ACOUSTIC EMISSION LEAK DETECTION OF BURIED OIL PIPELINES, RIVER AND ROAD CROSSINGS

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ABSTRACT

The undesirable fluid losses due to leaks constitute one of the bigger problems in industrial installations, refineries, power stations and, in general, anywhere there are moving or stored liquids or gases, with enormous, occasionally, environmental and economic repercussions.

Acoustic Emission offers a very effective solution to this problem and has been widely used for detecting and locating known or suspect leaks in buried pipelines. Access to the pipeline is required only every about 100-200m for mounting AE sensors. Pipeline is pressurized in 500-1000m sections at a time, while the AE sensors detect the turbulent flow at the leak orifice, and, with the use of digital AE systems and specialized data acquisition and analysis software, provide the position of the leak. The method has been proven effective, fast and accurate in detecting and locating leaks, and it is now being used also as a preventive leak control tool for long underground transfer pipes or short, buried pipe sections, such as dikes and road crossings.

The present paper deals with the technical description and the physics of the AE leak detection technique for buried pipelines, presents the advantages, limitations and requirements of the method, describes the necessary modern AE equipment for performing such a task, and, reports on specific case-studies of successful buried pipeline leak detection and location. The paper also presents results from the application of the novel concept of preventive leak detection which has been applied in numerous buried pipeline short sections, dikes and road crossings within industrial facilities, as well as in long distribution pipelines.

INTRODUCTION

Leaking buried pipelines pose a very serious problem to the pipeline owners for many reasons. Financially, due to the waste of valuable product, environmentally because the product may leak into surrounding soil and contaminate the ground, and safety-wise, particularly if the leak is inside industrial facilities, when the product is flammable. Shutting down a pipeline which is suspected to leak may also lead to serious operational and financial implications (shortages, inability to deliver, contractual issues etc.). Occasionally, there are indications of a leak e.g. when pressure is dropping for no other obvious reason or when product is visible in nearby valve wells, pipe ground exit points, sea-water, on the ground itself etc. Even then, it is generally difficult to reliably locate the exact position of the leak so as to take corrective measures. In the worst case, a leak may go on unnoticed, such as in some cases of complex networks, or when it is not large enough to become visible.

Nondestructive leak testing deals with the leaking of liquids or gases in pressurized or evacuated components or systems as a result of pressure differential. Acoustic Emission is widely used for locating such leaks [1]-[4]. The turbulence caused by the flow of a pressurized fluid through an orifice produces energy waves of both sonic and ultrasonic frequencies. A basic understanding of the leak mechanism and acoustic emission testing was given by Pollock and Hsu [2]. Laboratory tests and experiments to evaluate existing leak detection and location methods were carried out by Miller, Pollock, Finkel and others [3]. Standards such as ASTM or ASME describe the method for detecting and locating the steady-state source of gas and liquid leaking out of a pressurized system [4, 5].

Successful application of AE for leak detection of liquid filled buried pipelines were reported in previous work [8]. The present study, presents additional case studies from river and road crossings. In addition to that, it focuses on case studies from the application of the novel concept of preventive leak detection which has been applied in numerous buried pipeline short sections, dikes and road crossings within industrial facilities, as well as in long distribution pipelines. Finally the possibilities of continuous monitoring are discussed.

REQUIREMENTS, ADVANTAGES AND LIMITATIONS

It is a common understanding in most Leak Detection works, that acoustic emission can be produced by the highly unstable turbulent pressure field at the orifice, thus a detectability condition is that the Reynolds number Re>1000 at the orifice, so as to ensure turbulent flow. The corresponding AE signals generated are of a "continuous" nature. Additional sources that may produce AE in the occasion of a leak are local crack / orifice growth, cavitation due to local sub-pressure at the orifice, temporary entrapments and impacts of solid particles at the orifice, soil movements, or even external sources such as impacts etc. which are mainly "burst" type sources. The generated AE waves from such sources propagate through the fluid or through the pipeline itself. Acoustic emission sensors operating between 20 and 100 kHz are mounted on the pipeline, monitoring both continuous and burst type emissions through simultaneous acquisition of Time Driven Data (threshold independent sampling) and Hit Driven Data (threshold dependant). In addition to that, acquisition of AE waveforms or waveform streaming is often used as a further evaluation tool.

