Multi-sensor IIoT System for Monitoring Assets for Product Leaks

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1 ABSTRACT

Direct-C has been deploying hydrocarbon leak detection systems (LDS) globally using both cellular and satellite communication channels to send data to a client's custom dashboard. In response to client demands, a multi-sensor Industrial Internet of Things (IIoT) solution has been developed and deployed which adds a variety of other sensors to the monitoring solution which subsequently can then be incorporated into the client dashboard. Several examples of this will be described including gas, temperature, and water sensors. The units have been built with satellite communication for offshore use and cellular communications for use in onshore applications where cellular service is available.

Four different systems will be described in this paper which incorporate six different sensor types including Gaseous Hydrocarbon, Temperature, and Aqueous Liquid sensors. Besides the valuable extra data sets that these sensors can provide, fusing the data from the different sensors can provide validation and verification of the primary system function (such as oil leak detection) and enable operators to take better decisions on remediating actions.

Keywords: integrity management, corrosion, leak detection, condition monitoring, Industrial Internet of Things (IIoT), data analytics

2 INTRODUCTION

Being an asset-intensive business, asset monitoring, specifically for product leaks is critical for the oil and gas industry. Product leaks in pipelines and other oil and gas infrastructure can be disruptive, expensive, and can cause severe damage to the environment. Every day, pipeline companies transport almost 100 million barrels of oil and 120 million barrels of oil-equivalent gas across the globe [1]. With few exceptions, they do so safely and efficiently. However, the world's oil and gas infrastructure is aging. More than half of United States pipelines are at least 50 years old [2] and in the 20-year period from 1998 to 2008, 18% of the 'significant incident' is associated with an aging mechanism like corrosion [3]. In Europe, nearly 50% of major 'loss of containment' events are caused by aging plants mechanism such as erosion, corrosion, and fatigue [4]. The survey of accidents in the downstream oil sector conducted by Fabiano based on 1050 events showed that the main causes related to failure are related to the aging of infrastructure [5]. Oil and gas companies, specifically pipeline companies are being asked for increased risk analysis on aging infrastructure to ensure safety and environmental performance.

To extend the life of current infrastructure and ensure reliable operation and safety, continuous monitoring of oil and gas infrastructure is necessary. Any product Leaks in oil and gas assets can be disruptive, expensive, and environmentally damaging. Traditionally, SCADA systems used for the monitoring Oil and gas assets. But it has many drawbacks including the inability to accurately locate the leak, and the inability to identify leaks under 1% of throughput [6]. With recent developments in communication technologies and smart sensors, the internet of things (IoT) has emerged as an effective tool for Oil and Gas asset monitoring. IoT system includes sensors, actuators, network infrastructure, and data analytics tool to collect and analyze data [7]. The creation of smart assets through real-time data analytics and the quick notification capability of IoTs is critical for monitoring oil and gas assets. This approach can potentially reduce annual downtime by 70% and bring down the cost to 22 percent of the total, compared to 50 presently currently [8].

From production to distribution, Oil and gas capital assets range from drilling rigs, offshore platforms, and wells in the upstream segments, to pipeline, liquefied nature gas (LNG) terminals, and refineries in the midstream and downstream segments [9]. To reliably monitor these varieties of infrastructure is a challenge. As a solution, we have developed multiple smart sensors each tailored to specific monitoring sites, and an IoT system capable of handling a number of different sensor types.

The paper is organized as follows. First, it outlines a new IIoT system for oil and gas asset monitoring, in particular for product loss is presented and various components of it such as smart sensors, a standalone battery-operated controller module with wireless communication capability, and data analytics and client dashboard are described. It ensures continuous monitoring of assets and that operators get alerts on various smart devices as soon as any small leaks are detected. This is followed by the development of various smart sensors and environmental sensors to meet the diverse monitoring need of a variety of Oil and Gas infrastructures.

