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Detection and Localization of Leakages in Toxic/Flammable Chemicals Pipelines using Distributed Fibre Optic Sensors

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Over the past decades, several major industrial accidents led the chemical industries handling large quantities of dangerous substances and national regulation bodies to reinforce the safety and prevention measures of their installations, in compliance with local laws such as the Seveso II directive in Europe. Indeed, leakages of chemicals can be at the origin of toxic releases, which can have severe consequences on the installations as well as on the environment and nearby inhabitants. Industries are prompted to take all possible measures to reduce the occurrence of such catastrophic events by implementing additional technical safety barriers in order to prevent or mitigate any potential danger on their key structures such as pipelines, reactors, storages, transfer lines, etc.

Pipeline leakages may have different origins, such as corrosion, fatigue, material flaws, shocks, abnormal temperatures, extreme pressures, or excessive deformations caused by ground movement. In the case of liquefied or pressurized gases, leakages can be detected by the rapid drop of temperature due to the evaporation of the released liquid and its evaporation *gases or due to gas expansion. These local thermal anomalies can be reliably detected by a fiber-optic distributed temperature sensing system able to detect temperature changes of the order of 1°C, with 1m spatial resolution and 10s response time. A fiber optic cable is installed all along the whole length of the pipeline and is connected to a measurement system that can automatically detect temperature anomalies which are telltale of leakages and generate an alert to initiate appropriate response actions on the affected pipeline section. Such a system has been permanently deployed at several industrial and chemicals sites were functional and operational tests have also been carried out.*

This paper will present the system architecture and installation at an ammonia production, storage, shipping and processing site and 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 pipeline leakage detection.

INTRODUCTION

The tragic consequences of the September 2001 chemical factory explosion accident in Toulouse, France make it clear that risks had been underestimated - both from the point of view of safety management and urban planning. In the case of safety management, the controls to prevent such a catastrophic event were insufficient or inadequate.

Since the Toulouse incident, the legislation in France is much more detailed in the following ways: all risks with toxic gases and liquids must be evaluated including 100% of the line size (i.e., a guillotine pipe rupture), a 10 % equivalent of the diameter leak, and a 1% opening. The duration of the release scenarios vary from some seconds to at least 30 minutes.

In a French fertilizer production plant far more than 200 possible leak or loss of containment scenarios (NH_3, NO_x) have been documented. Each situation is studied with a fault tree analysis and HAZOP to answer the following:

- What can go wrong?
- What are the probabilities of undesired events?
- Are there preventive barriers? (including SIL analysis)
- What technical and organizational barriers are in place to reduce the release?
- Are these protective barriers effective?
- What are the consequences of the release?
- What is potentially the impact on the environment?
- Finally, what are the worst case scenarios?

Example of a Risk Study

Table 1 is an extract of a French SEVESO safety study for illustration.

Flow NH3 spill	%	Duration spill (minutes)	Distance toxic cloud with risks of fatalities (m)
~ 200 kg/s	100 « Guillotine rupture »	1	170
~ 40 kg/s	10 %	1	160
	10 %	30	465
~ 4 kg/s	1 %	30	125

Table 1: Risk analysis for different leak scenario

The scenario represented in Table 1 is unloading anhydrous ammonia at 750 ton/hour (P = 3.5 bars, T = -33 °C, or P = 50 psig, T = -27 °F), through a 300 mm (12 inch) diameter pipeline, with typical weather conditions. The last column indicates the maximum distance from the leak where fatalities can be expected.

It is not the goal of this paper to develop the causes which might contribute to loss of containment and how to avoid any accident. The goal here is how to detect and stop the release as quickly as possible.

Consider the following:

- A guillotine pipe rupture is easily detected by the process (measurement of flow or pressure) and automatic emergency shut-down of the installation is immediate.
- Smaller leaks, like a 10% scenario, are not detected by the regular process instruments.
- A 30-minute release is a typical scenario when NH3 detection is delayed because ammonia gas detectors might be too far or not exactly in the right wind direction. In other cases, the detection of the release is dependent on operators who may not be in the area for some time.

What is a Small NH_3 Leak?