Simplistic, threshold independent, estimation of the leak location can be made by measuring the continuous signal amplitude level variations at various positions along the pipe. Based on signal attenuation (known or measured independently at the pipe itself) and signal amplitude reduction with the distance from the source (leak), as measured at various positions, an amplitude variation ratio is recorded. Based on this ratio, the distance to the source can be roughly calculated. However, a more effective and accurate method to locate a leak on a buried pipeline is linear location of the received AE waves from the leak. Two (2) AE sensors placed on either side of the leak are required for this method. If an AE event occurs at a "x" distance from the first sensor, then $x=1/2(L-V\Delta t)$, where "L" is the known distance between the two sensors "V" is the (known or measured) AE wave velocity and Δt the difference in the time of the AE wave arrival on the two sensors measured by the acquisition system [6]. Finally, post-processing of streamed waveforms (continuous long waveforms) might be used to enhance both detectability and location accuracy.

To perform an AE leak detection test, pipeline surface access holes are excavated at pre-defined sensors distances (typically every 100m) along the pipeline, in order to expose a small part of the pipe (just a small exposed surface about 15x15 cm^2 on the top part of the pipeline is required). Any protective sleeve, insulation or fiber glass coating has to be removed for sensor mounting. The section of the pipeline that is tested at each time has to be isolated (in order to apply static pressure) and without any main flow (to avoid the associated noise).

During testing, pressure in the tested section is increased and kept stable. Although a single channel leak detection portable instrument might be used to acquire the average AE signal level of the pipe at the exposed points and identify the area that is suspected for the leak, as discussed above, a multichannel system is needed for reliable source location. Therefore, multiple AE sensors are placed on the exposed points along the suspected pipeline section and a multi-channel AE leak detection system is used to acquire the leak signals during pressurization. Special software is used to acquire the signals, to evaluate and to calculate the linear location of the associated leak-type sources. Once detected, the location of the leak can be calculated within, usually, a few minutes [6]. The use of a fixed array of sensors and monitoring during pressurization and/or pressure decay gives the best available detection sensitivity, since very small changes of the AE signal in time may be detected (by the use of averaging and/or advance post processing) when compared with, for example, periodic measurements using a portable instrument where the detector is repeatedly re-mounted.

Successful detectability of leaks with AE depends upon the distance of the leak from the AE sensors, the attenuation characteristics of the pipe material (thickness, material etc.) and the type of fluid (gas, liquid) inside the pipe. It also depends upon the surrounding environment (air, soil) and the condition (Reynolds number) at the leak orifice, which, in turn, depends on flow rate, differential pressure, orifice size, and type of fluid. Condition for detectability is the existence of turbulence at the leak orifice, ensured by adequate differential pressure. In case of a two-phase flow the detectability is enhanced. In general, the higher the Re number (i.e. the highest the pressure differential) the more detectable the leak is.

Leak detection can be performed in various types of pipelines with AE, including main pipelines, firewater pipes, aerial, river, road and railway bed crossings, pipes of pumping and compressor stations, gas distributing stations and pipelines inside refineries and industries.

In summary, practically speaking, depending on test needs and required sensitivity, local access on the pipe’s surface at about every 60 to 200 meters or even higher, is required for sensor mounting and measurements. Adequate pressurization is necessary, depending on test type and requirements, usually 7-8 bars and higher, while the pipeline is isolated, i.e. without main flow (in order to avoid additional noise).

A leak detection test may be performed during controlled pressurization with water (e.g. hydrotest) or with the regular product of the pipeline. Apart from testing pipelines suspected to leak, periodic testing or even permanent installations are possible for critical pipeline sections, even without indications of a leak. Provided above test conditions are met (local access, pressurization etc.), any buried pipeline can be tested in its entirety, even areas that are not possible to be tested with other NDT techniques. In the vast majority of cases, leaks can be located with good accuracy, fast and efficiently.

CASE STUDIES

TEST CASE 1: Pipeline leak detection in 400m, 12’’ diameter, buried pipeline.

Indication of a leak appeared as pressure drop during pigging inspection. During subsequent hydrotest of the pipe, pressure was falling from 12bar to 3bar in 1 hour. Since there were absolutely no visible indications of leak position, it was decided to apply AE in order to find the leak location.

Initial (ASL) measurements were executed using portable AE device (PAC 5110) at parts of the pipe that were already exposed during trials to locate the leak based on inspectors expectations and past history, while pressure was kept constant at about 9bar. These initial measurements narrowed down the potential leak location to a length of about 110m, out of which 70m were covered by concrete. Only two positions were further exposed (owner opened holes and cleared the insulation) and further AE testing was performed in the said section during pressurization, using 4 AE sensors and a multichannel AE system (16-channel PCI-DSP4 DiSP system by Physical Acoustics Corp.).

