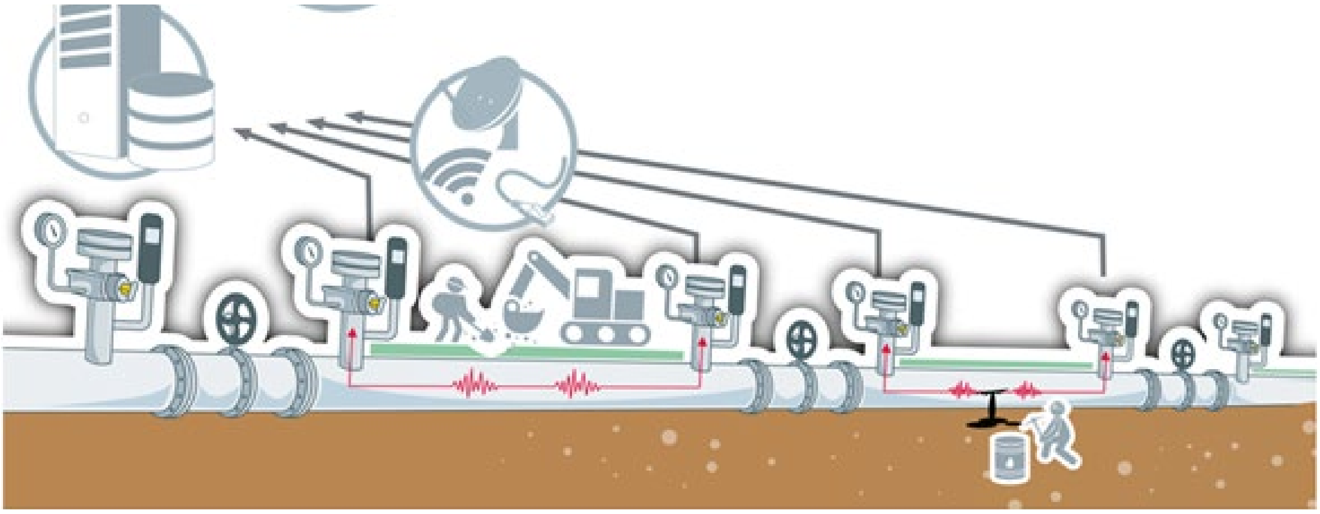

New Generation of AI Techniques Applied to Third Party Interference and Leakage Detection on Pipelines

A. P. GOMES, M. MARINO, M. BIAGINI, F. CHIAPPA > ENIVIBES

Abstract

This paper presents a pipeline monitoring system designed to detect, locate, and classify leakages and Third-Party Interference (TPI) incidents along a pipeline right-of-way using Vibroacoustic Technology. The system is ideal for retrofitting existing pipelines and focuses on real-time asset monitoring to detect activities such as excavation or impacts that could cause damage.

Vibroacoustic waves generated by anomalies, i.e., TPIs or leakages, propagate for several kilometers inside the pipeline. Strategically placed pressure sensors and accelerometers along the pipeline capture the data, that are then transmitted to computational units with advanced algorithms for noise reduction, event detection, and localization.

The system employs machine learning and deep learning techniques, including convolutional neural networks, to classify TPI events, enhancing detection accuracy and minimizing false alarms. This innovative AI-driven approach offers a robust solution for maintaining pipeline integrity with potential to become a key tool in pipeline asset protection.

1. Introduction to the Vibroacoustic Technology

The detection of leaks and TPI plays a pivotal role in ensuring the security and integrity of pipelines. Implementing robust monitoring systems that promptly and accurately identify leaks and TPIs in real-time serves as a deterrent against illicit activities while empowering the pipeline operator to intervene promptly. This enables the organization of effective emergency responses, thereby enhancing safety for the neighboring population, elevating environmental protection measures, and reducing remediation costs and operational downtime.

Vibroacoustic Technology (VT) operates through a network of sensors installed every few kilometers along the pipeline, continuously gathering and analyzing vibroacoustic data. The distinct signature of vibroacoustic waves generated by leaks and third-party interference (TPI) activities, when systematically analyzed, reveals the nature of the event and its precise location.

The signal recorded by the sensor blocks is continuously transmitted to a processing server. On this server, leak and TPI software modules analyze the pressure waves and micro-vibrations, allowing for the identification and localization of anomalous sources through advanced digital processing, real-time noise removal, and non-linear filters. The signal processing algorithms, built on exceptionally sensitive sensors, can detect even subtle and informative vibrations. An overview of the processing is shown in Figure 1.

The Leak and TPI software modules focus on distinct events therefore operate independently, generating separate alarms upon detecting an event. These alarms can be presented on a user interface, disseminated via email or SMS to a designated recipient list, integrated into the internal systems of the pipeline operator, and more.

The TPI detector system is primarily designed to analyze vibroacoustic data related to third-party interferences, aiming to detect and locate various activities such as excavations, civil works and impacts above the pipeline, among other actions indicating potential illicit activities. Following reported issues regarding alarms not related to actual infraction events, a statistical analysis of false alarms was conducted. The results revealed distinct spatial clusters of alarms associated with periodic activities along the pipeline, such as vibrations from railways, highways and airports.

To enhance the robustness of data processing, the current TPI computational strategy considers any pair of

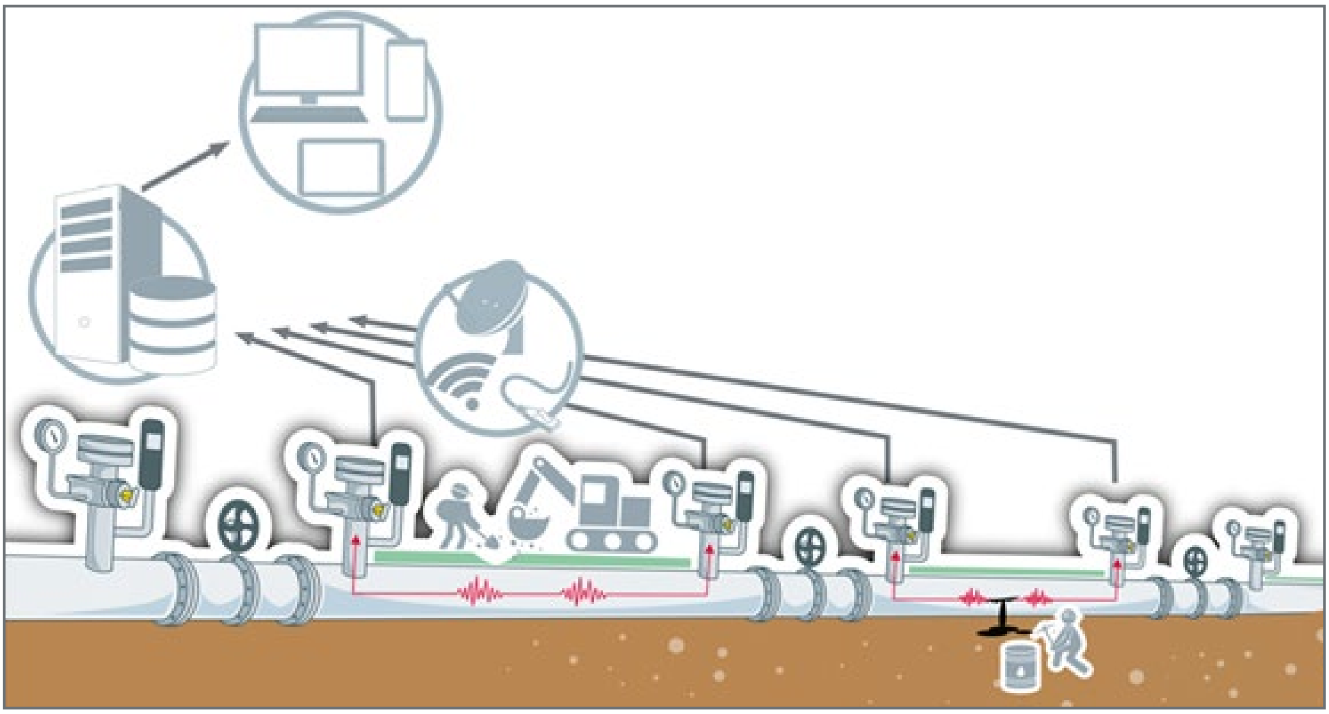

Figure 1: Vibroacoustic Technology Overview. Leakages, impacts, or excavations produce vibroacoustic waves that propagate along the pipeline. The anomaly reaches the sensors and recordings are sent to a central processing unit.

vibroacoustic sensors showing correlation above a pre-defined threshold as a candidate contributing to the TPI alarm, irrespective of the nature of the noise source. To address this challenge, an evolution of the computational system is proposed, with the primary goal of recognizing the nature of the noise source to enhance the efficiency of the VT TPI system during the detection phase.

The key concept involves classifying leak and TPI events based on their vibroacoustic signatures to identify the nature of events responsible for anomalies, i.e., events that differ from background noise. For example, a manual excavation produces a vibroacoustic response characterized by sequences of impulses resulting from shovel and/or pickaxe impacts on the ground. In contrast, the signature of a civil structure experiencing vibrational stress due to rush hour traffic generates wide-band random noise while drilling for irrigation water produces a narrow band of regular noise, and so forth.

Leakages give rise to vibroacoustic transients upon initiation, variation, or extinction, along with a continuous stationary jet noise throughout their duration. In contrast to TPI vibroacoustic signatures, leak signals exhibit such distinct characteristics that an initial filter segregates the data related to leaks and TPI. This segregated data is then directed to each VT detection module, ensuring that distinct information is provided for leak and TPI detection.

The challenge addressed in this work involves categorizing excavations and background noise of TPI vibroacoustic noise through a classification system. The most effective approach is to train an AI engine to recognize these types of vibroacoustic signals and integrate it into the current TPI software module. This enhanced system has the potential to become a versatile and powerful tool for ensuring the integrity of pipeline assets, filling a gap currently absent from the landscape of pipeline integrity monitoring applications.

2. Third Party Interference (TPI): Understand the System

The occurrence of TPI activities, whether or not they result in illicit tapping events, does not follow a universal rule, but typically involves a sequence of steps, including approaching the pipeline, excavation operations, and tapping preparation.

The VT leak detection system is able to detect some tapping preparations and the subsequent leakages. In contrast, the VT TPI system technology is capable of detecting excavation activities, a crucial aspect for effective prevention for buried pipelines. It is fundamental to emphasize that the time-domain and spectral signatures of these signals differ significantly from events caused daily activities, e.g., passage of trains, cars, etc. These distinctive features are crucial in discerning false alarms from real ones, a concept that becomes relevant when discussing convolutional neural networks (CNN).

Acoustic pressure data enables both detection and localization, while the vibrational component, ever-present on the pipeline shell, poses challenges in detection, requiring sensitive equipment and advanced signal processing techniques.

The TPI physical propagation model centers on the mechanical energy generated by ground vibrations, which is transferred to the soil, only then resulting in an elastic wave transmitted to the pipeline fluid and shell. This wave undergoes an acoustic conversion, creating a signal that propagates several kilometers within the pipeline.

There is an exponential relationship between the distance from the noise source to the fluid and the transferred energy quantity. In instances of excavation, mechanical energy is transferred first to the soil, then to the pipe shell, and finally to the fluid, following an exponential model. The maximum energy transfer occurs when excavation is performed on the top of the pipeline. If the energy is strong enough to create vibroacoustic waves that reach at least two sensor blocks, localization is achieved with high accuracy (less than 25m) by means of cross correlation techniques. However, if the vibroacoustic waves reach only one station, precise localization is not feasible, but it is still possible to issue an alarm to notify the pipeline operator of an anomalous event near the sensor block.

2.1 False Alarms Issue

Given the diverse nature of the signals generated and the extensive network of pipelines spanning numerous kilometers across varied environments, the VT

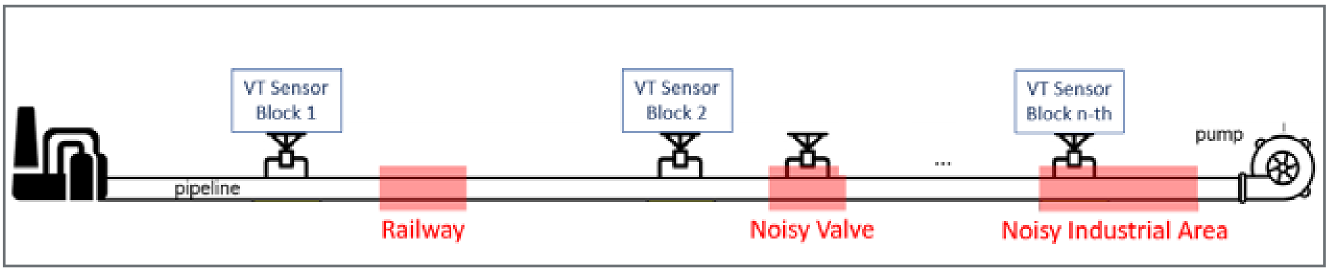

Figure 2: Examples of noise sources on pipelines

TPI system has the capability to discern signals issued from a multitude of sources. These sources may include, but are not limited to, trains, airports, highways, and other entities, as illustrated in Figure 2.

In this scenario, a significant challenge arises in the form of false alarms. To elaborate, signals detected from various sources have the potential to be classified as TPI events, leading to an undesirable influx of false alarms. To address this concern, the system necessitates a classification mechanism capable of discerning and categorizing the detected events. The subsequent section will delve into the adopted solution to mitigate this issue.

3. Introduction of the Classification Problem

The classification problem within the context of image analysis has witnessed significant advancements with the advent of Convolutional Neural Networks (CNNs). Image classification involves the assignment of predefined labels to images based on their visual content, and CNNs have emerged as a groundbreaking solution for this intricate task. Unlike traditional neural networks, CNNs are specifically tailored for grid-like data, such as images, by employing convolutional layers that capture local patterns and hierarchically learn complex features. This specialized architecture enables CNNs to automatically extract relevant features from images, making them exceptionally well-suited for tasks like object recognition and image classification. The transformative impact of CNNs in image classification lies in their ability to reduce the computational complexity of processing visual data, leading to more efficient and accurate recognition of intricate patterns within images.

As a result, CNNs have become a cornerstone in the field of computer vision, powering applications ranging from medical image analysis to autonomous navigation systems. Moreover, the success of CNNs in image classification stems from their ability to preserve spatial hierarchies through multiple layers of convolution, pooling, and fully connected operations. These networks excel at learning intricate spatial representations, enabling them to recognize patterns at varying levels of abstraction. The convolutional layers act as feature detectors, capturing local patterns like edges and textures, while pooling layers progressively reduce spatial dimensions, focusing on the most salient features. The hierarchical structure of CNNs allows them to automatically learn and adapt to the hierarchical nature of visual information in images, enhancing their capacity to distinguish between intricate classes. This adaptability makes CNNs particularly robust when faced with diverse datasets and real-world variations in image content.

The ongoing advancements in CNN architectures, coupled with the increasing availability of large annotated datasets, continue to drive breakthroughs in image classification, setting new benchmarks for accuracy and efficiency in the field of computer vision.

3.1 Our Approach

According to the principles of artificial intelligence in the field of audio processing, the initial image input for the process is constructed through the computation of the Fourier spectrogram from time-domain data that is considered as a real image. A spectrogram serves as a visual depiction of the frequency spectrum of a signal, illustrating how it evolves over time.

Figure 3 displays an example of the three types of possible real events: mechanical excavation, manual excavation and impacts on the pipeline shell. – the data was collected during the test campaigns described in Chapter 5. The CNN model has been trained using this methodology, specifically designed to differentiate genuine events from the noise sources previously described.

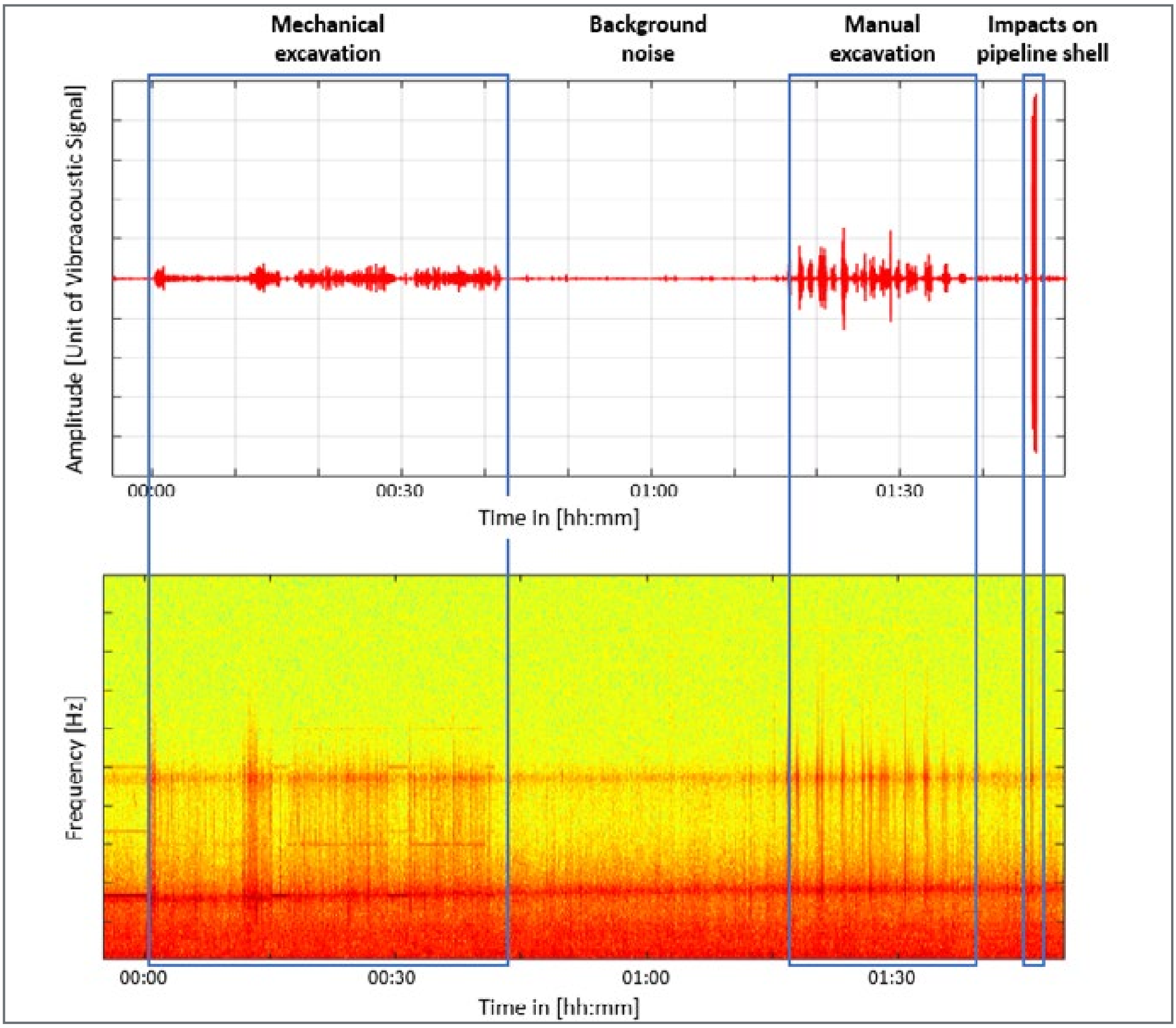

Figure 3: Vibroacoustic data obtained during TPI tests (top) and the corresponding spectrogram (bottom).

4. Test Campaign

This paragraph outlines the details of the test campaigns conducted to gather vibroacoustic data, aimed at comprehensively studying signal propagation beyond the pipeline and the associated energy conversion phenomenon occurring at the pipeline shell. This method enables the identification of channel propagation characteristics critical for understanding the system behavior.

This comprehensive test campaign incorporates tailored experiments designed to simulate authentic TPI events, thereby contributing to the calibration of the system. The tests performed include impacts on the pipeline shell, mechanical and manual excavation (Figure 4), calibrated weight-drop on the ground.

The calibrated weight-drop test (Figure 5) is non-invasive and facilitates the estimation of the energy transference from the ground to the pipeline, ensuring a repeatable calibration process. This device administers a constant amount of energy to the ground through a calibrated weight falling from a standardized height, ensuring precise calibration of the system.

Direct impacts on the pipeline shell were executed to illustrate variations in amplitude recorded by the sensors. This comparison highlights distinctions between noise sources originating directly from activities conducted on the pipeline shell and those initiated on the ground, relying on energy transmission to reach the pipeline shell.

Figure 4: TPI test campaigns. Mechanical excavation (left), manual excavation (center) and impact on the pipeline shell with hammer (right).

A total of three test campaigns were executed, spanning a total of 9 days, involving 28 excavation tests. These comprised 14 manual and 14 mechanical excavations conducted at various points along the pipeline. The outcome is a meticulously saved and annotated vibroacoustic dataset of high quality, poised for application in CNN analysis.