3 IIoT System

The presented IioT system is developed to monitor oil and gas assets for early detection of product loss and helps clients save significant downtime and cleanup costs. 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 system consists of:

1) Sensors (embedded or wrapped around oil and gas assets to be monitored),

2) IoT-enabled controller capable of collecting real-time data from the asset,

3) An advanced algorithm-based firmware that analyzes the data creating a self-aware smart asset,

4) Wireless communication through Cellular and satellite modules transferring data through cloud computing platform service, and

5) Client dashboard – a full-featured asset management software system that is used to monitor all field-deployed units. The clients can access this dashboard on their smart devices (app available on 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. Fig. 1 describes the IIoT system and its components.

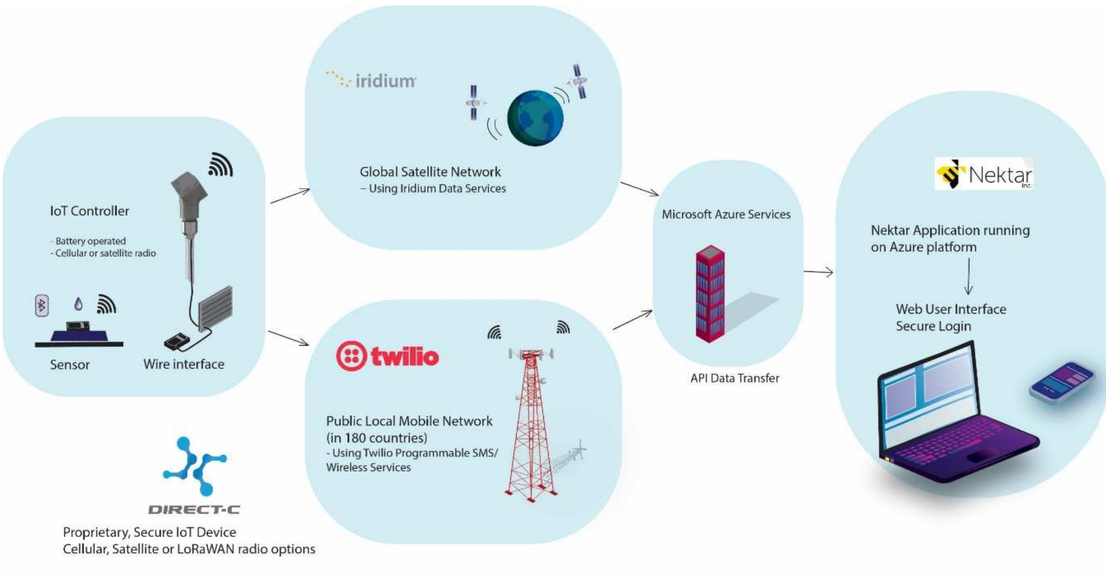

Fig. 1: IIoT system

According to I-Scoop, industry 4.0 implementation is based on an Industrial transformation pyramid with sensors and actuators as the foundation layer of the pyramid [10]. Sensors need to be sensitive, reliable, and accurate. For the IIoT system, we developed polymer nanocomposite-based smart sensors. The sensors comprising nanomaterials are known to be more efficient and sensitive. Detailed information on different nanotechnology-based sensors is described in the subsequent sections.

4 POLYMER NANOCOMPOSITE BASED SENSORS

Polymer nanocomposite-based sensors offer a novel approach to oil and gas asset monitoring, particularly for chemical leak detection. The sensors are formulated by admixing one or more nanoparticles including carbon nanotubes into proprietary polymers that are capable of absorbing or adsorbing chemicals that they need to detect. The sensing mechanism is attributed to the change in the electrical conductivity of the polymer nanocomposite due to physically absorbed or adsorbed chemicals [11].

The addition of highly conductive carbon nanotubes into the polymer matrix offers high electrical conductivity and reduces the concentration of particles required to achieve the percolation threshold. Thus, only a low concentration of nanoparticles is required to achieve the same conductivity as other conductive particles, thereby reducing material costs. Moreover, the geometry of nanoparticles facilitates elastic deformation (i.e. buckling rather than breaking), which leads to improvements in the robustness and stability of the nanoparticles/polymer composites over time. This geometry also provides nanocomposite materials with high surface areas and exceptional electrical, thermal, and chemical inertness, allowing them to have great potential as chemical detection sensors.

Fig. 2 illustrates the effect of hydrocarbon on polymer nanocomposite sensors.