Figure 1 shows an example of a leak signal arriving on the 4 different sensors. Channel 3 exhibits the strongest received signal. The acquired waveforms clearly exhibit the attenuation of the signal, apparent as signal amplitude drop (note difference in y-axis scales) from channel to channel. According to the amplitude vs. time graph (Fig. 1 bottom) the signal arrived at first on channel 3, meaning that the source is closer to channel 3. This is consistent with the observations of the top part of the graph. The arrival times on channels 1 and 4 are about the same, meaning that the source has about the same distance from channels 1 and 4 or, in other words, the source is very close to the middle between the 2 channels.

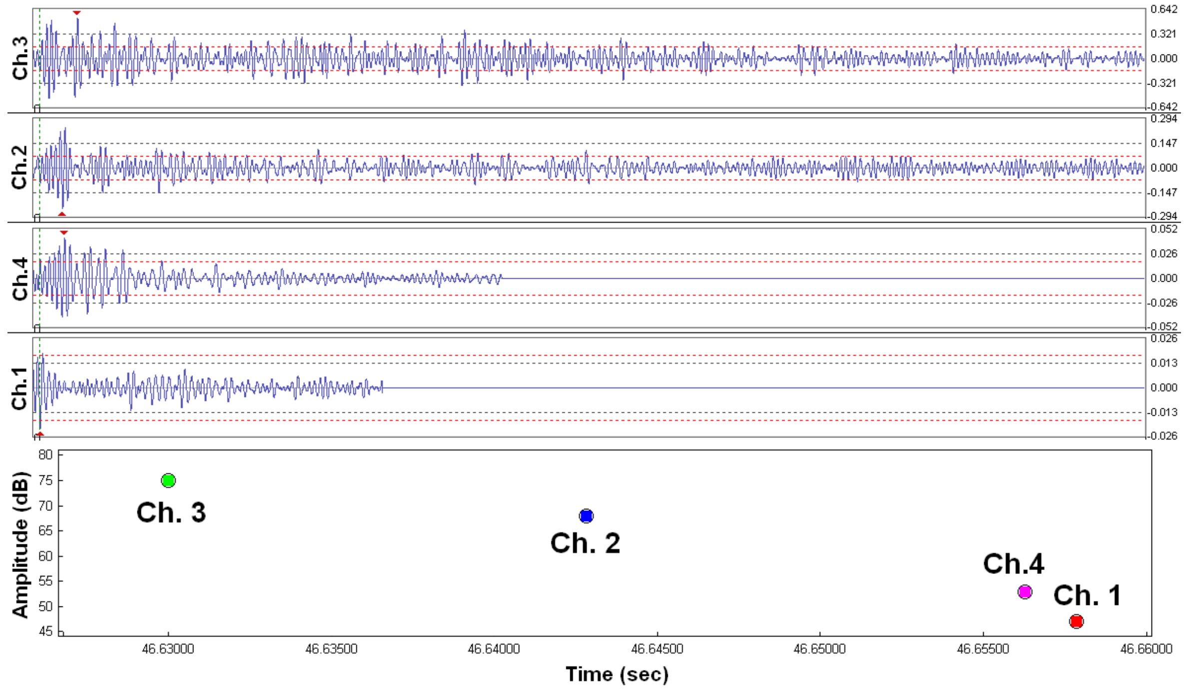

Figure 1. Waveforms and amplitudes vs. arrival times of a leak AE signal on 4 different channels

Figure 2 shows the ASL measurements on each channel and location graphs indicating the suspected location, based on data acquired for a period of 240 sec. The system gave an indication of a possible leak point (at about 15m from sensor 3, under the inaccessible concrete area).

Further analysis was made on-site using different location setups. The same location appeared also during post processing when only channels 1 and 4 (having a distance of about 110m) were used for locating the AE source. The pipeline was exposed at the advised location and a 7mm-hole leak was found. Total test duration was less than 1 day.