In process safety, a small leak is a release of anhydrous ammonia that has effects outside the plant. To have consequences outside the plant means it might start from some kg per second. On the other hand, in occupational safety, a small release is far less, and is some grams per second.

FIBER OPTIC DISTRIBUTED TEMPERATURE SENSING

Sensing Principles

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 behavior 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. 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 form 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 to 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 (≈20 miles) and obtain temperature readings every 1 meter (3 feet). 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 (0.2 °F) with measurement scan times as low as 10 seconds.

Figure 1 shows an example of a Raman interrogator.

Fig. 1: Distributed temperature sensing interrogator

Components

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

- Sensing cable to be installed along the pipeline (see Fig. 2).
- Interrogator (see Fig. 1).
- Multiplexer to allow multiple cables to be measured from one interrogator, or to provide interrogation of both ends of a cable for redundancy.
- Data analysis software with automatic detection of leaks and system function validation (proof testing).
- Relay module used to transfer alarm information to other plant systems (e.g. to initiate automated emergency shutdown sequence).
- User interface that shows the exact location of a leak (see Fig. 3).

Fig. 2: Distributed temperature sensing cable

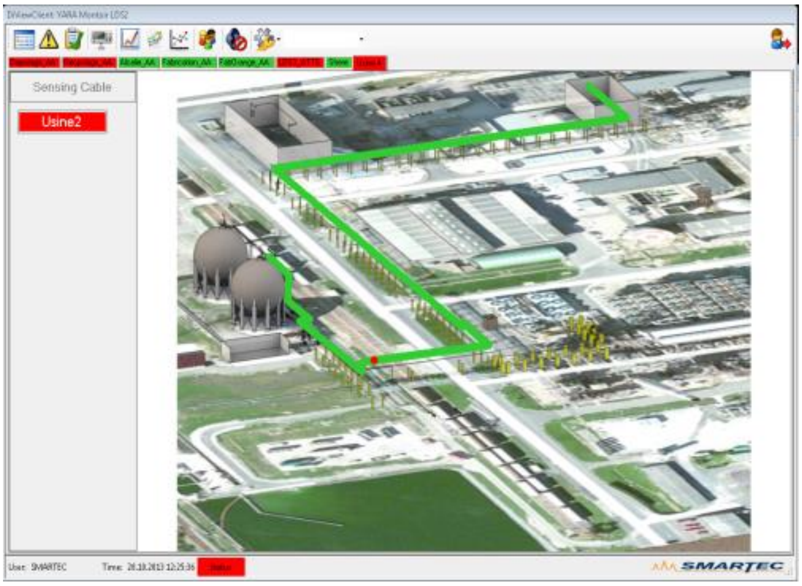

Fig. 3: Example of user interface showing location of event, e.g. leak

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. This case, however, was not analyzed in the presented qualification tests.

Reliability and Availability

For mission-critical applications such as ammonia leak detection, several strategies can be used in order to ensure the reliability and high availability of such a system. Optical fibers are always installed inside a cable to protect them mechanically, while ensuring the minimum possible thermal isolation. Additional strategies for increasing reliability and availability include the following:

- Using a looped cable, where both ends of the sensing cable are connected to separate channels of the interrogator. In case of cable damage, it is possible to measure temperatures up to the damage point. If it is looped from both ends of the cable, the whole length of pipe can still be monitored in case of a single failure point.
- Using cables containing multiple optical fibers ensures that if a single fiber is damaged the others can still be used.
- Using multiple cables along the same pipeline.
- Using two interrogators connected to different fibers in the same cable or to different cables. In this case it is also possible to implement voting criteria among the interrogators to optimize availability and reliability and reduce false alarms (see Fig. 4).

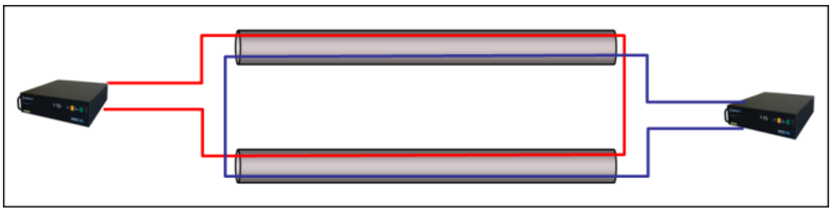

Fig. 4: Redundant setup with two interrogators and looped fibers

TECHNOLOGY VALIDATION

Short- and long-term tests and experiments were carried out to validate the technology for ammonia leak detection and for its compatibility with real-life fertilizer plant environments.