5. Results

This chapter presents a comprehensive analysis of the designed CNN architecture performance through the evaluation of three fundamental metrics: the loss function, the accuracy, and the confusion matrix. The results provide valuable insights regarding the quality of the CNN architecture designed based on the data attained in the test campaigns.

The objective is to be able to classify vibroacoustic data into manual or mechanical excavation to improve issued alarms and reduce false events. The data collected during the test campaigns was properly labeled to include the moments in which the tests were performed. There were 3 labels used: mechanical excavation, manual excavation and background noise.

Classic data augmentation algorithms were performed to created synthetic data based on real data in order to further reduce overfitting and to provide additional data for training the CNN model. The available data was then split into training (60% of the dataset), validation and test sets (20% of the dataset each). The training set is used to train the CNN model, the validation set is used to implement the early stopping the algorithm to avoid overfitting, and the test set is used to evaluate the final model and to ensure the system can generalize the classification.

Figure 5: Calibrated weight-drop tool used to estimate the energy transference from the ground to the pipeline

Upon selecting the CNN architecture, decisions were made regarding the number and type of convolution layers, filters, and the overall sequential structure. These choices were pivotal in defining the ability to capture intricate excavation patterns and features within the data. The comprehensive selection process aimed to create a robust and efficient CNN model tailored to the specific characteristics of our dataset.

In all neural networks, the most critical phase is the training or learning phase, during which the initial network parameters, known as weights, are randomly initialized and iteratively updated. The process of weight update in a neural network involves adjusting the weights of the network based on the error or loss function calculated during training. The loss function, chosen according to a specific application, computes the error between the network predicted outputs and the actual target values. This error is then backpropagated through all nodes of the network, guiding an optimization algorithm - the gradient descent algorithm, the prevailing method for weight updates - to adjust the weights across the entire network.

The loss function evolution during the training process (Figure 6) reveals a gradual decline over training epochs, indicating the increasing proficiency of the model in minimizing discrepancies between predictions and actual values.

Simultaneously, the accuracy graph (Figure 7), defined as the ratio between the number of correct predictions with respect of the total number of samples, depicts a consistent upward trend, affirming the ability of the model to make precise predictions. This upward trajectory in accuracy not only showcases the overall classification power, but also provides a dynamic view of the learning process and the model adaptation to the dataset. Delving further into the accuracy metric, we find that it not only serves as a global performance indicator, but also enables a nuanced understanding of individual class distinctions.

Moreover, both the loss function and accuracy are illustrated for both the training and validation datasets. This enables us to determine the optimal number of epochs and implement an early stopping algorithm to prevent overfitting. Analyzing accuracy per class provides valuable insights into the model strengths and potential areas for improvement across different categories.

The confusion matrix (Figure 8), with its visual representation of true positive, true negative, false positive, and false negative predictions, becomes instrumental in dissecting the intricacies of the model classification outcomes. Identifying areas of misclassification is crucial for refining the model architecture and enhancing its robustness across diverse data instances.

In essence, these results collectively contribute to a holistic evaluation of CNN's classification performance. They not only affirm its effectiveness in capturing overarching patterns but also provide a granular perspective, allowing for targeted improvements. These findings serve as a valuable guide for iteratively refining the model, ensuring its adaptability and reliability in handling various real-world scenarios.

Based on this analysis, it can be affirmed that the training process has exhibited remarkable stability, yielding an impressive accuracy of 99.63% on the test dataset. This high accuracy has, in turn, contributed to the exceptionally robust performance of the VT TPI system. It excels not only in the precise classification of excavation events but also in mitigating false alarms arising from various noise sources that collectively contribute to the overall background noise.

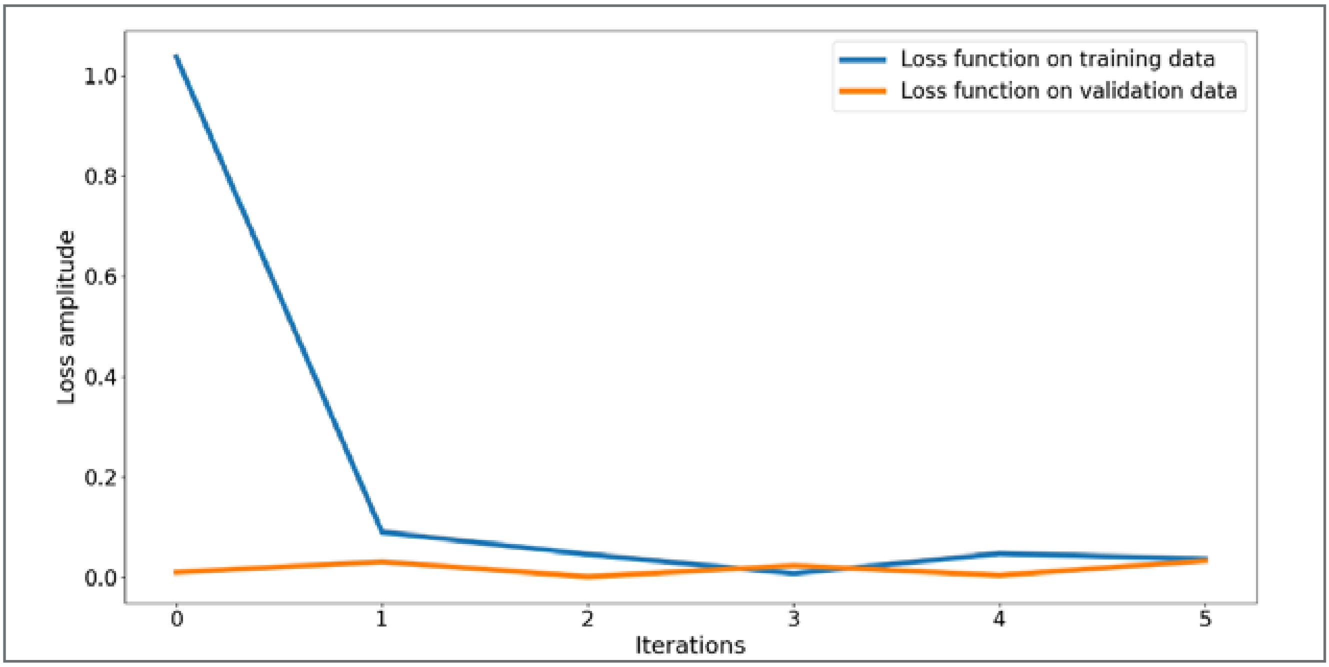

Figure 6: Iterative loss function. The gradual decrease in training data and the consistently low values on validation data indicate the growing proficiency of the model.

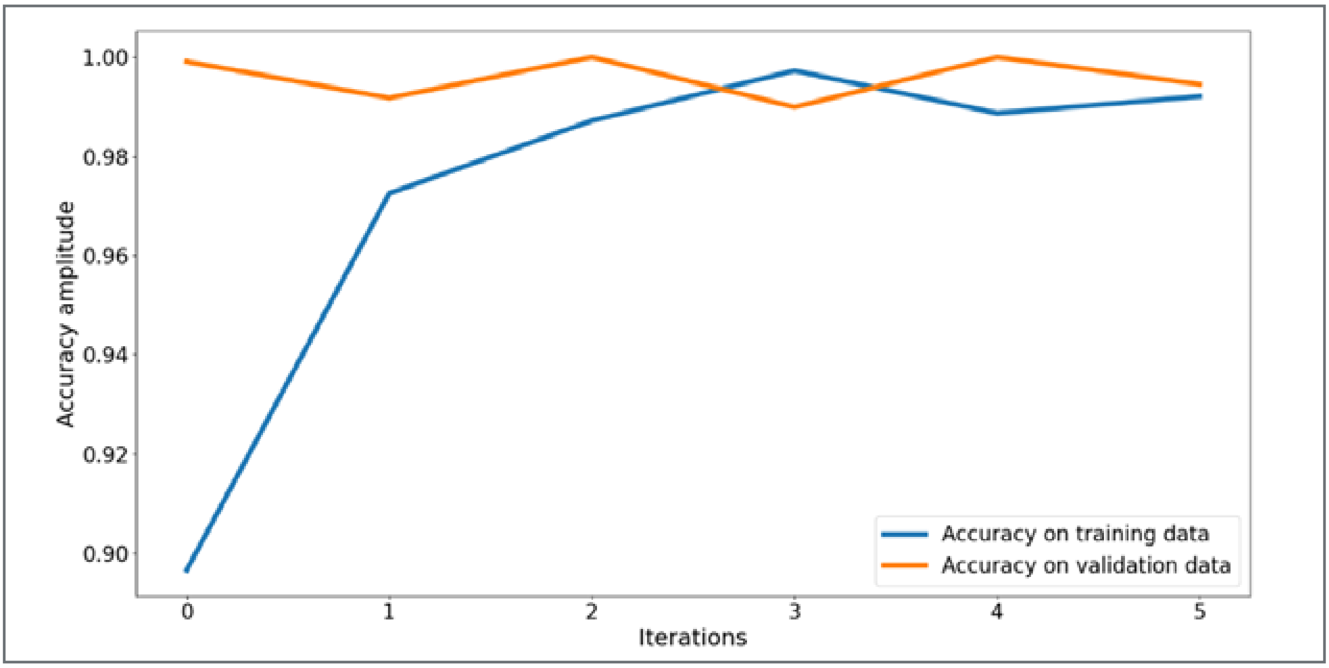

Figure 7: Iterative accuracy of the model. The gradual increase in training data accuracy and the consistently high values on validation data affirms the ability of the model to make precise predictions.

6. Final Remarks

Vibroacoustic Technology is a cost-effective and efficient approach for promptly detecting leakages and TPI incidents in real-time. It can be conveniently retrofitted to existing pipelines, offering an extensive event detection capability and support for pipeline operations with a minimal number of sensor blocks installed every few kilometers. This flexibility also extends to challenging environmental and remote scenarios, strengthening its suitability for installation in various conditions.

The installation of VT sensor blocks, and the test campaigns were successfully executed without any health, safety, and environmental (HSE) incidents. The authors extend their gratitude to the local teams for their support in conducting comprehensive test campaigns. The vibroacoustic data gathered was of utmost importance for training the CNN model.

The viability of this approach, incorporating an AI engine trained to identify and categorize TPI events and leaks, centers on the distinct vibroacoustic signatures associated with each activity. The first step involved segregating vibroacoustic data likely to contain leak signatures from data containing TPI signatures. This partitioned data is then directed to specific VT detection modules, ensuring that unique information is utilized for the detection of both leaks and TPI events.

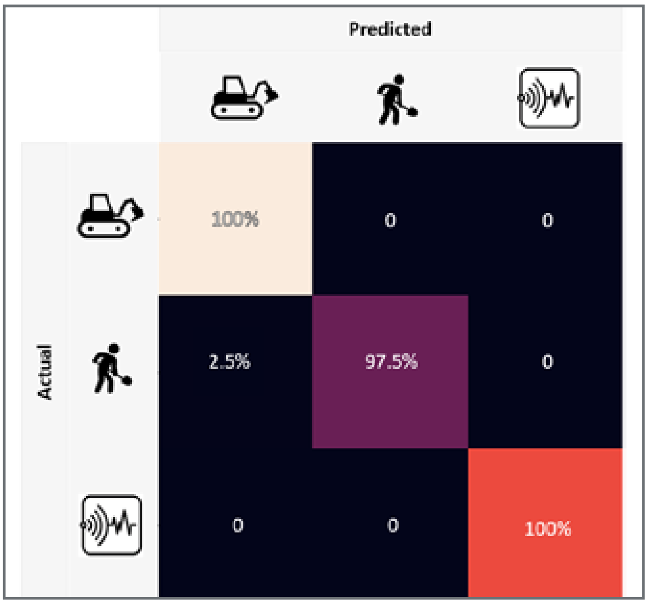

Figure 8: Confusion matrix of test dataset (mechanical excavations, manual excavations and background noise)

Regarding the labeling of the diverse TPI sources, the developed CNN model has delivered remarkable results, achieving an outstanding accuracy rate of up to 99.63%. This elevated accuracy contributes to the establishment of a highly reliable and robust VT TPI system. One key advantage of this enhancement is its heightened performance in detecting authentic TPI activities. By effectively eliminating sources of noise, such as railways, highways, industrial plants, etc., from the processing, the system significantly reduces the occurrence of false alarms.

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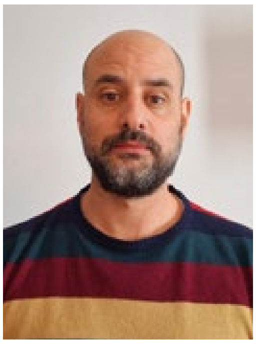

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From Pipelines to Home Heating: The Digital Transformation of Natural Gas Distribution

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Abstract

The distribution of natural gas through Istanbul's pipelines requires the control of temperature, pressure, draft, consumption, and composition to securely reach 16 million people. The digitalization journey begins at the gas takeover points and extends to the combi boilers of residents. SCADA is integrated into all regional and central metering stations, facilitating seamless communication and generating extensive data on gas behavior. Smart meters monitor natural gas consumption and velocity, collecting precise data from households for detailed analyses. By using this vast data for future predictions, management and optimization of the gas distribution network, AI could usher in a new era of data-driven technologies in natural gas distribution. From the pipelines to residents, the journey of natural gas is meticulously tracked, enhancing operational efficiency and paving the way for more intelligent systems in gas distribution management.

1. Introduction

Ensuring the safe distribution of natural gas to more than 16 million end-users in Istanbul requires meticulous control of gas flow from the takeover points to the homes of the residents. This complex network spans approximately 25,000 km of pipelines across the city, featuring two main regulating stations (RMS\A) on either side of Istanbul and over 800 regional regulating stations (RMS\B) represented at figure [1].

There are five main parameters to track to ensure the safety of the gas: temperature, pressure, draft, consumption, and composition. Temperature defines the gas temperature, while pressure relates to the gas pressure, which is regulated at the front and the back of the regulating stations. Draft and consumption are directly related to the gas speed and flow, which also affect temperature through the Joule-Thomson effect—a thermodynamic phenomenon where the temperature of a gas changes as it expands or is compressed without exchanging heat with its surroundings. Natural gas primarily consists of methane (CH_4), along with smaller amounts of ethane, propane, butane, nitrogen, carbon dioxide, hydrogen sulfide, and water vapor. Our gas chromatographs are set to release approximately 95% methane, blended with sulfur-containing odor chemicals, just before leaving the RMS/A.

Digitalization has become a necessity to control and track all these parameters simultaneously to understand the entire system in operation. Besides real-time monitoring, this data can be recorded hourly at each and every regulating metering station for all the aforementioned parameters.

Within İGDAŞ, digital tracking, monitoring, and data accumulation are carried out using two main tools. From the takeover point to homes, processes are managed by SCADA (Supervisory Control and Data Acquisition), while in homes, they are managed through the pilot use of smart meters.

2. Integration of SCADA

The Supervisiory Control and Data Aquisition (SCADA) Center, considered the brain of İGDAŞ, collects real-time data from 3,400 instruments on Istanbul's steel and polyethylene lines, totaling 350,000 data points.

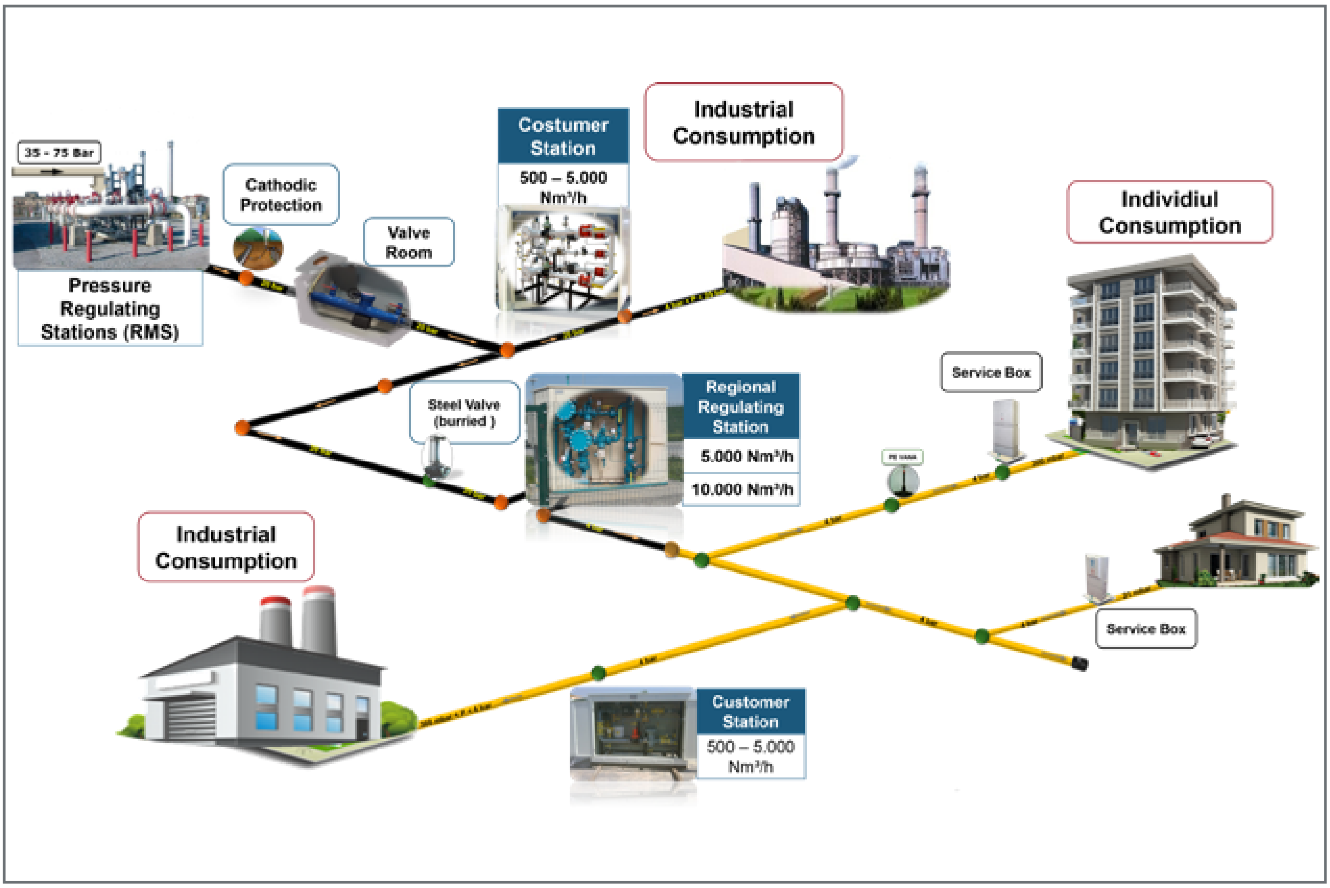

Figure 1: General Scheme for Natural Gas Distribution Elements

Figure 2: SCADA Control Room

Data is received instantly from RMS/A stations and every five minutes from other instruments. This data is used for various purposes, including reading, reporting, and archiving measurements and alarms, and remotely stopping gas supply for security. Through Remote Terminal Units (RTU) at pressure reduction and metering stations, crucial signals like inlet-outlet pressures, consumption data, and valve positions are transmitted to SCADA. Monitoring this integrated system generates alarms for immediate issues such as natural disasters, fires, malfunctions, and gas leaks, which are then handled by relevant units. Continuous service is provided based on information from the ALO 153 Solution Center and the 187 Natural Gas Emergency Line. This entire system is managed by the SCADA control room, as shown in Figure [2].

Before the implementation of SCADA, Maintenance and Network Superintendencies manually collected data from instruments at regular intervals throughout the day, with no alarm systems in place. Issues like gas outages and filter blockages were detected via the 187 emergency line or during periodic inspections. Now, with remote reading and automatic alarm transmission, superintendencies only check instruments when anomalies occur, leading to significant improvements in operational processes and cost reductions. SCADA data informs various functions: the Survey and Project Directorate uses it for investment planning simulations, the Gas Procurement Superintendency makes gas purchase decisions, and the Commercial Services Directorate remotely bills certain customer stations. The Cathodic Protection Superintendency analyzes its system, Maintenance Superintendencies enhance operations, the Disaster Management Superintendency remotely resets SI sensors at 832 Regional Regulators, RMS Operations Superintendencies monitor RMS/A data via local SCADA systems, and the Internal Installation Directorate benefits from customer Q_{min} and Q_{max} data.

