ACOUSTIC EMISSION LEAK DETECTION OF LIQUID FILLED BURIED PIPELINE

ATHANASIOS ANASTASOPOULOS, DIMITRIOS KOUROUSIS and KONSTANTINOS BOLLAS
Envirocoustics ABEE, El. Venizelou 7 & Delfon, 14452 Metamorphosis, Athens, Greece

Abstract

Several limitations and difficulties exist in the inspection and maintenance of underground pipelines that cannot use pigs (pipeline inspection gauges). Leaking is unavoidable in such buried pipelines and poses serious problem to the environment as well as the pipeline owners. Pipeline leakages are usually apparent either when the pressure is dropping for no other obvious reason or when valuable product is lost. However, even in the best-case scenario, where the operators can isolate specific pipeline sections suspected to leak, it is often the case that the operators cannot reliably locate the exact position of the leak so as to take corrective measures. Acoustic emission (AE) is an excellent tool for detecting and locating leaks in buried pipelines. Access to the pipeline is required only locally for mounting AE sensors. Pipeline is pressurized and AE tested in 600-to-1000-m-long sections at a time. The AE sensors detect the turbulent flow at the leak orifice, and with the use of digital AE systems and specialized software, the position of the leak is provided. The present paper deals with the technical description and the physics of the AE leak detection technique, presents the advantages, limitations and requirements of the method, describes the necessary functions of AE equipment for performing such a task, and, finally, reports on several case-studies of successful leak detection and location of buried pipelines. The case studies cover both new and in-service buried pipelines of different sizes.

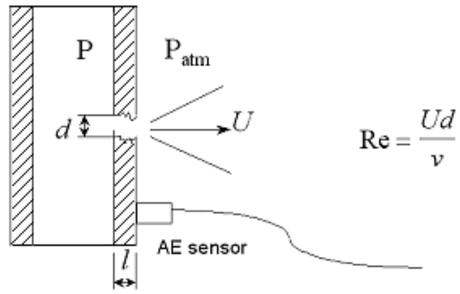
Keywords: Pipeline inspection, Leak test, Loss control, Pipeline integrity

Introduction

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 occasionally enormous, environmental and economic repercussions. 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 (AE) 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. Figure 1 presents some physical features related to and affecting the leakage flow. Pollock and Hsu [2] provided a basic understanding of the leak mechanism and AE testing. Miller and others [3] conducted laboratory tests and experiments to evaluate existing leak detection and location methods. 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].

It is a common understanding in all the above works that AE can be produced by the highly unstable turbulent pressure field at the orifice, and the condition of detection 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



U	= Mean fluid velocity through orifice
d	= Mean orifice diameter
l	= Orifice length
v	= Kinematic viscosity of fluid
P	= Pressure inside the pipeline
$\mathbf{P_{atm}}$	= Atmospheric Pressure
Re	= Reynolds number

Turbulent Flow Condition: Re > 1000

Fig. 1. Leaking flow features.

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 monitoring 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.

Simplistic estimation of the leak location can be made by measuring the amplitude variations of continuous signal at various positions along the pipe. Based on signal attenuation (known or measured independently on 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. Two (2) AE sensors placed on either side of the leak are required for this method. If an AE event occurs at an "x" distance from the first sensor, then $x = (L - V\Delta t)/2$, where "L" is the known distance between the two sensors "V" is the (known or measured) AE wave velocity and Δt the time difference of the 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.

Requirements, Advantages and Limitations

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

For 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, 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. 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 a few minutes [6]. The use of a fixed array of sensors and monitoring during pressurization and/or 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 advanced post-processing) when compared with, for example, periodic measurements using a portable instrument where the detector is repeatedly re-mounted.

Successful detection 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 detection 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, higher the Re number (i.e., higher pressure differential), 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 or railway bed crossings, pipes of pumping and compressor stations, gas distributing stations and pipelines inside refineries and industries.

Depending on test needs and required sensitivity, local access on the pipe's surface 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 fluid flow (in order to avoid additional noise).

A leak detection test may be performed during controlled pressurization with water (e.g., hydro test) 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: New pipeline leak detection in a 4.3-km, 16.5"-diameter, buried pipeline

During hydro test of a new pipeline at 80 bar, pressure was constantly dropping and the owner estimated a leak rate of about 120 l/hr. There was absolutely no visible indications of leak position and the leak could be anywhere within the 4.3 km of the pipeline section length. Trials to identify and locate the leak using audible frequencies and/or cross correlation of pressure signals failed.

Twenty-nine (29) small pits were excavated for mounting the AE sensors, every 125 m. Initial measurements of the Average Signal Level (ASL) were made during pressurization at 8.5 bar using a portable AE device (PAC 5120). The ASL results (Fig. 2) narrowed down the potential leak location to a length of 375 m (at points 1 to 4). Further AE testing in the said section during pressurization, with multi-channel AE system (PAC Mistras-2001) using linear location located the leak. After local excavation at the point indicated by AE the leak location was confirmed.

Directly measured leak rate was found 80 l/hr at 20.0 bars pipeline internal pressure. Total test duration was 4 days.

