Prevention and Detection of Leakage on Buried Pipelines Using Vibroacoustic Technology Within a Holistic Framework

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Pipeline Pigging and Integrity Management Conference

February 12-16, 2024

Organized by
Clarion Technical Conferences

https://doi.org/10.52202/072781-0073

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Abstract

This paper focuses on detection of leakage occurrences, particularly those that occur on buried pipelines and can be caused by factors such as corrosion, wear, or illegal tapping. Such events can cause considerable harm to the pipeline operator and the environment, including critical damage to the pipeline and surrounding lands, leading to large remediation expenses and operational downtime.

The management of assets has the primary objectives of ensuring reliability and integrity of pipelines during their operations. To achieve these goals, procedures and technological systems are implemented to quickly detect and address any possible or real hazards to the integrity of the assets. Vibroacoustic Technology presents a solution to this problem by detecting both the leakage and its precise location, as well as other anomalies involving the pipe and/or the transported fluid. This technology is currently operative globally, protecting thousands of pipeline kilometers, primarily on buried pipelines.

Initially developed for Leak Detection (LD) applications, the Vibroacoustic Technology has demonstrated excellent performance in detecting and localizing spillages and impact events in real-time. In certain conditions, it has also been shown to identify activities that precede a spill, such as illegal tapping preparation activities, corrosion, and wear. The present work highlights the outstanding performance of this technology in detecting illegal tapping in Italy, with multiple examples reported.

Before the implementation of this technology, Italian pipelines transporting refined products suffered numerous leakages due to fraudulent activities. However, after the extensive deployment of Vibroacoustic Technology across the pipeline network, illegal tapping almost ceased to exist. The use of this technology was later adopted as a prevention tool, and a complete presentation of the challenges and solutions put in place to overcome them is included in this work. The success of this implementation was due to a holistic approach and a high level of collaboration between multiple parties.

In conclusion, Vibroacoustic Technology presents a reliable solution to detect and prevent leakage occurrences, particularly illegal tapping, in pipelines. The technology has demonstrated outstanding performance in real-world scenarios, and its widespread deployment has resulted in a reduction of pipeline incidents, protecting both the operator and the environment.

The present work provides a comprehensive overview of the challenges and solutions involved in implementing this technology, highlighting the importance of a holistic approach and active collaboration between pipeline operator, local inspection teams and law enforcement to achieve successful results.

Introduction

In the constantly evolving oil and gas industry, innovative solutions are essential to effectively address pipeline integrity challenges. Pipelines, serving as energy transportation lifelines, demand paramount reliability and longevity. This paper explores the critical issue of detecting and localizing leakage

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occurrences, which pose significant threats to both pipeline operators and the environment, since they could lead to substantial damage, extensive remediation costs and operational downtime.

Effective asset management centers around ensuring the reliability and integrity of pipelines throughout their operational lifecycle. Established procedures and technological systems quickly detect and address potential or actual hazards to asset integrity.

Vibroacoustic Technology emerges as a game-changer in real-time sensing for pipeline integrity due to its versatile applications and easy deployment. This cutting-edge technology, retrofittable to existing assets, is cost-effective and employs advanced sensors to detect subtle vibrational and acoustic anomalies along pipelines. Vibroacoustic waves, generated by leaks, third-party interferences, and illegal tapping preparations, propagate upstream and downstream for tens of kilometers at the speed of sound.

In Italy, prior to the widespread deployment of Vibroacoustic Technology, pipelines transporting refined products suffered numerous leakages originated from illegal tapping. However, following the extensive adoption of this technology across the pipeline network, incidents of illegal tapping significantly diminished, nearly eradicated. Its application shifted from detection to proactive prevention, with this paper providing a comprehensive presentation of challenges and solutions. Success is attributed to active collaboration among pipeline operators, local inspection teams, and law enforcement.

In summary, Vibroacoustic Technology emerges as a reliable solution for detecting and preventing pipeline leakage, particularly illegal tapping. Its performance and broad deployment substantially reduce incidents, safeguarding operators and the environment. This paper offers a comprehensive overview of challenges and solutions crucial to technology implementation, highlighting the significance of a holistic approach for successful outcomes.

Understanding the Vibroacoustic Technology

This chapter analyzes the deployment of Vibroacoustic Technology, highlights common challenges, and provides a detailed explanation of leak detection techniques.