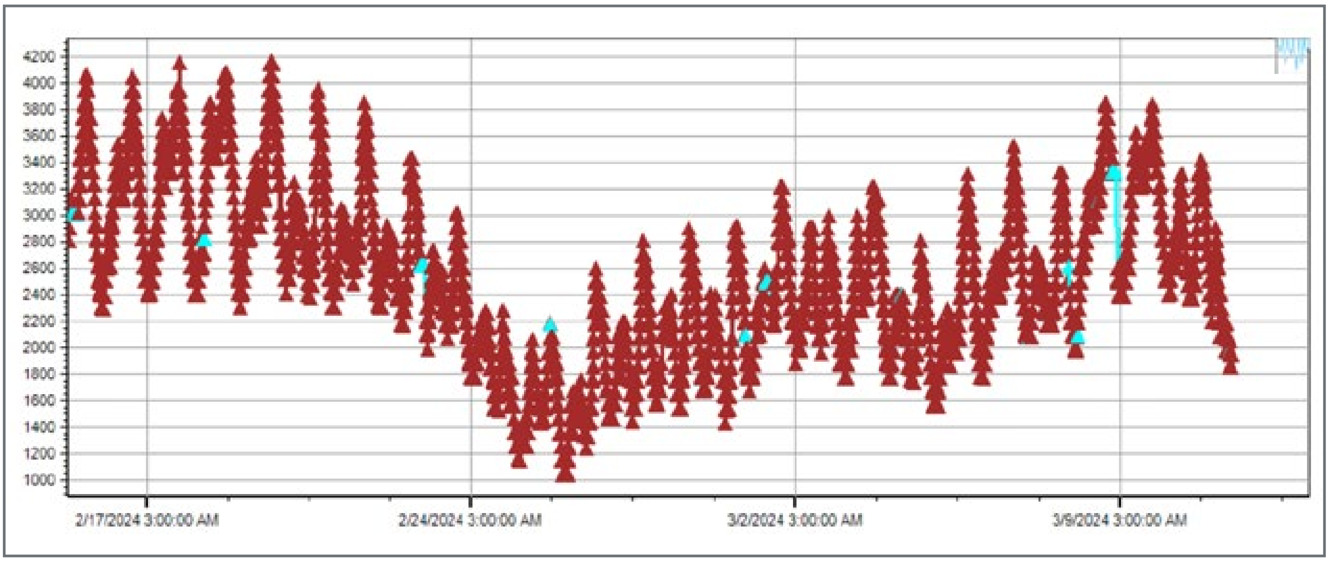

Figure 3: Gas flow trend for february-april 2024 –representative data

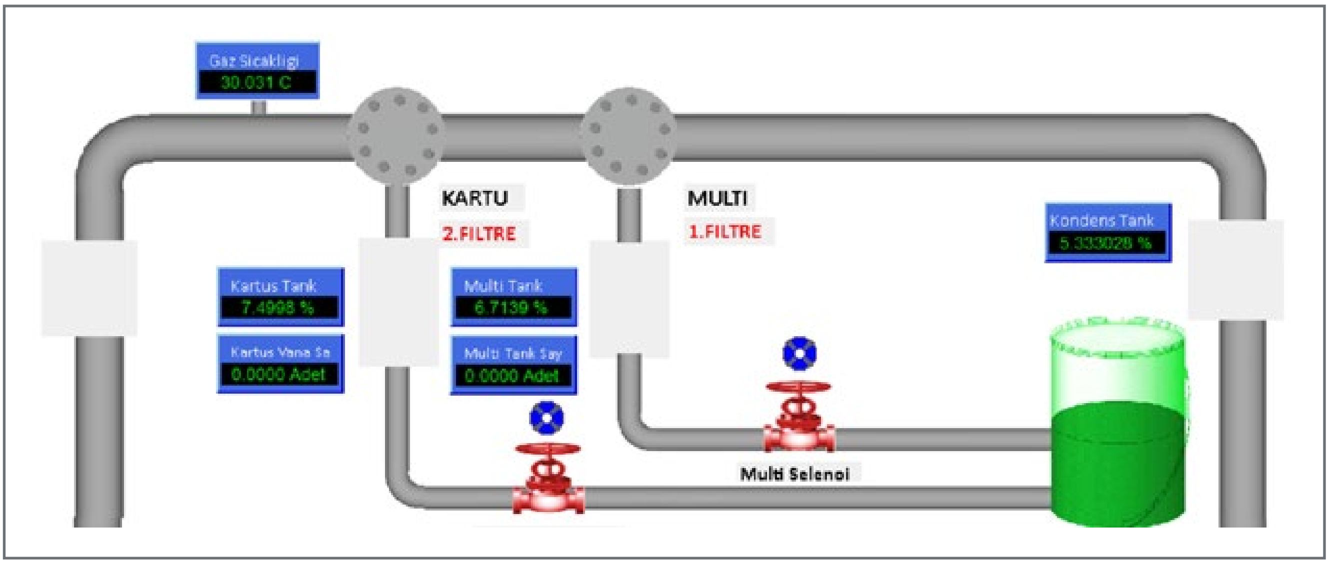

Figure 4: Regional Regulating Station for condensate accumulation and its SCADA view

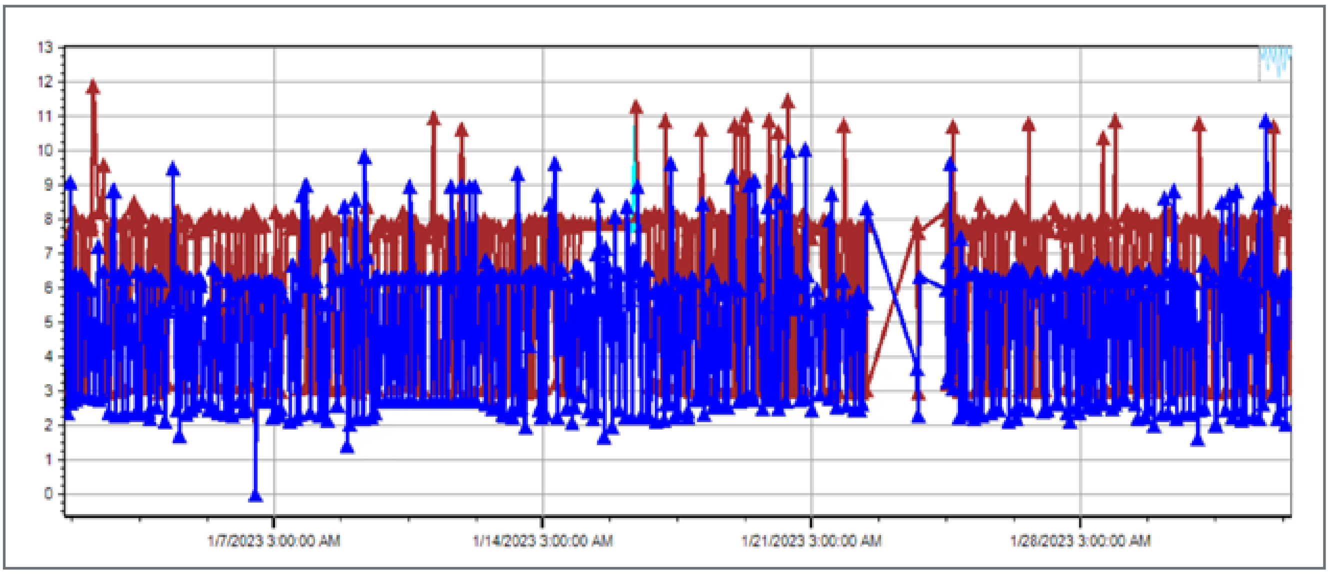

Figure 5: Odor fluctuations within the natural gas-representative data

The Research and Development department benefits from SCADA data to monitor gas conditions and compositions, allowing them to identify problems and potential solutions. The system enables us to chart trends in gas behavior at each main and regional regulating station. Representative data for gas flow between february and april-2024 is indicated at Figure [3]. One intance is the ability to visualize and track the accumulation of condensate, particularly at low allocation points within Istanbul. Condensate formation occurs due to sudden changes in gas temperature and pressure, leading to the accumulation of heavy hydrocarbons (C6+) within the gas stream. SCADA is integrated into the condensate accumulation regional regulation station, allowing us to track and evaluate the possibility of condensate occurrence with respect to various parameters such as temperature, pressure, and flow as shown at Figure [4].

Another example is the issue of odor within the gas composition. Odor fade is a phenomenon that occurs due to absorption on the surface of the pipelines or chemical reactions involving the contents of natural gas. TBM/THT is expected to be 70%/30% per 10 mg/sm³ concentration within the natural gas flow stream. Fluctuations in their concentrations are monitored at seven different points within Istanbul and two of them is indicated at Figure [5]. When the concentration falls below the threshold, an alarm system on the SCADA screen alerts the maintenance department.

Both of these examples illustrate the role of SCADA in ensuring the safety of natural gas during its journey to homes. Following the meticulous monitoring and control at the pipeline level, the next crucial step in digitalization involves the integration of smart meters with the SCADA system. This integration not only enhances real-time data acquisition but also ensures a seamless and secure delivery of natural gas to homes. Through this combined approach, both the broader network and individual household consumption can be effectively managed.

3. Artificial Intelligence and Data Analytics in SCADA Integration

Effective management of natural gas distribution networks is crucial for energy security, supply-demand balance, and sustainability. Artificial intelligence offers new opportunities for optimizing these networks, playing an increasingly important role in demand forecasting, anomaly detection, energy efficiency, and distribution optimization.

Natural gas demand forecasting with artificial intelligence can be applied for various periods and these forecasts can cover short-term (hourly or daily) and long-term (monthly or annual) periods. Forecasts can be performed using various machine learning and statistical methods such as linear regression (LR), random forest regression (RFR), artificial neural networks (ANN) and support vector regression (SVR). For data sets such as historical natural gas consumption data, temperature forecasts, seasonal variables, population information and natural gas prices can form the basis of these forecasts. Natural gas demand forecasts can be diversified depending on the data sets and methodology used and can be applied by selecting the most appropriate methods in line with the needs. Such models have the potential to increase efficiency in energy management and logistics processes. In addition, a study found a high negative correlation of -0.89 between natural gas demand and outdoor temperature, indicating that gas demand increases as temperatures drop (Hribar et al., 2018). This finding suggests that weather forecasts can play a critical role in natural gas demand forecasts. Artificial intelligence models have significant potential to more accurately predict future weather conditions by processing complex weather data. These forecasts can be integrated into natural gas demand projections, increasing efficiency in energy management.

Datasets used to detect anomalies in natural gas distribution include data from various sources, such as pipeline pressure data, flow rate, temperature, consumption patterns, and weather data, as well as time series data. This data is used to train artificial intelligence models. Datasets are usually created by simulating normal and abnormal situations, and models are trained with this data. Anomalies are detected by the models, while deviations from normal and unexpected changes are analyzed (Zheng et al., 2022). In this process, machine learning algorithms learn past data patterns and identify deviations from these patterns. Thus, anomalies such as leaks, pressure drops, and unusual consumption increases in pipeline systems can be detected quickly and accurately. These methods increase safety in natural gas pipeline systems and minimize economic losses and environmental damage.

The optimization process in natural gas pipelines involves analyzing large amounts of data collected from various sources, such as SCADA systems, sensors, maintenance records, and environmental data. Artificial intelligence algorithms can analyze these large data sets and provide insights in areas such as pipeline capacity planning and maintenance scheduling. For instance, smart pipeline inspection enables proactive maintenance by identifying problems such as corrosion, cracks, or deformations, while predictive maintenance solutions play a critical role in preventing failures and increasing operational efficiency by predicting potential failure points (Saboo, 2024). Smart route planning and capacity optimization determine the most efficient routes by taking into account demand forecasts, geographical barriers, and environmental constraints.

Artificial intelligence techniques provide significant benefits in areas such as demand forecasting, fault detection and energy efficiency by enabling the optimization of these networks. Demand forecasts using historical consumption data and weather forecasts improve energy management. With applications such as anomaly detection and network optimization, artificial intelligence increases safety and reduces economic losses, thus providing more efficient and sustainable solutions in natural gas distribution.

4. Smart Meters, Digitalization at Home Heating

Smart meters are digital devices capable of monitoring natural gas consumption with high precision and in real-time. These meters not only measure gas consumption and flow rates but also transmit the collected data to a central system for analysis.

4.1 Operating Principle and Data Management of Smart Meters

Smart meters play a crucial role in gas distribution systems and come pre-equipped with integrated modules, simplifying the installation process. SIM cards necessary for communication are installed at the factory, enhancing the meters' real-time data provision capabilities. These battery-operated meters ensure continuous and reliable operation, providing instant alerts in case of any anomalies or tampering. Sensors monitor the passage of gas through the meter and calculate consumption amounts. Data is processed by the microprocessor and transmitted to a central system at regular intervals, allowing users and operators to access and analyze historical consumption data.

The IoT portal serves as a central repository for all collected data. This platform uses a scalable data storage architecture to handle growing IoT data. Modern database technologies offer high availability, backup, and disaster recovery capabilities. Security measures, such as encryption, access controls, and audit logs, are implemented to protect data integrity and confidentiality. The IoT platform collects, processes, and analyzes data from smart meters in real-time. Collected data is analyzed through SQL queries or custom scripts to provide insights into user consumption habits, system performance, and potential fraud activities.

The data analysis component of the IoT platform utilizes advanced analytics and machine learning algorithms to derive patterns and insights from processed data. This process includes statistical models, predictive analytics, and data mining techniques. Various machine learning models are employed for applications such as fraud detection (e.g., One-Class SVM and LSTM models), load profiling (e.g., ARIMA and CNN models), demand forecasting (e.g., Linear Regression and XGBoost models), and predictive maintenance (e.g., RUL prediction and RNN models). These techniques assist gas distribution companies in improving their operations and delivering better services.

The IoT platform takes extensive measures to ensure data security and privacy. Encryption is used during data transmission, and unauthorized access is prevented. Only authorized users are permitted access to data, with regular audits conducted. Various security controls are applied during data storage, transmission, and usage. Data transmission is secured using TLS/SSL protocols or IPsec VPN. Disk encryption and endpoint security applications are used during data utilization. Additionally, necessary measures are taken to comply with personal data protection laws.

Regular backups are performed during data retention, and backups are encrypted. Disk encryption ensures secure data storage. The IoT platform collects, processes, and analyzes data from smart meters in real-time, providing insights into user consumption habits, system performance, and potential fraud activities. Additional security measures, such as access controls and audit logs, are implemented to protect data integrity and confidentiality.

AI and ML platforms play a critical role in data collection from IoT portals. These platforms provide a layer for data processing, visualization, and querying. The AI-based analytics engine analyzes consumption patterns, detects fraud activities, and helps users reduce energy usage. It also provides data for decision support systems, performs predictive maintenance, and optimizes network performance. This platform offers a standardized interface for data access and analysis from IoT portals, facilitating project participants' ability to interact with and analyze data.

4.2 Creation and Use of Different Consumption Profiles

Smart meters collect data on natural gas consumption on a daily, weekly, and monthly basis. This data is analyzed in a central system and categorized into segments such as low, medium, and high consumption users. This segmentation allows for understanding and optimizing energy consumption behaviors. Consumption profiles help in developing energy efficiency strategies and creating customized billing plans. They are also used to predict future energy demand and for planning purposes. Users can analyze and improve their habits through a platform that allows them to track their consumption. These processes are crucial for optimizing energy consumption behaviors and using energy resources more efficiently.

For this reason, data collected in the pilot project has been segmented into various categories: User Consumption Data (daily, weekly, and monthly consumption, peak and low usage periods, seasonal variations), Geographical Data (urban vs. rural consumption, regional habits and infrastructure), Demographic Data (age, income, household size, lifestyle for personalized services), Sensor and Device Data (real-time data from smart meters, meter status, anomalies), and Environmental Data (weather, temperature changes affecting consumption forecasts). These segments help create and utilize different consumption profiles, illustrating their significant impact.

4.3 Detection of Gas Leaks, Unauthorized Usage, or Abnormal Consumption Situations

One of the biggest challenges in gas distribution systems is detecting gas leaks, unauthorized usage, and abnormal consumption situations. As a gas distribution company serving 16 million customers, we utilize smart meters and AI-based platforms to address these issues. Smart meters continuously monitor and analyze gas consumption and flow rates in real-time. This allows for the immediate detection of any anomalies and rapid intervention. These systems significantly contribute to enhancing safety and efficiency, improving operational performance.

Smart meters are equipped with sensors that continuously monitor gas consumption and microprocessors that process this data. These sensors measure the flow rate, pressure, and total consumption of the gas, transmitting the data to a central system. Data analysis is used to detect possible fraudulent activities and abnormal consumption situations in the system. For instance, an unexpected increase or decrease in gas consumption could be an indicator of fraud or unauthorized usage.

Gas leaks can pose serious safety hazards. Smart meter data can detect leaks by monitoring sudden drops in consumption patterns. Data from the sensors, which monitor gas flow and pressure, trigger alarms in the event of sudden and unexpected changes. These alarms detect anomalies in the system and notify the central system. When a gas leak or abnormal consumption situation is detected, the central system quickly intervenes and takes the necessary safety measures. The collected data is continuously analyzed by the central system. Sensor data monitors gas flow, pressure, and consumption, providing instant alarms for any anomalies. These alarms are promptly communicated to central system operators and users.

4.4 Pilot Project and Advanced Data Analytics Techniques

Currently, we are conducting a pilot project involving approximately 2,500 smart meters across three different regions in Istanbul. In these trials, we use NB-IoT and LoRaWAN technologies for data transmission. Additionally, we are testing 5G network slicing technology to create flexible and efficient network segments for various applications. This pilot project aims to investigate how smart meters and advanced data analytics techniques can be utilized in energy management. Below, the analysis and application of this project in four main categories are detailed. With the foundational systems in place, we are now exploring the next phase through a pilot project focused on advanced data analytics and smart meter technology.

4.5 Fraud Detection

The IoT platform employs advanced machine learning models for fraud detection. These models are designed to identify anomalies in consumption patterns and detect potential fraudulent activities. Specifically, the One-Class SVM (Support Vector Machine) model learns normal consumption patterns and detects deviations from these patterns. LSTM (Long Short-Term Memory) models analyze time-series data to identify anomalies. These techniques allow for early detection of fraudulent activities, enabling rapid intervention and preventive measures.

4.6 Load Profiling

Load profiling involves analyzing users' gas consumption patterns to create different consumption profiles. This analysis helps understand and optimize users' energy consumption habits. Models such as ARIMA (AutoRegressive Integrated Moving Average) and CNN (Convolutional Neural Networks) provide short- and long-term consumption forecasts by analyzing consumption data. This profiling is crucial for energy management and optimization as it allows energy distribution companies to better manage demand fluctuations.

4.7 Demand Estimation

Demand estimation encompasses a range of techniques and models used to forecast future energy demand. Models such as Linear Regression and XGBoost predict future demand based on historical consumption data. Time-series analysis techniques like Exponential Smoothing and Holt-Winters provide more accurate forecasts by considering seasonal variations and trends. Accurate demand forecasts help optimize energy production and distribution planning, ensuring sustainable and efficient management of energy supply.

4.8 Predictive Maintenance

Predictive maintenance is an approach used to anticipate equipment failures and optimize maintenance processes. Prognostic Health Management (PHM) techniques and RUL (Remaining Useful Life) predictions are used to forecast when equipment may fail. Models such as RNN (Recurrent Neural Networks) continuously analyze sensor data to identify anomalies in equipment performance and predict potential failures. This allows gas distribution companies to proactively manage maintenance processes, preventing unexpected failures and outages, and enhancing operational efficiency. This pilot project represents a significant step in investigating and implementing innovations in the use of smart meters and advanced data analytics techniques for energy management.

5. SCADA & Smart Meters Integration and Future Prospects

The IoT-based data management framework has successfully met current requirements and is well-positioned to tackle future challenges. Future integration of new analytical tools and machine learning models could further enhance predictive capabilities, while additional data sources will improve prediction accuracy and provide deeper insights.

Integrating SCADA systems with IoT platforms is crucial for the future of gas distribution. SCADA's extensive monitoring and control capabilities, combined with IoT data, will enhance real-time analysis and decision support. This integration will allow more detailed and instant monitoring of gas consumption patterns, flow rates, and other critical parameters.

Looking ahead, the SCADA-IoT integration will boost efficiency, security, and sustainability in energy management. With growing cybersecurity threats, advanced measures like encryption and access controls will be vital to maintaining data integrity and privacy.

This approach will create a more resilient and sophisticated energy management system, delivering long-term benefits to users and infrastructure operators. It will also lay the groundwork for smarter, more flexible solutions in the energy sector, shaping the future of energy management.