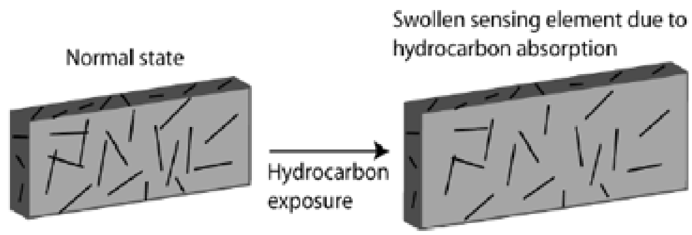

Fig. 2: Effect of Hydrocarbon exposure on Polymer Nanocomposite

Many polymer nanocomposite formulations are developed to meet the diverse needs of oil and gas infrastructure. Each type of sensor is described below:

4.1 LIQUID HYDROCARBON SENSORS

The proprietary polymer nanocomposite is formulated admixing silicone backbone polymer embedded with carbon nanoparticles including carbon nanotubes [12]. The polymer's characteristic of swelling in the presence of hydrocarbon molecules is exploited to detect hydrocarbon leaks. The polymer also provides the advantage of being hydrophobic and thus unaffected by water.

The novel nanocomposite formulated for leak detection application is not affected by natural gas (to eliminate any false positives from background gas) but rather tuned to detect liquid C5 to C24 hydrocarbons. The instantaneous reaction of the nanocomposite sensors to the exposure of various liquid hydrocarbons is shown in Fig. 3. The sensitivity of the sensor (%change in the electrical resistance) is extremely high in all cases. Since the detection method is based on the rate of change in resistance of the sensor, the type of hydrocarbon can be determined. This enables the detection, in a situation where several different hydrocarbons are being stored or transported close to a particular sensor, of which liquid hydrocarbon has leaked.

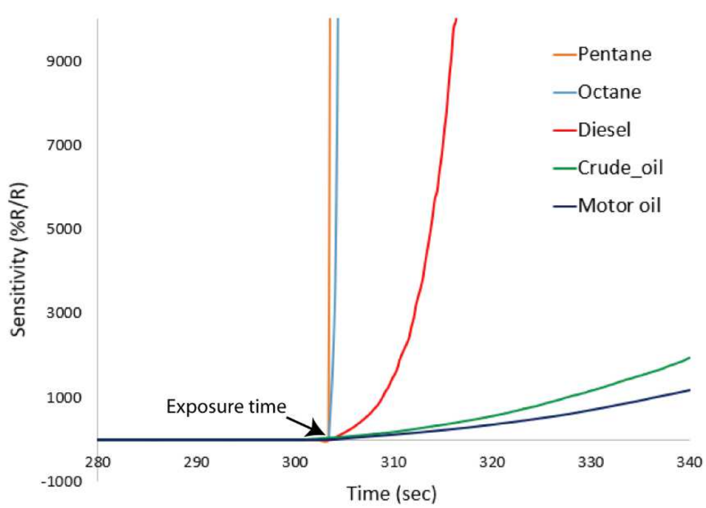

Fig. 3. The reaction of the Polymer Nanocomposite sensors to various hydrocarbons

This also eliminates the false positive caused by the "wrong" type of hydrocarbon encountering the sensor, for example, a spill of diesel fuel onto a sensor would trigger a different sensor response compared to a leak of crude oil from a pipeline onto the same sensor.

A common problem with leak detection systems that use a secondary measurement such as acoustic or flow measurements to detect leaks by inferring the presence of a hydrocarbon is False Positives generated by the system where the presence of a hydrocarbon is falsely inferred [6]. The only identified route to a false positive for the polymer nanocomposite sensor is, exposure to a chemical that causes swelling at the same rate, to give the same change in resistance, as exposure of the sensor to Oil. They are no environmentally common chemicals that are known to cause such a response, therefore environmental exposure will not generate this response. All other environmental effects such as hail, snow, rain, temperature, or wind show different noises in the detected signal which would be detected by the monitoring system and reported but would not give an alarm indicating the presence of oil lowering the possibility of false alarms.

