Cost Effective Remote Pipeline Vault Monitoring and Leak Detection System

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Abstract

Underground vaults are employed along pipelines to accommodate pumping and shut-off systems that require a large volume of space around the pipeline. Within each vault a number of flanges, valves, and other potential leak points are present. Monitoring vaults for leaks presents numerous challenges: a) aerial surveys are not an option, b) they are often in remote locations, c) they are prone to flooding due to rain and snow run-off. This paper describes the development of an Industrial Internet of Things (IIoT) vault monitoring system that detects an unexpected release of liquid hydrocarbons within the vault and monitors the presence and level of water. A case study on the deployment and operation of this new multifunctional system in underground vaults at multiple northern locations is described. Ground movement monitoring is currently under development as an additional monitoring capability within the same IIoT system and some initial trial data will be presented.

1. Introduction

Pipelines are the primary mode of transportation for petroleum products. Every day, pipelines transport almost 100 million barrels of liquid petroleum products across the globe. Oil pipelines are connected to other operational facilities such as storage tanks that store oil, injection stations where oil is injected into the pipe, pump stations located along the pipeline to keep the oil flowing, block valves or shutoff valve stations that allow a section of pipeline to be closed for maintenance or to isolate a leak, and delivery stations where product is distributed to consumers. These extensive networks of pipelines and operational infrastructure are heavily regulated for safety and reliability as any leaks from pipelines or other infrastructure can be disruptive, expensive, and may cause severe damage to the environment and public health.

In order to reduce the impact of spills, quick detection of leaks and a rapid response are necessary. Rapidly closing block valves and isolating the leaking pipeline section can reduce the amount of product loss, lessen environmental damage and reduce remediation costs significantly. Due to this, block valves are required to facilitate the isolation of pump stations, breakout storage tanks and lateral take-offs, and other points along the pipeline near designated water bodies and populated areas (high consequence areas (HCA)) to minimize the damage and pollution from an accident oil leakage [1].

Pipeline and Hazardous Materials Safety Administration (PHMSA) in the United States recently revised federal pipeline safety regulations (applicable to most newly constructed and/or entirely replaced onshore gas transmission, Type A gas gathering, and hazardous liquid pipelines with diameters of 6 inches or greater) to have rupture-mitigation valves (i.e. remote control or automatic shut-off valves) or alternative equivalent technologies, and establish minimum performance standards of those valves operation to prevent or mitigate the public safety and environmental consequences of pipeline ruptures [2]. This PHMSA revision was based on the study conducted by Oak Ridge National Laboratory [1] and the United States Government Accountability Office (GAO) [3]. Both studies concluded that automatic remotely controlled shut-off valves can reduce the size of pipeline leaks. However, GAO found that an automatic shutoff valve for an Oil pipeline can cause an incident when a valve closes and the subsequent pressure build-up instigates a pipeline rupture [3]. Apart from block valves, based on Pipeline Incident Data reported by the Government of Canada, more than 15% of liquid petroleum product releases are due to damage or deterioration of equipment, valve seals, or packing [4]. Clearly, monitoring valves on liquid pipelines is critical.

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However, block valves are often located in remote or hard to access locations and are typically housed in underground vaults straddling the pipeline. Access to these vaults for maintenance and inspection for leaks is difficult, time-consuming, and often requires enclosed space training and permits.

To address this issue, Direct-C has developed a remote vault monitoring system containing novel polymer nanocomposite sensors for leak detection. Polymer nanocomposite materials exhibit high hydrophobicity and anti-icing properties, preventing ice buildup around the sensor and giving it the capacity to detect oil in freezing underground conditions [5]. It provides early remote leak detection with real-time continuous monitoring of the vault for any hydrocarbon leaks. Its flexible architecture is intended for the detection of hydrocarbons underground in extreme environmental conditions and its remote communication system ensures rapid reporting of leaks. It consists of multiple individual sensor modules, placed underground, and connected through wireless communication technology to a gateway connected to a user station through cellular or satellite communication.