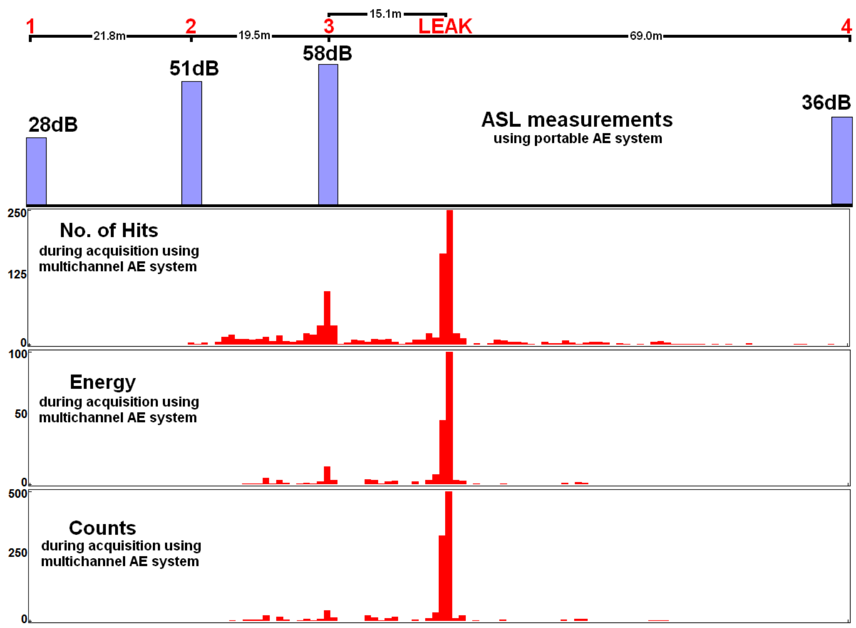

Figure 2. ASL vs. channel (top) and linear location (bottom) indicating the leak point based on number of hits, energy and counts of the acquired signals, after only 240 seconds of acquisition.

TEST CASE 2: Leak detection on a new-built 1000m long, 80cm dia. water pipeline crossing a small river.

Pipe was part of a new-built 20km water pipeline which was constructed along a bank of a small river. In some points the pipeline was crossing the river, buried under the river bottom. Hydro-tests were performed by the constructor on each km of the pipeline. The pressure inside the suspected part could not be raised more than 8.5bar giving the first leak indication. Pressure was decreased from 8.5bar to 5.5bar within 30 minutes.

Green paint was thrown by the constructor inside the pipe in order to locate the leak, without any success. As a result AE monitoring was applied. Totally 11 positions were excavated (points 2 to 12) at distances ranging between 70 to 100m, as shown in Figure 3. The exposed areas of the pipe were tested using portable AE equipment. Points 1 and 13 denote the isolated (blinded) edges of the pipe where two water pumps were connected to increase pressure inside the pipe.

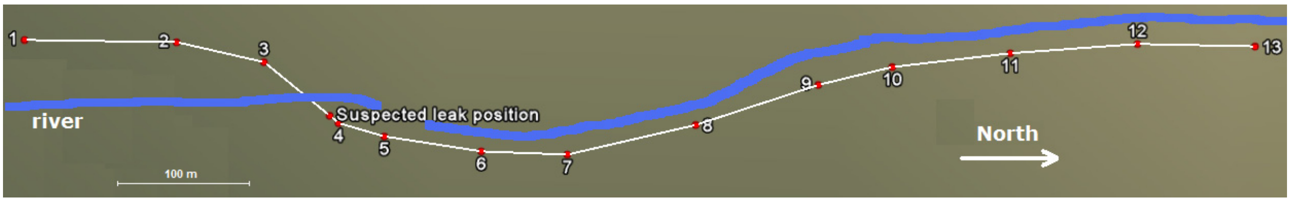

Figure 3. Pipeline drawing with sensor positions.

The pipe had been filled with water and the pressure was increased slowly. During pressure increase AE ASL measurements were performed across the pipe. The first indication appeared at approximately 8.3bar, where point 5 showed 12dB ASL for the first time. Point 4 was excavated at this stage (not exposed from the beginning of the test) after inspector’s suggestion and the ASL measurements showed 39dB (Figure 4), indicating potential leak between positions 3 and 5.

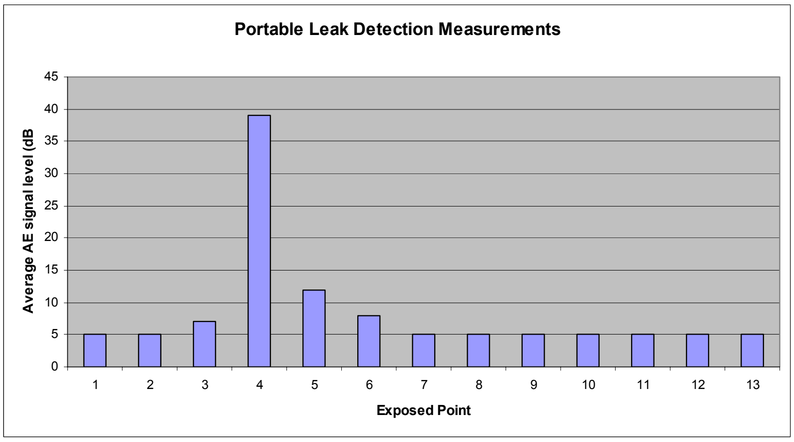

Figure 4. ASL measurements at 8.3bar.