Hardware and technology deployment

The Vibroacoustic Technology operates through a network of multiple sensor blocks, each one composed of a set of sensors, strategically positioned along a pipeline. These sensor blocks are connected to any telecommunication system for seamless data transfer to a central processing server. Specifically designed sensor blocks capture the complete elastic-dynamic wave field, measuring vibrations, acoustic pressure, and gauge pressure.

Upon the initiation of a vibroacoustic source, the generated acoustic and elastic waves propagate upstream and downstream at the speed of sound. The sensor blocks record these signals, and the remote-control unit continuously transmits data to the processing server. The leak detection modules, situated in the processing server, executes advanced digital processing chains, including non-linear

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filters, real-time noise estimation and removal, leak detection, and multi-channel localization as shown in **Figure 1**.

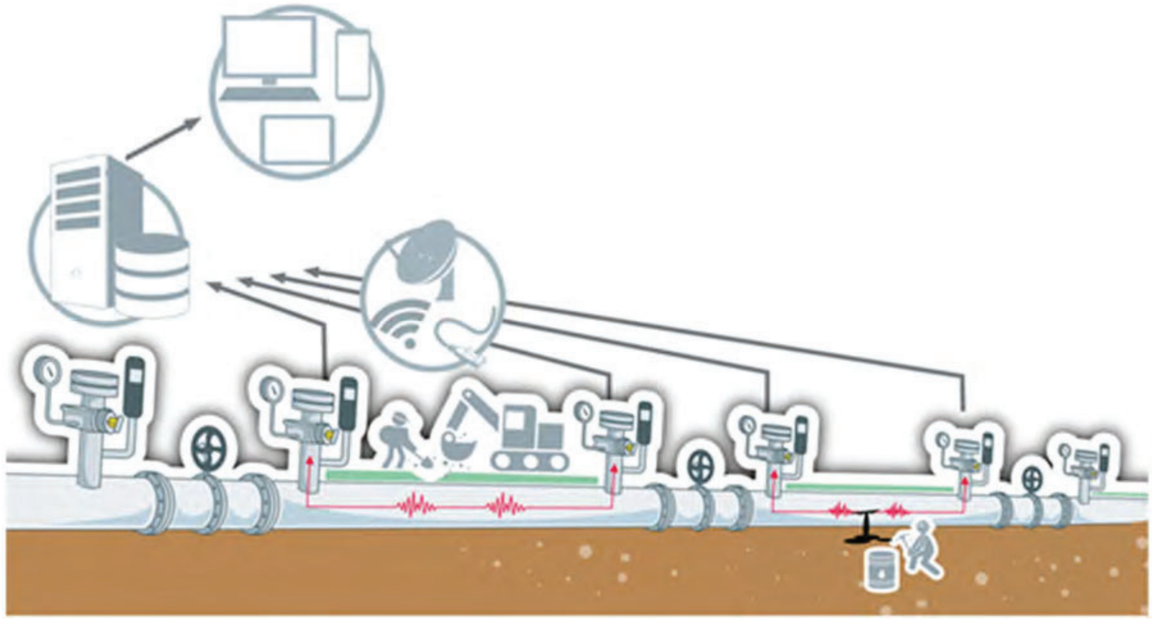

Figure 1. Vibroacoustic hardware structure: Mechanical disturbances, such as leakages, impacts, or excavations, engage with the pipeline, generating a vibroacoustic wave that travels along the pipeline. The anomaly reaches the sensors, and the recorded data is transmitted to a central processing unit.

The core processor analyzes pressure waves in conjunction with micro-vibrations and sound data. This integrated information facilitates the identification and precise localization of anomalous noise sources. The signal processing algorithms are sophisticated, and the system relies on highly sensitive sensors capable of detecting subtle yet informative vibrations.

A pipeline serves as an efficient wave-guide system: vibrations propagate through the solid shell, while the acoustic pressure field extends for kilometers within the fluid. Leveraging these characteristics, Vibroacoustic Technology achieves exceptional and superior detection performance levels compared to conventional pressure-based systems.

Vibroacoustic sensor blocks are suitable for retrofitting existing pipelines as they can be installed on pre-existing hydraulic derivations, eliminating the need for hot tapping. The standard sensor block exhibits resilience to harsh environmental conditions, while the shallow water sensor block can be submerged or buried **(Figure 2)**. The pipeline remains suitable for pigging after its installation.