4.2 Aqueous Liquid Sensors

Water plays many roles in oil and gas operations. It is used in many operations as well as produced during the extraction process. In the US, 2.5 billion gallons of produced water are extracted along the oil and gas every day [13]. Proper handling, managing, and disposing of contaminated water is critical for the oil and gas industry. The same approach is used to formulate polymer nanocomposite-based hydrocarbon sensor is used to formulate liquid water sensing polymer nanocomposite sensors.

These sensors are capable of detecting any aqueous mixtures (contaminated water) and can be used to detect a very small amount of water present. Fig. 4 shows the test setup of the water-sensitive polymer nanocomposite sensor exposed to ultra-pure water and the response of the sensor showing a very rapid response (resistance change of more than 500% in 40 seconds).

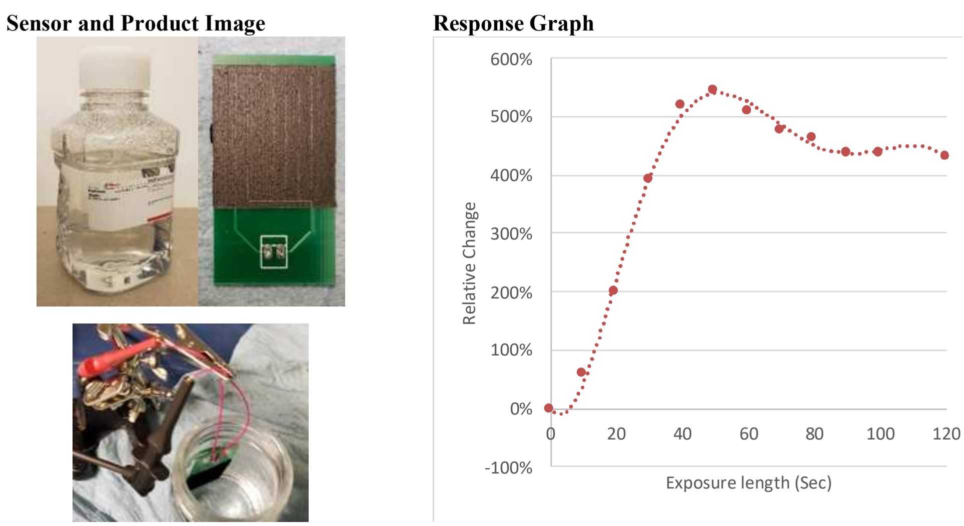

Fig. 4: Exposure of Nanocomposite Water Sensor to Ultrapure water

When exposed to 60% buffer solution (representative aqueous solution), the sensor showed an immediate response with more than 200% change in resistance within 100 seconds of exposure. The experimental setup and response graph are shown in Fig. 5.