6. Acknowledgment

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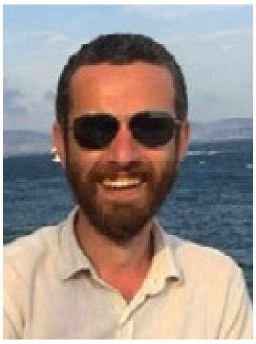

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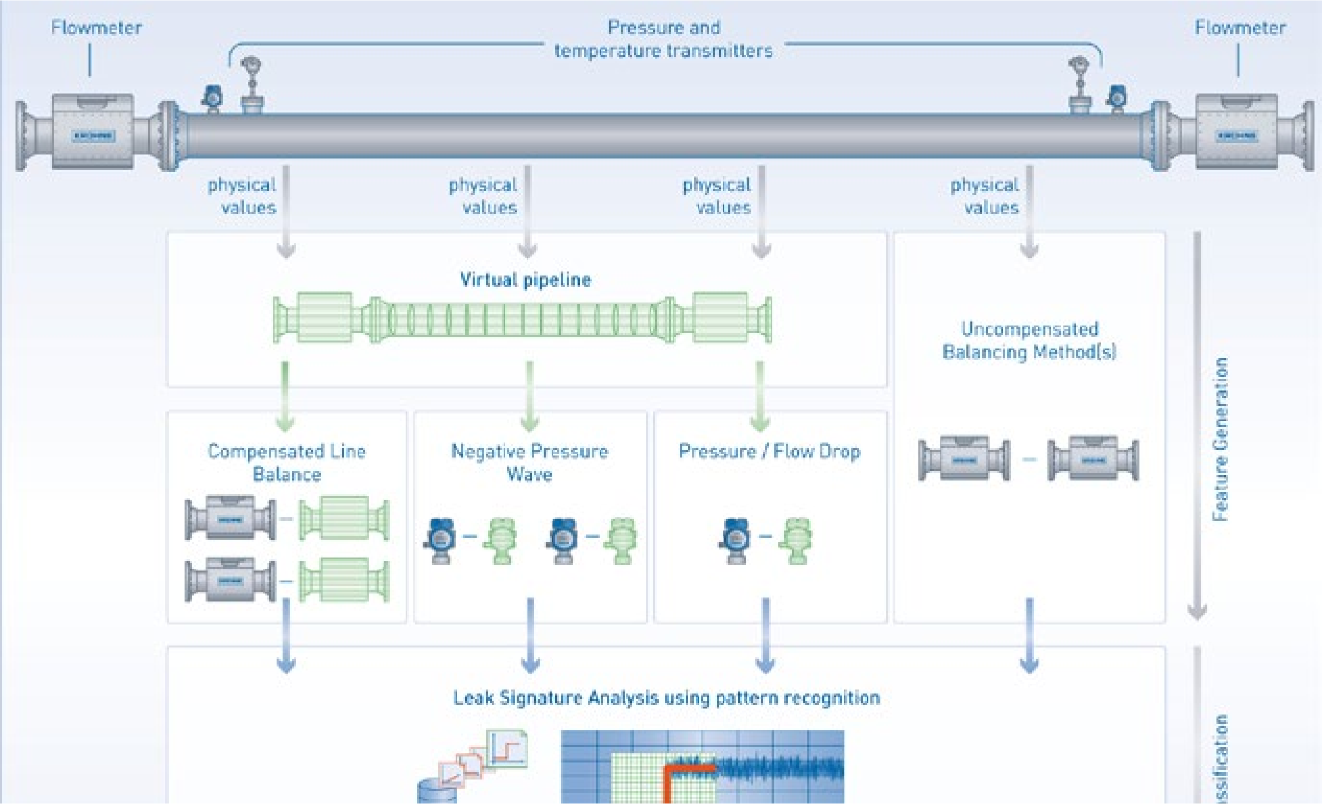

How to select the right Leak Detection Methods to cover Legal and Operational Requirements

M. IHRING, D. VOGT > KROHNE SOLUTIONS

Abstract

Leak detection systems are a crucial part in pipeline safety. Unfortunately, general knowledge about these systems is still limited. Due to advantages and limitations of single leak detection technologies the selection process can be difficult – especially when regulation and different operating scenarios have to be considered. Single methods might work well for some standards, regulations and specific operating scenarios while not covering others.

The paper shows how different leak detection methods can be used to fulfil the requirements of regulations and standards such as German TRFL (Technical Rules for Pipelines) or API 1130. The different requirements and special features of these applications for leak detection are described. Furthermore, it also describes how different leak detection technologies can be applied so that pipeline operation during changing operating scenarios such as steady-state, transient or shut-in operation is monitored allowing leak detection during all operating conditions. This is shown by presenting a real project example. Finally, a systematic approach for the leak detection method selection is presented considering application, operational and legal requirements.

1. Introduction

Leak detection systems are a crucial part in pipeline safety. Unfortunately, general knowledge about these systems is still limited. Due to advantages and limitations of single leak detection technologies the selection process can be difficult – especially when regulation and different operating scenarios must be considered. Single methods might work well for some standards, regulations and specific operating scenarios while not covering others.

Different leak detection methods can be used to fulfil the requirements of regulations and standards such as German TRFL (Technical Rules for Pipelines) or API 1130.

The "Technical Rules for Pipelines" (German: TRFL) are published by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. TRFL is consolidated from three former regulations:

- Regulation for pipelines transporting dangerous liquids (TRbF 301: Richtlinie für Fernleitungen zum Befördern gefährdender Flüssigkeiten)
- Regulation for pipelines transporting products dangerous for water (RRwS: Richtlinie für Rohrleitungen zum Befördern wassergefährdender Stoffe)
- Technical rules for high pressure gas pipelines (TRGL: Technische Regeln für Gashochdruckleitungen)

They were originally intended only for applications within the German federal territory, but now they provide a model for other national regulations.

The requirements of TRFL cover all operating conditions of the pipeline when it comes to detection of leaks. Two continuously operating technical processes based on different physical variables are required that can detect leaks in the steady state. One of these methods, or an alternative method, must also detect leaks in transient operating conditions. The rules also require a process that can detect leaks during standstill conditions (paused flow or shut-in) as well as a process that detects gradual leaks. Finally, the rules also require a process for leak localisation.

On top of regulatory requirements is that pipeline leak detection systems should be selected based on the application and operation of the pipeline. While some methods only work during single operating scenarios, different leak detection technologies can be applied so that pipeline operation during changing operating scenarios such as steady-state, transient or shut-in operation is monitored, thus allowing leak detection during all operating conditions. This can be achieved by combining methods in one common overall monitoring system.

2. Selection of different leak detection methods to cover legal and operational requirements for a pipeline distribution network according to TRFL

In a distribution network for benzene with three participants it was required to have a continuous monitoring under all operating conditions in accordance with

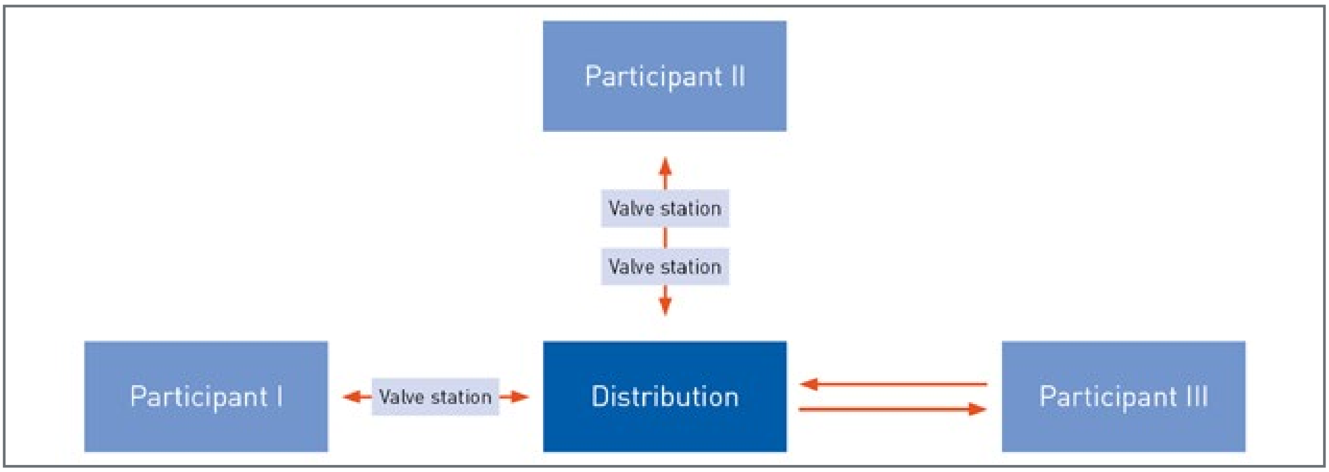

Figure 1: Distribution network for benzene with 3 participants

TRFL. These included the steady-state operation, the transient operation, standstill operation, completely or partially blocked lines and the detection of gradual leaks. In total the pipeline was operated in 12 different operating scenarios.

The regulatory and operational requirements for the detection of leaks were fulfilled by using a multi-method approach. This was achieved by implementing a horizontal combination of methods according to the requirements of TRFL. On top of that a vertical combination of methods using model calculations and leak signature analysis with pattern recognition was implemented to improve the sensitivity of the system and avoid false alarms. Due to this approach, it is possible to achieve detection times in minutes.

This approach does not only improve sensitivity and robustness, but also allows better individualisation and optimisation to the applications. Furthermore, it allows individual redundancy concepts and an optimal adaption to the operator environment due to the selection of the best matching methods for the application.

In the application the methods E-RTTM, E-NPW, statistical line balance, tightness monitoring using a pressure-temperature-method, gradient intersection method and extended negative pressure wave method were combined in one common overall system. E-RTTM was implemented as one of two continuously operating technical processes that detects leaks in steady-state operation. It also covers the requirements for detecting leaks in transient operation.

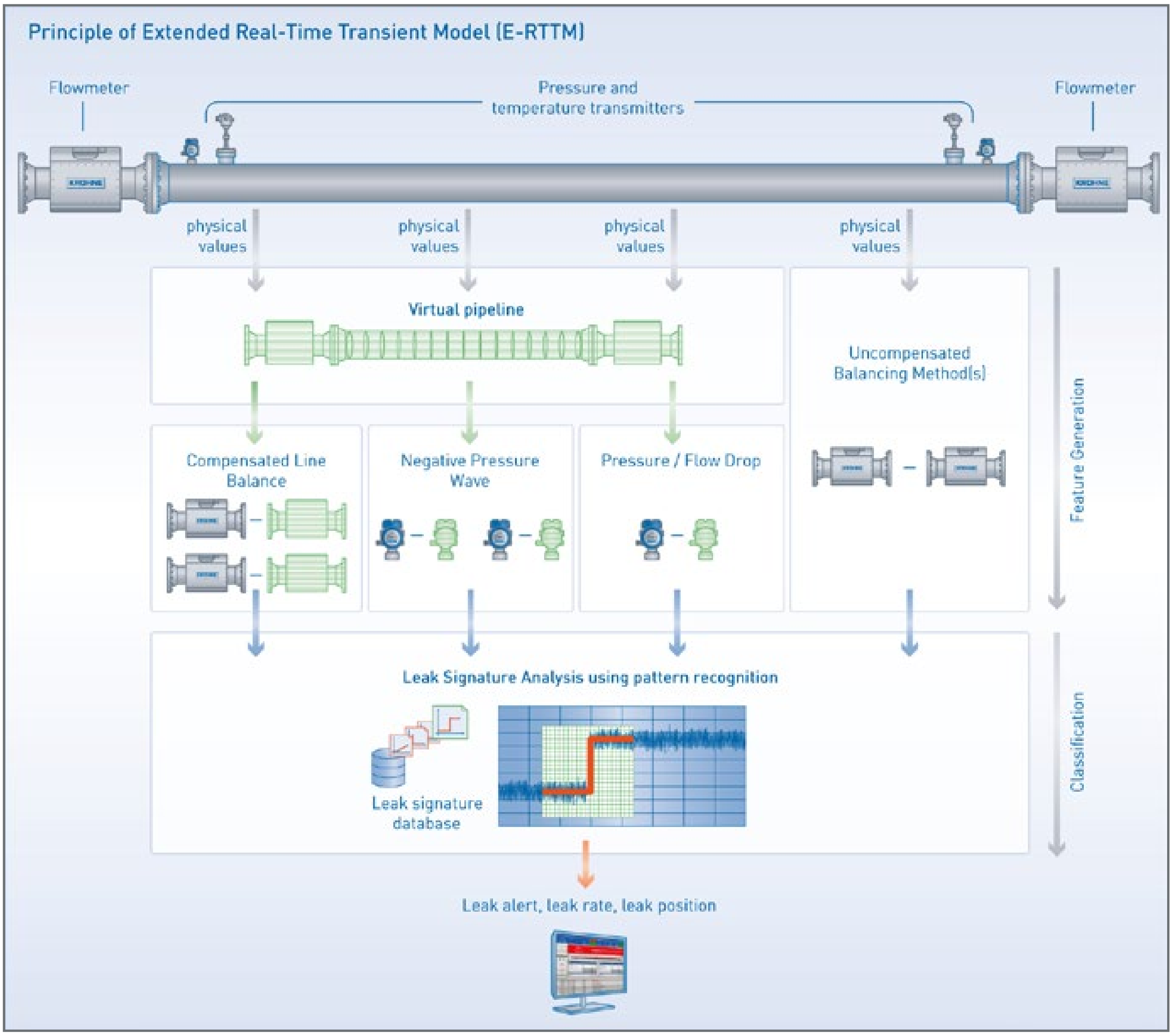

Figure 2: Horizontal and vertical combination of pipeline leak detection methods

E-RTTM stands for Extended-Real Time Transient Model, which extends a feature generation module with leak signature analysis using leak pattern detection. It is a model-based method improved by the classification in accordance with 1.2.2 of Annex VIII to the TRFL. An E-RTTM leak detection system creates a virtual image of a pipeline based on measured data. Measured values from flow, temperature and pressure sensors installed at the inlet and outlet of the pipeline and along the pipeline in places such as pump and valve stations are crucial. The flow, pressure, temperature and density at each point along the virtual pipeline are calculated from the measured pressure and temperature values. The model compares the calculated flow values with the actual values from the flow meters. If the model detects a flow discrepancy, the leak signature analysis module then determines whether it was caused by an instrument error, a gradual leak or a sudden leak.

Pattern recognition techniques can significantly enhance pipeline leak monitoring systems through the application of artificial intelligence (AI). The leak detection system based on E-RTTM exemplifies this approach by continuously recording vast amounts of data from the pipeline. This data includes various parameters such as flow rates, pressure levels, and temperature variations, which are crucial for identifying potential leaks. By categorizing this information, the E-RTTM system provides a structured dataset that facilitates the system's self-learning capabilities. The latest versions of such system use InfluxDB, a high-performance time-series database, to store this data efficiently.

InfluxDB's ability to handle large-scale data storage and rapid querying makes it an ideal choice for managing the vast and continuously growing datasets generated by pipeline monitoring. The AI leverages this data to identify patterns and anomalies that may indicate leaks, thereby improving the accuracy and efficiency of leak detection over time. This integration of pattern recognition with AI enables proactive maintenance and reduces the risk of undetected leaks, ensuring the safety and integrity of pipeline operations.

E-RTTM provides a high degree of sensitivity and quick leak detection with real-time comparison of existing measuring results against leak signatures, which are stored in a database. Comparing of measured values with the leak signatures is also critical to the reliability because it provides a high degree of protection from false alarms. E-RTTM-based leak detection systems can handle transient conditions that are not recognised by less sophisticated internal leak detection systems. An E-RTTM-based leak detection system works with dynamic values, which also boosts robustness, the system becomes independent of the absolute accuracy of the virtual pipeline. It can adapt automatically and very quickly to changes in the operating conditions such as sensor failure, communications failure, a valve closing or a product change in the pipeline making it robust against transient operation.

E-NPW stands for Extended Negative Pressure Wave. It is a pressure wave method improved by a model and classification in accordance with 2.1 of Annex VIII to TRFL that fulfils the requirement to detect leaks during standstill operation during shut-in conditions. It also provides an additional process for detection of leaks during steady-state operation.

Statistical line balance is a mass balance method improved by a statistical component in accordance with 1.1.1 of Annex VIII to the TRFL that is implemented for the detection during standstill operation with open valves.

Tightness monitoring using a pressure-temperature-method provides detection of gradual leaks for pipelines in shut in conditions. It is an automated pressure-temperature measuring method (D-T method) in accordance with 6 of Annex VIII to TRFL according to VD TÜV bulletin 1051. The monitored section needs to be isolated by tight valves or isolating plates. The pipeline needs to be filled with product and no gas pockets should be present. If an isolated section leaks, pressure in the section will decrease. Since temperature does also influence pressure within a pipeline where a temperature drop will cause pressure to decrease and rising temperature will cause pressure to increase, the pressure-temperature-method also considers the temperature of the product.

Gradient intersection method and **extended negative pressure wave method** are two methods for the localisation of leaks. Due to the different nature of leaks, e.g. due to corrosion, material errors or external influence, the two methods are combined to guarantee accurate leak localisation independent of the cause of the leak.

Requirement	Implemented modules
Two continuously operating technical processes based on different physical variables that can detect the leaks in steady state operation Process for detecting leaks during transient operating conditions	E-RTTM A model-based method improved by the classification in accordance with 1.2.2 of Annex VIII to the TRFL
	E-NPW A pressure wave method improved by a model and classification in accordance with 2.1 of Annex VIII to TRFL
	Statistical Line Balance A mass balance method improved by a statistical component in accordance with 1.1.1 of Annex VIII to the TRFL
Process that can detect leaks during standstill conditions	E-NPW A pressure wave method improved by a model and classification in accordance with 2.1 of Annex VIII to TRFL
	Statistical Line Balance A mass balance method improved by a statistical component in accordance with 1.1.1 of Annex VIII to the TRFL
Process that detects gradual leaks	Tightness Monitoring An automated pressure-temperature measuring method (D-T method) in accordance with 6 of Annex VIII to TRFL (VDTÜV1051)
Process for leak localisation	Gradient Intersection Method Gradient intersection method in accordance with 12 of Annex VIII to TRFL
	(Extended) Negative Pressure Wave Method A pressure wave method improved by a model and classification in accordance with 2.1 of Annex VIII to TRFL

Table 1: Overview of the regulatory requirements and implemented leak detection modules

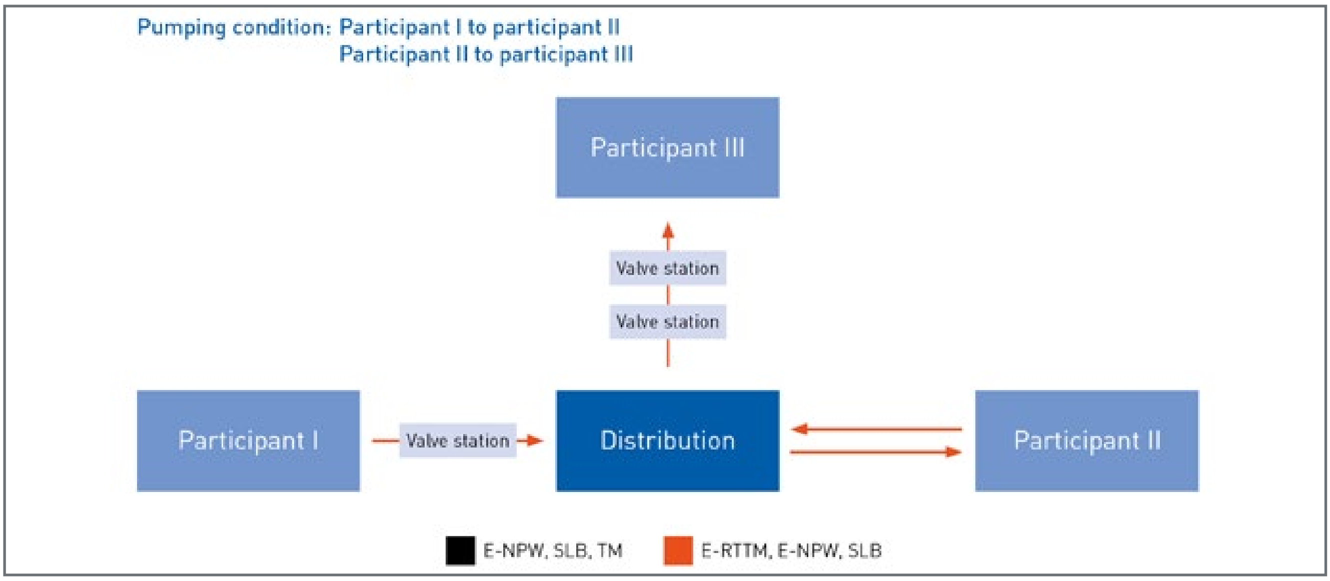

Figure 3: Operating scenario 1 of the distribution network and overview of leak detection methods for the individual pipeline sections

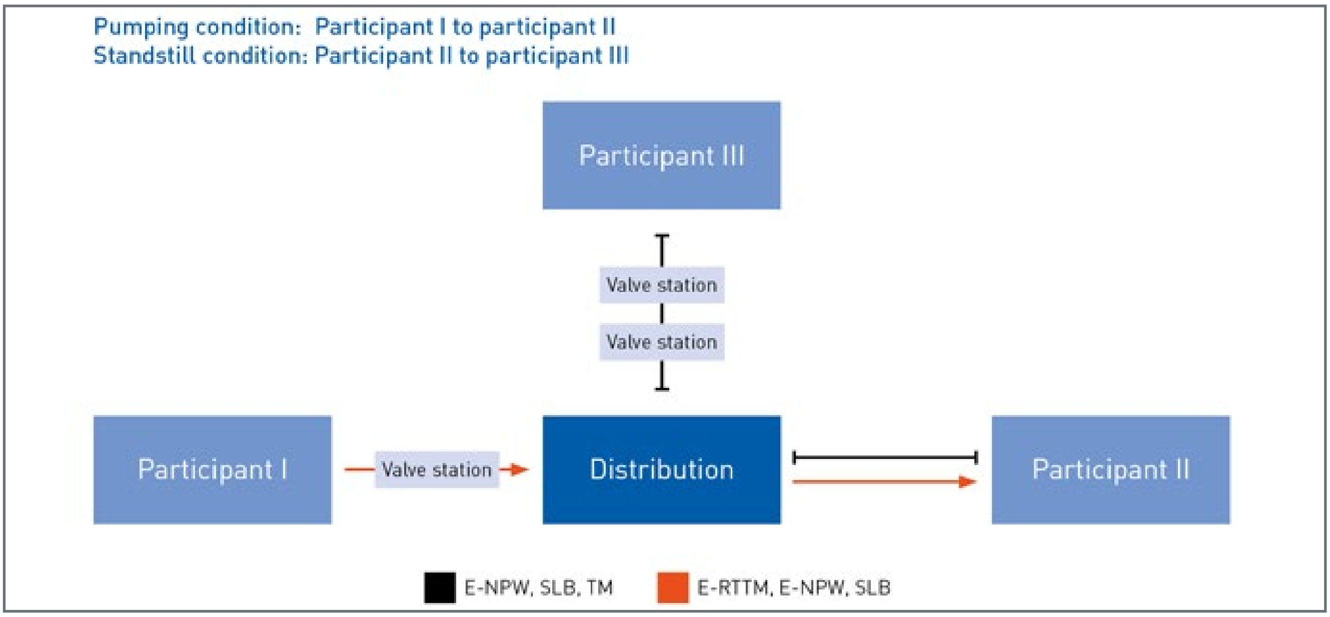

Figure 4: Operating scenario 2 of the distribution network and overview of leak detection methods for the individual pipeline sections

The table and figures give an overview of the regulatory requirements, the implemented leak detection methods for the regulatory requirements and the individual operating scenarios.