This paper is organized as follows: first, it outlines the need for a rapid leak detection system (LDS) and describes the capabilities of the remote vault monitoring system. This is followed by a case study in which the described system is installed in remote northern locations with significant winter environmental conditions. The paper then concludes with the results of the case study.

2. Need for Remote Rapid Leak Detection

Pipeline Operators engage in continuous efforts to improve safety and perform a variety of leak detection activities to monitor their systems and identify leaks. These activities include periodic external visual monitoring using aerial/ground patrols and internal monitoring using a Computational Pipeline Monitoring (CPM) leak detection system, closely integrated with existing SCADA systems used for normal pipeline operations. CPMs incorporate various methods such as line balancing, compensated mass balancing, real-time transient monitoring, etc [6]. Typically, pipeline operators prefer to have two sources of information confirm an incident, such as an alarm from a pipeline sensor and a visual conformation, especially if shutting down the system is the likely response to the incident [3].

Current survey-based detection methods for remote areas such as Aerial and Satellite Remote sensing methods are only active intermittently and not useful for monitoring underground valve vaults. Ground access to these remote underground valve vaults is not always possible due to bad weather, seasonal environmental challenges, etc. The myriad varieties of CPMs have proven, over time, to have several drawbacks, including the inability to accurately locate the leak, the inability to identify leaks under 1% of throughput and the generation of a high volume of false alarms due to the reliance on components and communications external to the LDS [7]. Therefore, for remote underground valve vaults, none of the common currently used leak detection methods are ideal.

Relatively recently, several “external” LDS solutions have come to market, including hydrocarbon sensing cables and acoustic/temperature sensing fiber optic cables. While they offer improvements in accuracy and sensitivity, issues with reliability, robustness, and cost (capital and operating) remain. The pipeline operators’ search for a LDS that is sensitive, accurate, reliable, and cost-effective remains in full flight. The United States’ landmark 2012 DOT/PHMSA comprehensive LDS study details the history of US oil and gas pipeline leaks, their typical causes, and whether LDSs were installed at the time of the leak. The report indicates that pipeline operators do not rely on LDSs due to their known, significant operational issues, unreliability (generating false alarms) as well as their

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high cost to install and operate [7]. Most external LDS are also not ideal for remote underground valve vaults.

To monitor underground valve vaults, a leak detection system with high sensitivity, high accuracy, and low false alarm capability is needed. Because of the often remote locations, it should also have remote communication capabilities and a standalone energy feature as inaccessibility of a power source is an issue at these sites.

Underground valve vaults also often come in contact with groundwater, rainwater, and in some locations snow and ice. In subarctic and other Arctic regions thawing of permafrost can be an issue as it creates uneven surface topography that includes pits, troughs, mounds, and depressions causing significant ground movements [8] which affect underground vaults. A vault monitoring system with the capability of detecting water presence and ground movement can be an asset along with leak detection for locations like artic regions and earthquake-prone locations.

In this section, the need for remote rapid leak detection for underground vaults has been highlighted and the various requirements for the ideal monitoring system were identified. In the next section, a novel vault monitoring system is described and a case study of its installation and operation is detailed afterwards.

3. SubSense Leak Detection System

Direct-C has developed a subsoil leak detection system called SubSense. SubSense Leak Detection Systems consist of a SubSense ground probe which is wired to Direct-C's IIoT. These are installed near underground oil and gas infrastructure as containment monitoring for hydrocarbon leakage. Fig. 1 shows one such installation.