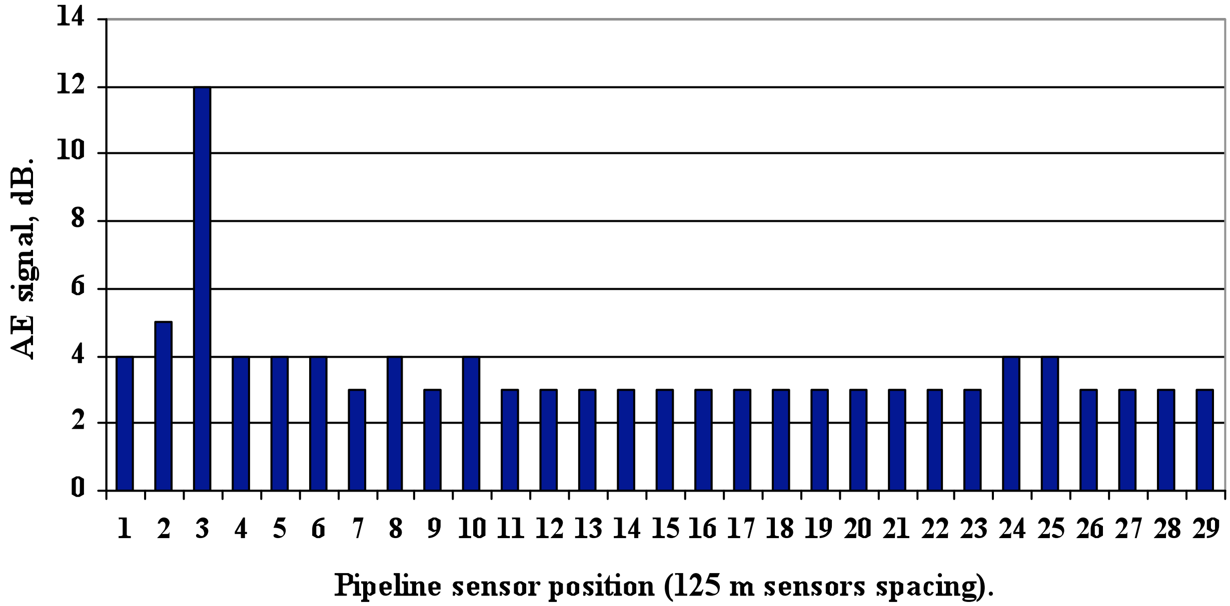


Fig. 2. Average Signal Level (ASL) measurements across the pipeline.

Test Case 2: Pipeline leak detection in 400-m, 12"-diameter, buried pipeline.

Indication of a leak appeared as a pressure drop during pigging inspection. During subsequent hydro test of the pipe, pressure was falling from 12 bar to 3 bar 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 9 bar. These initial measurements narrowed down the potential leak location to a length of about 110 m, out of which 70 m were covered by concrete. Only two positions were 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 (PAC 16-channel PCI-DiSP4 System).

Figure 3 shows an example of a leak signal arriving at the 4 sensors. The acquired waveforms clearly exhibit the attenuation of the signal, apparent as signal amplitude drop (note difference in y-axis scales). According to the amplitude vs. time graph (Fig. 3 bottom) the signal arrived at first on channel 3, meaning that the source is closer to channel 3. 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 4 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 110 m) were used for locating the AE source. The pipeline was exposed at the advised location and a 7-mm hole was found as the cause of the leak. Total test duration was less than 1 day.

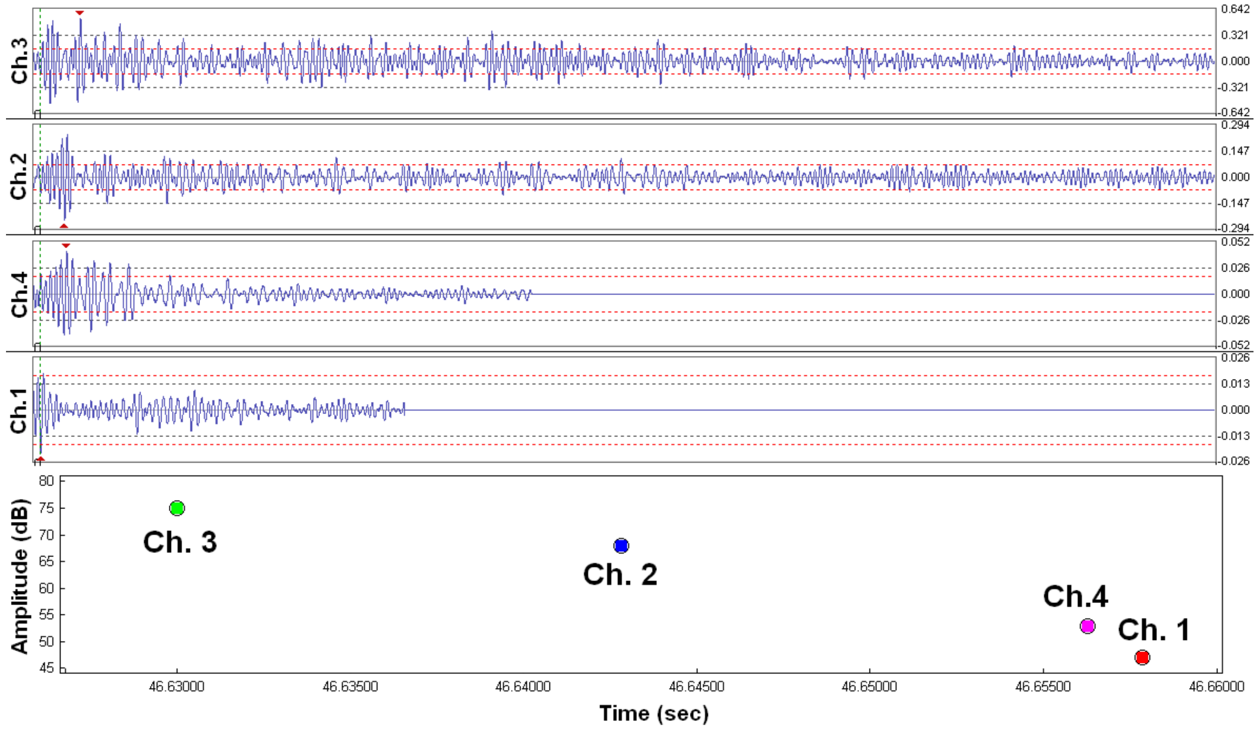


Fig. 3. Waveforms (Top part), and amplitudes vs. arrival times of a leak AE signal on 4 different channels.