On-Site Leak Simulations

Several tests were performed on-site at the Yara plant in Le Havre, France. These tests consisted of pouring liquid ammonia on pipelines equipped with an optical fiber sensor and verifying the temperature drop measured by the system. Typically, 1 kg (2 lb) of ammonia was poured on a pipe section of 0.5 m (1.5 ft) over the duration of 1 min (see Fig. 5).

Fig. 5: Ammonia pouring test setup

Figure 6 shows the temperature drop recorded by the measurement system at the leak location. Temperature drops of 5 °C (9 °F) over 20 seconds and 10 °C (18 °F) over one minute were recorded in all tests. This response can differentiate between the normal temperature change that occurs when the line is put into service for a product transfer in the following ways:

- The rate of temperature change from the leak is higher than the one recorded during the initiation of ammonia transfer.
- The operational changes, such as initiation of ammonia transfer, of temperature affect long sections of the pipeline uniformly, whereas the leaks only affect a small portion of the pipeline.

Tests were also performed on pipelines covered with ice, showed that the ammonia quickly melts the ice and comes into contact with the sensing cable (initially covered by ice itself).

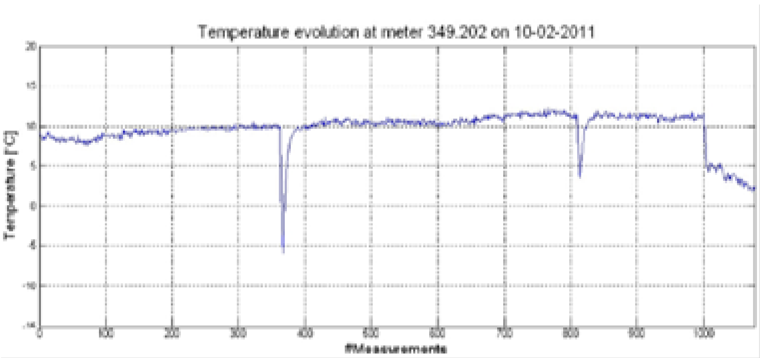

Fig. 6: Temperature drop recorded during two ammonia leak tests and a pipeline restart

Laboratory Leak Simulations

In a series of laboratory experiments carried out at the French INERIS laboratory (part of the French Ministry of Environment), the performance of the system was evaluated in the presence of a real leak from a pipeline. These tests were necessary to verify the field test results – that is, the necessary temperature drop would also be produced in real leak conditions.

The experiment consisted of a pipeline section including a cut with an equivalent section of 5%. The pipe contained anhydrous ammonia at 7 bars (100 psig) and the cut produced a leak of 38-45 g/s (5-6 lb/min) after opening the quick-release plug. High-speed and infrared cameras were used to capture the dynamics of the leak and the resulting temperature changes. Both vertical and lateral leaks were tested with the cable placed under the pipeline.

The experiment showed a very quick temperature drop of more than 10 °C/min (18 °F/min) that was easily detected by the system. The high-speed video images, showed no significant spray or dripping of ammonia on the cable, therefore the temperature drop was attributed mostly to the ammonia gas cloud and its re-condensation and evaporation on the pipe and on the sensing cable.

The two drops of temperature clearly visible in Figure 7, taken approximately 20 seconds after the release starts, are due to the loop configuration used for the sensing cable. The cable passes twice in the leak zone, on its way out and on its way back to the instrument.