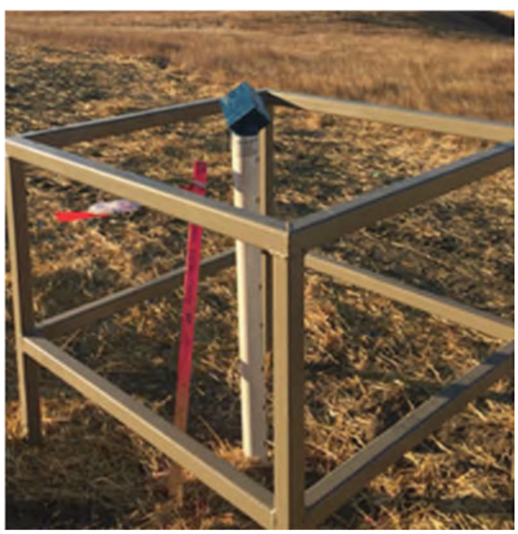

Fig. 1: SubSense monitoring an underground transition point of a buried pipeline

The ideal location for the ground probe is in the original pipeline trench, right next to the pipeline itself so that when any hydrocarbon product escapes it can easily reach the nanocomposite hydrocarbon sensors. SubSense also contains a water level sensor and tilt sensor. All three sensors are described in the subsection below. These sensors are connected to Direct-C's IIoT-enabled edge

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devices which communicate with a cloud-based asset and data management system. This industry 4.0 enabled system digitizes oil and gas assets (smart infrastructure) and wirelessly communicates to a user dashboard providing the status of the asset. The client dashboard is a full-featured asset management software system that is used to monitor all field-deployed units. Clients can access this dashboard on their smart devices (app available for iOS and Android devices) or their laptops. The dashboard provides precise information on asset location, the status of the monitored asset, and any product loss event with time and location. The data from this the dashboard can be integrated into a client's existing data management system.

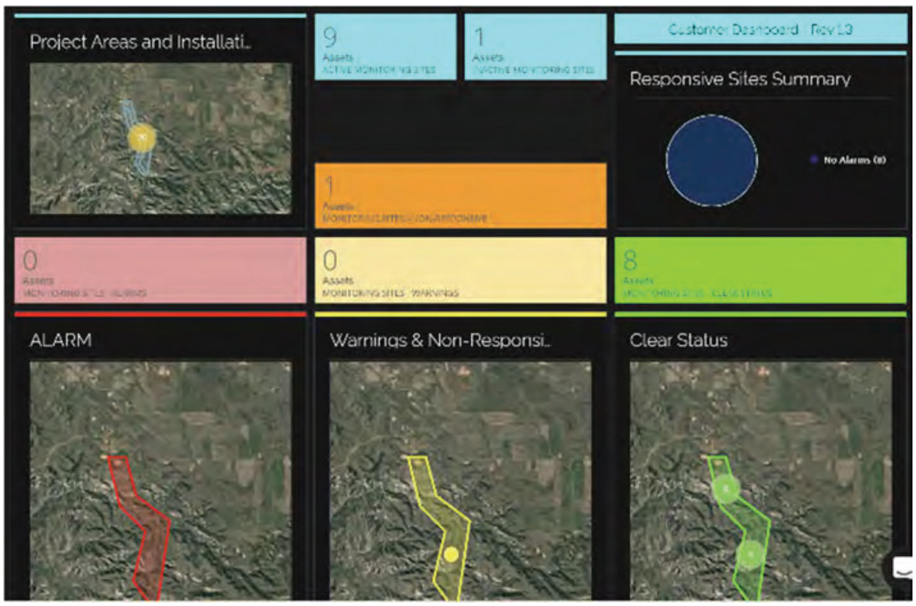

Fig. 2: Web and mobile-based asset management portal screenshot

3.1 Polymer Nanocomposite-Based Hydrocarbon Sensors

Polymer nanocomposites are advanced functional materials manufactured by admixing nanoparticles into a polymer matrix. A proprietary polymer nanocomposite material was developed for novel leak detection [9]. The sensing mechanism is attributed to the swelling of the polymer in the presence of hydrocarbons as shown in Fig. 3, causing the conductive network of nanoparticles to move further apart, thus increasing the electrical resistance of the nanocomposites as shown in Fig. 4.

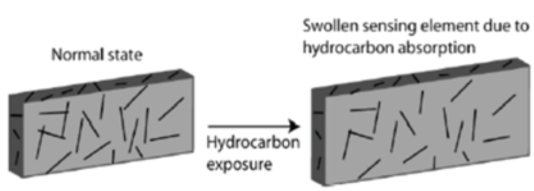

Fig. 3: Hydrocarbon sensing mechanism for polymer nanocomposite sensors

The hydrocarbon sensors were exposed to a sample of North Slope crude to identify their response to the product. Fig. 4 shows the response of the hydrocarbon sensor.