Test Case 3: Pipeline leak detection in a 1.5-km, 4"-diameter pipeline.

When pressurized to 34 bar the pressure was dropping to 0 bar in an average rate of 2 bar/hr, which suggested a small, active leak. For the test, the pipe had been filled with water and the pressure was kept nearly constant at approx. 9 bar. A portable AE device (PAC 5110) provided initial information (ASL measurements) for the existence of a leak in the pipe. After this indication the investigation was focused on a road crossing, about 92 m of the pipe.

A desktop, multi-channel Acoustic Emission system (MISTRAS 2001) was used to find the actual position of the leak. Real-time linear location indicated a possible leak at approx. 4.6m from the position of sensor no.3. Figure 5 presents the location graphs that provided indications about the leak position. A 3m length of the pipe was exposed at the location suggested by AE and a small dripping leak was found.

Test Case 4: Pipeline Leak detection in a 100-m, 5"-diameter pipeline.

The pipe was reported to lose pressure from 30 bar down to 3 bar after 10 minutes when pressurized. For the AE test, the pipe had been filled with water and the pressure was kept nearly constant at approx. 25 bar. A desktop system (PAC 24ch.-DiSP) was used to find the exact position of the leak. Real-time linear location indicated a possible leak located near sensor No. 3. Figure 6 shows the ASL measurements (top graph) and the linear location (two bottom graphs) during the AE acquisition where both manual and automatic threshold adjustments ("smart threshold") were employed. Note that the linear location graph based on the number of hits (2nd

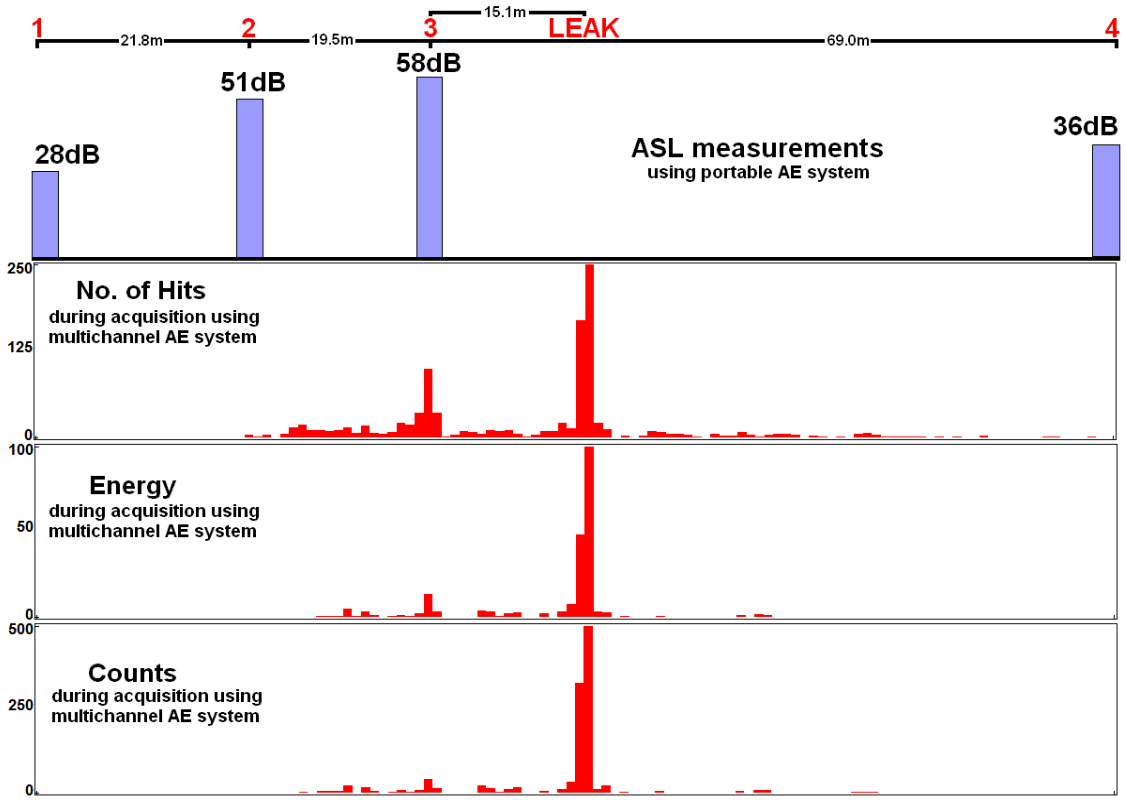


Fig. 4. ASL vs. channel (top) and linear location indicating the leak point based on number of hits, energy and counts (bottom) of the acquired signals, after only 240 seconds of acquisition.