Point 4 was very close to the river and ASL was not measured before the pressure increment at 8.3bar as it wasn’t exposed at that time. In addition to that, according to the constructor, there was a possibility that due to the strong river stream the pipe could have been exposed and could have been in contact with the river water causing leaking noise to channel 4. It was decided to decrease the pressure under 8bar and measure the ASL on point 4 in order to eliminate the above mentioned possibility. After the pressure decrement the ASL on point 4 was reduced to 5dB.

In order to locate the leak, three AE PAC R3i sensors were coupled at positions 3, 4 and 5 and AE monitoring performed using digital multichannel AE system (PAC DiSP). A location group was setup and the linear location graphs indicated the suspected area at about 9m from position 4, between positions 3 & 4 (Figure 5). Although for this particular case further off-line post processing was not necessary, advanced processing applied as a mean to validate the methodology and increase our confidence on the real-time location results.

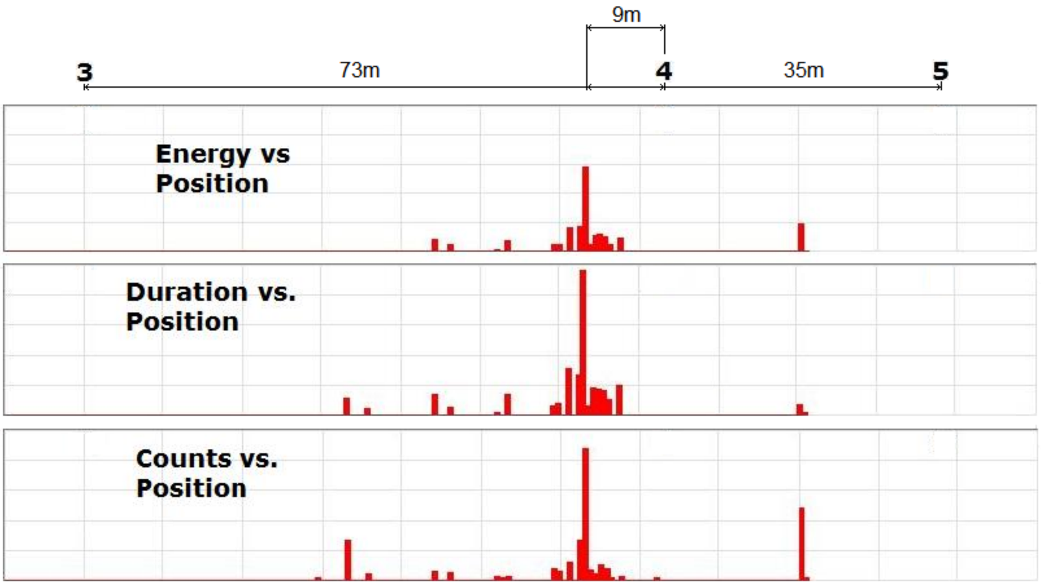

Figure 5. Location graphs as recorded by the multichannel system at 8.3bar.

The customer started to expose the upper part of the pipe from point 4 to point 3 for about 11 meters. At this point the green paint thrown by the customer in the past, appeared together with water from the river inside the excavated area (Figure 6), making any immediate follow-up activities difficult. Since the confirmation of the leak was not an easy task, it was decided to use again the portable instrument as a mean to narrow the search and identify the leak area close to sensor 4.

ASL measurements using PAC's 5110 leak detector were performed along the 11m exposed pipe, but all measurements showed similar ASL values (about 39 to 42 dB) and nothing was indicating the exact position of the leak. In this case it was decided to use the portable leak detector PAC 5131 (VPAC). The instrument showed the highest ASL (42dB) at the indicated point (9m from point 4), while the ASL values left and right of this point were lower (18-39dB).

Figure 6. Picture of exposed pipe flowed with river water.

Due to the high amount of soil above the suspected point and due to the existence of the small river next to it, water was covering the excavated areas of the pipe, while the wet soil rendered the process dangerous to proceed to full recovering of the suspected point. The constructor decided to stop excavation until drying the area. The above test was completed within one day.

TEST CASE 3: Preventive check of 73 different buried gasoline pipe sections under roads or dikes, using portable AE system only.

The customer (refinery) had evidence of gasoline leakages inside the site and asked for a preventive check of 73 different buried gasoline pipe sections that were underground, crossing roads or dikes. Pipe sections had various lengths (2m to 45m) and various diameters (3”-24”).