Sensor and Product Image **Response Graph**

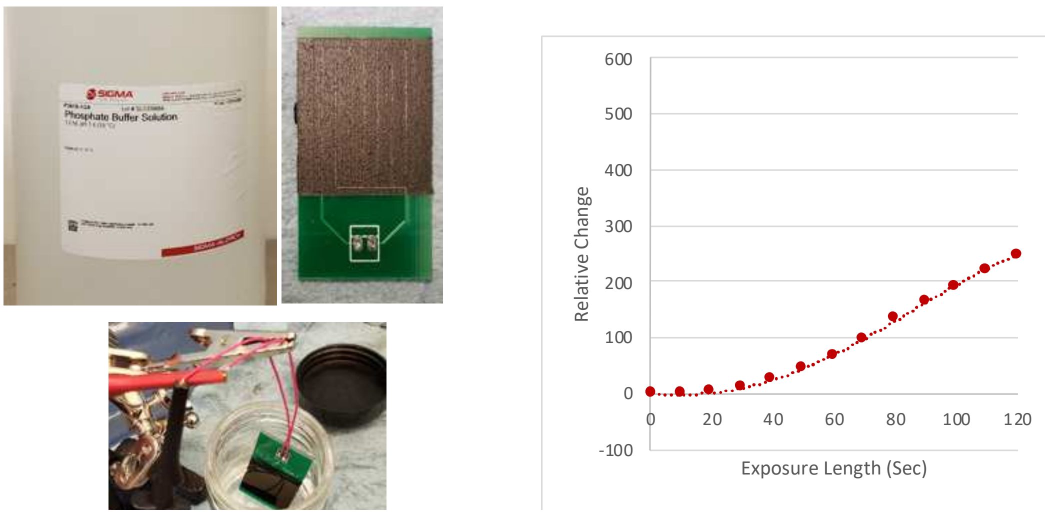

Fig. 5: Exposure of Nanocomposite Water Sensor to 60% water buffer solution

Response of the water-sensitive nanocomposite sensor showed a stronger response for pure water compared to aqueous mixtures and can be deployed to detect small amounts of liquids in situations where environmental water is not expected. A wide variety of applications are being explored with the majority of them being in chemical and pharmaceutical plants to monitor for process equipment failures at flanges, valves, fittings, etc.

4.3 Gas Sensors

Hydrocarbon gas sensors are also developed to detect escaping gas from oil and gas assets. Unlike polymer nanocomposite sensors for hydrocarbon liquid and aqueous mixtures where the sensing mechanism is based on the absorption of liquids into a polymer matrix, polymer nanocomposite-based gas sensors interact with gases through adsorption of the gases on the nanomaterials embedded in the polymer nanocomposite sensors. The sensor consists of nanomaterials that improve the sensitivity, reduce the working temperature, and improve the detection performance of the gas sensors [14].

Proof of concept tests was conducted on small (25 x 15 mm) coupons coated with gas-sensing polymer nanocomposite sensors. Calibrated gases flowed over the top of the sensor in an enclosed compartment with a small leak path to enable the gas to escape. Fig. 6 shows the response of the gas sensor when exposed to calibrated 1000 PPM of butane in air and Table 1 shows the result of the gas sensors.

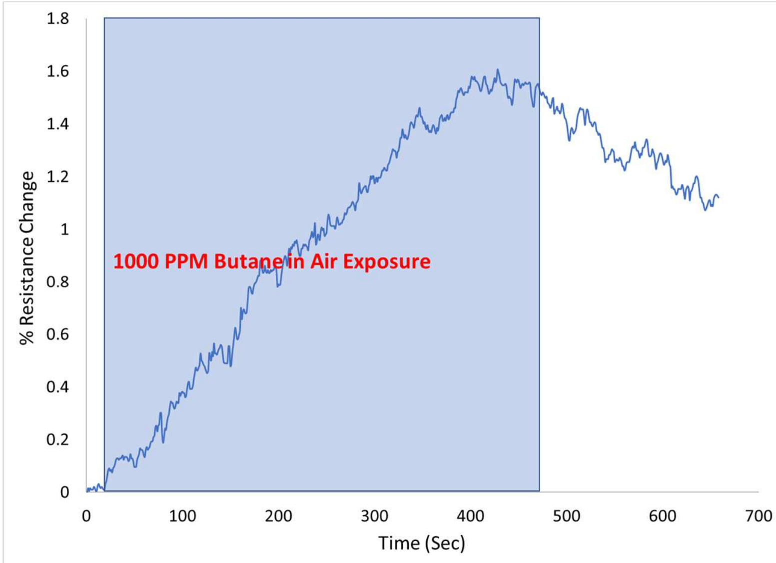

Fig. 6: Exposure of Nanocomposite Gas Sensor to 1000ppm Butane

Table 1: Gas Test Exposure Results

Gas	Max. Resistance Increase	Time to Max Resistance Change (sec)
Primus Prime Gas Propane/Butane Mix	37%	11
1% NH_3	0.9%	120
5% CO_2	0%	-
2.5% Methane (50%LEL)	0%	-

These initial results indicate that this sensor can detect propane/butane in the presence of methane due to the higher adsorption of C2 to C4 Hydrocarbons by the nanomaterials. This shows that these sensors would be an idea for the detection of butane in the presence of methane for use in offshore applications on rigs. We are also developing a system for the detection of gases in Surface Casing Vents (SCV) on oil wells.

It also has a significant but much slower reaction to ammonia so it could be used for ammonia detection, but it is unaffected by CO2. Customization of the nanoparticles is feasible which will open up routes to selective detection of other chemical species, which could be gaseous or liquid.