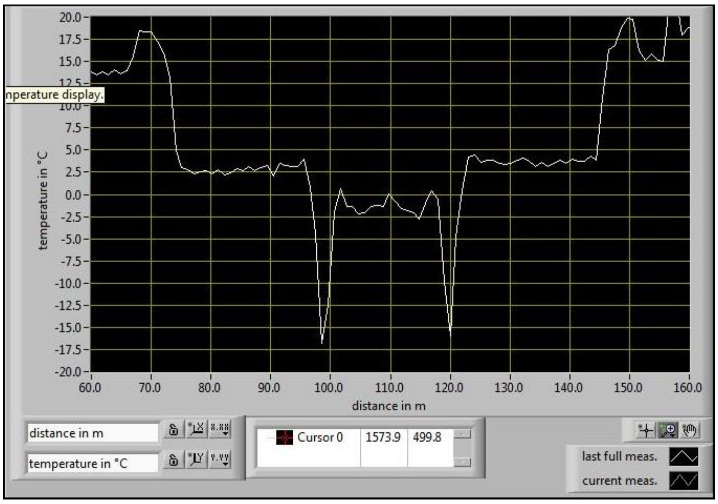

Fig. 7: Plot of temperature as a function of distance during leak test

Performance without Leaks

To evaluate the temperature variations occurring during normal plant operations, without ammonia leaks, a sensing system was installed on a transfer pipeline used to refill trucks. This type of pipeline is subject to frequent and sudden temperature changes due to the start-and-stop nature of these operations. This scenario creates complex temperature patterns compared to the constant flow in a production transfer line.

A test period spanning both summer and winter seasons, collected data every 10s over 250 m (825 ft) of a pipeline. The data was analyzed statistically and it was found that the maximum temperature variation between two measurements was 2.5 °C (4.5 °F) well below the rapid changes observed in the case of a leak. It is therefore possible to operate such a system without triggering false alarms in normal operational conditions. Figure 8 shows the tests results, including a leak simulation test performed at the end of the test period that clearly exceeded the threshold.

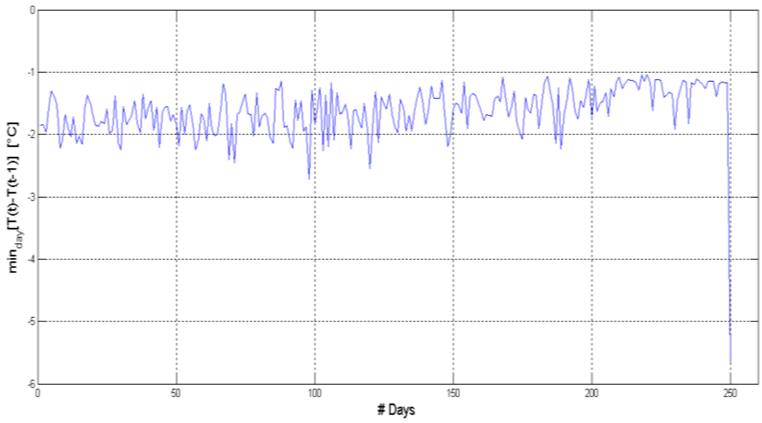

Fig. 8: Maximum daily rate of change without leaks and with a leak test at the end

RELIABILITY AND CONFIDENCE LEVEL

A leakage detection system is likely to sit idle for all its life, hopefully never detecting any real leakage. This presents a challenge for reliability, since the system will be "forgotten" most of the time and it is difficult to guarantee that it will perform perfectly the day it's really needed. Insuring and certifying a high confidence level becomes imperative in these conditions. As with all safety systems, it is important to be able to assess the reliability of the DTS system and to test whether the DTS system is functioning properly. In the past, such assessment and testing have been performed periodically on annual or quarterly basis by pipeline personnel. Such periodic testing typically involves a worker manually exposing the sensing line to a cooling or heating source to produce a localized cold or hot spot.

For calculating plant-level safety and accident probabilities, it is necessary to assign a Safety Integrity Level (SIL) or equivalent confidence level to such DTS systems. However, in order for the DTS system to be SIL-certified, certain requirements have to be met, inter alia, targets for maximum probability of a dangerous failure. These requirements can be complied with by establishing a rigorous development and documentation process, or by establishing that the system has sufficient operating history to demonstrate that it has been proven in use. This evaluation must be specific to each leaking fluid. In the case of a DTS, due to the complexity of the software used to operate it, it may not be possible to demonstrate compliance with SIL certification requirements by way of a rigorous development and documentation process. Accordingly, in such cases, the only way to show compliance with SIL certification or equivalent confidence level requirements is through extensive proof of use. With current testing of the DTS systems being performed manually only a few times a year, it is difficult to generate sufficient data required to evidence the DTS system's reliability through proven use. Based on the foregoing, it would be advantageous if a DTS system could be provided with an independent testing system that could easily be incorporated into a sensing line and that would be operable to test the reliability and functionality of the DTS system on a relatively high-frequency basis in a continuous and autonomous manner.