The operator was very satisfied with the implementation of the pipeline leak detection system and a third party approved the overall system by evaluation of actual leak testing. The system was fully integrated into the SCADA system and realised in redundant configuration in a virtualised environment under consideration of the operator's cyber security standards. For all implemented leak detection methods, the existing instrumentation was used and all 12 operating scenarios are automatically detected based on the valve positions. The overall system achieved detection of leaks down to 0.4 t/h (<0.5% leak rate) in 11 minutes (amount leaked: 73 kg).

3. Systematic approach for the leak detection method selection using pipeline leak detection audits

Selecting leak detection methods can be a challenging task looking at the variety of options. There is no "one-fits-all"-solution as each of the methods have their advantages and limitations, so it is important that the best set for the operator's application is chosen. On top of that, having the best technologies for leak detection might be not enough, when the operator's personnel are not prepared for the leak case and alarm management.

Pipeline leak detection audits offer a support in selection the right technology as well as leak detection philosophy. They are a service to perform a "health check" on all areas of leak detection on an operator's pipeline or pipeline network to ensure functioning in all required areas of leak detection. These areas include the capability of leak detection methods for the pipeline application, improvement of KPI's, the readiness of the organisation to deal with emergency, compliance with regulations, the physical state of the system and its performance. To find the best fit for the operator's pipeline application and identify any gaps in the alarm management the program includes a dedicated set of tests. These are the Snapshot, the Checklist and the Company Readiness tests.

In the **Snapshot**, the operator's application is analysed for critical characteristics when it comes to the selection of the leak detection methods and if they have been considered in the selection of customers leak detection techniques. This includes the pipeline itself, from material to wall thickness and fluid transported. But also, the operation of the pipeline is analysed as well as the topology of the pipeline and likely consequences of leaks. The test is also in line with the PHMSA and 49 CFR 195.444 requirements which require operators to identify a process for and conducting the evaluation of capability of their leak detection capabilities and covers the minimum required factors as well as additional factors supporting the operator's selection and evaluation process.

The **Checklist** is a management approach which supports the operator in continuous improvement of their leak detection performance. This approach is also reflected in API 1175 and is part of a leak detection strategy. Within the leak detection audit, the installed methods are investigated based on current KPIs (Key Performance Indicators) against the operator's desired performance, industry best practice and Best Available Technology (BAT). Based on the investigation and information of the pipeline operation, instrumentation and communication, recommendations are given on how to achieve the desired KPIs.

In the **Company Readiness check**, the alarm management and procedures are analysed with the overall goal of identifying opportunities for improvement of real leak cases. When there is a leak, it is crucial that the company and its personnel know how to react and initiate the right procedures in a fast manner and still avoid making false decisions. This is where the Company Readiness check supports the operator. Necessary training needs for the control room staff and the implementation of work procedures will be identified and solutions are given to close the identified gaps. The leak detection audit is a service to check all leak detection areas of a pipeline or a pipeline network of an operator to ensure the functionality in all required areas of leak detection. It is therefore the most comprehensive test program available for leak detection and covers the physical state of the system, performance of the system, compliance with regulations including API, 49 CFR 195, CSA Z662 and TRFL and the readiness of an organisation to deal with emergency.

At the end of the audit, the operator receives a detailed report of all the tests performed including an overview of the extent to which all requirements have been met. The report also includes recommendations depending on how critical points can be improved and a certificate for the direct proof for the leak detection capabilities.

4. Summary

Different leak detection methods can be used to fulfil the requirements of regulations and standards such as German TRFL (Technical Rules for Pipelines) or API 1130. KROHNE has successfully proven this by using multi-method approaches in a variety of applications. This approach also allows the detection of leaks during all operating scenarios of a pipeline including changing operating scenarios such as steady-state, transient or shut-in operation as well as accurate leak localisation. By using pipeline leak detection audits, a systematic approach for the leak detection method selection is available that considers application, operational and legal requirements to support operators and engineering companies in finding the right leak detection technologies and philosophy.

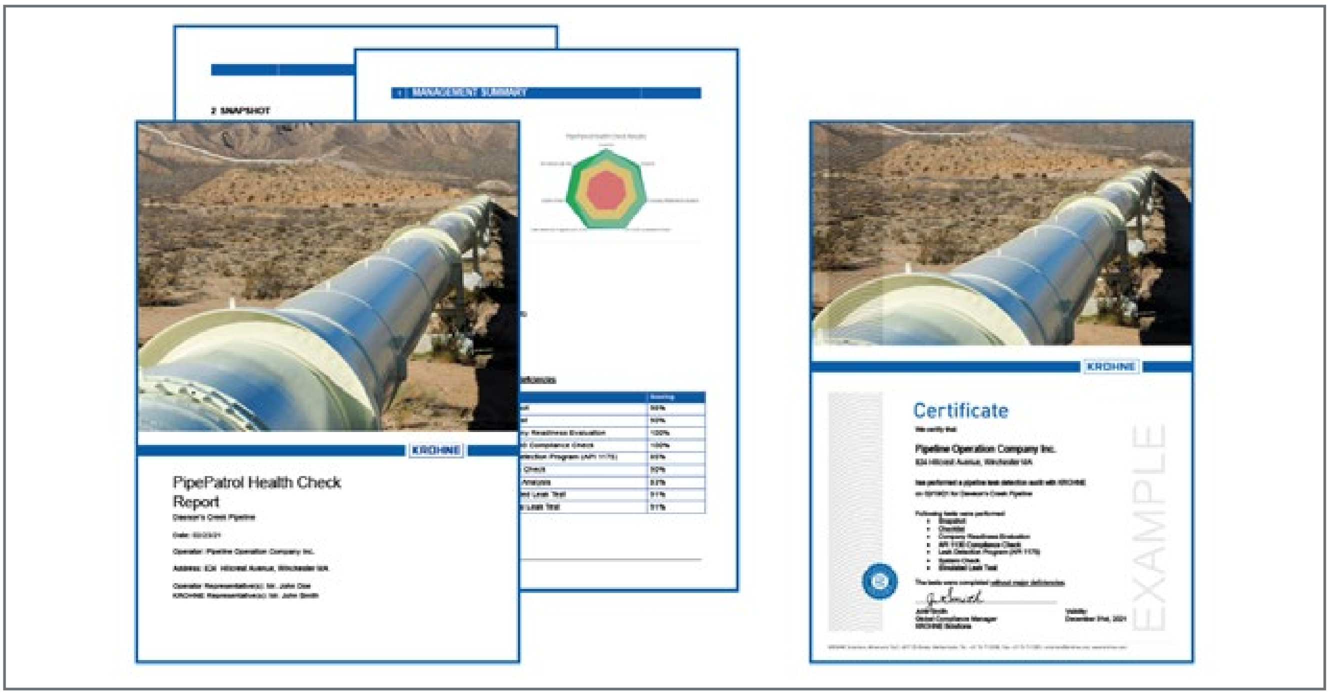

Figure 5: Pipeline leak detection audit report and certificate sample

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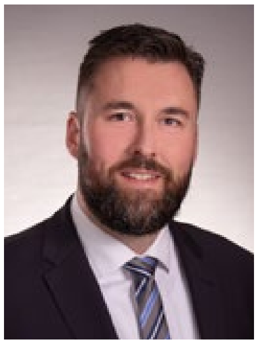

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Comparative Assessment of Levelised Cost of Different Hydrogen Transportation Technologies

M. ANEKE, N. CURSON, C. LOW > PENSPEN

Abstract

Hydrogen, a vital energy vector, is widely accepted as essential for decarbonising the global energy system. Hydrogen has a variety of roles to play in a low-carbon economy. Hydrogen can replace fossil fuels as a zero-carbon feedstock in chemical and fuel production [2]. It can also be used to extend the scope of climate transition to sectors that the electrification of energy cannot reach, as well as long-distance transport and heat-intensive industries such as steelmaking [1], and it can be used as storage, making it an enabler in most national decarbonisation roadmaps [3].

In a future hydrogen economy, the vision is for hydrogen to be transported across borders from countries with a high excess of renewable energy that can be used to generate green hydrogen to countries without access to renewables. In the UK, the Scottish Government's hydrogen Policy Statement aims to deliver 5GW of renewable and low-carbon hydrogen production by 2030 and 25 GW by 2045. The European Commission has also established a global ambition, targeting 10 million tons of hydrogen to be imported by 2030. In Europe, the Port of Rotterdam is an established energy hub, already imports 13% of Europe's energy, and has ambitions to become the hydrogen hub of Europe. A challenge in exporting hydrogen is choosing the best means of transportation. In this paper, different technologies for transporting hydrogen from Aberdeen Harbour to the Port of Rotterdam were assessed and compared using the levelized cost as a reference.

1. Scope and Novelty

Few pilot/demonstration studies are currently focusing on hydrogen transport across borders. This research will investigate and compare the levelized cost of different green hydrogen transport technologies, including:

- Cryogenic liquid in a ship.
- Using a Liquid Organic Hydrogen Carrier (LOHC) in a ship.
- As ammonia in a ship.
- As a compressed gas (ambient condition) by road
- As a gas using a pipeline.

To maintain the same basis for all the different technologies, the inlet battery limit is assumed to be 100% green hydrogen produced from 5GW (equivalent to 1 million Nm3/h of hydrogen) atmospheric water electrolysis process with produced hydrogen battery limit conditions of 1.2 bar and 30 oC. The delivery battery limit is hydrogen supply at a pressure of 20 bar and 10 to 30 °C temperature. The hydrogen is assumed to be produced at Aberdeen Harbour, UK and delivered to the Port of Rotterdam in Netherlands. The details of the delivery routes assessed in this study are presented in the next section. Table 1 shows the inlet and outlet battery limit for all the hydrogen transportation technologies assessed.

2. Process Description of the Different Transportation Routes

2.1 Hydrogen Transport as Cryogenic Liquid Using Ship

In this option, the gaseous hydrogen produced in the electrolysis plant assumed to be in the Aberdeen Harbour area with battery limit condition of 20 bar and 30oC is liquefied in a hydrogen liquefaction plant and loaded in a ship designed to transport liquid hydrogen (LH2) at -253oC and 1 atm. The LH2 is transported to the Port of Rotterdam via the sea route shown in Figure 1, representing 524 nautical miles [6]. As the ship arrives at the Port of Rotterdam, it is assumed that the liquid hydrogen is pumped and vaporised directly into the hydrogen backbone pipeline at a battery limit of 20 bar and 10 – 30oC.

2.2 Hydrogen transport as LOHC using ship.

The gaseous hydrogen produced in the electrolysis plant, which is assumed to be close to Aberdeen Harbour and has a battery limit condition of 20 bar and 30°C, is used to produce LOHC in a nearby LOHC production facility.

The produced LOHC is loaded in a ship at 1 atm and 30oC and transported to the Port of Rotterdam via the sea route shown in Figure 1. As the ship arrives at the port, the LOHC is dehydrogenated in a nearby dehydrogenation facility. The hydrogen is purified while the LOHC is returned to Aberdeen Harbour.

2.3 Hydrogen transport as ammonia using ships.

Hydrogen from the electrolysis plant is supplied to the nearby ammonia production facility, where it is used for ammonia production. Like the LOHC, the produced ammonia is liquid at atmospheric pressure and -33°C. It is loaded into the ship and transported to the Port of Rotterdam via the shipping route shown in Figure 1. As the ship arrives at the port, the ammonia is offloaded and pumped to a nearby ammonia cracking plant, where it is cracked into hydrogen and nitrogen. The hydrogen is purified.

2.4 Hydrogen transport as a compressed gas (ambient condition) by road

In this scenario, the produced hydrogen from the electrolysis process is compressed to a pressure of 250 bar and stored in long cylindrical pressure vessels, otherwise known as tube trailers. The stacked tubes are hauled from Aberdeen Harbour to the Port of Rotterdam by road using trailers. The road route considered for this assessment is shown in Figure 2. At Harwick, the trailer is ferried to Hoek van Holland before continuing its journey by road. The estimated travel distance is about 719 miles (1157 km).

2.5 Hydrogen transport as a gas using pipelines.

The assessment for the pipeline route is based on a subsea pipeline from the Aberdeen harbour to the hydrogen backbone in the Port of Rotterdam. The pipeline is assumed to be straight, and the length is 723 km (assumed to be similar to the straight length between the two sites) as shown in Figure 3.

Common Parameters	Value
Inlet Battery limit	Hydrogen from electrolyser
Composition	100% pure hydrogen
Flowrate	1 million Nm^3/h
Temperature	30°C
Pressure	1.2 bar
Outlet Battery limit	Hydrogen supply to hydrogen backbone
Composition	>99.9% hydrogen
Temperature	10 – 30°C
Pressure	20 bar

Table 1: Common Process Parameters for the Different Options

Figure 1: Sea Route from Aberdeen Harbour to Port of Rotterdam (yellow represents the shipping route) [5]

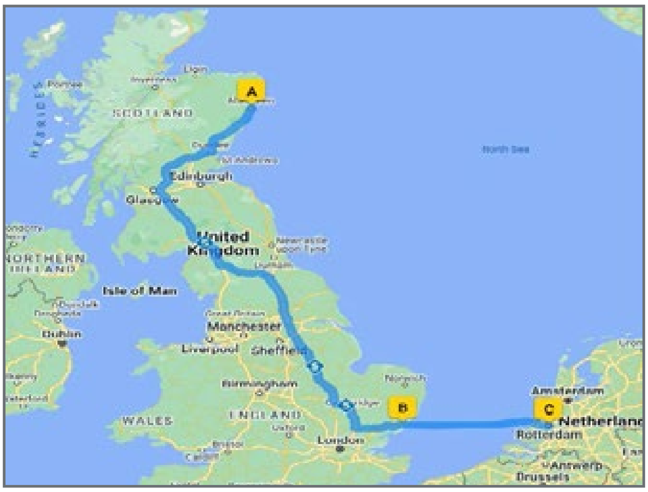

Figure 2: Road Route from Aberdeen Harbour to Port of Rotterdam

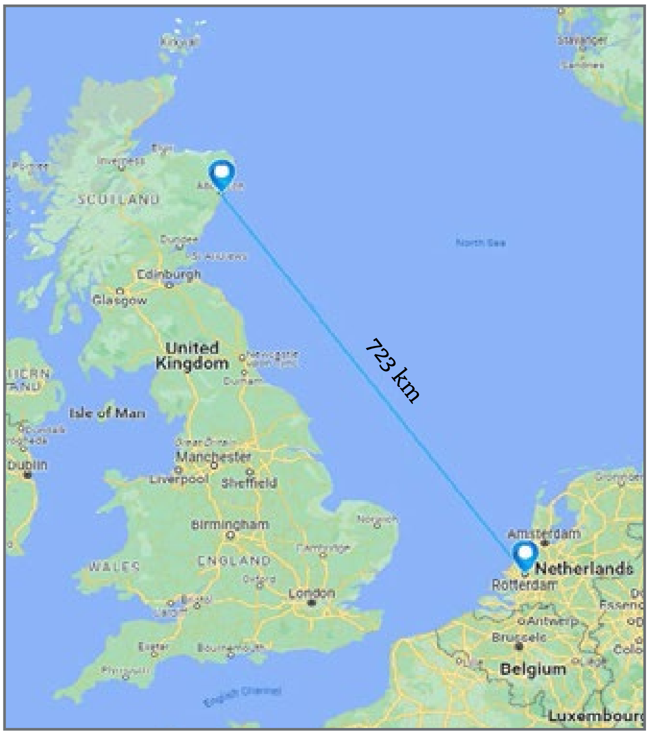

Figure 3: Pipeline route between Aberdeen Harbour and Port of Rotterdam

3. Process Description and Modelling of the Different Hydrogen Conversion Technologies

3.1 Hydrogen Liquefaction Process

Figure 4 shows the process diagram of the hydrogen liquefaction system considered in this study. The liquefaction technology is based on a mixed refrigerant pre-cooling cycle and a hydrogen Claude cycle, as described in [5]. The process is modelled using Aspen Hysys® simulation software using process parameters presented in [5].

3.2 LOHC Production and Dehydrogenation Process

The LOHC is assumed to be methylcyclohexane (MCH) which is produced via exothermic catalytic hydrogenation of toluene based on the chemical equation shown below.

$$C_6H_5CH_3 + 3H_2 \rightarrow CH_3C_6H_{11} \quad (1)$$

The hydrogenation reaction is assumed to occur at a temperature of about 150oC [8] with kinetic parameters in the form of the Arrhenius equation shown below.

$$r_{mch} = kP_t^{0.5}P_h^{0.8} \quad \text{...(2)}$$

$$k = Ae^{\left(\frac{E}{RT}\right)} \quad \text{...(3)}$$

where,

P_t and P_h = Partial pressure of toluene and hydrogen

A = Pre-exponential factor (2000) [8]

E = Activation energy (46.9 kJ/mol) [8].

The toluene hydrogenation process is modelled in Aspen Hysys® using a plug flow reactor and kinetic parameters shown above. As the reaction is exothermic, the reactor is cooled to maintain the reaction process.

