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Return of Experience on the Efficacy and Reliability of Fiber Optic Ammonia Leakage Detection Systems

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Distributed Fiber optic sensing system is a unique tool for the evaluation of distributed temperature over several kilometers. It is a powerful diagnostic instrument for the identification and localization of potential problems, such as leakages in ammonia pipelines, hot-spots in urea reactor vessels and other events creating temperature anomalies. Such distributed temperature sensing (DTS) systems have the advantage of being relatively easy to deploy over long ammonia pipeline sections and have been shown to detect leakages events with good accuracy and reliability. However, when distributed fiber optic sensing systems are deployed in security-critical environments, where availability and reliability are crucial, it is important to continuously verify and assess the correct functioning and reliability of the whole system, including the sensing cables, the measurement system, the data analysis software and the alert transmission (in the past, such testing has been performed periodically by the plant maintenance personnel). The DTS Automated Trip Testing System is a fully independent device that is able to produce a controlled and localized thermal anomaly (hot spot or cold spot) and verify its correct detection. This allows a continuous verification of the DTS system reliability and functionality and a periodic statistical evaluation of the confidence level (proven by experience, SIL rating). This paper will present more specifically the development, the functioning and deployment, and its applications of an automated system and method for testing the efficacy and reliability of distributed temperature sensing (DTS) systems, in particular those DTS systems used for ammonia pipeline leakage detection.

Fiber optic ammonia leak detection systems have been installed at 7 fertilizer plants in Europe. The paper will present the return of experience of the last 2 years ammonia leak detection installations in 5 fertilizer plants through the use of ATTS data and statistical analysis of alert records.

1. INTRODUCTION

Recent developments of distributed optical fiber temperature sensing techniques provide a cost-effective tool that allows monitoring over long distances (some km) with high spatial resolution (typically every meter). Using a limited number of very long sensors it is now possible to monitor the behaviour of pipelines with a high measurement speed at a reasonable cost.

Unlike electrical and point fiber optic sensors, distributed sensors offer the unique ability to measure temperature along their whole length. This capability allows the measurement of thousands of points using a single transducer.

Using this technology, it is possible to detect leaks from liquefied ammonia pipelines, by observing the characteristic temperature drop associated with such leaks. After a comprehensive testing and qualification phase [1, 2, 3] several systems are now permanently installed in real operating leak detection installations.

In this paper we will review the experience gained in those installations and provide recommendations for future similar installations.

2. AMMONIA LEAK DETECTION WITH DISTRIBUTED FIBER OPTIC TEMPERATURE SENSORS

The most developed technology of distributed fiber optic sensors is based on Raman scattering. These systems make use of a nonlinear interaction between the light and the glass material of which the fiber is made. If light at a known wavelength is launched into a fiber, a very small amount of it is scattered back at every point along the fiber. Besides the original wavelength (called the Rayleigh component), the scattered light contains components at wavelengths that are different from the original signal (called the Raman and Brillouin components). These shifted components contain information on the local properties of the fiber; in particular the intensity of the Raman peak shows strong temperature dependence. When light pulses are used to interrogate the fiber, it becomes possible, using a technique similar to RADAR, to discriminate different points along the sensing fiber by the different time-of-flight of the scattered light. Combining the radar technique and the analysis of the returned light, one can obtain the complete profile of temperature along the fiber. Typically it is possible to use a fiber with a length of up to 30 km and obtain temperature readings every 1 meter. In this case we would talk of a distributed sensing system with a range of 30 km and a spatial resolution of 1 m. Systems based on Raman scattering typically exhibit a temperature resolution of the order of 0.1 °C with measurement times as low as 10 seconds.

The typical components of a distributed temperature sensing system are the following:

- Sensing cable to be installed along the pipeline.
- Interrogator.
- Multiplexer to allow multiple cables to be measured from one interrogator, or to provide interrogation at both ends of a cable for redundancy.
- Data analysis software with automatic detection of leaks.
- Relay module used to transfer alarm information to other plant control systems (e.g. to initiate automated emergency shutdown sequence).
- SCADA Interface.
- Automated Trip Testing System.
- User graphic interface that shows the exact location of a leak.