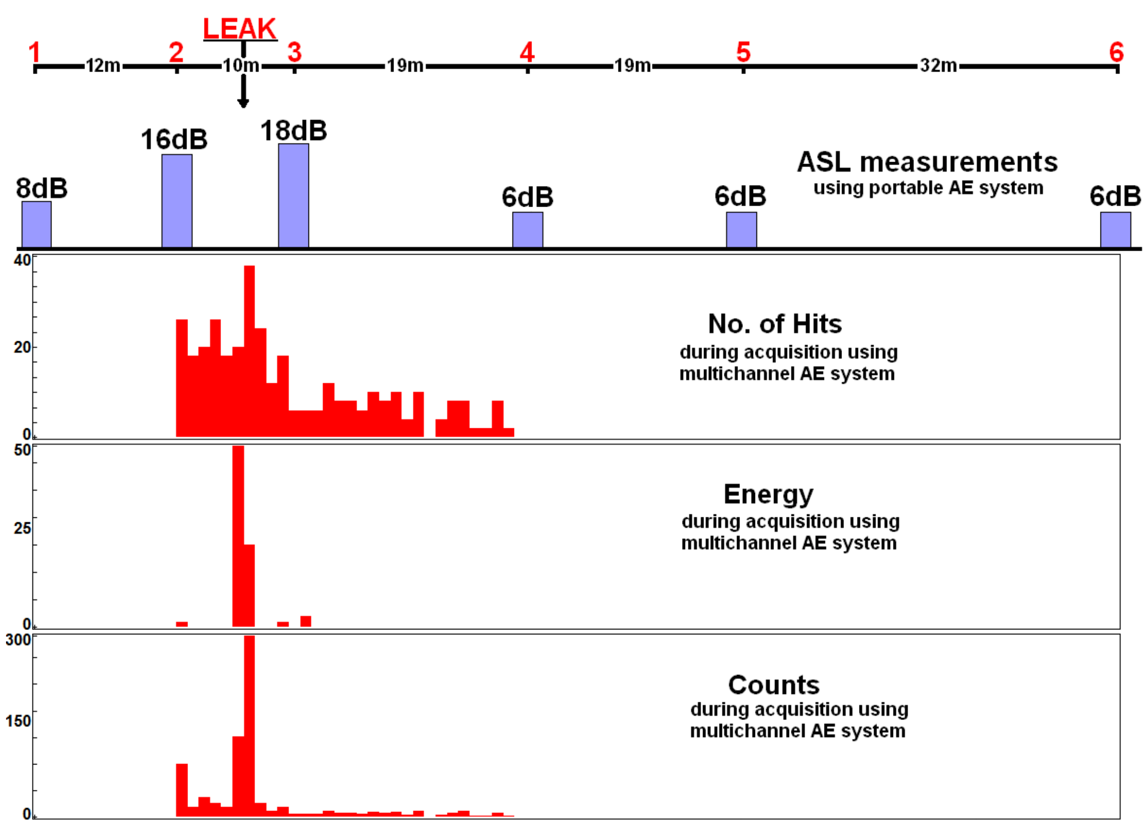


Fig. 5. ASL measurements indicated the suspected leaking area between channels 2 and 3. AE system graphs located the exact leak position, after 27 minutes of acquisition.

graph) shows higher activity between channels 2 and 3, while the linear location graph based on the energy of the signals shows higher activity between channels 3 and 4. The part of the pipe between channels 2 and 3 was buried at shallow depth (about 40 cm) while the part between channels 3 and 4 was buried deeper in the ground (about 1.5 m). This probably results in significant attenuation difference between the two sections. This fact and the variability of threshold combined with the high ASL values that indicate a strong source may have resulted in the linear location not being exact.

Initially, a 5-m length part of the pipe was exposed starting from channel 3 to channel 2. ASL was getting lower when measuring towards channel 2 along the pipe. Thus, it was decided to expose the part indicated by the energy graph and a big leak was found (Fig. 7).

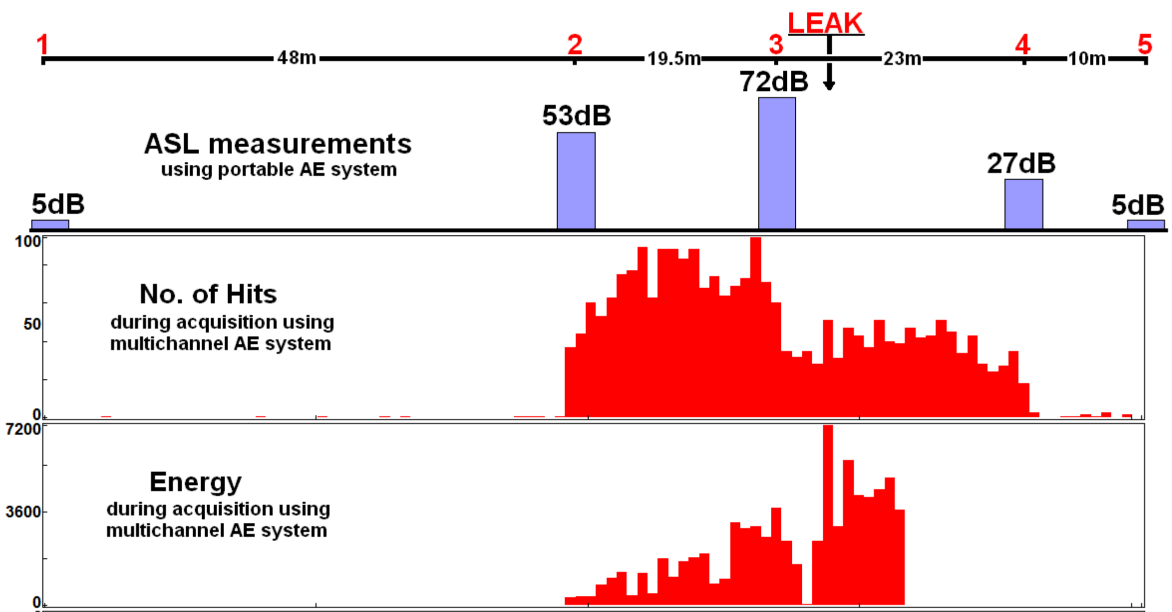


Fig. 6. ASL measurements (top) indicating the suspected area. AE acquisition linear location each one showing different locations near channel 3, after 25 minutes of acquisition.