5 Multifunctional IIoT System developments

As described above, the oil and gas industry is an asset-intensive industry requiring different types of monitoring resources and sensors. To satisfy our client's requirements, we have developed a multifunctional IIoT system comprising other environmental/field condition sensors along with the polymer nanocomposite-based sensors described above. These multifunctional IIoT systems provide additional environmental/field information at the monitoring sites which can be critical. These systems and their use cases are described below.

5.1 Group probe Multifunctional IIoT system with Water level Sensor

We have developed an underground leak detection system called SubSense LDS. SubSense LDS systems are installed near the oil and gas facilities as containment monitoring for hydrocarbon leakage underground. Fig. 7 shows one such installation.

Fig. 7: Liquid hydrocarbon sensor featuring water level sensor

The ideal location for the ground probe is to be close to the groundwater table or partially submerged in the groundwater so that when any hydrocarbon product escapes it can reach to nanocomposite hydrocarbon sensor. At 3rd party testing facility, we tested our ground probes in the flooding conditions (15% water content) and they showed no response due to water but as soon as it was exposed to crude oil, the sensor responded immediately sending alarms. Fig. 8 shows the test setup and the response of the sensors when exposed to crude oil.

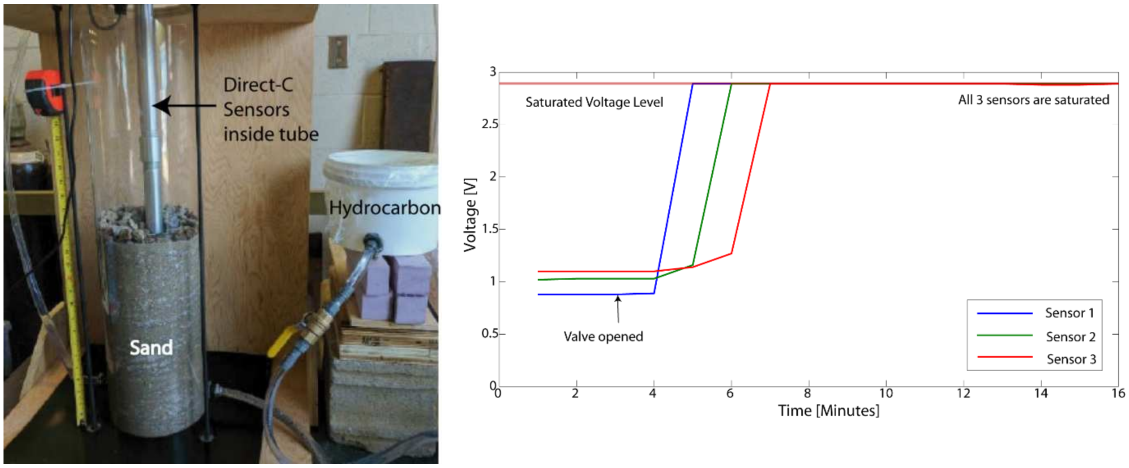

Fig. 8: Testing of SubSense LDS in representative field environment

However, if the probe is completely submerged in the water, oil cannot reach hydrocarbon sensors. To avoid this situation, we configured a multifunctional IIoT system with a polymer nanocomposite-based liquid hydrocarbon sensor on one side and water level sensors on the other. To monitor sensor submersion, we deploy water level sensors on the back side of the sensor that indicates the presence of any type of water by closing an open circuit and causing a large drop in resistance. These sensors are not meant to distinguish between different types of water, merely they indicate the presence of it.

Typically, two water level sensors are deployed for each SubSense probe. These two sensors have separate warnings (not alarms) that are shown on the operator dashboard when the water level causes the open sensor circuit to close. Based on data from existing installations, most of the water ingress happens due to rainstorms or spring meltdowns and is temporary in nature lasting from hours to a few days. In some instances, it can be due to water table movement that causes the sensor to stay submerged for long periods. In this case, the sensing probe will need to be moved to a more elevated position. So, the multifunctional ground probe provides not only hydrocarbon leak alarms but water-related environmental warnings also.

5.2 Group probe Multifunctional IIoT system with Conductivity Sensor

Besides knowing the water levels present in an underground monitoring well, it is often necessary to distinguish between naturally occurring water (due to rain or groundwater) and that stemming from equipment or storage release. Various industrial or oil and gas processes use water as an enabling medium and the resulting liquid is often contaminated with salts, metals, and other substances that can be harmful to the environment. Quickly alarming the presence of these high-conductivity liquids without any false positives due to natural water is very valuable to operators.