The MCH dehydrogenation process is an endothermic reaction with reaction equation shown below.

$$CH_3C_6H_{11} \rightarrow C_6H_5CH_3 + 3H_2 \quad \text{...(4)}$$

The dehydrogenation process is modelled in Aspen Hysys® using a plug flow reactor at a temperature 382 oC with rate equation and kinetic parameters shown below [9].

$$-r_{mch} = kP_M^{0.753}P_T^{-0.419} \quad \text{...(5)}$$

$$k = 0.0305\,\frac{gmoles\ methylcyclohexane}{atm^{0.332}\ (\text{min.gram catalyst})} \quad \text{...(6)}$$

where,

P_T and P_M = Partial pressure of toluene and methylcyclohexane

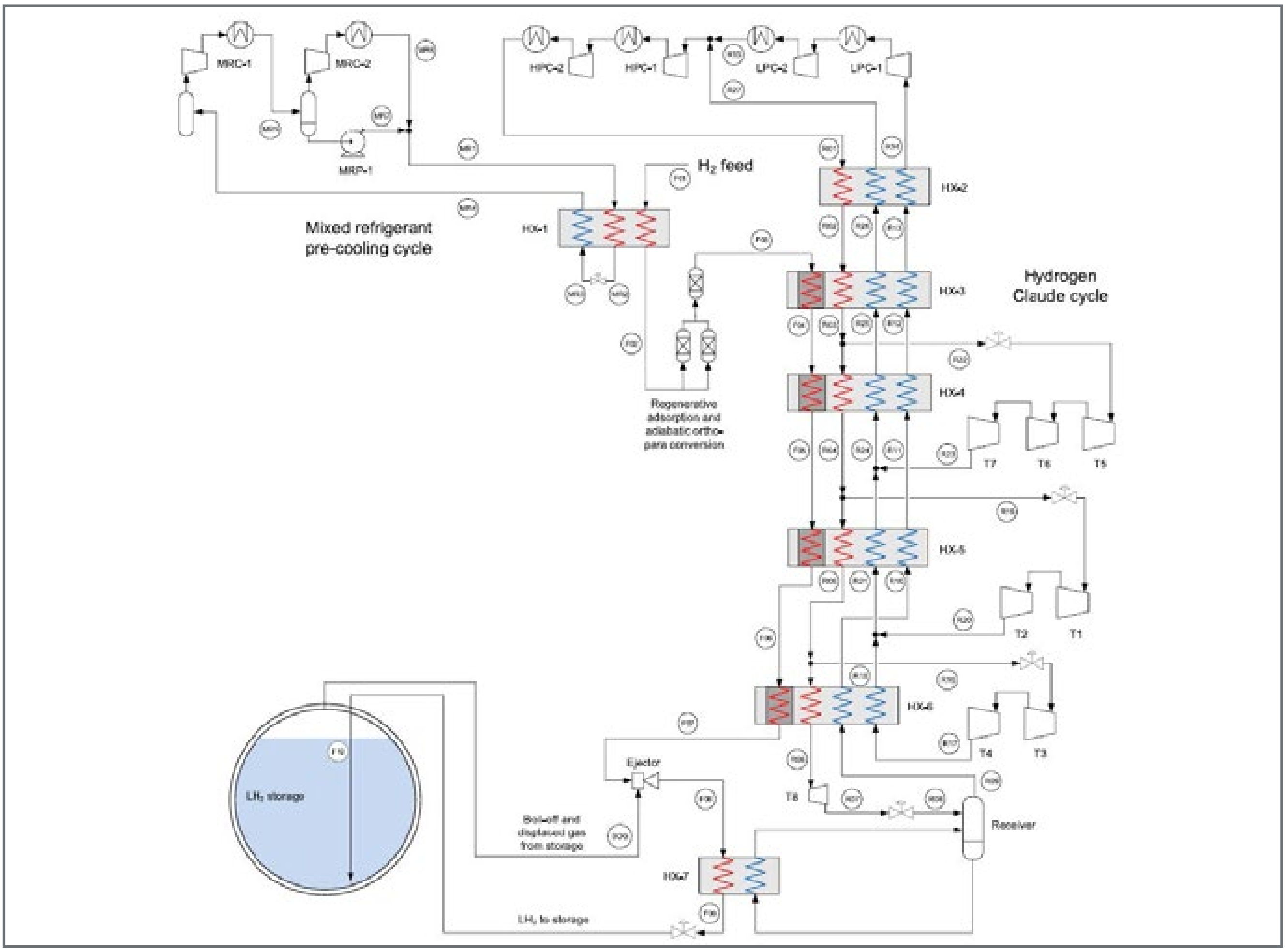

Figure 4: Hydrogen Liquefaction Process [5]

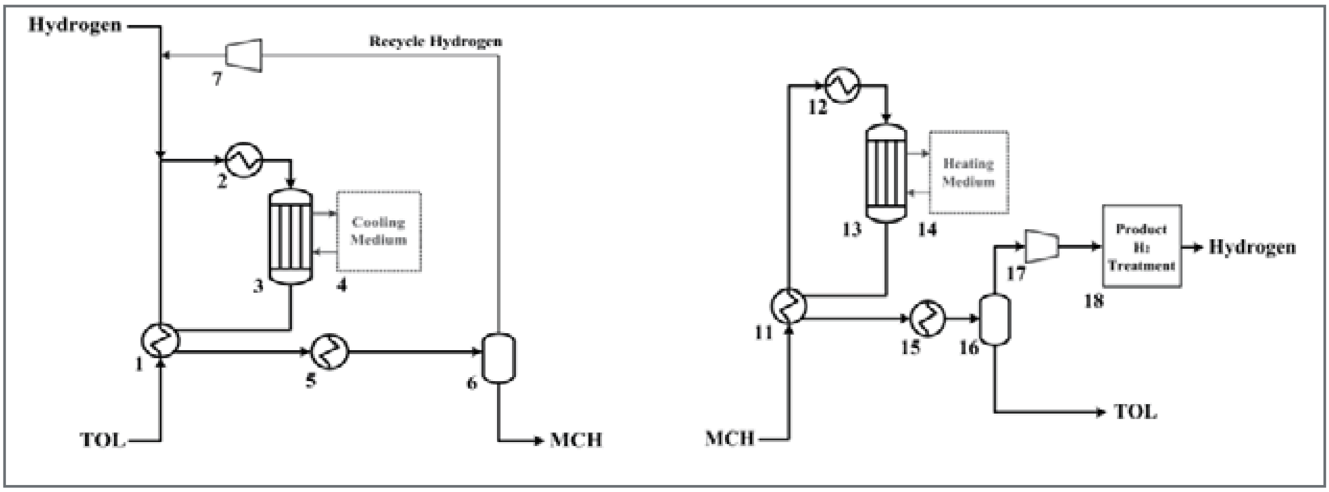

Figure 5: LOHC (MCH) Production Process & MCH Dehydrogenation Process

The simplified process flow diagram of the LOHC (MCH) dehydrogenation process is shown in Figure 5 [7]. For this assessment, toluene is assumed to be purchased as feedstock for the MCH production.

3.3 Green Ammonia Synthesis and Cracking Process

Figure 6 [10] shows the process flow diagram of the green ammonia synthesis process. The process uses nitrogen generated from the cryogenic air separation unit with hydrogen from the electrolysis process to produce ammonia.

The ammonia synthesis process is modelled in Aspen Hysys® using a plug flow reactor operating at a pressure of 150 bar and temperature range of 270 – 450°C. The rate equation and kinetic parameters are presented below.

$$N_2 + 3H_2 \leftrightharpoons 2NH_3 \quad (7)$$

$$r_{NH3} = k_f P_N^{0.5} P_H^{1.5} \quad (8)$$

$$-r_{NH3} = k_r P_{NH3} \quad (9)$$

where,

k_f and k_r = the rate constant for the forward and reverse reactions, respectively

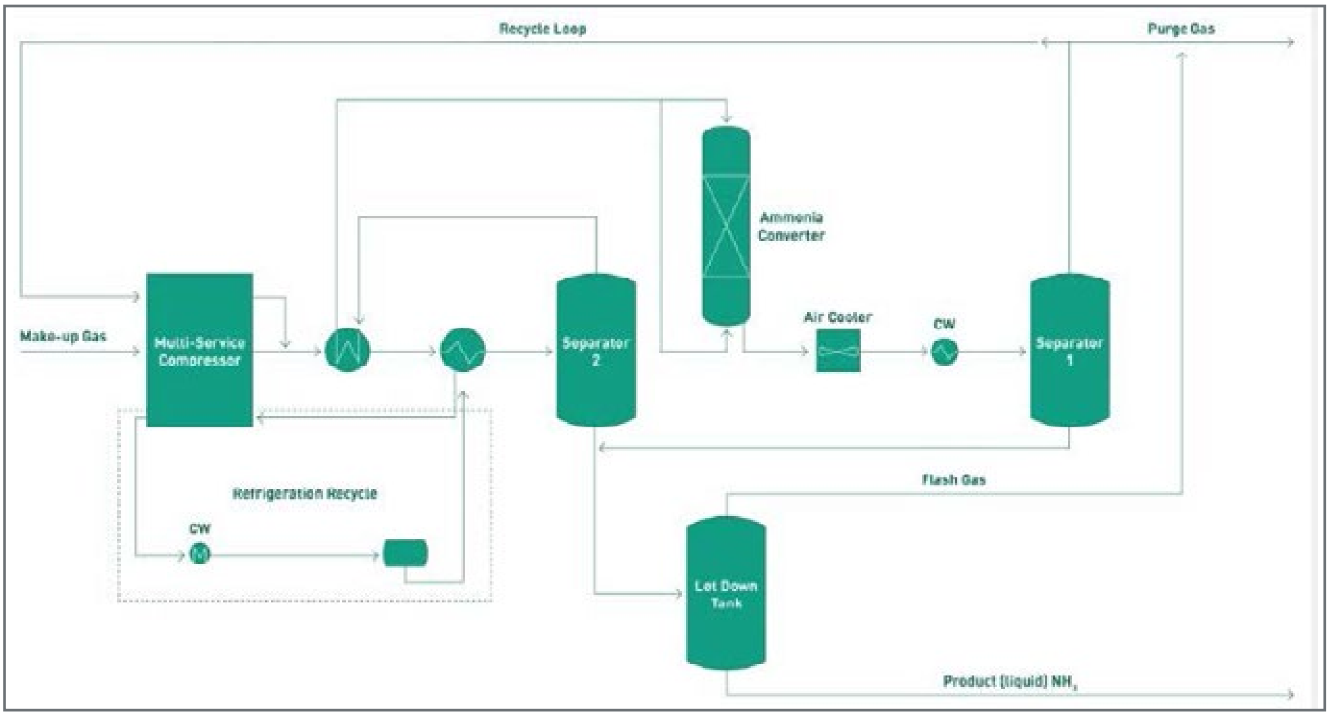

Figure 6: Green Ammonia Synthesis Process

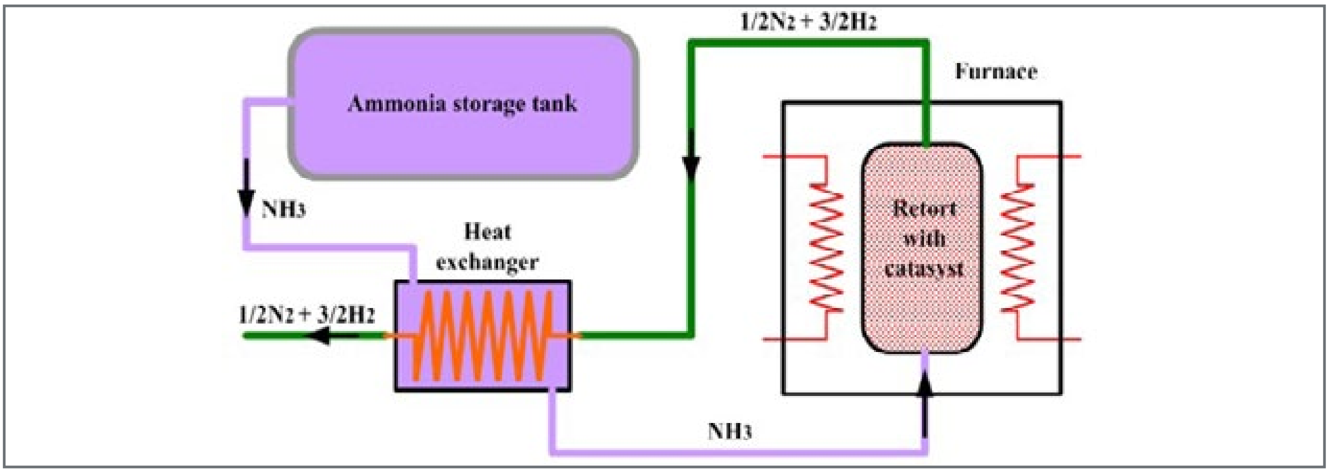

Figure 7: Ammonia Cracking Process

P_N, P_H and P_{NH_3} = Partial pressure of nitrogen, hydrogen, and ammonia, respectively.

$$k_f = A_f e^{\left(\frac{E_f}{RT}\right)} \quad (10)$$

$$k_r = A_r e^{\left(\frac{E_r}{RT}\right)} \quad (11)$$

where,

A_f and A_r = Pre-exponential function for the forward and reverse reaction (10000 and1.3 $x10^{10}$, respectively

E_f and E_r = Activation energy for the forward and reverse reaction respectively = 9.1 $x10^4$ kJ/kgmole and 1.41 $x10^5$ kJ/kgmole respectively

Figure 7 shows the ammonia cracking process, which is modelled in Aspen Hysys using the kinetic parameters for the reverse reaction, as shown above.

3.4 Hydrogen Compression into Tube Trailers

For the hydrogen transport using tube trailers, it is assumed that the hydrogen is compressed from the electrolyser battery limit condition of 30oC and 1.2 bar to the tube trailer storage pressure of 250 bar (assumed based on the most matured technology at the time of writing). The compressors are modelled as equal-stage compressors. The number of compressor stages is estimated by assuming each stage's maximum compressor discharge temperature as 135oC. The adiabatic efficiency of each compressor stage is assumed to be 85%. The compressor intercooler and aftercooler target cooling temperatures are assumed to be 30oC. The compressor shaft losses are assumed to be 2%, while the motor's efficiency is assumed to be 95%. Based on the assumptions, the system will require 7 compressor stages.

3.5 Hydrogen Compression and Pipeline Transport System

For the pipeline transport option, the system is designed to achieve a tie-in condition of 20 bar and a temperature of 10 to 30 °C at the Port of Rotterdam. Based on this tie-in condition and a maximum compressor discharge temperature of 135°C, it is estimated that the system will require 5 compressor stages with a discharge of 46.5 bar for a 723 km subsea pipeline with a diameter of 36 inches.

4. Levelised Cost

The levelized cost of hydrogen transport for any given technology option is calculated as the ratio of the technology's total costs relative to the amount of hydrogen to be transported over the technology's lifetime.

$$LCOHT = \frac{Total\ Cost\ of\ Technology}{Mass\ of\ hydrogen\ transported\ per\ annum}$$

For the case of transporting hydrogen using hydrogen carriers

Total Cost of Technology
=Cost of converting the hydrogen to carrier compound (LOHC,Ammonia or liquid hydrogen)
+Cost of converting the carrier compound back to gaseous hydrogen at the receiving facility

The total cost covers all CAPEX and OPEX for the entire process.

4.1 Levelised Cost of Hydrogen Transport by Road/Ship using Tube Trailers

For transportation by road, the hydrogen will first be compressed and stored in tube trailers before being transported by road to the destination. The transportation time for delivery by truck or ship can be calculated based on the equation below.

$$t_{RT}(hrs) = 2 * \frac{D}{v} + LT + UT \quad (12)$$

where,

D = distance to the location of delivery

v = average speed of the truck

LT = loading time at the filling station

UT = unloading time

The number of round trips NRT per year follows from the number of hours per year the truck is utilised and the roundtrip time.

$$N_{RT} = \frac{U}{t_{RT}} \quad (13)$$

where,

U = utilisation time of the truck/ship over a year (it is assumed the only time the truck is not utilised is during loading and unloading)

The quantity of hydrogen to be transported by the truck or ship is given as

$$Q = K * N_{RT} \quad (14)$$

where,

K = Capacity of the ship or truck.

For the case of road transport using tube trailers, the annual capital cost (CC) is the sum of the cost associated with compressor, tractor, trailer, and storage vessels (tube trailers), considering the annuity factors (AF) that might be different:

$$CC = AF_{compressor} * CAPEX_{compressor} + AF_{tractor} * CAPEX_{tractor} + AF_{tubetrailer} * CAPEX_{tubetrailer} \quad (15)$$

For the case of transport by ship, the annual capital cost (CC) is the sum of the cost associated with the hydrogen conversion plant, pump, ship, and storage vessels, considering the annuity factors (AF) that might be different:

Hence for transporting the hydrogen using a LOHC,

$$CC = AF_{LOHCpro\&dehy} * CAPEX_{LOHCpro\&dehy} + AF_{ship} * CAPEX_{ship} \quad (16)$$

For transporting the hydrogen as liquid Ammonia,

$$CC = AF_{Ammoprod\&crack} * CAPEX_{Ammoprod\&crack} + AF_{ship} * CAPEX_{ship} \quad (17)$$

For transporting the hydrogen as liquid hydrogen

$$CC = AF_{liqu} * CAPEX_{liqu} + AF_{ship} * CAPEX_{ship} \quad (18)$$

The annual operating cost (OPEX) consists of compressor electricity costs, fuel costs, labour costs for the driver, and annual maintenance costs.

$$OPEX = C_{ele} + C_{utility} + (P_f * C_f * 2 * D * N_{RT}) + (U * C_d) + C_{OM} \quad (19)$$

where,

C_{ele} = Annual electricity cost for operating the plant (compressor, pumps etc)

$C_{utility}$ = Annual utility cost (cooling water)

P_f = truck/ship fuel cost (assumed to be diesel-powered)

C_f = truck/ship fuel consumption

C_d = hourly wages (driver, ship captain and ship crew members)

C_{OM} = annual maintenance cost (assumed to be 3% CAPEX for all cases)

For the shipping option, the assumed fuel consumption of the ship for the lightest commodity (liquid hydrogen) is corrected to include the influence of weight on fuel consumption of ship. The correction factor is calculated using the following equation.

$$Fuel\ Con = Fuel\ con(liquid\ hydrogen)\left(\frac{Weight\ of\ commodity\ transported}{Weight\ of\ equivalent\ volume\ of\ Hydrogen}\right)^{2/3} \quad (20)$$

4.2 Levelised Cost of Hydrogen Transport using Pipeline.

For pipeline transport, the capital cost includes the cost of the pipeline, the cost of subsea pipeline installation from Aberdeen Harbour to the Port of Rotterdam, and the cost of the compressor.

$$CC = AF_{compressor} * CAPEX_{compressor} + AF_{pipeline} * CAPEX_{pipeline} \quad (21)$$

The operating cost will cover the electricity cost of compressors and the cost of operating personnel.

$$OPEX = C_{ele} + C_{utility} + (U * C_p) + C_{OM}$$

where

C_{ele} = Annual electricity cost for operating the plant (compressor, pumps etc)

$C_{utility}$ = Annual utility cost (cooling water)

C_p = hourly wages (operating personnel)

C_{OM} = annual maintenance cost (assumed to be 3% CAPEX for all cases)

For each of the transport options, the Annuity Factor (AF) is defined as,

$$AF = \frac{(1+WACC)^n * WACC}{(1+WACC)^n - 1} \quad (21)$$

where,

WACC = Weighted Average Cost of Capital assumed to be 8% for all options

n = Depreciation period (assumed to be the design life of the system)

Table 2 shows the assumed design life of the different technologies considered in this study.

5. CAPEX Estimation, Result and Discussion

The CAPEX for the different technologies is estimated by sizing the individual process equipment that makes up the technology and using the ACCE +/-50 methodology to evaluate the total plant CAPEX. The electricity consumption for the compressors and pumps is estimated using the results of the Aspen Hysys® simulation software. The cooling water consumption is also estimated using the simulation results from Aspen Hysys®. It is assumed that the cooling water and electricity are supplied over the fence.

Table 3 summarises the results for the transport technologies analysed in this study based on 8000 hours of operation per year.

The results show that pipeline transport has the lowest overall levelised cost among the different technologies investigated while the ammonia option has the highest. For shipping transport, LOHC shows the lowest overall levelised cost of transport, followed by liquid hydrogen and then ammonia. However, for CAPEX-only analysis, ammonia production and cracking show a lower levelised cost of transport followed by liquid hydrogen and LOHC. The high overall levelised cost associated with ammonia transport arises from the high operational cost of the plant, especially the cost of electricity consumption associated with the air separation unit, feedstock compression, ammonia refrigeration, as well as the cost of water required for cooling the intercooler and aftercooler heat exchangers.