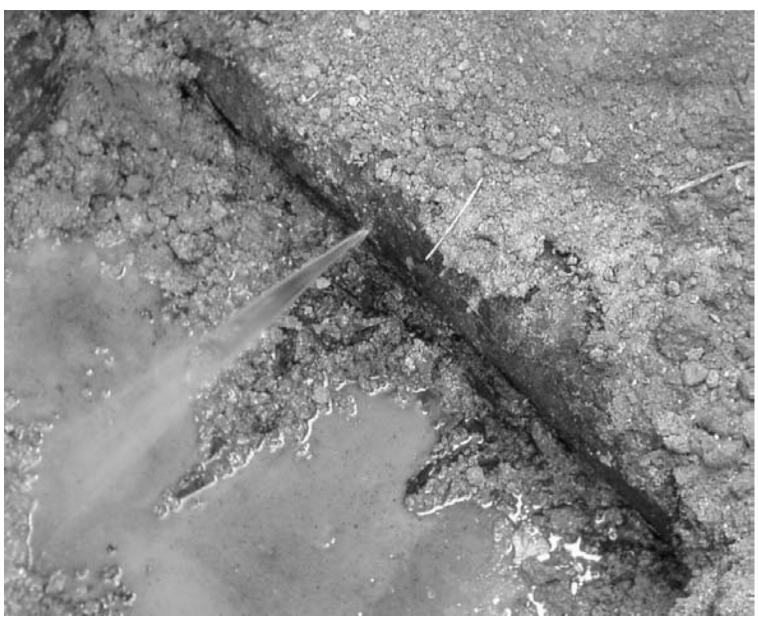
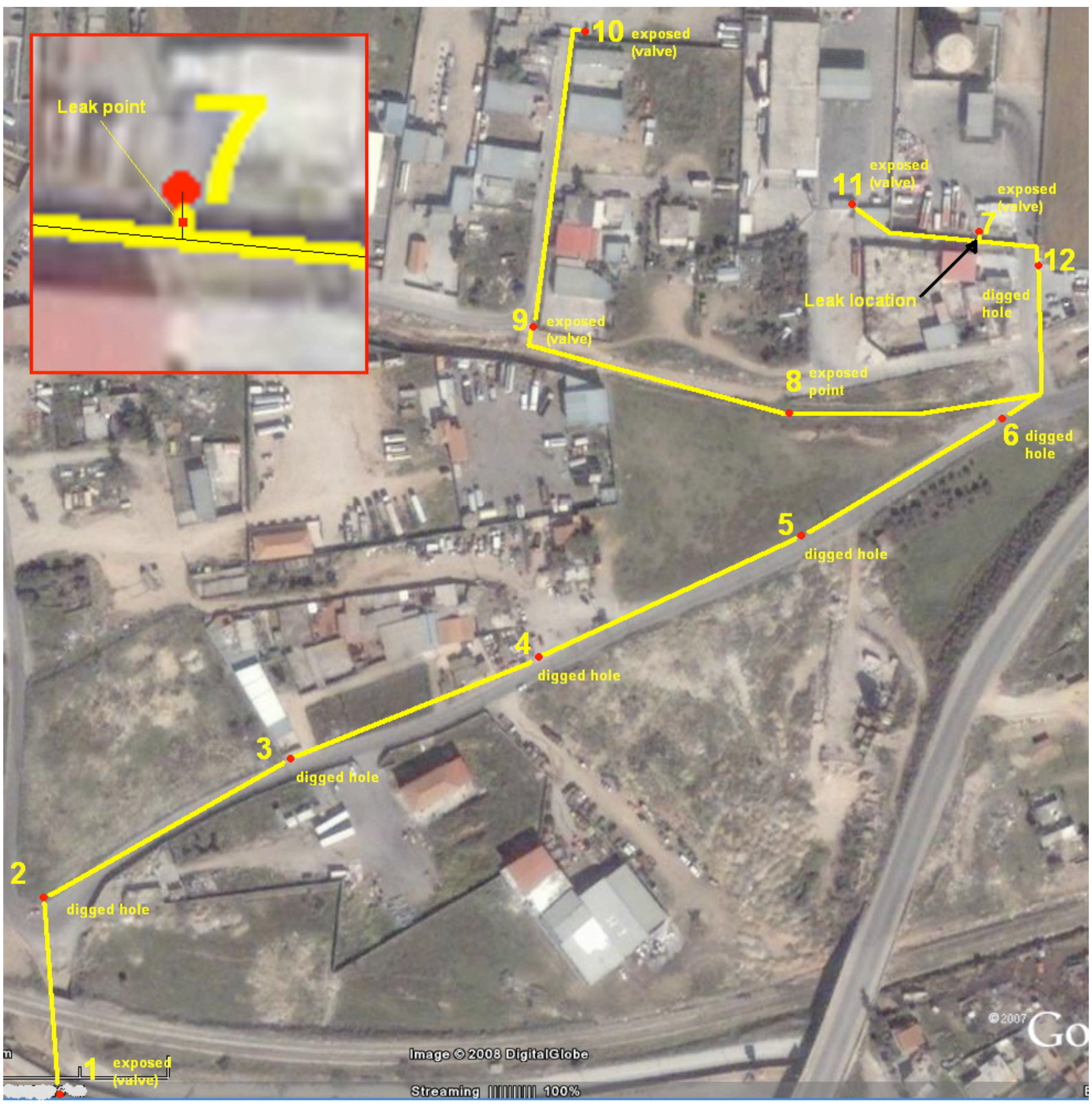


Fig. 7. Picture of the leak found by AE.