Automated Trip Testing System

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. 5). The ATTS cools or heats a 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.

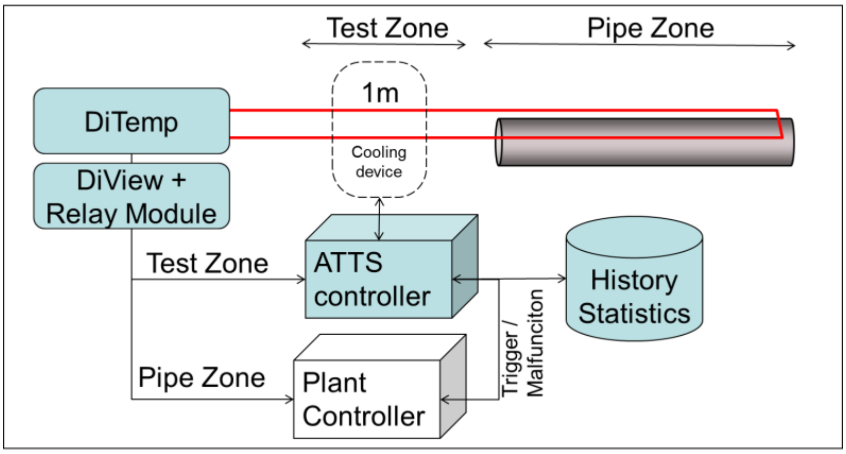

Fig. 5: ATTS block diagram

The ATTS is typically operated as follows:

- At fixed (e.g. every hour) or random times the cooling/heating of the test zone is initiated.
- The time of start is recorded.
- Optional: the temperature of the test zone is verified with a local temperature sensor.
- The ATTS waits for the DTS to detect the simulated leak and closing relay.
- The time of alert received is recorded or a timeout is reached.
- The reaction time is calculated and recorded or failure is logged if timeout was reached.
- Repeat.

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% or the simulated leaks are correctly detected.

The heating or cooling of the test section can be produced in several ways, but the simplest implementation foresees the use of a Peltier cell with a coil of fiber in thermal contact with the heating or cooling surface. By reversing the electrical current direction in the device it is possible to operate the device in heating or in cooling modes. Figure 6 shows an ATTS device implementation.

Fig. 6: Example of ATTS implementation

Figure 7 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.

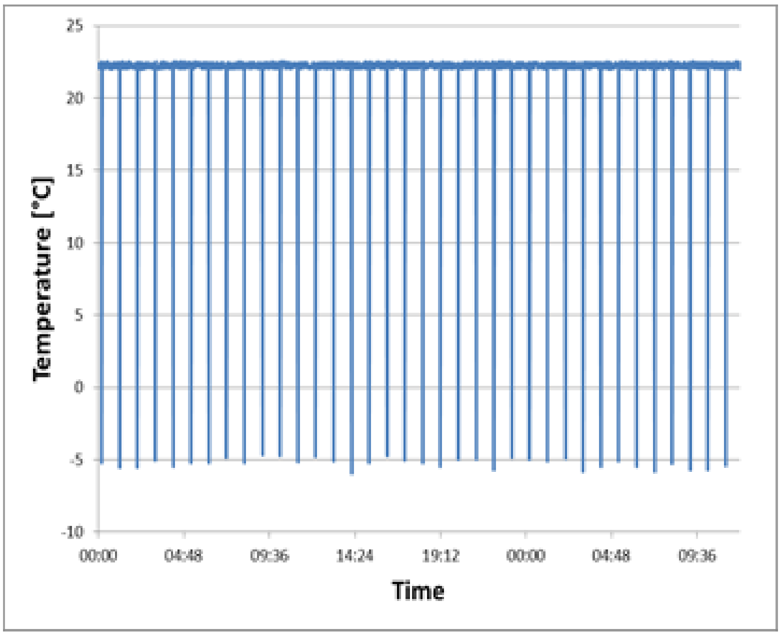

Fig. 7: Example of ATTS temperature recording at the cooling location

About 10 such devices are currently in use in different ammonia and LNG leakage detection projects in Europe. Some of the systems have been in service for almost one year and show an availability exceeding 99%, corresponding to a confidence level of 2 (SIL 2 equivalent).