The selection of the sensor block type depends on project-specific characteristics. While regular sensor blocks are suitable for countries with high rainfall rates, such as Brazil [1], they cannot be buried or submerged. The installation does not necessarily need to be directly on the pipeline; it can be on bypasses available above the soil without a decrease in performance. In swampy areas like the Niger river delta, the Shallow Water sensor blocks are deployed due to the terrain's nature and to conceal sensors outside operator facilities [2].

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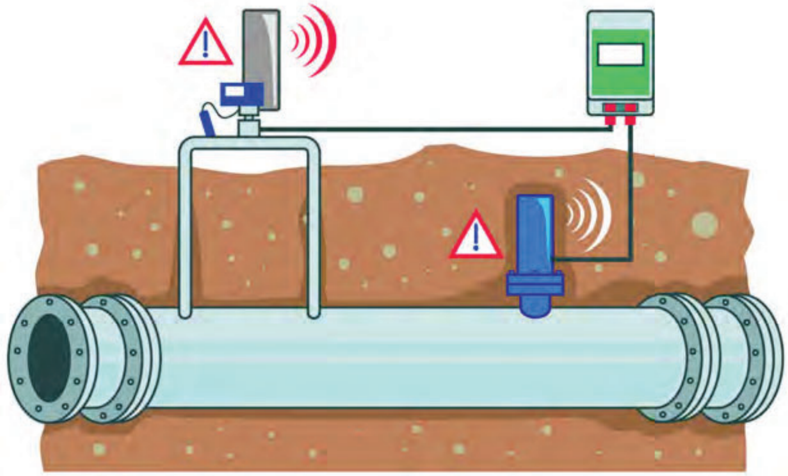

Figure 2. Vibroacoustic sensor blocks installation on buried pipelines: regular sensor (gray, upper left) and shallow water sensor (blue, bottom right)

Both types of sensor blocks can be configured to acquire data at various frequencies and with different rationales, depending on the chosen leak detection methods for a particular pipeline. These sensors hold ATEX certification (Ex i), ensuring suitability even for sour fluids, i.e., mixtures containing hydrogen sulfide (H_2S).

The sensor blocks are linked to an acquisition unit. This acquisition station is responsible for promptly collecting and transmitting real-time data to the central processing server. The network data transfer requires less than 20 kbit/s and utilizes any available communication channel, such as LAN, Wi-Fi, ADSL, UMTS, or Satellite.

The acquisition units have low power consumption, drawing less than 20W, and can be powered by solar panels, fuel cells, or directly connected to the mains. In the case of temporary installations, portable sensor blocks are powered by a 12V battery.

Exploring different leak detection methods

Leaks can arise and evolve through various mechanisms, producing distinct discernible indicators. This diversity demands the use of distinct leak detection methods to identify all types of leakages. By exploring the characteristics of leaks, three primary vibroacoustic leak detection methods can be established: advanced negative pressure wave, acoustic noise, and mass balance.

Advanced negative pressure wave method

The advanced negative pressure wave method is known for its highly effective real-time leak detection and localization capabilities. It excels in promptly identifying the initiation, variation, or cessation of a leak, and can detect strong deforming impacts and most precursor events of illegal tapping.

Elastic waves generated by sudden leak-related events are robust, abrupt, and predictably propagate in both directions. Subsequently, once the negative pressure waves are detected and linked between sensor blocks, the multi-channel time difference of arrival (TDOA) method is employed to pinpoint the location of the leakage.

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This method exhibits exceptional sensitivity, capable of triggering alarms even in the absence of outflow. Notably, it remains independent of both the volume and duration of the leak. It displays top-tier leak detection performance, effectively identifying leaks with hole diameters as small as 0.1-inch while typically requiring the installation of one sensor every 30 km (18.6 mi), with the potential to extend up to 50 km (31 mi).

Figure 3 illustrates a real case in which an incomplete illegal hot tap was attempted to steal refined product. In this case, there was no access to the fluid inside the pipeline, and as a result, no pressure drop was registered by the pressure sensors. Nevertheless, the vibroacoustic sensor blocks installed along the pipeline successfully detected and localized the attempt. The distance between sensor blocks 1 and 4 is approximately 80 km (50 mi).