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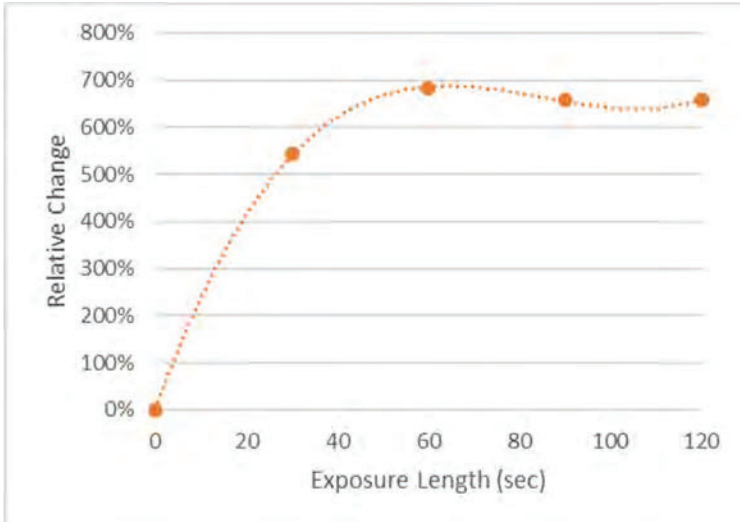

Fig. 4: Hydrocarbon sensor response to *North Slope crude*

The change rate (60 sec) is 11.4% per second. The SubSense LDS has an alarm threshold of 15% therefore the Direct-C IIoT will generate an alarm a few seconds after exposure to North Slope crude.

3.2 Water Level Sensors

These sensors allow the SubSense LDS to identify if water is present at various levels in underground vaults. A SubSense LDS unit has multiple water level sensors at different heights each consisting of two conductive pads which are monitored for electrical current flowing through them. In normal conditions, because there is no conductive media present in-between them, there is no flow of current (open circuit), so it shows the open circuit voltage (1.8 V). When it comes in contact with water, the electrical current is able to flow between these two conductive pads decreasing the electrical voltage between them. The graph in Fig 5 shows an example of SubSense LDS water level sensor data from a field installation between February and October 2023.

