Fast Detection and Localization of Small Ammonia Leaks Using Distributed Fiber Optic Sensors

In the case of ammonia, small leaks can be detected by the rapid drop of temperature due to the evaporation of the released liquid ammonia. These local thermal anomalies can be reliably detected by a fiber optic distributed temperature sensing system that is able to detect temperature changes.

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Introduction

Over the past decades, several major industrial accidents have led the chemical industries and national regulatory bodies to reinforce the safety and prevention measures of their installations. Some of these measures are in compliance with local laws such as the Seveso II directive in Europe.

Chemical leaks, such as ammonia, can be the origin of toxic releases. These releases 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 and the consequences of such events by implementing additional safeguards.

The tragic consequences of the September 2001 accident in Toulouse made 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.

Risk Studies

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 scenarios

The scenario represented in Table 1 is unloading anhydrous ammonia at 750 ton/hour (P = 3.5 bar, T = -33 °C, or P = 50 psig, T = -27 °F), through a 300 mm (12 in) 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 shutdown 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 NH_3 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.

French Legislation

In the Chemical industry, equipment with associated major risk is considered acceptable by the authorities if and only if the following is true:

- There are two independent appropriate technical barriers (human detection is not considered as reliable) to prevent the risks from occurring.
- Considering only one technical detection system is functioning, the remaining probability is still acceptable ($<10^{-5}$).
- The consequences outside the plant cause no irreversible effects.

If a risk has consequences outside the plant it may be necessary to increase the distance to urbanization, which may include expropriation and the associated high costs.

Challenge Production Sites 2010.

It was a challenge to accomplish the requirement for two independent technical barriers. We needed to find a reliable technology, in addition to actual NH_3 detectors, that was able to detect a small ammonia leak in a very short time (typically 20-30s).

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 kilograms 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 kilometers) 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.

Figure 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 Figure 2).
- Interrogator (see Figure 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 an automated emergency shutdown sequence).
- User interface that shows the exact location of a leak (see Figure 3).

Figure 2. Distributed temperature sensing cable

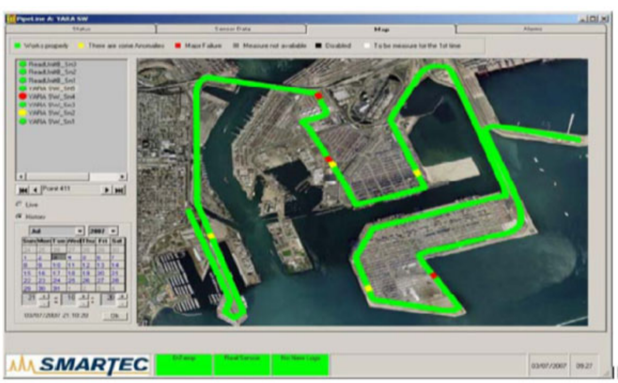

Figure 3. Example of user interface showing location of multiple events, e.g. leaks

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 aboveground 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 Figure 4).

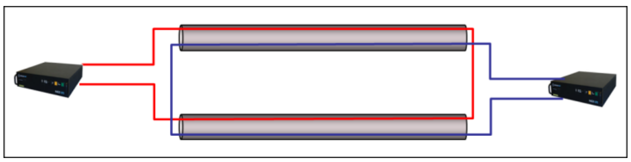

Figure 4. Redundant setup with two interrogators and looped fibers

Other Uses

Distributed temperature sensing technology has been in use for 15 years for the monitoring of other industrial and civil structures including the following:
- Buried oil pipelines [1]
- Buried and aerial gas pipelines [2]
- Hot spots in reforming reactors [3]
- Leaks in dams and dykes [4]
- Detection of hot spots in power cables [5]
- Fire detection in tunnels, ships and buildings [6]

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 Figure 5).

Figure 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 leaks only affect a small portion of the pipeline.