An example of a rack cabinet containing two fully redundant systems as above-described is shown in Fig. 1, while Fig. 2 shows an example of graphical user interface.

Fig. 1: Fully redundant leak detection system

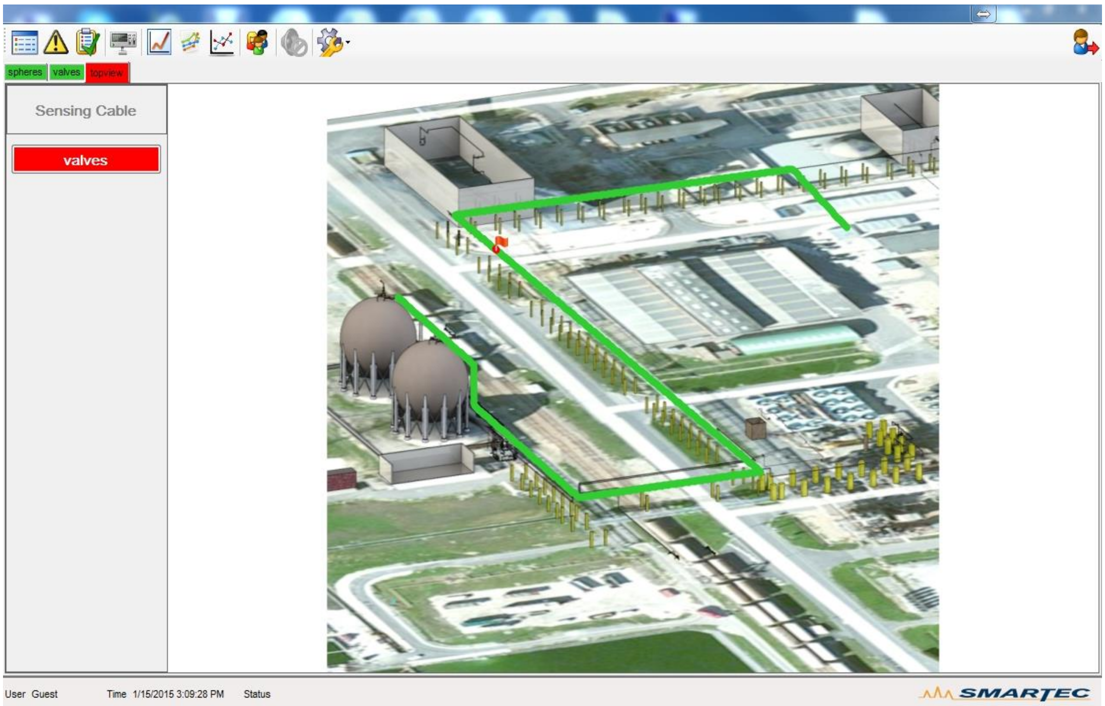

Fig. 2: Example of user interface showing location of event, e.g. leak detection

The basic principle of pipeline leak detection through the use of distributed fiber optic sensing relies on a simple concept - when a leak occurs at a specific location along the pipeline, the temperature distribution around the pipeline changes. This change in temperature is localized both in space (a few meters around the leak location) and in time (the onset of the leak). This makes the algorithmic detection of leaks relatively easy to implement. The origin of the temperature disturbance around the pipeline depends on the type of pipeline and its surroundings.

In the case of ammonia leaks from above-ground pipelines, the main effects are the following:

- The liquid component of the ammonia leak drops to a temperature of -33 °C (-27 °F) and wets the sensing cable directly through dripping, splashing and spraying, provoking a fall in the recorded temperature.
- The gaseous component of the ammonia leak forms a cold plume that also cools down the sensing cable.
- Part of the gaseous component of the ammonia leak condenses on the pipe and cable surface, producing an additional liquid phase.
- The leak also produces a drop in temperature of the pipeline itself that is transmitted to the sensing cable.