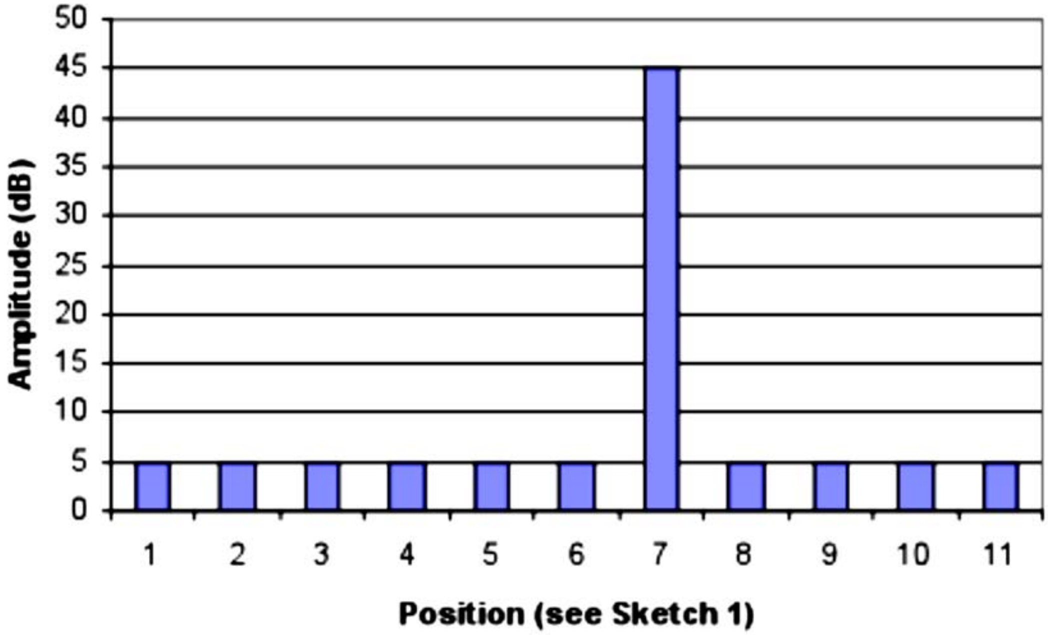
Test Case 5: Complex network pipes leak detection in a 100-0m, 4”-diameter pipeline.

Complex network of pipes, transferring product from refinery to neighbour tank farms and filling stations was suspected for leak. The numerous branches of the lines connected to the main line made the detection difficult. Therefore, the primary aim of this test was to identify the suspect line and narrow the area of inspection prior to detailed investigation.

When pressurized to approximately 25 bar, the pipe was reported to lose pressure (down to 0 bar) after 5-6 hours. Five (5) excavated areas provided access to the pipeline surface every 100 m. Together with the 6 pre-existing access points of the pipe, ASLs at totally 11 points were initially measured using portable AE equipment (PAC 5110) while the pressure was kept nearly constant at approx. 25 bar. The measurements provided a rough indication (see Fig. 8(b)). The test was focused at the area near point No. 7 and one more point was excavated providing additional access (point No. 12). The suspected leak area was narrowed down between points 11, 7 and 12 (see Fig. 8(a)). One more hole was opened near point No. 7 and a T-joint of the pipe was exposed (see Fig. 9). The high ASL measurements at the T-joint confirmed once more the initial indication of the leak.



(a)



(b)

Fig. 8. (a) Aerial photo of the complex pipe network and measuring points. (b) ASL vs. channel measurements gives the first indication of the suspected leaking area (near channel 7).

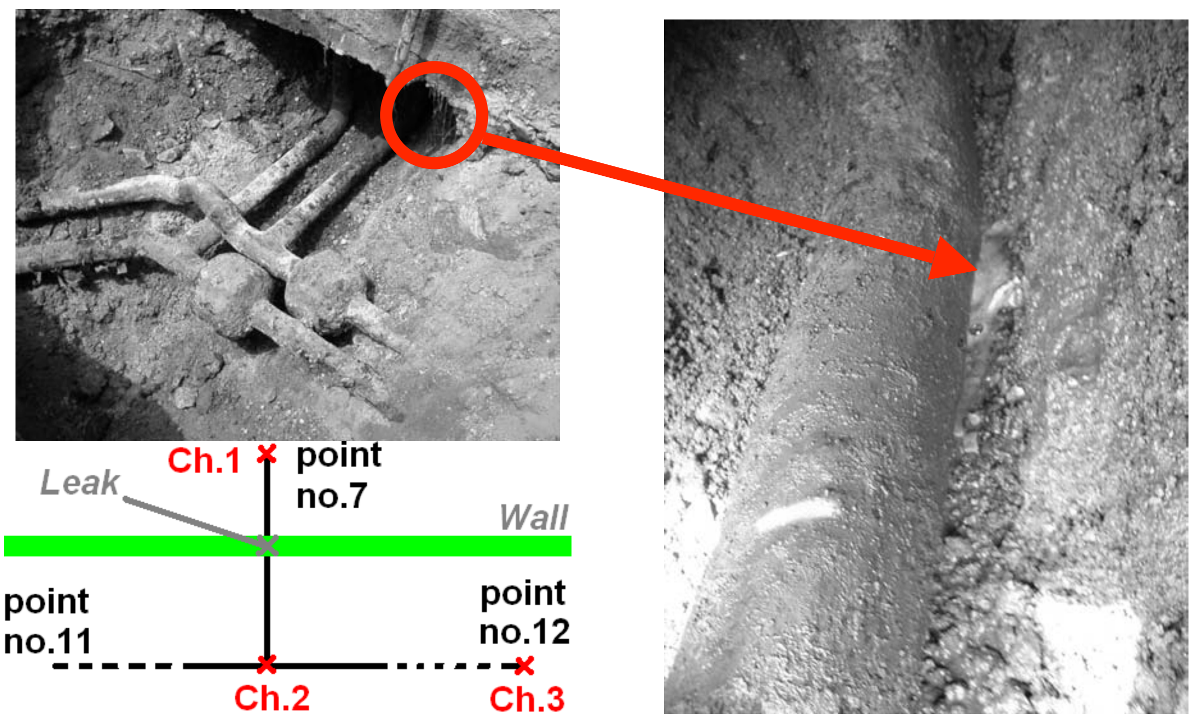


Fig. 9. Picture of the T-joint (top left), with an enlarged picture of the small leak found (right). Schematic of the complex topology of the pipe near the leak point and sensor positions at the suspected area (bottom left), with sensor 2 on the T-joint.