These sensors can determine the conductivity of the liquid by sampling over a much longer timeframe than our other sensors (10's of seconds vs 1 second) and accounting for the polarization and water dissociation effects that occur during the measurement. The alarms can be configured to trigger only for water samples with specific levels of conductivity (typically 1 to 10% or higher).

Fig. 9: Produced Water Sensor Installation

When a multi-functional ground probe IIoT system is configured with hydrocarbon and conductivity sensors, it can detect leaks of produced water from storage units or from producing wells. The hydrocarbon sensors would detect any residual oils present either as an emulsion with the water or as droplets, particularly in producing wells scenarios. A typical installation is shown in Fig. 9 with the sensors installed just below ground level at the lowest point of the lease where any spill would quickly pool.

One of these installations enabled the early detection of a product leak for a client in Canada which prevented a potentially $1M in clean-up costs.

5.3 Multifunctional IIoT system with Temperature Sensor

We also developed a multifunctional IIoT system with a traditional thermistor on the back to provide temperature data on the monitoring asset. It can be combined with a polymer nanocomposite-based hydrocarbon gas sensor or aqueous water sensor in the front.

IIoT system containing a polymer nanocomposite water sensor on a flexible substrate and a thermistor on the back is designed to detect hazardous water-based liquids for produce water facility or pharmaceutical plants. These flexible sensors can be inserted in the flanges of process equipment to provide early detection of leaks.

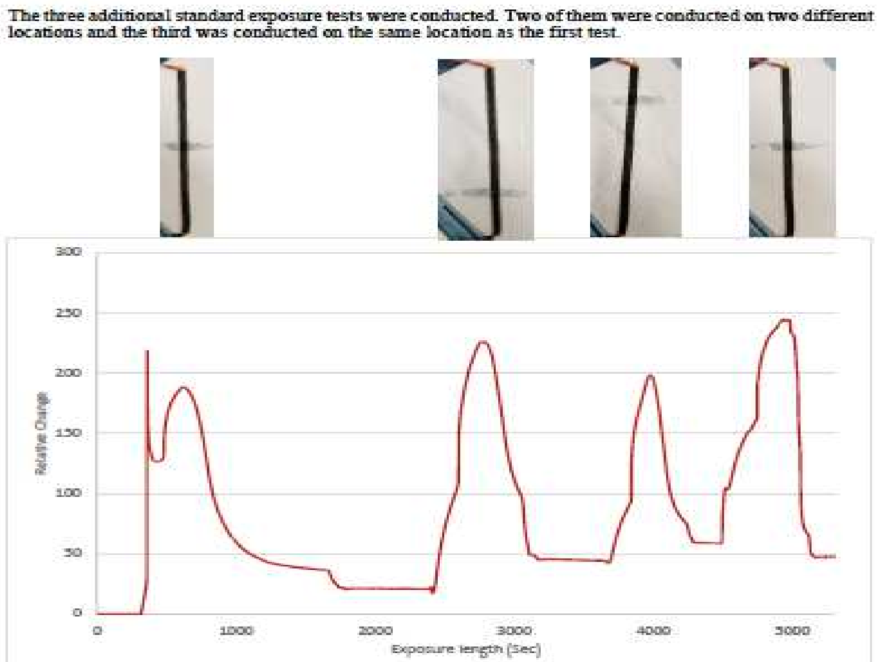

Figure 10: Multiple exposures of water sensors to tap water

Fig. 10 shows multiple water exposure tests done on such a flexible sensor showing its capability to withstand multiple exposure events and produce alarms.

IIoT system that contains a hydrocarbon gas sensor on a flexible substrate with a thermistor on the back is also envisioned. It can be deployed in a collection channel at the end of the annulus of an offshore flexible pipe to detect the presence of butane if any part of the inner seal of the flexible pipe is compromised.