On each buried section (under road or dike) two AE R3i sensors were mounted on the exposed parts of the section at either sides of the pipe. All AE ASL & location measurements were performed using portable AE equipment (PAC’s Pocket AE). The pipes had been filled with product (gasoline) and the pressure was raised to maximum possible pressure, varied from 4 to 37 kg/cm^2 (depending on the section). Pressure was controlled manually by site personnel and it was not recorded by the AE system.

Figure 7 shows two Pocket AE graphs as recorded during AE acquisition on a leaking section (11m length, 6” dia.). The variation of the ASL is caused by the pressure variation (0-6kg/cm^2). Higher applied pressure gives higher ASL. Note that the ASL on channel 2, on maximum pressure, reaches 50dB while the ASL on channel 1 reaches 30dB, meaning that the leak is probably closer to channel 2. The location graph shows a peak of AE events located at about 7m from channel 1. Figure 8 shows the same graphs as presented on pattern recognition software (Noesis) [7].

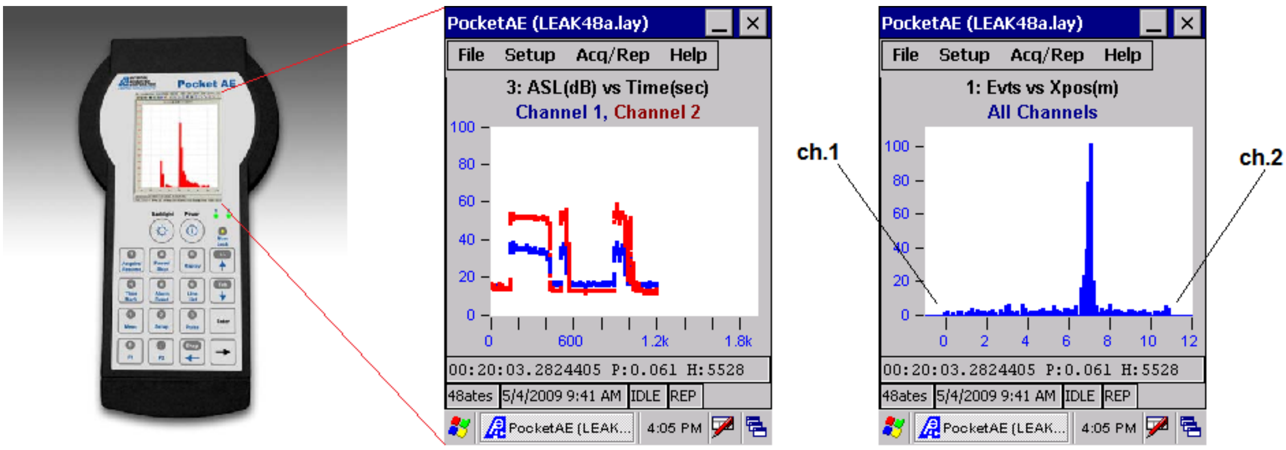

Figure 7. Left: Pocket AE system. Centre: AE graph showing 2-channels ASL vs. time during pressure raising and dropping inside the leaking pipe. Right: AE graph indicating the location of a leak at about 7 meters from channel 1.

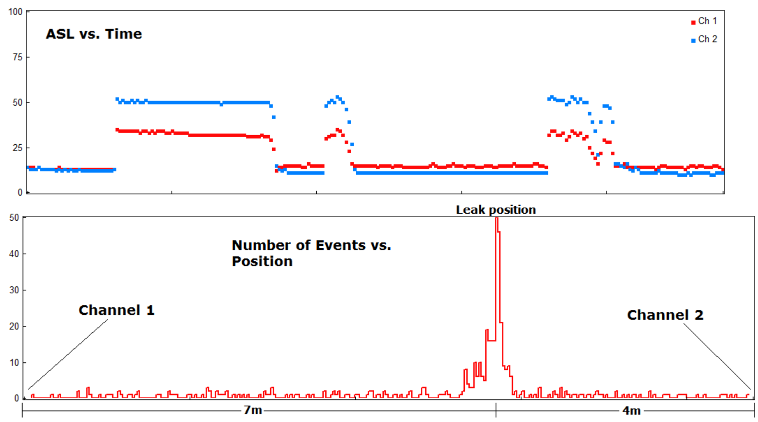

Figure 8. Acquired data from Pocket AE as presented on pattern recognition software (Noesis).