The distance between the T-joint and point No. 7 was 4 m and the pipe was crossing a wall. Although it was obvious that the leak was a few meters next to this area, even after opening the holes there was no visual evidence of any leak (e.g., smell, sludge or humid ground). Therefore, AE sensors were placed at the points showing on Fig. 9 for further detailed investigation. A

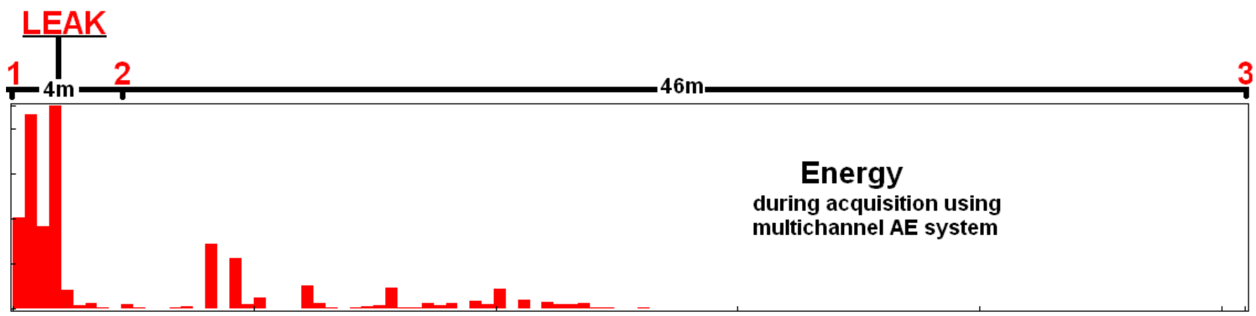


Fig. 10. Real-time linear location graph based on signal energies.

desktop system (PAC-DiSP 24 ch.) was used to locate the actual position of the leak. According to the system (Fig. 10) the leak was located between sensors 1 and 2 (between point No. 7 and the T-joint). The area was excavated and extended right below the wall where a small leak was found.

Test Case 6: Leak detection on a newly built 1000-m long, 80-cm-diameter water pipeline crossing a small river.

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

The constructor injected green paint inside the pipe in order to locate the leak without success. As a result AE monitoring was applied. Totally 13 positions were excavated at distances ranging between 70 to 100 m, as shown in Fig. 11. The exposed areas of the pipe were tested using portable AE equipment. Points 1 and 13 were the blinded edges of the pipe where two water pumps were connected to increase pressure inside the pipe.

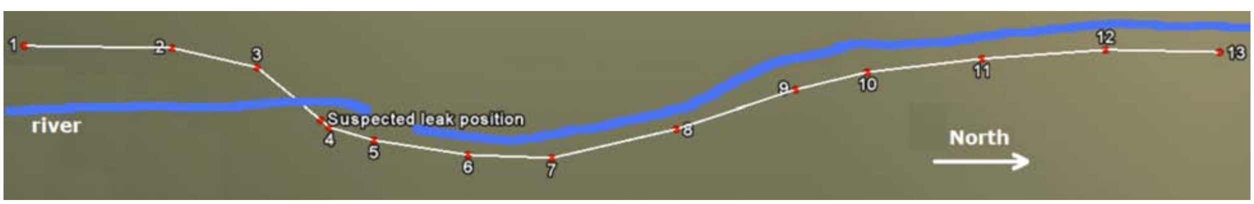


Fig. 11. Pipeline drawing with sensor positions.

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 8.3 bar, where point 5 showed 12-dB 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 39 dB (Fig. 12), indicating potential leak between positions 3 and 5.

In order to locate the leak, three PAC R3I resonant 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 9 m from position 4, between positions 3 and 4 (Fig. 13). Although for this particular case further off-line

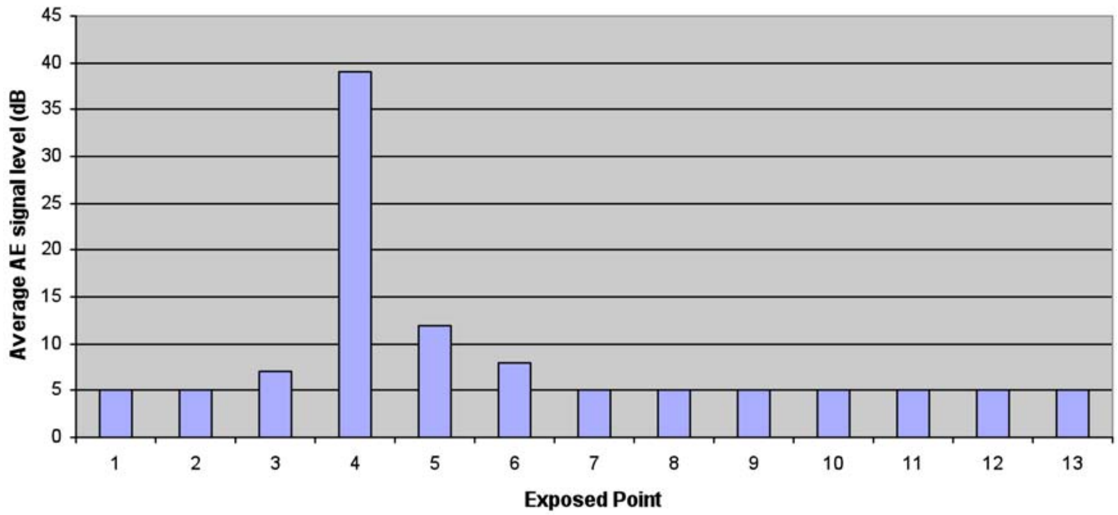


Fig. 12. ASL measurements at 8.3 bar.