Process	Design life (n) (years)
Tractor	10
Trailer	30
Pipeline transport system, including compressors	30
MCH Production and Dehydrogenation Plant	30
Hydrogen Liquefaction and regasification plant	30
Ammonia Synthesis and Cracking Plant	30

Table 2: Design Life of Different Technologies

	Road Transport	Pipeline	Ship		
			LOHC	Ammonia	Liquid Hydrogen
Condition	Compressed Gas in Tube Trailer at 30°C 250 bar	Compressed gas to meet the discharge	Liquid organic hydrogen carrier as MCH at 1 atm and 30°C	Liquid Ammonia at 1 atm and -33°C	Liquid Hydrogen at 1 atm and -253°C
Maximum Volume of containment	Tube trailer $26m^3$	N/A	Vessel 266000 m^3		
Technology Requirement	Gas compressor + storage in tube trailers at 30°C, transporting the tube trailer via the road to the destination using tractors, discharge the tube trailer at destination.	Gas Compression and transport to destination via subsea pipeline	Converting the gaseous hydrogen to MCH, loading the MCH in the Ship, moving the ship to destination and unloading the MCH, dehydrogenation of the MCH at destination, purifying the resultant hydrogen	Converting the gaseous hydrogen to liquid ammonia, loading the ammonia in the Ship, and moving the Ship to destination. Unloading the ammonia at the destination and cracking the ammonia to produce hydrogen. Purifying the hydrogen	Converting the gaseous hydrogen to liquid hydrogen. Loading the liquid hydrogen on the Ship and moving the Ship to destination. Unloading the ship at the destination and re-gasifying the liquid hydrogen.
Travel Distance (one way)	1300 km	723 km	970 km		
Average Travel Speed	50 m/h	N/A	15 knots		
Total Travel Time (hours)	28.76	N/A	69.87		
Loading Rate (m^3/h)	Based on hydrogen supply rate of 1 million Nm^3/h from electrolyser to the conversion technologies				
	Assume tube trailer swap	N/A	1978.8	709.7	1163
Offloading Rate (m^3/h)	Assumed to be the same as loading	N/A	Assumed to be the same as loading rate		
Loading Time (hours)	Based on 95% fill (Tube Trailer = $26m^3$ and Ship =266000 m^3) and respective loading rates				
	0.08	N/A	127.70	356.07	217.28
Offloading time (hours)	0.08	N/A	127.70	356.07	217.28
Total Cycle Time (hours)	32.57		509.52	782.00	504.43
Mass of Medium Transported per trip (kg)	600	N/A	190,485,260 (MCH)	172,973,150 (Ammonia)	19,551,399 (Liquid Hydrogen)
Mass of Hydrogen Transported per trip (kg)	6000	N/A	11,596,930	30,410,593	19,551,399

CAPEX Estimate (Plant Equipment)					
Total Plant (Equipment) CAPEX Estimate	Compressors & intercooler/after coolers $2,105,263	Compressor, intercooler/afterco oler, subsea pipeline $3,374,946,501	MCH production and dehydrogenation Plant $2,908,402,321	Ammonia synthesis and cracking plant $3,312,508,733	Hydrogen liquefaction and Gasification Plant $5,973,490,104
Fixed OPEX (3% of CAPEX)	$63,158	$101,248,395	$87,252,070	$99,375,262	$179,204,703
CAPEX (Transport Equipment)					
Trailer (500 units)	$112,500,000				
Tractor (1 unit)	$200,000				
Ship			$430,000,000		
CAPEX (Feedstock)					
Toluene Required for full ship load of MCH (kg)			178,752,226		
[1]Toluene Cost for initial loading ($)			$182,327,270		
Variable OPEX Associated to Plant Operation (Utility)					
Electricity Demand (kW)	700	181,652	352,111	2,315,487	1,397,991
[2]Total Annual Electricity Cost ($)	$130,686	$552,222,228	$369,071,387	$6,670,169,006	$4,249,891,466
Cooling Water Demand (m^3/h)		13,560	109,454	396,748	113,702
[3]Total Annual Water Cost ($)		$178,986,271	$1,444,790,424	$5,237,072,504	$1,500,861,397
Variable OPEX Associated with Hydrogen Transport (Fuel)					
[4]Fuel Consumption	0.35 l/km	N/A	364,932 g/d (to) 347,078 g/d (re)	342208 g/d (to) 80000 g/d (re)	80000 g/d
Annual fuel cost ($)	$446,016	N/A	$25,359,409	$12,767,671	$11,628,154
Variable OPEX Associated with Hydrogen Transport (Feedstock)					
Toluene Recovered during Dehydrogenati on (kg)			176,678,700		
Toluene Make-up Required (kg)			2,073,526		
Toluene Required to keep the plant running during Shipping (kg)			41,994,240		
[1]Toluene Cost to keep the plant running during Shipping ($)			$42,834,125		
[1]Toluene Make-up Cost per year			$33,207,982		

Variable OPEX Associated with Hydrogen Transport (Personnel)					
Number of Crews/Operators	2 crews 2 drivers	10 plant operators	20 crews 2 captains 4 plant operators	20 crews 2 captains 4 plant operators	20 crews 2 captains 4 plant operators
Total Annual Personnel Cost ($)	$280,000.00	$1,400,000	$1,620,000		
Levelised Cost Results					
Levelised cost of CAPEX (Equipment)	$1.27	$0.42	$2.72	$0.95	$1.71
Levelised cost (Fixed OPEX)	$0.43	$0.14	$0.58	$0.32	$0.58
Levelised Cost (Variable OPEX)	$6.80	$1.02	$9.21	$37.32	$18.58
Total Levelised Cost of Transport	$8.63	$1.58	$12.72	$38.71	$20.99

[1]Tolune price = ($1.02/kg), [2]Electricity price ($/kWh) = 0.38, [3]Water price ($/$m^3$) = 1.65, [4]Based on fuel consumption of 8000 gallons per day (g/d) corrected based on commodity weight, [5]Crew member hourly wage of $20, [6]Driver hourly wage of $50, [7]Captain hourly wage of $65, [8]Plant operator hourly wage of $70.

Table 3: Summary of Input Parameters for the different transport options

In terms of the quantity of hydrogen transported per annum, the pipeline transport system shows the highest throughput of 719,563,280 kg, followed by Ammonia of 311,106,390 kg, then liquid hydrogen of 310,073,616 kg, LOHC of 182,085,737 kg and tube trailer of 147,593 kg.

6. Conclusion

This study presents the levelised cost of hydrogen transport, including gaseous hydrogen using tube trailers, gaseous hydrogen using a pipeline, liquid ammonia using a ship, liquid organic hydrogen carrier using a ship, and liquid hydrogen using a ship. Unlike most published literature based on generic CAPEX and OPEX data from publications, the work presented in this study was carried out through detailed modelling of the individual processes involved in the transport process. By taking this approach, we can accurately evaluate the OPEX of the different options (in terms of electricity and water consumption) that have the most impact on levelised cost estimates.

In terms of evaluation, the study doesn't consider the cost of carbon emissions in burning fuel (diesel), embodied carbon, and developments in air separation and cracking technology, which could reduce the cost of ammonia transportation. These are all subject to further study.

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Circular Economy Concept for Aboveground Storage Tanks - Change In Service

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Abstract

Along with extending the life cycle of products, the oil and gas sector has recently implemented the circular economy. Its goals are to increase longevity, manage waste more effectively, and provide an optimal design that makes it simpler to repair, reuse, or remanufacture outdated products. In order to decrease waste and increase the lifespan of items, many materials and products may be repaired, altered, or reused.

Asset Integrity Management is a key element of operational excellence along with optimizing the efficiency while maintaining the safety and environment. Storage tanks have been widely used in industries, particularly in oil refineries, petrochemical plants, storage terminals and others to store a multitude of different products. An important objective in supply distribution is to meet user demands on time and in a cost-effective manner. Changing the service of an existing Above Storage Tank (AST) is a common strategy in ensuring a continuous flow of product which can contribute significantly to improved efficiencies and higher lifetime earnings.

Change in service of existing ASTs requires careful evaluation and assessment based on several factors affecting the tanks design, inspection, maintenance and operations. This is a multi-discipline evaluation looking into different aspects of the tank design and functionality. The paper mainly refers to "Aboveground Storage Tanks Change in Service" through covering a sample procedure based on recognized standards and best practices. This paper will address the effective techniques of changing service through listing all the input parameters and factors along with the description of each item that might affect the change in service

1. Introduction

Recently, circular economy is introduced in oil & gas industry to extend the life cycle of products. It is intended in improving durability and efficient management of waste, and getting an optimized design making it easier to benefit from old product to be repaired, reused or remanufactured. Thus, many products and materials can be reused or refurbished to reduce waste and extend life cycle of products. It could also lead to new business models based on utilizing the equipment for less critical or low risk areas.

One of the main areas to implement this approach is storage tanks, which are used throughout the oil and gas industry for the bulk containment of fluids at different stages of the refinery process. Most often, products are stored for a short duration before being transported for further processing. In general, industrial fuel storage tanks, known as petroleum tanks also, can store various fluids. Thus, they are manufactured to various design standards & codes and sizes to store variety of fuels and industrial liquids.

There are two main storage tanks classifications: Underground storage tanks (UST) and aboveground storage tanks (AST). Choosing the right tank can have a significant impact on profitability based on the type of storing products.

The UST are safer, offer space efficiency and/or value of their property by burying underground at least 10% of the tank stored volume. However, they cannot be inspected often and the probability of leaks and generating pollution is higher.

ASTs are essential assets of the plant and critical to the plant's operation and products storage. An important objective in supply distribution is to meet user demands on time and in a cost-effective manner. Changing the service of an existing AST is a common strategy in meeting the demand. It is intended for variety of reasons such as change in product stored, utilizing mothballed existing ASTs, etc. American Petroleum Institute (API) recognizes the need for change in service and provides guidelines for evaluating the existing ASTs for a new service.

The most widely recognized industry standard for the evaluation of field-erected ASTs is API Standard 653, "Tank Inspection, Repair, Alteration and Reconstruction". This also references API Standard 579, "Fitness-for-Service" for performing more detailed fitness-for-service evaluations when circumstances warrant a more comprehensive assessment.

This paper will focus on the AST and will describe the methodology for changing service of existing ASTs as a circular economy concept. Also, the paper aims at developing a systematic review and technical evaluation through listing the input parameters and factors along with the description of each item that might affect the change in service.

2. Methodology

Change in service of existing ASTs require careful evaluation and assessment based on several factors affecting the tanks design, inspection and operations. This is a multi-discipline evaluation looking into multiple aspects of the tank design and functionality. The systematic review and technical evaluation, here by listing the input parameters and factors along with the description of each item that might affect the change in service will help the designer and maintenance engineers to expand their propagability for implementing circular economy in their areas.

As a case study in Saudi Aramco, we expanded our efforts in circular economy and successfully switched one of the existing fixed dome roof Heavy Diesel Oil (HDO) aboveground Storage Tank to Fire Water Tank. But, before this decision was taken, we considered and evaluated number of parameters and factors, which can affect the change in service of the existing ASTs with no negative impacts on the plant's operations. Following items were evaluated to make sure that the system integrity is maintained:

1. *Specific gravity*: Increase in specific gravity of the new service fluid will impact the tank shell thicknesses and lead to effects on foundation loads. Thus, calculating the maximum allowable design and normal liquid levels will be needed to mitigate the impact on foundations.

2. *Volatility*: Volatility of the new service fluid will impact the suitability of the existing tank roofs. Volatile fluids will require to add Internal Floating

Roofs (IFR) in existing fixed cone or dome roof tanks, which will have potential impact on the liquid levels, internals, venting requirements and the foundation loads.

3. *Fluid corrosivity*: If the new service fluid is more corrosive than the existing service fluid, corrosion study shall determine the mitigative actions like adding corrosion allowance, recalculating cathodic protection or applying suitable internal coating.

4. *Design pressure*: Increase in design pressure (internal &/or external) of the tanks for new service will impact the tank shell thicknesses and foundation loads. This may also potentially require assessment of the tank for applicability of API 650 Annex F & V and subsequent alterations to the tank roof and roof-to-shell junction.

5. *Design temperature*: Increase in design temperature of the tanks for new service may impact the tank shell thicknesses and the foundation loads. This might also potentially require assessment of the tank for applicability of API 650 Annex M.

6. *Liquid levels*: Tank users have to be flexible with liquid levels as it may not be possible to maintain the existing liquid levels. As indicated above under specific gravity, maximum allowable liquid levels may be reduced due to increase in the specific gravity. For volatile fluids, when IFR is added the liquid levels have to be reduced to accommodate the IFR.

7. *Material of construction (MOC)*: Existing AST MOC shall be verified for suitability to new service. The physical and chemical properties of the existing materials shall be compatible with the new service and operating conditions.

8. *Process internals*: Liquid inlet distributors may have to be added when IFR is added to the existing tanks. Other tank internals like floating suction, floating skimmers or stilling wells may have to be added based on the type and criticality of the new service.

9. *Tank accessories*: Tank accessories like the requirement of instrumentation nozzles, mixers, heaters, etc., shall be reviewed by the process engineer.

10. *Filling and discharge rates*: Any increase in the filling and discharge rates may impact the tank inlet and outlet nozzle sizes. Tank process nozzle sizes verification will be required to be performed by the process engineer based on the new filling and discharge rate changes. Tank nozzle modifications shall be performed in accordance with API-653.

11. *Venting requirements*: Any increase in the filling and discharge rates or higher flammability of the new process fluid may impact the tank venting requirements. Thus, the existing venting capacities shall be verified for suitability for new service by process engineer in consultation with the vents manufacturer.

12. *Peripheral seals*: Compatibility of the seals for new service shall be verified. The secondary seal fabrics check shall be performed when the tanks are cleaned. Hydrotest the roof drain as a precaution.

13. *Cathodic protection (CP)*: Integrity of the existing cathodic protection systems shall be verified prior to reusing the existing CP system. In addition, the existing internal CP system shall be redesigned if the corrosivity of the new service is higher than the existing.

14. *Fire protection (FP)*: Based on the flammability of the new service, FP requirements of the tank and the area around the tank shall be considered while planning of retaining or repairing the tank.

15. *Coating requirements*: Based on the corrosivity of the new service, the internal coating systems shall be assessed by the corrosion or coating engineer.

16. *Insulation requirements*: Based on the flammability and design temperature of the new service, the tank shall be assessed if a heat conservation insulation is required.

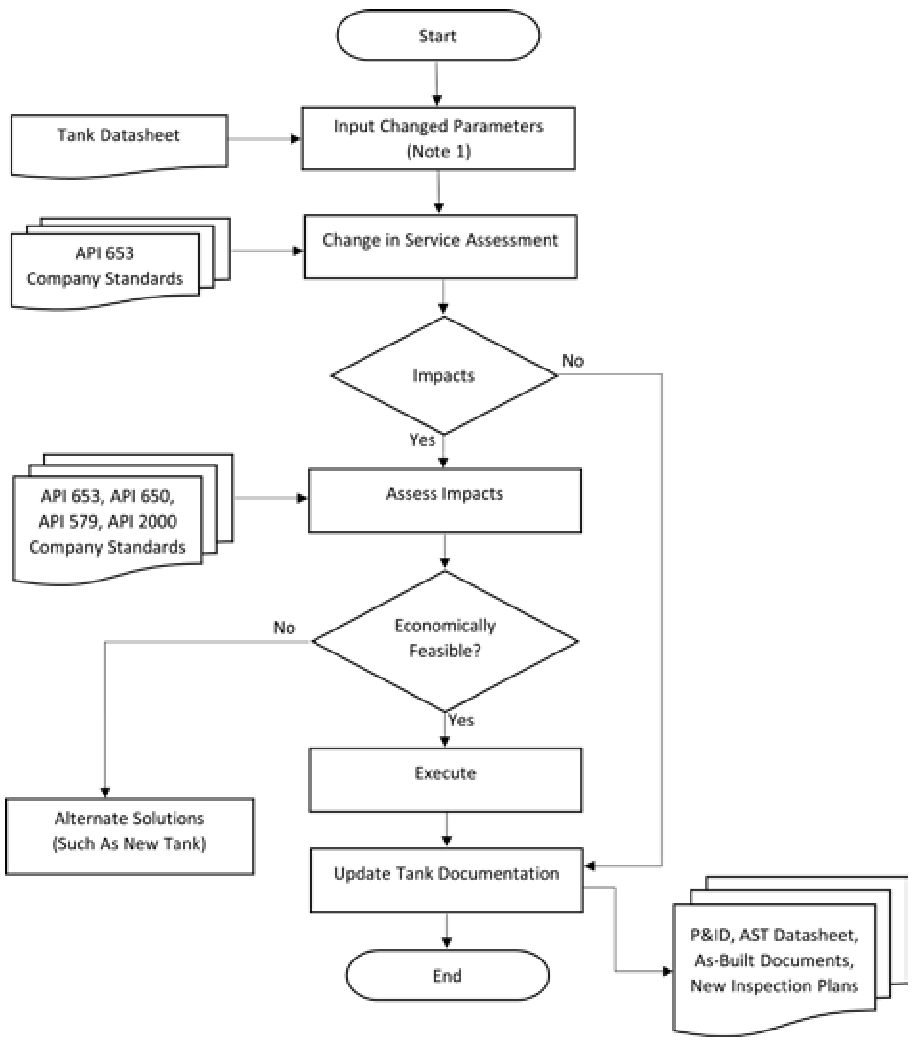
17. *Foundation loading*: Increase in specific gravity without changes to the liquid levels will have impact on the foundation loadings. Adding IFR in a fixed roof tank will also have impact on the foundation loadings. Foundation loading assessment has to be

performed by the civil engineer to verify the adequacy of the existing foundations to be used as is. Mitigative actions could be to alter the liquid levels to retain the foundation loadings to existing, if it is feasible from operation point of view.

18. *Maintenance and Inspection data*: Inspection records play a prominent role in assessing the physical condition and remaining life of the tank. Recent Ultrasonic Thickness (UT) readings and tank floor Magnetic Flux Leakage (MFL) reports shall be used in the mechanical design and integrity check for the new service. Mitigative actions such as altering liquid levels, repairing the tank components (shell, bottom plates, roof, etc.) shall be considered for adopting the tank to new service.

19. *Past repairs*: Decision to retain or repair the tank shall be based on past repair records. All the past repairs are to be factored in while verifying the suitability of the tank for new service.

20. *Mechanical integrity*: AST mechanical integrity check shall be performed based on the new operating fluid parameters and operating conditions. Evaluation of the stress levels plays a critical role in the process of changing the service of an AST, underestimating the actual stress or overestimating the allowable stress may lead to overstress or failure of the AST. Many a times lack of existing AST technical documentation is a major challenge in establishing the existing design criteria. Hence, mechanical integrity assessments shall be performed by an experienced AST engineer.



Note 1: Specific gravity, design temperature, design pressure, flowrates, liquid levels

Note 2: Shell thicknesses, foundation loads, weights, vent capacities, nozzle sizing, process internals, internal coating, internal floating roof, tank accessories, insulation, additional non-destructive examinations, new inspection plan.

Figure 1: Change in Service Flowchart

Comprehensive inspections of existing AST shall be performed by a certified API 653 authorized inspector. After that, the Tank Engineering Specialist shall decide any additional non-destructive testing or hydrotest requirement based on the mechanical integrity check. AST settlement survey should be also evaluated in accordance with the provisions of API 653, Annex B if hydrotest is performed.

After completion of the AST change in service assessment and put into operation, a new internal inspection plan has to developed for the new service.

Maintaining accurate and up-to-date documentation is essential for tracking AST design changes. It is imperative to update the AST datasheets, Vendor As-Built drawings, tank accessories Original Equipment Manufacturer (OEM) manuals, inspection records, repair & maintenance records for future reference.

As a summary, Figure 1 describes the required assessment and its steps and processes that should be followed for any change in service for aboveground storage tanks.

For our case study that was done to change the service of existing fixed dome roof Heavy Diesel Oil (HDO) Tank to Fire Water Tank, the results of the assessment were analyzed and recommended to switch the service for the tank as summarized in the Appendix-1.

Factors Evaluated	Existing Service	New Service	Remarks
Service	Heavy Diesel Oil	Fire Water tank	
Design Code	API 650	API 650	
Specific gravity	0.875	1.0	Heavier fluid will impact thickness and foundation loads.
Volatility	Less volatile	Not volatile	No requirement of floating roof.
Fluid corrosivity	Less corrosive	More corrosive	Validated corrosion allowance and internal coating requirements by corrosion specialists.
Design pressure	0.29 psig	0.29 psig	No change.
Design temperature	190° F	190° F	No change.
Liquid levels	42ft - 6 in.	42ft - 6 in.	No change.
Material of construction	Carbon Steel	Carbon Steel	Validated for new service.
Filling rate	750 GPM	1650 GPM	
Discharge rate	130 GPM	4530 GPM	
Venting requirements	1 - Emergency Vent 3 - Breather valves	Adequacy of the venting capacities to be verified.	Adequacy check by valve vendor based on the new filling and discharge rates is in progress.
Cathodic protection	Existing available	Required	Site survey report indicates cathodic protection system in healthy condition.
Coating requirements	Phenolic epoxy	Existing Phenolic epoxy is suitable	Validated by coating specialist.
Foundation loading	Existing	Foundation loading increased due to specific gravity increase	Design engineering specialist hired to validate the existing foundation adequacy.
Maintenance and Inspection data	Recent UT readings and tank floor MFL reports verified.	Recent UT readings and tank floor MFL reports verified.	No major material loss reported.
Past repairs	None	Not applicable	
Mechanical integrity	Tank in good condition for current service	Acceptable for new service	Tank mechanical integrity was checked using a tank design software adopting the actual thicknesses from recent UT report and new operating conditions.
Process internals	None	None required	
Tank accessories	Heater & Mixer	None required	Recommended to demolish Heater & Mixer and blind the nozzles.

Table 1: Appendix – 1

3. Conclusion

In conclusion, the AST is an essential and critical asset in oil & gas industry as a kind of the circular economy efforts. AST change in service may be required for various reasons and is technically feasible. Thus, this paper summarizes most of the critical technical requirements to be evaluated and to ensure that the change in service is performed safely and in accordance with industry international standards. This kind of assessments shall be conducted systematically and its evaluation shall be performed by qualified team consisting of certified inspectors, process engineers and tank specialist to avoid any undesirable effects. This technical assessment is worthwhile to be conducted since the main advantages of change in service are not limited to significant cost saving, meeting required demand, fast and feasible solution but it will be more than our expectations.