It has to be noted that if the ambient temperature is close to -33 °C (-27 °F), the evaporation of liquid ammonia is limited and the gas release will be small, detection will be more difficult, but in these cases the impact on the environment is reduced. Knowing the above effects, one can determine the ideal sensing cable placement around the pipeline. The same system setup can be used for leak detection of buried ammonia pipelines, because a localized temperature drop is also expected in that scenario.

3. Redundancy, Reliability and Availability

Although a system like the one described in the previous paragraph is able to detect leaks with high reliability and confidence, it is often necessary to also insure that the leak detection system presented has an availability which is compatible with the operational requirements of the plant.

To address those needs, we have developed different redundancy solutions that aim to achieve different levels of availability and maintainability.

3.1 Basic configuration

The simplest solution includes a single cable and a single readout system:

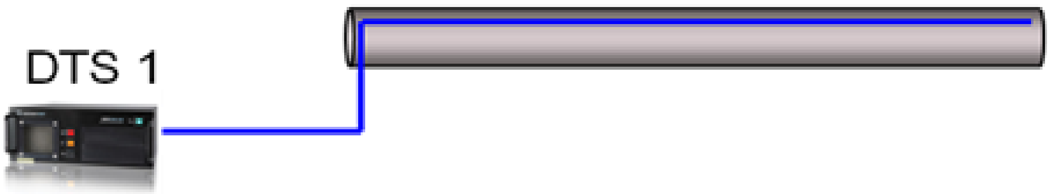

Fig. 3: Example of simple leak detection system with no redundancy

One optical cable contains 4 optical fibers and this already presents a minimum redundancy in case of fiber failure. Furthermore, two optical fibers are lopped together at the end of the cable, so that the readings can occur from the two ends of the loop formed by the two fibers. This allows continuing the measurements over the whole length of the pipeline, even in the case of failure of a single fiber.

3.2 Automated Trip Testing System

The next level of availability is achieved with the addition of an automated testing system. This allows a higher level of self-diagnostic capability and insures that any issue in the system is rapidly detected. The ATTS (Automated Trip Testing System) is a device, fully independent from the data acquisition system, which can create an artificial leakage along the sensing cable and verify the correct response of the alert system (see Fig. 4). The ATTS cools or heats 1m section of optical fiber at a rate similar to the one observed in the case of real leakages and observes the signal coming from the relay module to verify alarm triggering. A dedicated relay is allocated to the ATTS fiber section, so that the alert in this zone does not trigger any pipeline shutdown sequence. The ATTS is placed at the beginning and at the end of the fiber loop, so that the integrity of the whole fiber can also be verified. Typically, a leakage simulation can be simulated every hour, so that thousands of tests are carried out every year.

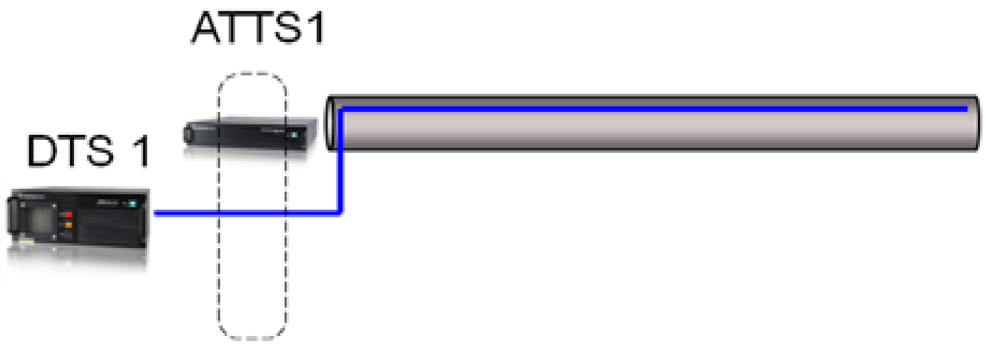

Fig. 4: Example of simple leak detection system with additional self-testing capability

3.3 Fully redundant system

If the plant operator needs to guarantee a high availability of the system and therefore requires that the system can remain operational even during maintenance of single components, we can opt for a fully redundant system where all components are doubled. This is depicted in Fig 5.