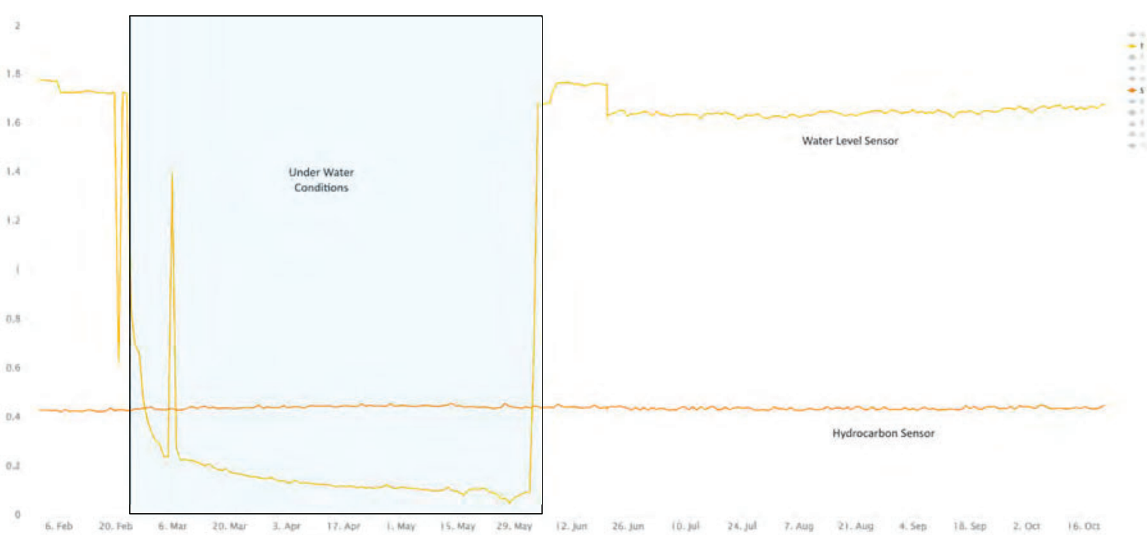

Fig. 5: Water level sensor readings

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One of the water level sensors (orange line) shows that the SubSense probe was partially submerged in water when the thawing of ice and snow started in early March. The sensor stayed submersed until end of the May when the water receded sufficiently. The graph also shows that water ingress around the SubSense probe had a negligible impact on the hydrocarbon sensor (red line). It is important to monitor the water level since if the entire sensor is submerged, the hydrocarbon sensor will not function so if it stays submerged for long periods, the sensor will need to be moved. If partially submerged, the hydrocarbon sensor will be effective.

3.3 Tilt sensor

Another sensor set available in the SubSense LDS is a triaxial tiltmeter sensor. The sensor measures the tilt and acceleration of the SubSense probe casing in three axis (Fig. 6), providing a measure of ground movements primarily in the lateral directions (XY direction or ground plane).

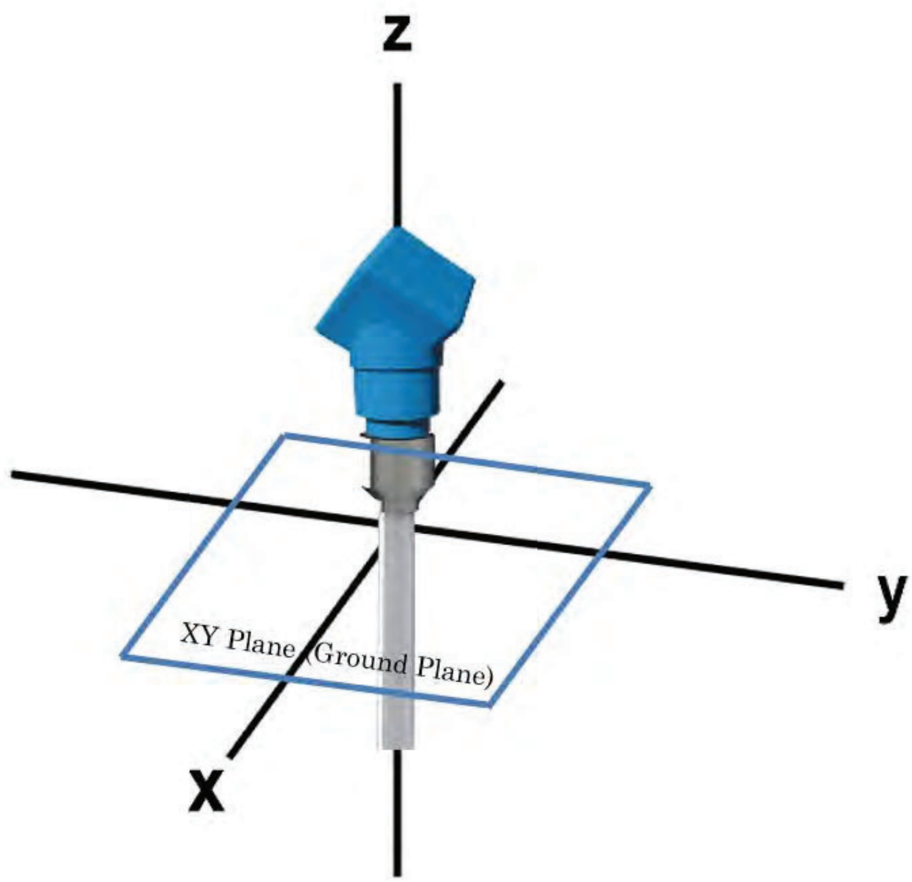

Fig. 6: Tiltmeter directions

Fig. 7 shows 3 months of tilt data from a field installation indicating the movements of SubSense in X and Y directions (horizontal plane). Most of the movements are small which are typically due to wind. However, in late July, there was a sudden movement of almost 3.5 degrees in the X direction and 1.5 degrees in the Y direction showcasing a position disturbance event of an unknown origin. As the changes were small enough and within the operating envelope for this site, no alarm threshold

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was reached and no action needed to be taken but these events highlight the capabilities of these sensors to monitor for even small angular displacements of vault chambers.
Further trials are currently underway to determine the capabilities of this system.