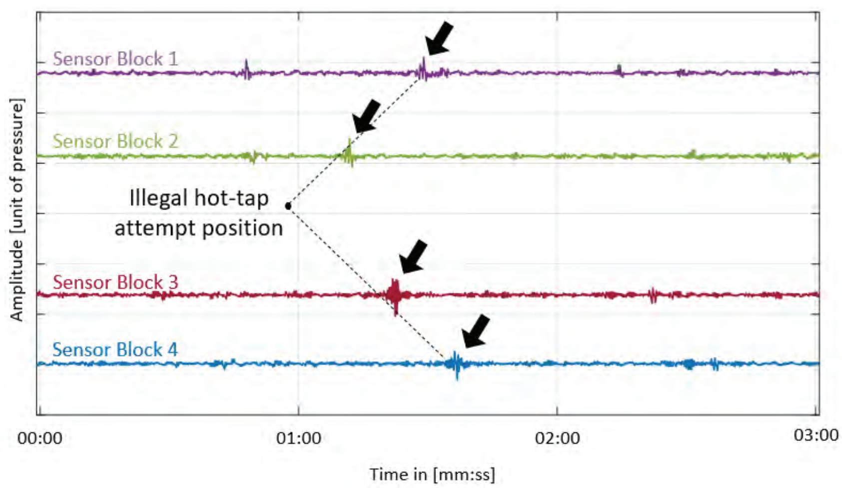

Figure 3. Illegal tapping attempt signal (indicated by the black arrows) propagating and being registered by all sensor blocks.

Figure 4 shows a real case of product theft in an 18 km (11 mi) pipeline transporting crude oil. Sensors 1 and 2, as well as 3 and 4, are positioned at the extremities of the pipeline with approximately 300 m (984 ft) to facilitate active pump noise removal. The noise removal algorithm is as a robust tool, enabling the detection of very small leaks, even during active product transfer when pumps are in operation. The raw signal is depicted in blue, while the red signal represents the processed signal after the noise removal procedure has been applied.

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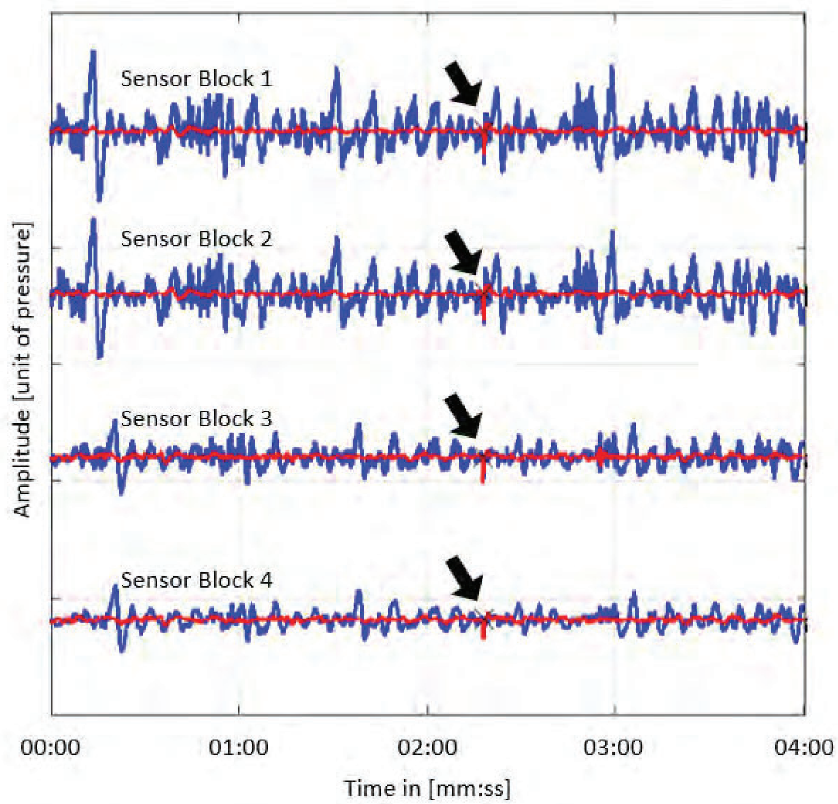

Figure 4. Product theft signal (indicated by the black arrows) propagating and being registered by all sensor blocks.

Compensated mass balance method

The real-time transient model (RTTM) compensated mass balance method is built on the principle of mass conservation. The pipeline is segmented into mass balance sections defined by flowmeters or closed valves. The RTTM model provides density and area profiles. In the event of a leak, mass is released, resulting in a negative rate, and the imbalance corresponds to the leaked mass.