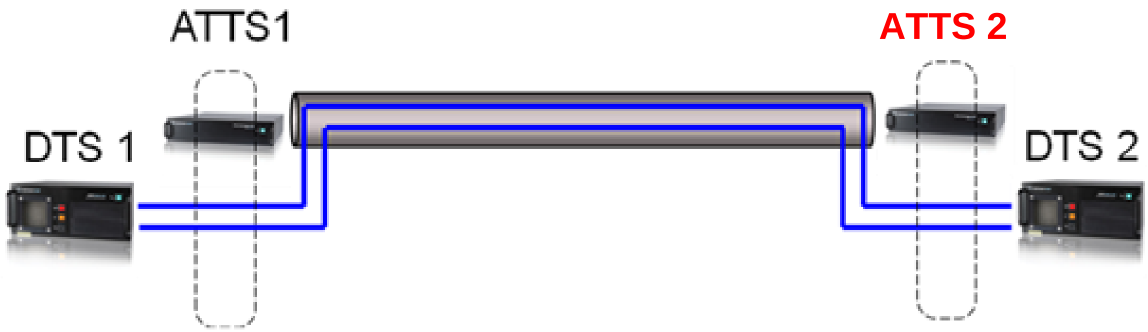

Fig. 5: Example of fully redundant leak detection system with self-testing capability

In this configuration it is possible to operate the system even in the case of cable damage and simultaneous unavailability of one of the measurement instrument. Furthermore, when both systems are operational we can rely on a voting system, e.g. 2 out of 2, to verify that both systems agree on the presence of a leak. This can further reduce the probability of any false alert.

If, on the other hand, one wants to maximize the probability of detection, it is recommended to use a 1 out of 2 voting system as illustrated in Fig 6.