6 Conclusions and Future work

In this work, we described a novel Multi-functional IIoT system for monitoring oil and gas assets using multiple sensors. IIoT system contains battery operated standalone controller module which communicates with our server wirelessly via an internal cellular or satellite model. Satellite communication is ideal for remote applications and several of these systems have been deployed successfully in remote locations in Alaska and Northern Alberta. In the event liquid hydrocarbons are detected, an alarm is sent immediately to our server which in turn automatically notifies the operator via email and a notification alert on their phones or tablets.

Following new developments arising from this work:

1) We developed three types of polymer nanocomposite-based smart sensors, a) Liquid hydrocarbon sensors, b) Aqueous water sensors, and c) Gas Nanocomposite sensors.
2) Liquid-detecting nanocomposite sensors are based on a polymer absorption mechanism while gas sensors are based on the adsorption of gas species on the sensor surface. All these sensors are successfully tested with each showing excellent response to respective exposure.
3) Environmental monitoring sensors such as Water level sensors, conductivity sensors and temperature are developed and tested.

4) The incorporation of these environmental monitoring sensors within it improved the effectiveness of the IIoT system considerably. This was highlighted as our multifunctional IIoT system detected a product leak at a client's site in Canada preventing a potentially $1M in cleanup costs.

We are in process of further developing new multifunctional IIoT systems incorporating several new smart nanotechnology-based sensors and environmental sensors. The platform polymer nanocomposite technology can be tuned to specific chemicals based on the customer's requirements. Such advanced multifunctional IIoT has the potential in a monitoring complete range of oil and gas infrastructure.

References

[1] Statista Research Department, https://www.statista.com/topics/8216/global-oil-and-gas-transportation-industry, Jan 31, 2023.

[2] B. Burns, Aging Pipeline Infrastructure in the United States: How do a changing policy mix, issues of energy justice, and social media communication impact future risk analysis?, Master Thesis Dissertation, Michigan Technological University, 2020.

[3] M. Baker, Pipeline Corrosion – Final Report, USDOT PHMSA, Nov. 2008.

[4] T. Vairo, A. P. Reverberi, M. F. Milazzo, B. Fabiano, "Ageing and Creeping Management in Major Accident Plants according to Seveso III Directive", Chemical Engineering Transactions, Vol. 67, 2018.

[5] B. Fabiano, F. Currò, From a survey on accidents in the downstream oil industry to the development of a detailed near-miss reporting system, Process Safety and Environmental Protection 90, 357-367, 2012.

[6] Shaw D., Phillips M., Baker R., Munoz E., Rehman H., Gibson C., Mayernik C., 2012, "Final report: Leak detection study-DTPH56-11-D-000001", U.S. Department of Transportation and Hazardous Materials Safety Administration.

[7] R. Minerva, A. Biru, and D. Rotondi, "Towards a definition of the Internet of Things (IoT)," IEEE Internet Initiative, vol. 1, no. 1, pp. 1–86, May 2015.

[8] A. Slaughter, A. Mittal, V. Bansal, "Bringing the digital revolution to midstream oil and gas", The new frontier (https://www2.deloitte.com/xe/en/insights/industry/oil-and-gas/digital-transformation-midstream-oil-and-gas.html), 2018.

[9] R. Nicholson, J. Feblowitz, C. Madden, and R. Bigliani, "The Role of Predictive Analytics in Asset Optimization for the Oil and Gas Industry-White Paper," 2010, http://www.tessella .com/wp-content/uploads/2008/02/IDCWP31SA4Web.pdf.

[10] https://www.i-scoop.eu/industry-4-0, accessed on Feb. – 2023.

[11] K. Parmar, S. Park, 2016, "Robust Direct Hydrocarbon Sensor based on Novel Carbon Nanotube Nanocomposites for Leakage Detection", Proceedings of the 11th International Pipeline Conference, Calgary, CA.

[12] S. Park, K. Parmar, "Sensing Element Compositions and Sensor System for Detecting and Monitoring Structures for Hydrocarbons", US Patent App. 15/030,029, 2016.

[13] E. Allison, B. Mandler, "Water in the Oil and Gas Industry", Petroleum and Environment, Part 2/24, American Geosciences Institute, 2018.

[14] D. Lun, K. Xu, "Recent Progress in Gas Sensor Based on Nanomaterials", Micromachines, 13, 919, 2022.