Clamp-on flowmeters gauge the mass flow rate, while the RTTM processes pressure and temperature for real-time compensation, enhancing leak detection. Localization is restricted to the control volume, sensitivity hinges on flowmeter accuracy, and detectability is contingent on the leak's volume and duration rather than its initiation or conclusion.

Acoustic noise method

The acoustic noise method utilizes the continuous noise produced by the fluid jet outflow for both detection and localization. The fluid jet consistently generates stationary noise that travels within the pipeline, reaching the vibroacoustic sensors. The data from adjacent sensors is analyzed, and if the correlation peak exceeds a predefined threshold, it indicates the presence of a noise source associated with a leak. The TDOA is then utilized to pinpoint the noise source.

Detectability is contingent on the outflow rate and the duration of the leak, remaining unaffected by when the leak initiates or concludes.

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Application overview: integrity monitoring capabilities vs different leak types

This chapter presents examples of detecting and localizing various leak occurrences, including micro-vents caused by corrosion, small holes resulting from wear, with emphasis on illegal tapping.

Corrosion micro-vents

Amidst the COVID-19 pandemic, characterized by reduced energy demand, certain pipelines experienced a temporary shutdown. One such example involved a crude oil transportation pipeline that had remained inactive for several months. As preparations for reactivation unfolded, concerns arose about potential corrosion-related damage during the shutdown, which could manifest as issues upon reactivation.

To assess the asset's integrity during the reactivation process, the existing permanent Vibroacoustic Technology installation system played a pivotal role in monitoring pressure tests. This involved effectively segmenting the 90 km long pipeline using shut-down valves and installing an additional four vibroacoustic sensor blocks across four consecutive pipe segments, each isolated by closed valves.

Throughout the pressure tests, data processing of the pressure measurements by the vibroacoustic sensor blocks revealed an abnormal pressure drop in one specific pipe segment when compared to others. A more comprehensive analysis, leveraging computational fluid dynamics, provided substantial evidence supporting the hypothesis of a minor leak within the suspected critical segment. Subsequent inspection of the identified segment confirmed the presence of a minor vent on a pipe derivation located at a hydraulic junction, as shown in **Figure 5**.

Figure 5. Corrosion micro-vent detected by the Vibroacoustic Technology upon reactivation of a pipeline

Localization of an existing leak during pressure test

A portable version of the Vibroacoustic Technology was set up in a water injection pipeline, where a leak was detected in a buried segment spanning 3 km (1.9 mi). While pressure sensors could easily

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identify the presence of a leak by monitoring pressure variations in an isolated segment over time, a more sophisticated detector was necessary for precise localization.

To achieve this, three hydraulic junctions along the pipeline were employed to deploy three blocks of vibroacoustic sensors. The Vibroacoustic Technology use accurately pinpointed the location of the leak. Excavation was carried out based on the predicted location, leading to the discovery of a leak hole measuring approximately 25mm^2 (0.0387 in^2), with an error margin of less than 25m (82 ft).

Illegal tapping

Illegal tapping refers to the act or attempt to steal transported fluids through unauthorized connections along a pipeline. Pipeline operators worldwide grapple with this issue. However, it tends to be more prevalent in areas where pipeline security measures are inadequately enforced, economic challenges foster illicit activities, regulatory measures are insufficient, or effective monitoring and surveillance systems are lacking.

Efforts to combat illegal tapping often require a combination of technological solutions, law enforcement initiatives, and community engagement.

Illegal tapping poses significant risks to public safety, the environment, and the integrity of the pipeline. Awareness campaigns encouraging the local population to report suspicious activities along pipeline routes through an anonymous, toll-free call to authorities are helpful, but they alone cannot eliminate the problem.

Law enforcement initiatives play a crucial role in combating illegal tapping for several reasons. Visible and effective law enforcement efforts act as a deterrent, discouraging potential perpetrators from engaging in illegal tapping activities. It ensures that individuals involved in illicit activities face legal consequences. However, even if law enforcement agencies have the authority and resources to investigate and prosecute cases of illegal tapping, this alone does not eradicate the problem.

Regarding the role of technological solutions in combating illegal tapping, there are various pipeline monitoring systems, sensors, and surveillance tools designed to detect instances of product theft. It is crucial to invest in technological solutions that offer real-time monitoring capabilities, enabling continuous tracking of the pipeline's status and precise pinpointing of the location of illegal tapping attempts. However, it is important to note that the sole reliance on technology does not eliminate the problem.