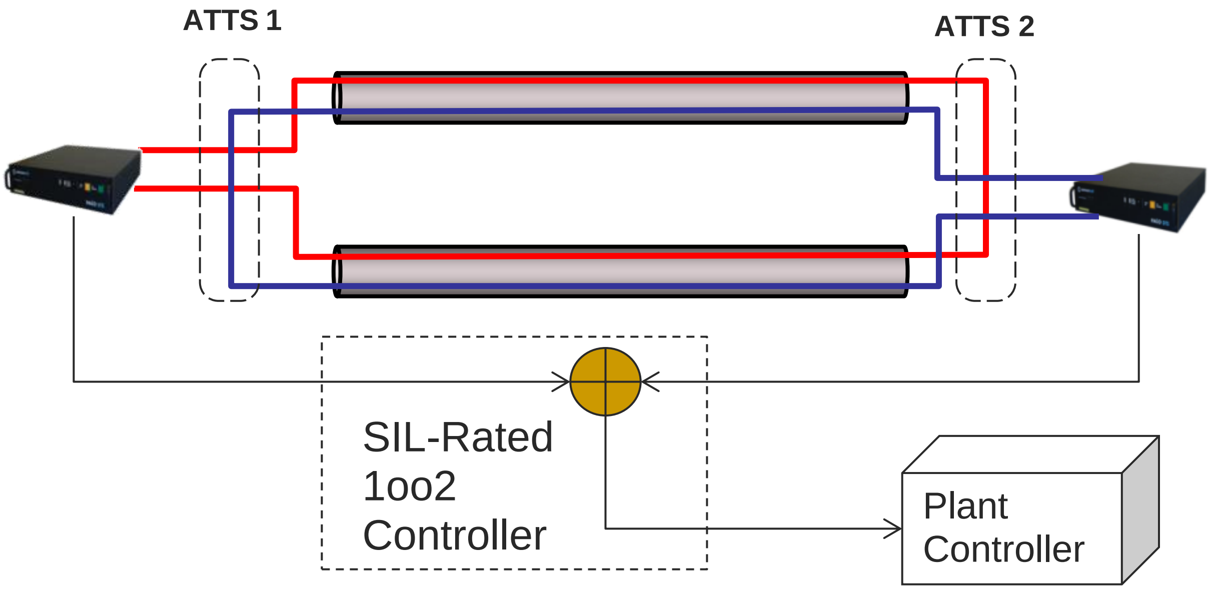

Fig. 6: Example of fully redundant leak detection system with voting system

4. FIELD INSTALLATIONS

The ammonia leak detection system described in the previous chapters has been installed in a number of plants in Europe, as illustrated in the following table.

Plant	Country	Year of installation	Approx. length of monitored pipe	System configuration
Yara Ravenna	Italy	2006	5 km	2 x basic
Yara Le Havre	France	2010	10 km	2 x fully redundant
Yara Montoir	France	2013	2 km	1 x fully redundant
Yara Pardies	France	2013	1.5 km	1 x basic + ATTS
Yara Ambès	France	2014	2 km	1 x fully redundant
Borealis Grandpuits	France	2013	2.5 km	1 x fully redundant
Borealis Ottmarsheim	France	2010 pilot project	0.4 km	1 x basic (pilot test)
TOTAL			**23 km**	**14 systems**

For confidentiality reasons, the return of experience described in the following chapters will not make reference to a specific site, but rather summarize the lessons learned across all projects.

5. RETURN OF EXPERIENCE

5.1 Detected leaks

Fortunately, none of the instrumented plants has suffered any major ammonia leak since installing the fiber optic detection system. There have been however two cases where a minor leak was detected.

The first instance concerned a very small leak from a bolted joint that was discovered during the commissioning of one of the systems. The leak was correctly identified by the system and was later confirmed by visual inspection. This leak was well below the minimum leak rate that requires immediate action.

A second occurrence concerned a coupling to a transportation vessel that leaked during an ammonia transfer operation. Also in this case the leak was correctly identified by the system and an alert was generated. The ammonia transfer was stopped and resumed after fixing the issue. Fig 7 shows the temperature evolution at the location of the leak. It is possible to observe how the temperature dropped from an initial value of about 20 °C (ambient temperature) to about -40 °C due to the leak. The location of the leak can be clearly identified at meter 887, but a larger section of cable is affected by the cooling effect of the ammonia evaporation cloud.

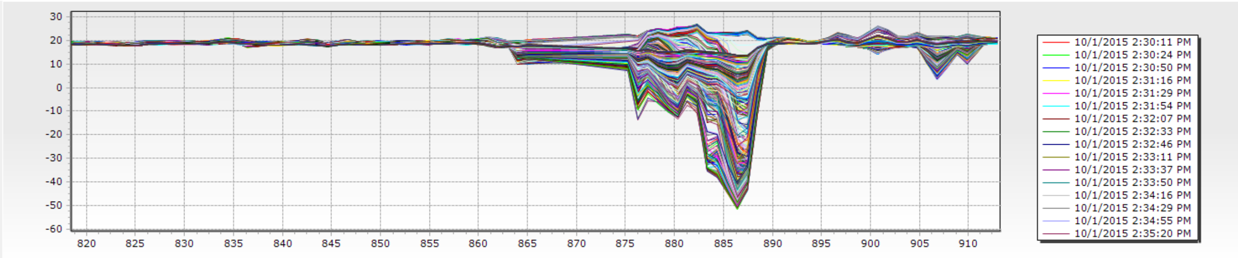

Fig. 7: Temperature distribution along the sensing cable during a leak

The time evolution of the temperature at the leak location can be observed in Fig 8.