A simple way to get an indication of a leak is by observing the “time-driven” ASL (e.g. acquired every 0.5 sec). In case a leak exists, continuous turbulence noise will raise the average signal level of an AE sensor in accordance with its distance from the leak. Smaller distances from leak mean higher ASL. Additionally, as discussed above, the AE signal level is expected to be correlated with the imposed pressure. Thus, in order to get leak evidence, the pressure inside the pipe has to be raised in a way that will not give any non-related AE signals (e.g. noisy pumps have to be away from the suspected area). First, ASL measurements have to be performed before any pressure increment, in order to measure the background noise. According to the ASL graph of Figure 7 (middle) and Figure 8 (top), the background noise for both channels is about a little below 20dB. Then, when raising the pressure, the ASL is also raising, in correlation with the pressure, which is a leak indication.

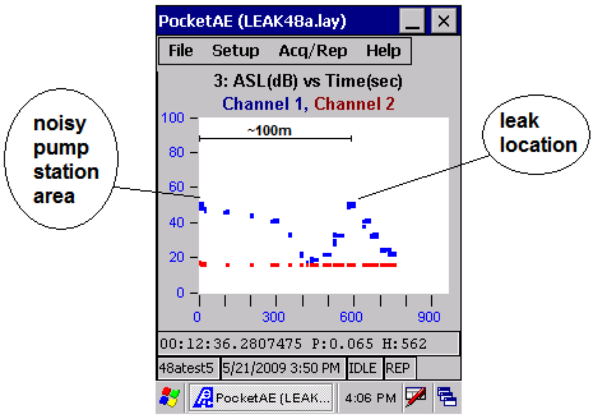

Figure 9. Pocket AE acquisition graph showing recorded ASL changes vs. time on channel 1 (blue colour) along the pipe (every 10-20m). Pressure was kept stable at 6kg/m^2. Pump station doesn't affect the ASL at the leaking area.

Pocket AE offers the capability to create an approximate "ASL scan" over a long pipe section and display it on screen. The ASL vs. Time graph on Figure 9 was created by acquiring time driven AE signals, keeping the pressure inside the pipe stable on its maximum possible level (in this case 6kg/m^2). Signals were acquired every 10-20m, for 5-10 seconds on each point (by pausing the acquisition after every measurement), using only one sensor (channel 1), along the pipe, starting from a noisy pump station which was about 100m away from the leaking point. As shown, the ASL is decreased down to 20dB at about 70m away from the noisy pumps. While approaching the leaking section, the ASL started to rise again, reaching a maximum at the points where the pipe entered the dike. ASL decreased again after this point. According to these ASL measurements, even if both sensors were installed on longer distances left and right from the dike (up to 30m), there would be still an evidence of the leak.

Figure 10 shows an example of a non-suspected section. Pipe was pressurized up to 37kg/cm^2 and ASL was not changed.

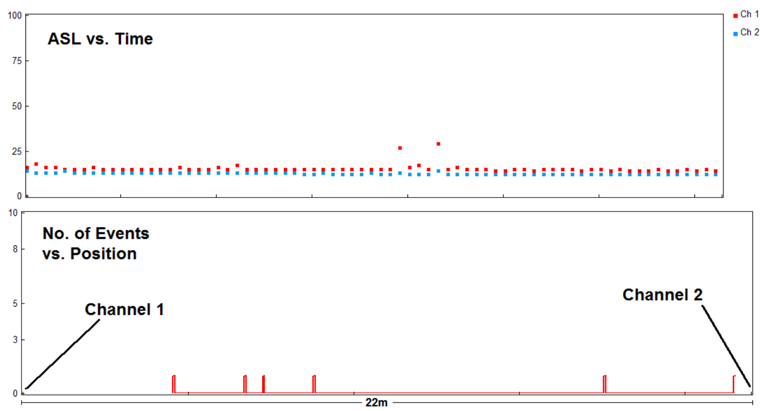

Figure 10. Example of non-suspected section.

On sections close to external noise sources (such as pumps, leaking valves, workers etc.) with high ASL, the customer was advised to reduce that noise. In cases where the customer wasn't able to reduce the noise, the sections were marked as "untestable". Figure 11 shows an example of data containing noise from pump. ASL increment is caused by the pump that was used for the inspection very close to the inspected section. No located sources are observed between the two sensors. The customer reported that after pressurizing up to 10.45kg/cm^2 the pressure was not reduced and the section was characterized as "not suspected".