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

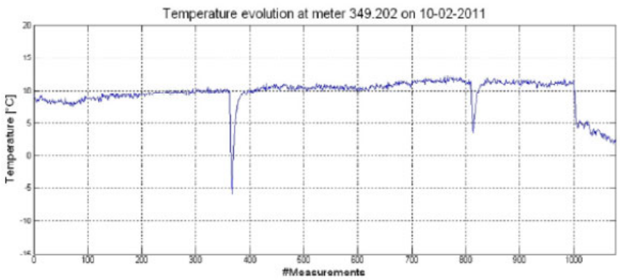

Figure 6. Temperature drop recorded during two ammonia leak tests and a pipeline restart

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 started, are due to the loop configuration used for the sensing cable. The cable passed twice in the leak zone, on its way out and on its way back to the instrument.

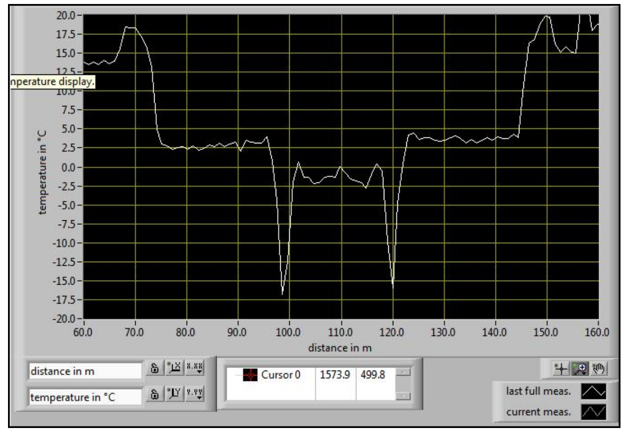

Figure 7. Plot of temperature as a function of distance during leak test

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.

In a test period spanning both summer and winter seasons, data was collected every 10 s 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.

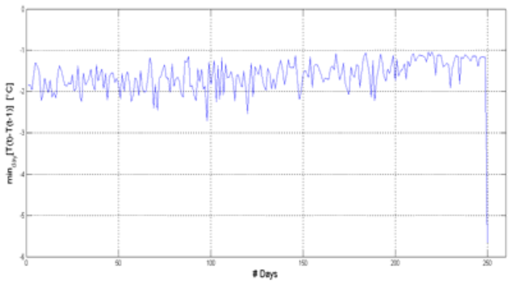

Figure 8. Maximum daily rate of change without leaks and with a leak test at the end

Recommendations

The following recommendations are based on the knowledge accumulated during the laboratory and field tests. They serve as a starting point for the implementation of such an ammonia detection system in a plant.

Cable Installation on Different Types of Pipelines

The cable installation procedure aims at maximizing the probability of detection. It is recommended to install the cable(s) in a way to increase the likelihood of contact with the leaking liquid ammonia and the resulting gas cloud. To maximize the likelihood of detection we make the following recommendations:

- In the case of horizontal pipeline sections, install the cable at the bottom of the pipeline and attach it with ties to the pipe every 50 cm (≈1.5 ft). The cable does not need to be in contact with the pipe along its whole length, since it will catch dripping liquid ammonia and the cold ammonia gas.
- For vertical sections, install the cable in a spiral with a pitch of 1 m (3 ft) in order to catch any down flow of ammonia.

These recommendations are also valid for insulated pipelines, where the sensing cable can be installed outside the insulation cover in the same positions.

Additional pipeline elements such as valves, splits and pumps require specific installation schemes that exceed the scope of this publication.

Performance of Data Acquisition Unit

Based on the test results and the experience gathered on several plants in France and Italy, we recommend the following configurations, minimum performance and testing for ammonia leak detection.