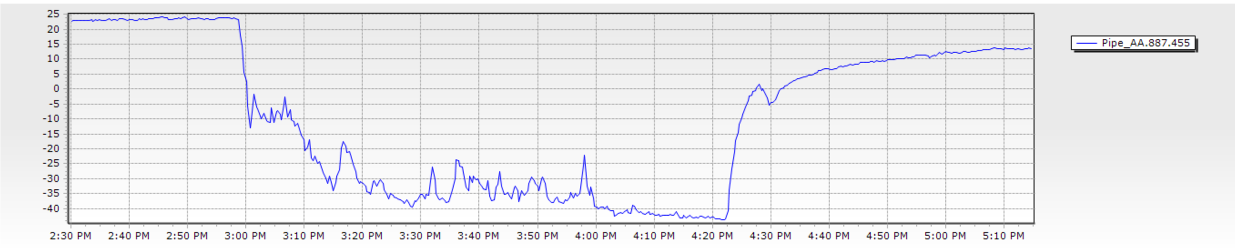

Fig. 8: Temperature evolution at the location of the detected leak

5.2 Availability

Availability data from the sites was evaluated to quantify the reliability of the different components of the leak detection system.

At the time of writing, the 14 systems that are in operation have added up 34 years of operation, with an average of 2.4 years per system.

The recorded mean time between failures (MTBF) of the individual sensing components was evaluated to 8 years. The failure and/or maintenance of the individual sensing components (interrogator, ATTS, server) have prevented operation of the 34 systems for a total of 0.9 years, corresponding to an uptime of 97%. Considering only redundant system the uptime was 99% (with at least one of the two redundant systems available).

5.3 ATTS data

Figure 9 shows an illustration of temperature recording at the location of the cooling zone as a function of time. It can be observed that with an hourly frequency the apparition of the cooling peak is easily observable.