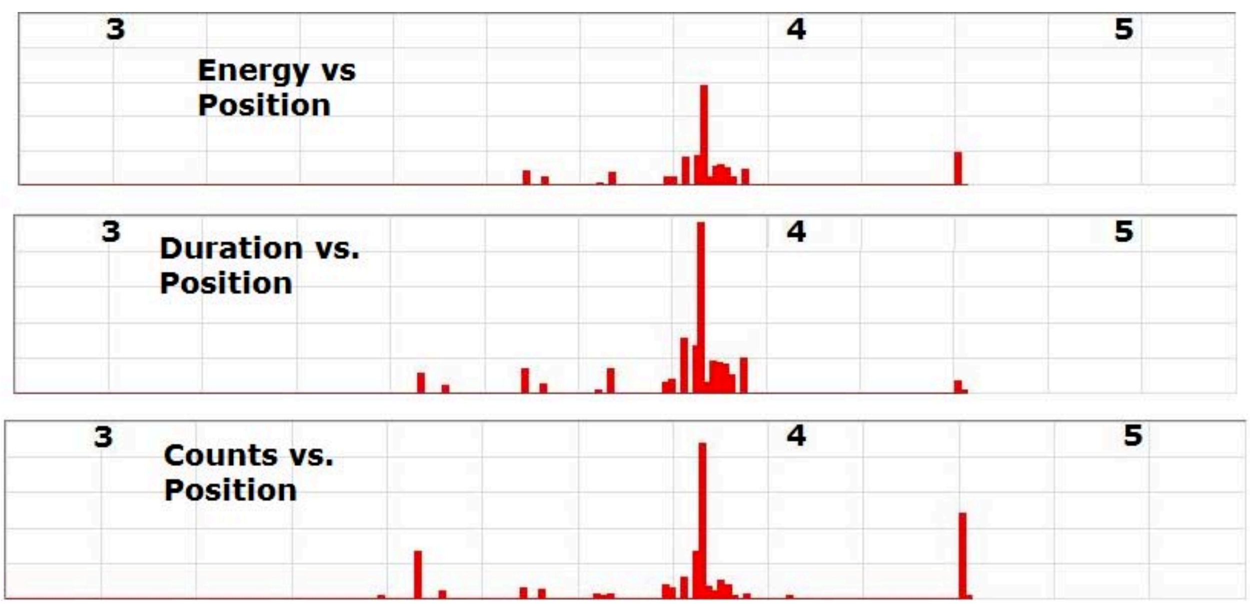


Fig. 13. Location graphs as recorded by the multichannel system at 8.3 bar.

post-processing was unnecessary, advanced processing applied as a mean to validate the methodology and to increase our confidence on the real-time location results.

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 injected by the customer in the past, appeared together with water from the river inside the excavated area (Fig. 14), making the 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-5110 leak detector were performed along the 11-m exposed pipe, but all measurements showed the same ASL (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 show the highest ASL (42 dB) at the indicated point (9 m from point 4), while the ASL values left and right of this point were lower (18-39 dB).

Fig. 14. Picture of exposed pipe overflown 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. Test completed within one day.

Discussion and Conclusions

The use of AE for pipeline 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 10 bar. Based on experience, excavations and measurements are performed using low-frequency resonant sensors at about every 100 m. In case that 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 precise leak position within a few minutes, without any further analysis and the leak is confirmed 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 broader, giving location indications over a long part of the pipe (can be up to 7 m) 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 usually 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 offer increased dynamic range (e.g., using 18-bit resolution) and low noise together with the option of waveform streaming (e.g., PCI-2-based systems of PAC). The waveform streaming enables the recording of continuous waveforms of the AE activity independently of threshold adjustment at high sensitivity and offers 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] might be used in order to discriminate noise from leak signals and to provide the leak position reliably and/or to automate the evaluation process, especially in the case of remote pipeline monitoring.

Given the successful application of AE for the leak detection of liquid-filled pipelines, 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.

References

1) ASM Metals Handbook, Vol. 17, Nondestructive Evaluation and Quality Control, p. 113, p. 132, Leak Testing, Revised by G. L. Anderson, ASM International, Ohio, 1989.
2) A.A. Pollock and S.-Y.S. Hsu, Leak Detection Using Acoustic Emission, Journal of Acoustic Emission, **1** (4), 1982, 237-243.
3) Miller, R.K., et al., The development of acoustic emission for leak detection and location in liquid-filled, buried pipelines, Acoustic Emission: Standards and Technology Update, ASTM STP 1353, Vahaviolos, S.J., Ed., American Society for Testing and Materials, 1998.
4) ASTM E1211-02, Standard Practice for Leak Detection and Location Using Surface-Mounted Acoustic Emission Sensors, 2002.
5) ASME Section V, Article 10, Leak testing, Appendix X, Ultrasonic leak detector test.
6) Envirocoustics document FT-DE-1.5.2E(2), "Buried Pipe Leak Detection and Location"-Method Description.
7) NOESIS Ver. 5.2, Envirocoustics, user manual.