The minimum configuration (without redundancy) is as follows:

- 1 data acquisition system with 2 channels
- Measurement scan time of 10 s per channel
- Temperature resolution of 0.2 °C (0.4 °F) for a 10 s measurement scan time
- Spatial resolution of 1 m
- Cable configuration consisting of a single cable with 4 optical fibers, 2 fibers connected at the far end to form a loop connected to the two interrogator channels
- Automated Trip Testing System (ATTS)

The ideal configuration, which includes redundancy, is as follows:

- 2 data acquisition systems with 2 channels each
- Measurement scan time of 10 s per channel
- Temperature resolution of 0.2 °C (0.4 °F) for a 10 s measurement scan time
- Spatial resolution of 1 m (3 ft)
- Cable configuration consisting of two cables with 4 optical fibers each with the two cables connected at the far end to form a loop. Each loop connected to the two channels on each interrogator.
- Voting system (see next paragraph)
- ATTS

Reliability and Confidence Level

An ammonia leak detection system is likely to sit idle for all its life, hopefully never detecting any real leak. Idleness presents a challenge for reliability. The system will be "forgotten" most of the time, and it is difficult to guarantee that it will perform perfectly the day it is really needed. Ensuring and certifying a high confidence level becomes imperative in these conditions.

Since it is difficult to frequently carry out leak simulations on the line to verify the system response, we have developed a device that can carry out such tests in a fully automated way. The Automated Trip Testing System (ATTS) is a device, fully independent of the data acquisition system, which can create an artificial leak along the sensing cable. In so doing, the correct response of the system and alarms can be verified. The ATTS uses a Peltier cell to cool a 2 m section of optical fiber at a rate similar to the one observed in the case of an ammonia leak. The system 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 and is not transmitted to the operator. Instead, it is recorded in the plant event log. The ATTS is placed at the end of the fiber loop, so that the integrity of the whole fiber can be verified in one test. Typically, a leak simulation can be simulated every hour, so that thousands of tests are carried out every year.

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.

Detection Algorithms and Thresholds

We recommend the following initial settings for ammonia leak detection:

- An absolute temperature threshold set at the average pipe temperature of -20 °C (-4 °F)
- Rate of change thresholds of -3 °C/10 s (-5 °F/10 s) and -10 °C/min (-18 °F/min)

It is suggested to carry out a test period during summer and winter to adjust the thresholds before using the system as part of an automated safety loop.

Annual Testing

In addition to the regular tests carried out by the ATTS, it is good practice to carry out an annual test on the real line. This test should be done such that it verifies the whole system including detection, alarm chain functionality, and valve shutdown action. During this test, a valve bypass can be opened to ensure continuity of flow. The test can be carried out by pouring ammonia directly on the line, or using a CO_2 fire extinguisher. The point is to simulate similar temperature drops to a real ammonia leak.

Cost Estimation

The cost of such an installation can vary depending on the length and geometry of the pipes, ease of installation and access, and the selected redundancy level. As a reference, the typical cost for a normal system implementation is in the order of 150 k€ (≈200 kUS$). The cost can reach 500 k€ (≈650 kUS$) for very complex and redundant implementations. These costs include design and implementation.

Ongoing annual service and maintenance costs are about 10-15% of the initial cost and include regular maintenance of the measurement equipment and availability of hot-swap units for quick replacement in case of failure. These costs compare favorably with those associated with alternative solutions, including detection analyzers and thermal cameras. These systems typically have higher maintenance cost and require the installation of a large number of units to achieve a similar level of coverage and sensitivity for small leak detection.

Future Work and Development

Our future work plans include the installation of production systems on several plants in France and other countries. From these real-life installations, we will gather operational statistics such as ATTS-recorded availability levels, analysis of temperature anomalies in normal operations, false alarms and system reliability. It is also planned to explore the use of the same technology to detect leaks of other harmful fluids and gases and to address leaks from buried ammonia pipelines.

Conclusions

This system is deployed at several industrial sites including Yara France, GPN, and Borealis. This technology significantly contributes to improved process safety for the following reasons:

- The fiber optic cable system developed by SMARTEC SA is able to provide early detection of small ammonia leaks.
- The technology is equipped with an Automatic Test and Trip System to increase reliability.
- Functional and operational tests, in association with INERIS, have been carried out and have demonstrated that leak rates less than 50 g liquid NH_3 /s (≈6 lb/min) can be detected in about 20-30 s anywhere along the whole pipeline. This sensitivity exceeds the requirement and expectations identified in the process safety risk studies.

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