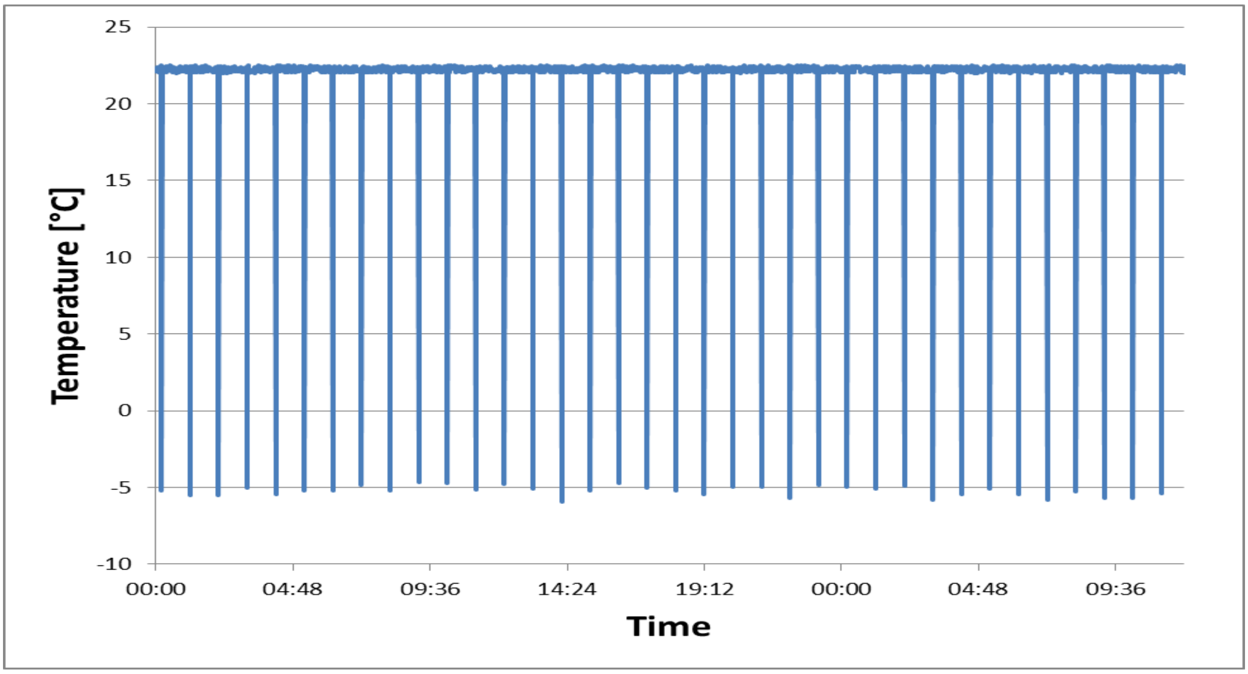

Fig. 9: Example of ATTS temperature recording at the cooling location

Once hundreds or thousands simulated leakage events are generated, it becomes possible to calculate the probability of answer on demand (% of successful detections) and generate statistics on the reaction time (average and maximum delay). For example, a confidence level of 2 requires that 99% of the simulated leaks are correctly detected.

The data from the installed ATTS systems corroborates the availability data presented in the previous paragraph, respectively 97% for individual detection systems and 99% for redundant systems.

When the systems were in service, the ATTS triggered an alert in 99.9% of the tests, demonstrating the high reliability of the ATTS device itself.

5.4 False positive

There have been no reported cases of false alerts, where an alarm was triggered without a corresponding temperature drop. There have, however, been numerous cases of false positives where unforeseen circumstances have triggered a "true" alert that did however not correspond to a real ammonia leak.

The main causes of such false positives were the following:

- Trigger levels: temperature changes that would trigger an alert were initially set too aggressively and have generated false positive due to temperature variation induced by normal operation or weather conditions. After an observation period, the trigger levels were re-assessed and optimized to eliminate such false positives.

- Singular points: at some locations, extreme temperature changes were recorded due to external events. Examples include nearby fast cooling devices or vapour blows that would heat and cool the sensing cables. Those localized points were easily spotted by observing how false positives cumulated at the same location. It was then easy to correct those points by physically shielding the cable from the disturbance or adjusting the trigger levels of those isolated points.

5.5 Other encountered issues

The main obstacles that were encountered on the path to a successful deployment of ammonia leak monitoring system were organizational rather than technical. One common challenge in many sites concerned the transfer of system ownership from the project team to the exploitation team. In some cases this transfer did not occur with a sufficient training of the final operators. This caused misunderstandings on the way the system works and false expectations. To avoid such, it is recommended to involve the exploitation team from the beginning of the project and carry out in-depth training of all shifts to make sure the system functionality is properly understood. In those cases the system sometimes became “orphan” since nobody was really taking ownership of it. It was then well possible that alerts generated by real leaks or warnings about failed components got un-noticed.

In some other cases the opposite problem arose, when the system was transferred too soon to exploitation, before the initial false positives were completely eradicated. This caused a general mistrust in the system that had to be reversed later on.

In general, most safety systems that have no direct benefit on the day-to-day plant activities need to strike the right balance between staying out of the way of normal exploitation and not becoming forgotten and abandoned.

In two other sites, damage to the cable was caused by insufficient training of the maintenance personnel. They simply did not know how to handle the sensing cable if they need to service components supervised by the ammonia leak detection system. An early involvement of the maintenance staff is therefore highly recommended. At another site, the maintenance team was on the contrary able to inform us about the most usual maintenance interventions that can affect the pipe and ancillary devices. It was then possible to install some extra length of cable at those locations to allow displacing the sensor and easing future maintenance.

6. Conclusions

The large number of field deployments of fiber optic based ammonia leak detection system has allowed learning valuable lessons on the technical and organizational sides. It was possible to improve the reliability and availability of the systems by implementing automated self-testing capabilities. The data gathered by the 14 systems currently in operation show an availability of 97%. All cases of non-availability were quickly identified so that they can be corrected rapidly or alternate safety measures could be implemented.

By monitoring false positives it was possible to improve the leak detection algorithms and standard thresholds so that only real leaks would trigger alerts.

Finally, the process for deploying a system to a new site was improved by involving the right project and site team and make sure that the system is finally owned by the people using it daily.

Only one real leak of significant (although very small) size was recorded and correctly set off an alert.

Acknowledgements

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