Besides allowing a quantitative and traceable evaluation of the real confidence level of a DTS system, the ATTS was appreciated by the uses for providing a constant "heartbeat" to the plant controllers, providing a tangible proof that the detection system is up and running at any time.

Redundancy

If multiple redundant reading units are used, it becomes possible to increase both availability and system reliability by using a voting system on the relay outputs. We recommend using a 2oo2 (two out of two) configuration and implement a fallback to 1oo1 if one system is unavailable as shown in figure 8. An example of such an installation is depicted in figure 8.

With a 1oo2 or 2oo3 voting system, it becomes possible to further increase the confidence level of the system.

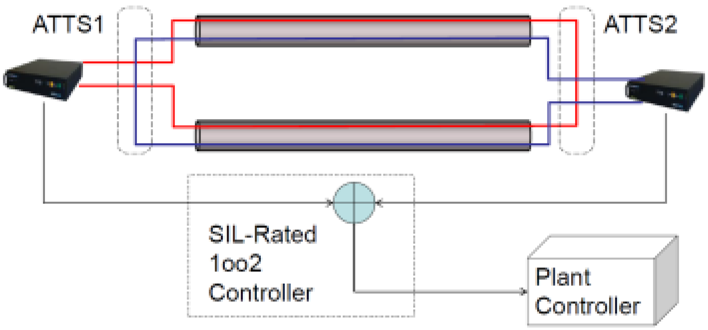

Fig. 8: Redundant system with 2 DTS, 2 ATTS and a voting device

Fig. 9: Implementation of a leakage detection system, including fully redundant DTS, multiplexer, realy module, ATTS and processing PC

Applications

Distributed temperature sensing technology has been deployed in a number of ammonia pipeline monitoring projects worldwide, including:

- Yara Ravenna (Italy, 2006).
- Yara Le Havre (France, 2010).
- PecRhin Borealis Ottmarsheim (France, 2010).
- Yara Montoir (France, 2013).
- Yara Pardies (France 2013).
- GPN Borealis Grandpuids (France, 2013).

The same sensing technology is routinely used since 15 years for the monitoring of other industrial and civil structures including:

- Oil pipelines [1].
- Gas pipelines [2].
- Hot spots in reforming reactors [3].
- Leakages in dam and dykes [4].
- Detection of hot spots in power cables [5].
- Fire detection in tunnels, ships and buildings [6].

In all this cases, the phenomenon to be detected is identified by a change of temperature. Therefore it is possible to implement the ATTS concept to continuously verify the functionality and readiness of these systems. In each case, the ATTS should be configured to reproduce a temperature increase or drop that is similar to the smallest expected event.

CONCLUSIONS

The technique presented above and referred to as Distributed Temperature Sensing (DTS) is a non intrusive fiber optic monitoring system that allows a continuous monitoring and management of pipelines, increasing their safety and providing protection over the entire length of the pipeline. Distributed temperature sensing (DTS) solution is based on detecting the temperature changes in the environment in the event that there is a leak in the pipeline. In the event of a leak, this can be detected in real time and the location pinpointed to within a few meters. The pipeline operator can therefore react instantly thus minimizing the potential environmental and safety hazards. Distributed temperature sensing (DTS) solution offers the most advanced performance available today providing over 100,000 points along the entire length of the pipeline, thus providing the operator with total integrity over the entire length of the pipeline. To meet safety rules, it is important to assess the reliability of the DTS system and to test whether the DTS system is functioning properly. The DTS Automated Trip Testing System is a fully independent device that is set to reproduce a temperature rise or drop of the same magnitude as the one expected in the case of an anomaly, e.g. a leakage. This allows a continuous and full automatic verification of the efficacy and reliability of leakage detection systems in pipelines.

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