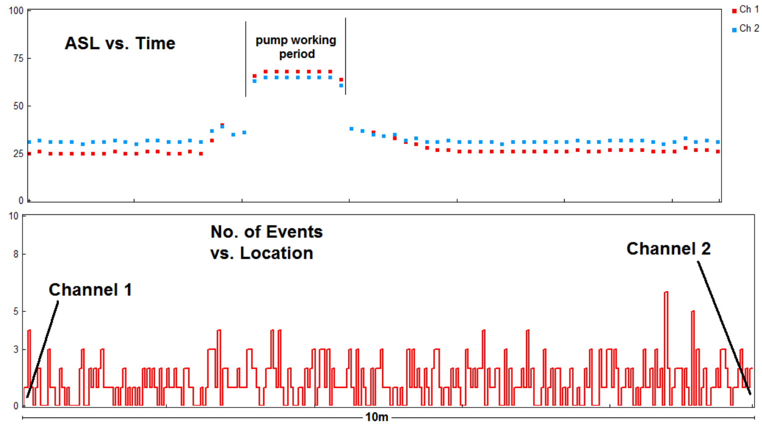

Figure 11. Example of non-related data, caused by pump noise.

In a summary of 73 sections, 2 sections (both crossing dikes) were reported for suspected leak. After testing all sections the customer performed hydrotest on both suspected sections and leaks were confirmed. Customer exposed the sections and leaks were found. In addition to that, the recorded AE location graphs were also confirmed.

Test was completed within 5 days, by testing 10 to 16 sections per day.

CONTINUOUS MONITORING

New AE systems are provided today by Physical Acoustics Corp. (PAC) for continuous monitor to track damage in a pipe such as leaking corrosion, defect growth and areas of concern (Figure 12).

AE Remote Pipeline Monitoring is designed for local monitoring of known areas of concern in underground pipelines. The monitoring is performed by permanently attaching AE sensors on the pipe with a 2 channel, independent, wireless, remote monitoring system. The sensors are placed underground attached to the pipe with the main unit above ground in a lockable, outdoor box.

The system is solar powered with wireless internet connections. It also measures other standard AE parameters as part of the alarm decision and includes sensor coupling checks. Any AE defect information occurring between the sensors will be detected by the two sensors, using a "time difference of arrival" analysis to determine the source location between the two sensors. A location filter will assure that any location data is coming from a pre-programmed small area somewhere inside the sensor array.

Figure 12. AE Remote Pipeline Monitoring system.

A cellular modem interface is also installed as part of the system, relaying status and alarm information to the client. Also available is an optional Remote Internet Monitoring website for visual status reports in the form of activity graphs, location and clustering graphs and alarm messages via an email alert to the customer.[9]

DISCUSSION & CONCLUSIONS

The use of acoustic emission for pipelines leak detection and leak location has been presented. An important requirement for executing the test is that the pipe or the suspect section can be isolated and pressurized to at least a minimum pressure, which starts from as low as 4 to 9 bar, while the desired minimum pressure is above 10bar. Based on experience, excavations are required at about every 100m and measurements are performed using low frequency resonant sensors. In case there is no indication of the leak, either with the use of portable or multi-channel AE system, new areas are excavated at smaller distances and new measurements are performed. Real-time linear location during acquisition provides, most of the times, a very precise leak position within a few minutes, without any further analysis and the leak is confirmed on-the-spot, immediately.

The AE signal attenuation appears to be higher on small diameter pipes (4”-6”). In that case, sensors have to be placed on smaller distances. In addition, on small diameter pipes, the AE location graphs are not as sharp, giving location indications over a long part of the pipe (can be up to 7m) instead of just one point.

Noise sources, like truck passing over the buried pipeline, bangs coming from pumping station or refinery installations, ground movements at the sensors due to the opened holes, sand dropping on the pipe due to wind, etc. may occasionally appear and have to be filtered. In case that the pipe passes through different types of ground or depths, signal attenuation changes and might complicate source location.

Today’s modern AE systems, offering increased dynamic range and low noise (e.g. using 18bit resolution) together with the option of waveform streaming (e.g. PCI-2 of PAC), enabling the recording of continuous waveforms of the AE activity independently of threshold adjustment at very high sensitivity, offer enhanced evaluation and location capabilities to the operator. In case of small pipe lengths the test can be fully performed with the sole use of a 2-channel portable instrument, such as PAC’s Pocket AE, that can provide ASL and location indications. Furthermore, advanced processing using special pattern recognition software [7] can be used in order to discriminate noise from leak signals and reliably provide the leak position and/or to automate the evaluation process, especially in the case of remote pipeline monitoring.

Given the successful application of AE for liquid-filled pipelines leak detection, Remote Pipeline Monitoring is feasible and can be implemented specially for local, continuous monitoring of known areas of concern in underground pipelines. Modern AE systems, solar powered with wireless internet connections are well suited for remote monitoring and control of pipelines.

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