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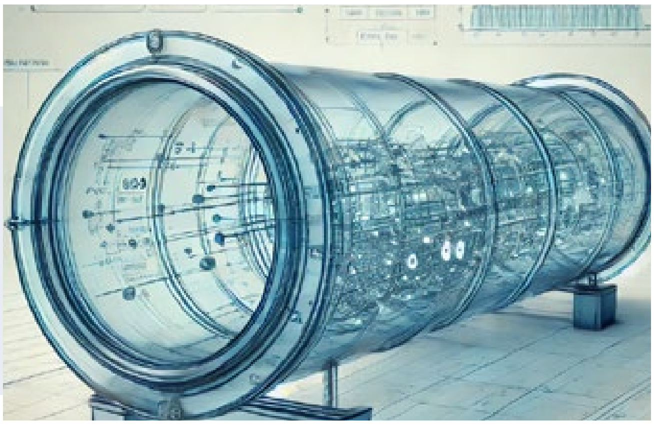
Ask the Experts



Digitalization & Security

Q1) Where do you see the main possibilities of AI for pipelines in the future?

Ove Heitmann Hansen: I see immense potential for AI, Machine Learning and Hybrid models in the pipeline industry's future. The power lies in interoperability and utilization of complex systems, but you need to get the foundation right with structured and qualified data. The main possibilities cover:

I. ***Predictive Maintenance:*** AI can analyse data from sensors to predict when parts of the pipeline might fail, allowing for proactive maintenance, faster replacements, and reduced downtime.

II. ***New infrastructure:*** Optimal route selection of new pipelines utilizing geospatial analysis of local and global datasets.

III. ***Data analysis:*** Process vast amounts of data to provide insights and trends that can inform decision-making and strategic planning. AI can assess complex datasets faster and more effectively, enhance data quality and accuracy, and fill in data gaps.

IV. ***Leak detection:*** AI and advanced algorithms can detect anomalies in pressure and flow data, identifying leaks more quickly and accurately than traditional methods.

V. ***Optimization of operations:*** AI can optimize the flow of materials through pipelines, adjusting parameters in real time to maximize efficiency and reduce costs.

VI. ***Safety enhancements:*** Simulating "perfect storm" failure scenarios across a pipeline network and connected datasets by identifying pre-markers that will lead to those scenarios. AI can monitor pipelines for potential safety hazards, such as corrosion or external damage, and alert operators to take preventive measures.

VII. ***Environmental monitoring:*** AI can help monitor environmental impacts, ensure compliance with regulations, and minimize ecological damage.

VIII. ***Automation:*** AI can automate routine tasks, freeing up human operators to focus on more complex issues and create training material for new engineers as well as

Q2) How can AI algorithms be utilized to predict and prevent potential pipeline failures or disruptions, and what are the best practices for implementing these solutions?

Ove Heitmann Hansen: Digitalization and AI capabilities depend on trust and quality of the data. The data quality assurance and certification can range from trivial rules to complex evaluations and verifications based on reasoning mechanisms, Machine Learning, and AI, emphasizing data quality, confidentiality, integrity and availability. To predict and prevent potential pipeline failures or disruptions, we need to establish the following capability levels:

I. ***Descriptive Level:*** The current state is described and visualised by cleaning the data and making it accessible to understand what is happening. This could, for example, be a 3D model.

II. ***Diagnostic Level:*** By adding sensor information to the descriptive model, decisions about the current state or condition can be made by identifying correlations in data to understand why it is happening.

III. ***Predictive Level:*** By adding intelligence and analytics to the diagnostic model, one can start to predict future states, like remaining useful life, to understand what will happen.

IV. ***Prescriptive Level:*** Adding more advanced intelligence, AI, and hybrid models can recommend actions based on the actual condition, such as replacing a specific part within a certain timeframe.

V. ***Automated Level:*** By connecting AI algorithms and the complex system to other systems, it could generate actions automatically, i.e., closing the control loop.

Establish capability levels I-IV at minimum to predict and prevent potential pipeline failures or disruptions.

We at DNV have developed a Digital Trust framework, together with the industry, of standards covering best practices:

- DNV-RP-0497 Assurance of data quality management
- DNV-RP-0317 Assurance of data collection and transmission in sensor system
- DNV-RP-A203 Technology Qualifications
- DNV-RP-0510 Assurance of data-driven applications
- DNV-RP-0665 Assurance of machine learning applications
- DNV-RP-0513 Assurance of simulation models
- DNV-RP-A204 Assurance of digital twins
- DNV-RP-0575 Cyber Security
- DNV-RP-0670 Asset information modelling framework
- DNV-RP-0671 Assurance of AI-enabled systems

Q3) With increasing cyber threats, especially in the context of geopolitical tensions, what are the key elements of a robust cybersecurity strategy for pipeline operations, and how can operators stay ahead of evolving threats?

Jon Hopkins: Pipeline operators should develop and maintain a comprehensive threat intelligence plan to stay ahead of evolving cybersecurity threats. This plan should involve continuous monitoring for new and emerging threats, analysing their potential impacts, and proactively addressing any identified vulnerabilities. By staying informed about the latest threat landscape, operators can better anticipate and mitigate risks before they materialize.

Regularly running tabletop exercises is another crucial strategy. These exercises simulate potential security incidents, allowing the organization to test and refine its response plan. Tabletop exercises should not be a one-and-done affair; rather, they should be revisited multiple times a year to ensure incident response plans run as smoothly as possible. Through these simulations, operators can identify weaknesses and areas for improvement. Iterating on these findings helps build a more resilient security posture that is ready to handle real-world threats.

Furthermore, vigilance against phishing attempts is essential. Phishing remains one of the most common and effective methods for cyber attackers to gain unauthorized access. Now, with generative AI usage on the rise, we are seeing more sophisticated phishing tactics, making detection that much harder. Educating employees about how to recognize and report suspicious emails and other forms of communication is vital. This awareness can significantly reduce the risk of data breaches and unauthorized access, protecting the organization's sensitive information.

By implementing these measures, pipeline operators can enhance their cybersecurity posture and better protect their critical infrastructure from evolving threats.

Q4) What are the key considerations and challenges when using simulation models to transition existing pipeline systems to accommodate hydrogen?

Tony Alfano: Transitioning existing pipeline systems to accommodate hydrogen presents several unique challenges that must be addressed through careful simulation and modelling. The key considerations include:

I. Material Compatibility: Hydrogen can cause embrittlement in certain metals, potentially leading to cracks and failures. Simulation models must accurately predict how different materials in the existing infrastructure will interact with hydrogen over time.

II. Flow Dynamics: Hydrogen has different flow characteristics compared to natural gas. Models need to account for these differences to ensure proper pressure management and flow control.

III. Leak Detection: Hydrogen molecules are smaller and more prone to leakage. Simulation models must be adapted to detect and predict potential leak scenarios specific to hydrogen.

IV. Blending Scenarios: Many transitions will involve blending hydrogen with natural gas. Models need to simulate various blending ratios and their impacts on the system.

V. Safety and Risk Assessment: Given hydrogen's high flammability, safety simulations are crucial for risk assessment and mitigation planning.

The main challenge lies in the accuracy of these models, given the limited real-world data on large-scale hydrogen pipeline operations. At DNV, we're developing and validating these models through a combination of laboratory testing and pilot projects, leveraging our extensive experience in natural gas and hydrogen systems. Overcoming these challenges requires a multidisciplinary approach, combining materials science, fluid dynamics, and risk assessment expertise.

Q5) How are digital twins being used to enhance predictive analytics capabilities in pipeline monitoring, and what are the main technological and data challenges to be addressed?

Ove Heitmann Hansen: Network demand, especially for natural gas, can fluctuate greatly not only day-to-day, but hour-by-hour. Internal pressure associated with high demand and increased flow places higher stress on the pipe, which brings it closer to its failure state. Overlaying and aligning network analysis/hydraulic modelling, maintenance records, operational history, integrity assessments, corrosion control data (e.g. CP performance, CIS and VG surveys, coupon sampling), and other complementary datasets, including externally available data, is already occurring to help operators pinpoint potential risk along a pipeline. The next step is providing an engineer or analyst with the ability to leverage these aligned datasets (i.e. "Digital Twins) daily, empowering them to work smarter and faster; however, this relies on implementing a robust enterprise data platform with a well-planned architecture. The future will be an interface/application that allows those engineers to "drag and drop" data from various datasets to build their own AI/ML models that will enable them to make critical, thoughtful, and tactical decisions while removing the more tedious data cleansing tasks that many are burdened with today. The two biggest challenges are:

I. *Digital Architecture and Data Platform:* Implementing a Digital Data Platform that integrates various information models, ensures interoperability, and provides shared services across the company is fundamental, as well as hosting, validating, contextualizing, securing, and managing structural data.

II. *Data Alignment and Relationships:* Understanding how data is aligned is a critical first step to ensuring that a digital twin is represented correctly. The relationship between data and the asset it is associated with can sometimes be complex, and a reflective approach may be required on a case-by-case basis (e.g., time-series SCADA data, which is a point associated with segments of pipe within a pressure network).

Hence, an assurance process of digital twins for Data-driven verifications and predictive analytics needs to comply with technology qualification, capability and data quality assessments, and verifications of all simulation models and AI-enabled systems.

Q6) What strategies can pipeline operators employ to ensure the interoperability of various digital systems and platforms across their operations?

Ove Heitmann Hansen: Ensuring interoperability across diverse digital systems is crucial for maximizing the benefits of digitalization in pipeline operations. Steps that can be taken to ensure interoperability between digital systems and the data they own and manage are as follows:

I. *Unique identification across digital systems:* Assets have one unique identifier that is utilized in all digital systems (i.e., one asset does not have different names/IDs in different digital systems). For example, a mainline valve is identified in the Work Management System, in the SCADA system, and GIS.

II. *Data Standardization and Protocols:* Deploying Data Standards that establish common data formats and standards across the organization ensures that different systems can easily share and understand data. Minimizing free-form text fields and utilizing domains whenever possible will alleviate future misinterpretations, both by humans and computers (e.g., machine learning models).

III. *Data Relationships and Connectivity:* Create data relationships that can be programmatically deployed when combining data sets across digital systems. Most often, companies will utilize Middleware to develop rule-based bridges between different systems that enable them to exchange data and function together.

IV. *One System of Record:* There should be one system of record that is identified as the "truth" and cascades to other applicable digital systems automatically (i.e., an update to the system of record gets pushed to all other applicable digital systems). This minimizes the effort to update an asset and its data and ensures that other systems that utilize this data are quickly kept up to date.

V. *Benchmarking:* Benchmarking current work processes and data flows to ensure they are running optimally. When gaps or opportunities are identified, a thoughtful approach to streamline these processes will reduce the time it takes for data to move from capture to storage. This can be critical in making informed decisions based on all available.

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

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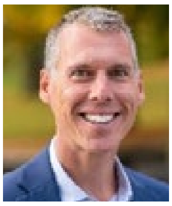
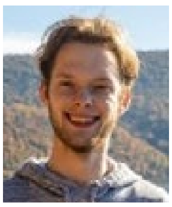


Tony Alfano, Pipeline Product Line Director, DNV
Tony Alfano leads the Pipeline Product Line at DNV Digital Solution, bringing decades of experience in helping clients navigate complex safety and reliability challenges. As a trusted advisor, he combines deep industry knowledge with innovative approaches to optimise risk strategies for pipeline networks and facilities worldwide. A recognized thought leader, Tony has authored international publications and frequently speaks at industry workshops. His passion for integrating science and technology drives DNV's development of cutting-edge solutions, significantly enhancing pipeline safety for clients across the globe.

Ove Heitmann Hansen, Senior Principle Digital Trust, DNV
Ove Heitmann Hansen leads the Digital Trust initiatives and services in North America, enabling our customers and their stakeholders to manage digitalization risk and complexity with confidence. Ove is a recognised Digital Trust advisor and drives DNV's development of qualification and assurance processes of digital solutions, where quality and trustworthiness need to be continuously assessed. He has authored international publications and frequently speaks at industry conferences. His passion for Digital Trust significantly enhances the digital transformation for clients across the globe. Ove claims that "If you cannot trust your digital representation, technology or data, you cannot use it in the real world".



Jon Hopkins, Synergi Pipeline Security Lead, DNV
Jon Hopkins is the Security Lead of Synergi Pipeline in DNV Digital Solutions. As a new member of the Pipeline Integrity team, he's dedicated to fostering a culture of security awareness and continuous improvement within DNV's Software Engineering unit.

A Spotlight on the Future: Young Professionals Shaping the Pipeline Industry

Constantin Schreiber
Managing Editor
EITEP Institute

As Editor of the Pipeline Technology Journal I am proud to announce a new column in the ptj. In our Pipeline People segment on the ptj website we already have interviewed young professionals in the pipeline industry. But with the **ptj Young Pipeliner** column we add another way of supporting the new generation of people who have decided to work in this field and give them a opportunity to reach out to pipeline professionals all over the world.

The pipeline industry, a cornerstone of global infrastructure, is undergoing a transformation. As we look to the future, it's clear that innovation, sustainability, and technological advancements will be key drivers of change. However, the most critical factor in ensuring the industry's continued success is its people. In this column, we aim to shine a spotlight on the young professionals who are joining the pipeline industry and shaping its future.

These young engineers, technicians, and other specialists bring fresh perspectives, new ideas, and a deep understanding of emerging technologies. They are the innovators who will develop the next generation of systems and programs, the problem-solvers who will find creative solutions to complex challenges, and the leaders who will guide the industry into a sustainable future.

In each installment of this column, we will feature papers of young pipeliners who are making a contribution to the pipeline industry. Ultimately, the goal of this column is to be a spotlight that highlights the ideas and innovations coming from this new generation of pipeline professionals.

Sincerely Yours,

Constantin Schreiber
Managing Editor
EITEP Institute

Validation of ILI Performance, the Importance of ILI Validation in the Energy Transition to Hydrogen Fuels

T. OLDFIELD > ROSEN GROUP

Abstract

Validation of ILI performance is a critical component of any in-line inspection campaign to ensure that the ILI performance specification has been achieved. This allows high confidence integrity decisions to be made using the ILI data. The issues posed by the energy transition and the introduction of Hydrogen into existing gas networks present acute challenges for the accurate sizing of crack-like features and the subsequent validation of ILI performance in accordance with API 1163.

This paper discusses the current challenges of validating crack-like defects and the implications of the current industry practice with regards to the requirements of the Hydrogen transition.

1. Introduction

In-line inspection (ILI) tools can measure a range of different defect types with a high degree of accuracy especially considering the harsh environments that the tools operate in. However, there are occasions when the specification of the tool can not be met due to the operating conditions, feature specific morphology and other factors. It is essential therefore to understand if the tool has performed within its specification on a run by run basis. In the US this is a legal requirement under PHMSA, but is seen as best practice in most other countries around the world.

Validation of crack like defects is a manual process which is significantly influenced by the procedure utilised and the skill and experience of the in-field operator. Significant variability can therefore be seen in the tolerances of these inspections which has significant implications on the validation of the ILI tool.

The introduction of Hydrogen into the gas networks will reduce the critical flaw size of crack-like indications due to the potential embrittlement of the material. The inclusion of additional uncertainty in the ILI tolerance could be detrimental to the integrity of the pipeline network.

If in-field verification of an unknown quality is used to validate the ILI for hydrogen conversion pipelines, the additional uncertainty that can be attributed to crack sizing of unknow quality can be significant enough to cause failure in a number of features in cross country pipelines.

2. ILI Validation

Despite advances in technology, ILI validation is still a very manual process and the tolerances associated with each feature are significantly influenced by user skill and experience as well as technology selected. User variance is most significant in crack sizing where there are a number of different technologies that have the capability to size cracks all with pros and cons for various morphologies and combined feature types.

However, independent user tolerance is rarely known in in-service inspections due to the variability and challenges with understanding system performance. Therefore conservative tolerances should be adopted, like the ones seen in BS 7910. These are fine to use for individual integrity assessments as the conservative nature of the measurement means that safe repair options will be utilised. However applying these conservative tolerances to ILI validation measurements puts a significant amount of uncertainty in the ILI measurement. A ±3 mm tolerance for shear wave UT is recommended by BS 7190 [1], which at a 1 mm detection threshold would make most features unacceptable in cross country hydrogen pipeline.

In order to reduce the tolerance of the in-field inspection, a blind trial is required to understand specific inspector tolerance using the chosen inspection system.

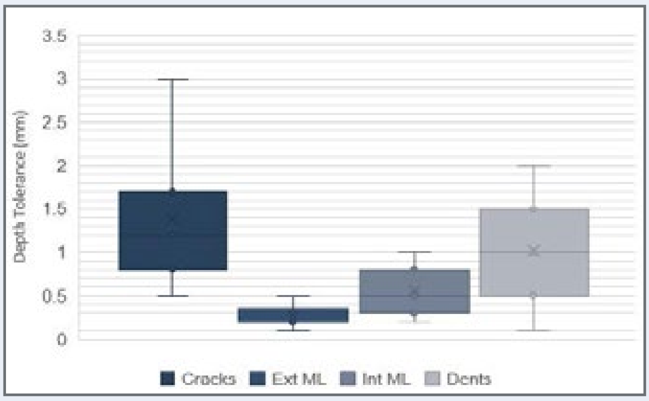


Figure 1: Potential tolerances of various feature types

3. Hydrogen Effect on Validation

The EPRG review on integrity assessment methods for hydrogen conversion [2] discusses how the tolerable crack dimensions are affected by the introduction of hydrogen into the gas networks with various charpy toughness's and are shown in Figure 2.

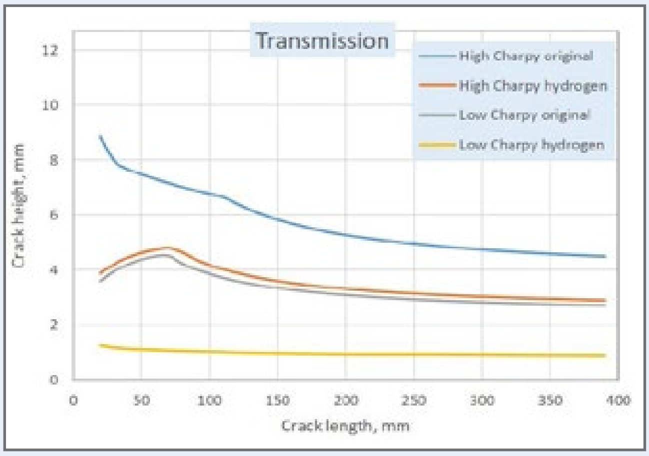


Figure 2: Tolerable seam weld axial cracks for transmission pipelines

The introduction of hydrogen will reduced the tolerable feature size for crack depths (especially for weld of low toughness's), which means that the confidence in the ILI tolerances are more important because there is less scope for uncertainty in the assessments.

4. Validation to API 1163

When validating ILI performance to API 1163 [3] a validated feature is considered within specification if the following criteria is met:

$$\delta e_{comb} = \sqrt{[\delta(\frac{d}{t})_{ILI}]^2 + [\delta(\frac{d}{t})_{FIELD}]^2} \quad (1)$$

Equation 1 has numerous implications but the most significant in this instance is that bigger the in-field tolerance can result in a measurement which is acceptable, but inadvertently lowers the confidence in the ILI measurements.

Therefore a validation tolerance which has minimal influence (Ideally less than 10% of the stated ILI tolerance) on the combined tolerance is the only way to guarantee the ILI specification is representative of the validation.

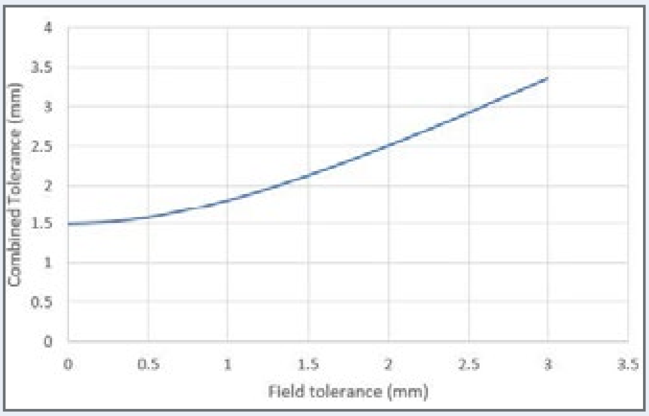


Figure 3: Influence of field tolerance on the combined tolerance

5. Conclusion

The introduction of Hydrogen into the gas network is going to reduce the tolerable crack size which means that having higher confidence in the ILI measurement and tolerance will become more critical to avoid failures. This can only be achieved in-field by understanding the tolerance of the individual inspectors and creating a small influence on the combined tolerance from API 1163. This can be accomplished by blind trials on individual inspectors.

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1. British Standard, BS 7910, Guide to methods for assessing the acceptability of flaws in metallic structures 2022.
2. EPRG, Project number 14223, Integrity assessment method review, 2022.
3. API 1163, In-line Inspection Systems Qualification, 2021.

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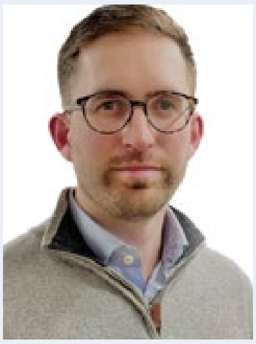

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