Coping with illegal tapping

This chapter presents the experience of a country, Italy, that, like other European countries, has historically grappled with challenges related to illegal tapping [3]. However, with the successful implementation of the items above, the number of events decreased dramatically in just a few years of intense efforts.

In 2013, Vibroacoustic Technology was implemented for the first time in two pipelines in central Italy. The leak detection system demonstrated reliability, detecting and accurately locating tens of events each year. Initially, the disruptive capability to arrive promptly at the right location was evident, confirming expectations that real-time intervention in illegal tapping is risky.

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Multiple well-organized illegal tapping groups were encountered, involving different professionals engaged in creating unauthorized taps and operating the product removal multiple times a day. Confiscation of equipment was a common occurrence, with each confiscation representing thousands of dollars' worth of equipment alone.

Building on the success of the Vibroacoustic Technology deployment and enhanced coordination between the pipeline operator and law enforcement upon event detection, additional pipelines in northern Italy were equipped with the technology in 2016, focusing on the region with the highest pipeline density.

In 2017-2018, the Vibroacoustic Technology was implemented in the remaining pipelines, ensuring comprehensive protection for the entire pipeline network.

Between 2019 and 2021, no incidents of illegal tapping were detected across the entire network for over three years. Additionally, the global COVID-19 pandemic contributed to this period of inactivity.

Insights gained

After years of experience working actively to solve the illegal tapping problem in this pipeline network, it can be said that it is most definitely a continuous effort, as seen in **Figure 6**.

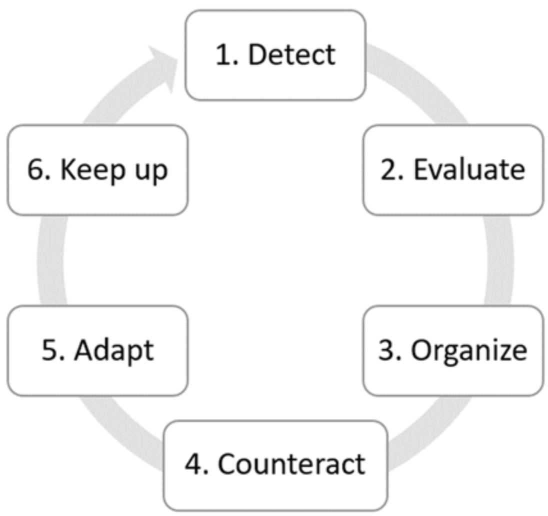

Figure 6. Holistic framework applied to the Italian pipeline network to combat illegal tapping

The initial step involves implementing a robust and reliable leak detection system capable of real-time detection and accurate localization of leaks across the entire pipeline network, leaving no vulnerable areas unprotected.

Integrated automated alarm systems, coupled with technological solutions, can promptly alert operators and law enforcement authorities upon detecting irregularities or potential illegal tapping events. This swift notification streamlines a rapid response.

https://doi.org/10.52202/072781-0073

Despite the technology facilitating timely intervention to prevent considerable damage, it is imperative that the intervention does occur. Evaluating and organizing law enforcement responses to detected events is crucial for effectively counteracting the illegal tapping organizations.

Finally, it is essential to adjust actions, emergency protocols, and even technological capabilities to stay ahead, ensuring the success of this holistic approach to guarantee the security and integrity of the pipeline network.

Final remarks and future developments

The applications presented in this paper demonstrate the reliable performance of Vibroacoustic Technology in detecting and accurately localizing leaks caused by various factors in real-time. All leak detection methods reviewed in this work can be integrated to create a comprehensive leak detection suite using the same hardware set.

The fast response time and precise event localization provided by Vibroacoustic Technology are essential elements that assist pipeline operators in coordinating and preparing a suitable emergency response, thereby reducing profit losses due to stolen product and remediation expenses resulting from faulty illegal tapping attempts.

Future developments include the detection of corrosion, made possible by the fact that the presence of corrosion alters the acoustic channel observed between two vibroacoustic sensor blocks. Another capability of the system is the detection of third-party interference [4] along the pipeline right-of-way and PIG tracking [5] using the same hardware deployed for leak detection.

The holistic framework presented in this work for coping with illegal tapping enhances the understanding of potential vulnerabilities and aids in implementing preventive measures. Given the extensive nature of pipeline networks, located in either remote or densely populated areas, the deployment of integrity monitoring systems is of extreme importance to guarantee the safety not only of the assets but also of the environment and the population in its surroundings.

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