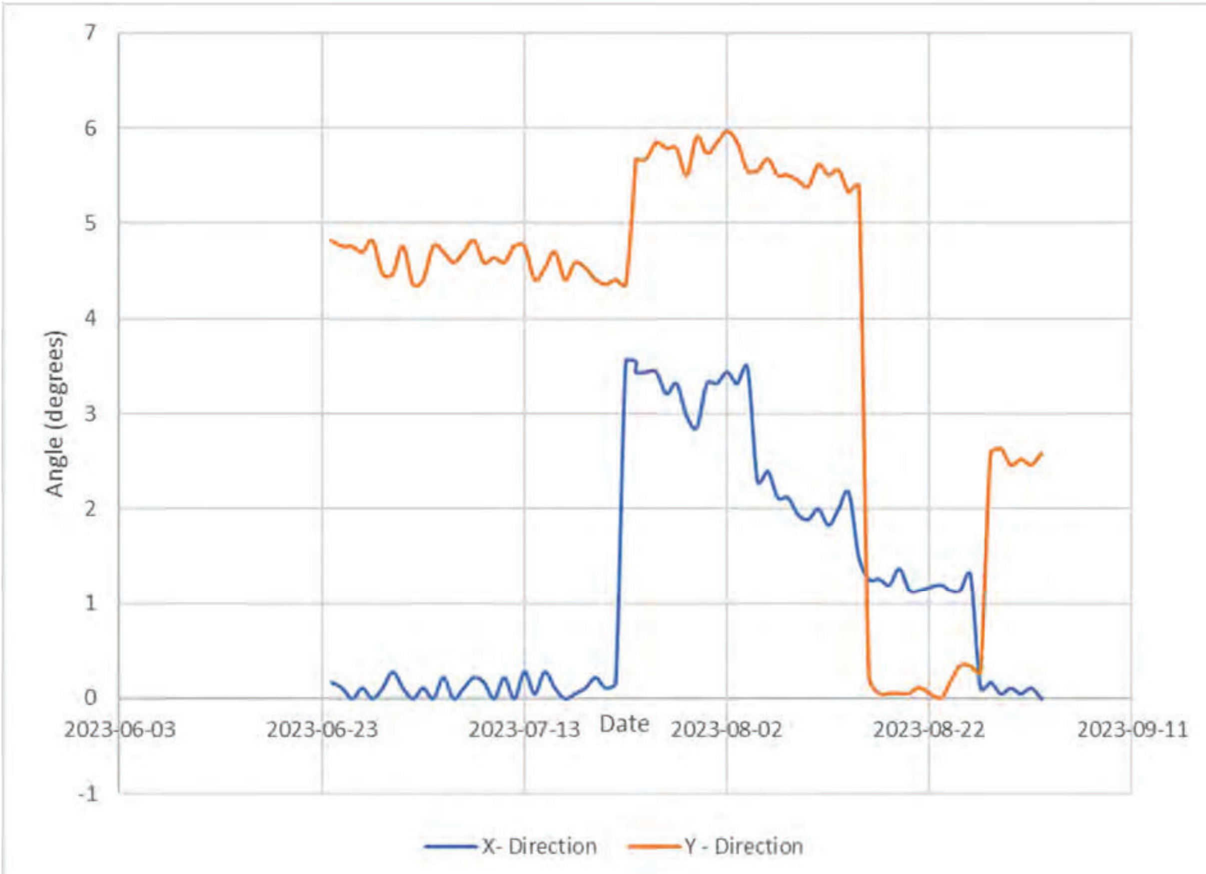

Fig. 7: X-Y direction movements recorded by the Tilt sensor

3.4 SubSense LDS Solution Summary

Direct-C's SubSense leak detection system can address many of the challenges of monitoring pipeline underground vaults and complement existing leak monitoring systems. The system can identify small leaks (50 mL) in real-time and remotely communicate through cellular or satellite communication to provide alarms and information about their location and severity. Some of the benefits are listed below:

1) Direct monitoring of unexpected hydrocarbon releases using novel polymer nanocomposite sensors (reduces/eliminates false positives as it only reacts to the presence of liquid hydrocarbons)
2) Applicable to work in underground locations periodically containing water or ice (coating has hydrophobic and anti-icing properties)
3) Real-time monitoring and alarming of very small leaks. High sensitivity- 3 ml of product only.
4) Remote communication (cellular or satellite communication)
5) Battery-operated standalone system requiring minimum maintenance and no external power
6) Extremely cost-effective, equipment is leased so no major CAPEX required.

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7) Quick, easy, non-intrusive installations (no hot work permit or enclose space permit required)
8) IIoT-enabled system with a cloud-based data analytics dashboard providing oil spill alarms with precise site name, location, and map.

Case study: SubSense Installations in Northern Climate locations

4.1 Project Requirements

A Major Operator faced a challenge – how could they improve their Leak Detection Program to enhance the response time to a small leak inside a vault? As vaults normally have a closed lid, aerial surveys were not an option, and to complicate matters many of their vaults are in remote locations. Additionally, operating in a northern climate means freezing temperatures & snow for months at a time. A final complication is that the vaults often have varying levels of water ingress, sometimes as deep as 4-5 feet.

The client desired a 24/7 monitoring system with real-time alarming that could be easily deployed, had internal communications, and didn't require external power. Furthermore, due to the logistical challenges of getting to many of the vaults, frequent false positives would incur crippling costs as they were investigated.

The solution? Direct-C's SubSense ground probes. A fully self-contained system, it features extremely sensitive leak detection (as little as 3mL), has both cellular or satellite communication options, and is battery powered (battery life is 3 – 5 years).

4.2 SubSense Installation at client sites

Fig. 8(a) shows the SubSense probe with sensors housed inside and ready for installation. Fig. 8(b) shows the installed SubSense LDS (sensor & IIoT).

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(a) SubSense probe before installation (b) SubSense LDS after installation

Fig. 8 Installation of SubSense LDS

Installations for the pilot project of SubSense probes at various sites happened in the Summer of 2020. The Operator had identified some of their highest consequence locations in remote areas with harsh winter environmental conditions. The images above show typical vault installations. The SubSense probe is installed directly into the vault and features liquid hydrocarbon sensors that are 2-meters (6-feet) long inside a protective, porous tube. The base of the sensor probe rests on the bottom of the vault. As the sensors are hydrophobic, the fact that the vault may have water present is not an issue and still ensure that in the event a leak begins, the escaped product floating on top of the water will still contact the hydrocarbon sensor and trigger an alarm to the Operator.

The pilot was a successful – no false alarms occurred, alarm & notification systems were validated, and the identified risk was mitigated. The Operator has continued to install additional SubSense systems at other vaults (and other non-vault asset locations) every year since the successful pilot completion. Due to the remoteness of many of the locations, satellite communication is frequently employed for this operator.

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5. Conclusions

In this work, we described the reason for underground valve vaults on liquid pipelines. The block valves are critical features of the oil and gas pipelines and with new regulations by PHMSA, remote-controlled automated shut-off valves are mandatory on any gas gathering and hazardous liquid pipeline with diameters 6 inches or greater. These valves are typically housed in underground vaults in remote and HCA locations. To ensure the safety and reliable functioning of these valves, it is critical to monitor them for any leaks. The novel vault monitoring system described here with proprietary polymer nanocomposite sensors, remote communication capabilities, and standalone battery operation provides an ideal and cost-effective monitoring solution for underground valve vaults. The case study of installations and operations in northern climates showcases its capability to operate under extremely cold temperatures and in remote locations. Direct-C is currently working on two new projects for two Operators with vault concerns in California highlighting the Oil & Gas Industry's enhanced focused on the challenges for monitoring leaks within underground vaults.

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