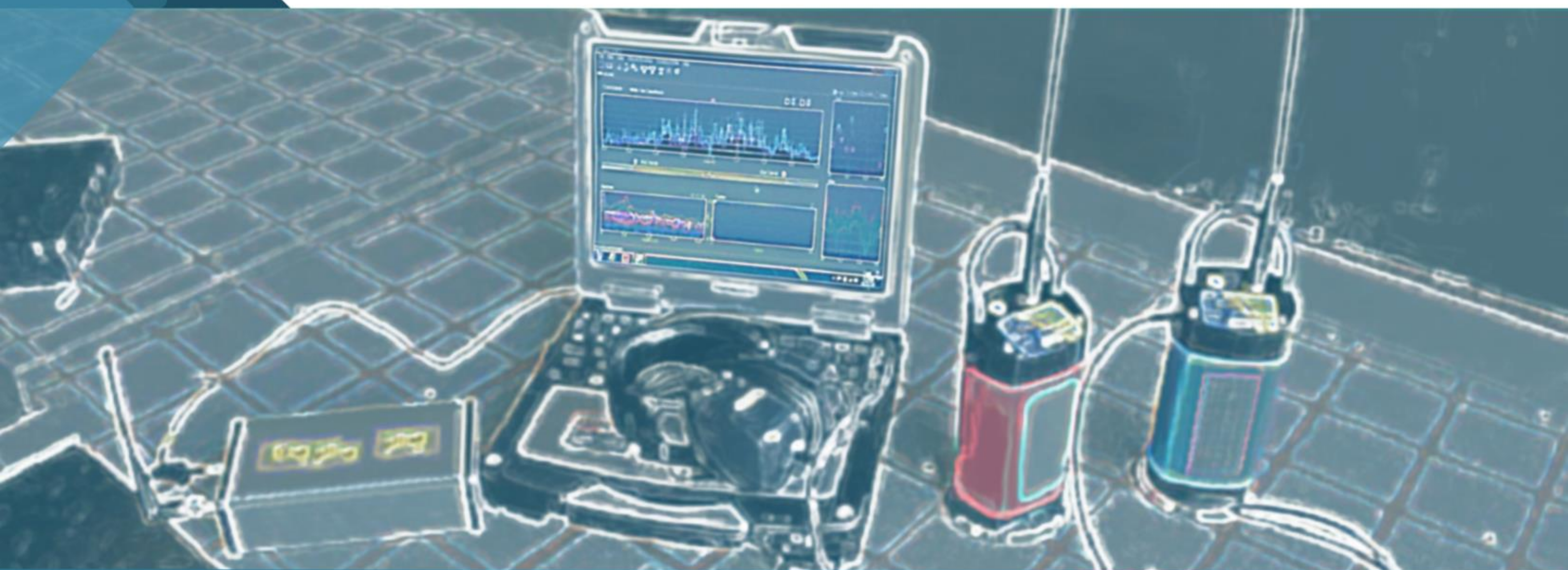
SPECIFICATIONS FOR NONDESTRUCTIVE TESTING, SURVEYING, IMAGING AND DIAGNOSIS FOR UNDERGROUND UTILITIES

2,2 ACOUSTIC EMISSION METHOD FOR LEAK DETECTION IN PRESSURIZED WATER-CARRYING UTILITIES (VERSION.1)

[NDTSID-UU-2,2]



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SPECIFICATIONS FOR NONDESTRUCTIVE TESTING, SURVEYING, IMAGING AND DIAGNOSIS FOR UNDERGROUND UTILITIES

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Foreword

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ACOUSTIC EMISSION METHODS FOR LEAK DETECTION IN PRESSURIZED WATER-CARRYING UTILITIES

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A – Acknowledgement to Steering, Technical Workgroup 2,2

This document (2,2) is one of the specifications prepared for accrediting laboratories/survey companies conducting underground utility surveys. The document was prepared after three consultation meetings held from March to August 2019, as well as incorporating comments provided by various Government departments. The project team expresses the greatest appreciation and gratitude to the following parties for providing support during the drafting and implementation of this specification.

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B - Background

B1 – History

Year	History
1935	A. L. Smith patented a leak detection device with sound pick-up unit and microphone using acoustic methods (Cole, 1979; Smith, 1935).
1971	United States Water Conservation Corporation patented a leak detection device that detected leak frequency sound signals using a microphone, amplifier and oscillograph mounted in a truck (Cole, 1979; Talmon, 1971).
Since 1974	Low-frequency acoustic emission monitoring (AEM) systems with high-temperature accelerometers have been employed to monitor leakage in valves at nuclear reactors (Application of Acoustic Leak Detection Technology for the Detection and Location of Leaks in Light Water Reactors, 1988).
1982	British Gas adopted an acoustic leak detection method that used a loud speaker to introduce sound waves into the gas pipe and the transmitted waves were received by geophones (Electromagnetic and Sound Waves in Underground Detection, 1982).
1988	Saipem Australia patented a pipeline leak testing method that involved the generation of acoustic waves within a liquid-filled pipeline and then the wave travel time was recorded in order to determine the acoustic velocity (WO8805530A1, 1988)

B2 – Significance, Applications and Scope of Specification

B2,1 Significance and application

Underground utilities are the veins of any city. Within such underground facilities, the occurrence of leaks in pressurized water utilities presents by far the most serious problem. The discussion of acoustic emission (AE) methods in this specification covers the history, theories and principles, equipment, field procedures, use of non-destructive methods, and interpretation of data relating to near-surface pressurized water supply systems. The approach suggested for conducting AE investigations is the most commonly used, widely accepted, and well proven. It examines two data acquisition modes: (a) ground-based survey and (b) in-line inspection. For (a) ground-based survey, the three-step procedure for leak detection comprises: (1) leak localization by noise logging, (2) leak locating by leak noise correlator (LNC), and (3) leak pinpointing by listening device. For (b) in-line inspection, the survey procedure moves directly to steps (2) and (3). However, other approaches or modifications, which are technically sound, may be substituted if technically verified, validated and documented.

The **AE records** are the major deliverables of surveys aimed at assessing leak locations. However, the ways these records are produced based on proper test / survey / diagnostic procedures vary significantly between companies and individuals. Erroneous or incomplete information concerning the utilities map can mislead users, causing unnecessary damage and exposing the public and workers to danger. Experience and knowledge of the subject area greatly enhance the credibility of the utilities map and, most importantly, help clarify when the test / survey / diagnostic results are uncertain due to site, materials and equipment limitations rather than the Signatory / Survey Officers' abilities. The successful management of the above factors can be summarized in a **4M1E** framework, namely **M**an/woman, **M**achine, **M**aterials, **M**ethods and **E**nvironment, which can be applied within an accreditation framework following 'ISO/IEC 17025: 2017: General requirements for the competence of testing and calibration laboratories'. In view of the above needs, this document provides a unified specification and standard for AE inspection of underground utilities based on 4M1E, which aims to help utility companies, laboratories / survey companies, developers, estate managers, contractors and consultants to maintain consistent standards of UU testing, surveying, imaging and diagnosis.

B2,2 Scope

1. This acoustic emission testing specification covers the history, theories / principles, equipment, field procedures, non-destructive testing methods, and interpretation of data for leak detection in pressurized water-carrying utilities, such as fresh & salt water pipes, rising, cooling, and chilled water mains.

2. The suggested approach to conducting leak detection (localization, locating and pinpointing) by AE methods is the most commonly used, widely accepted, and well proven. However, other approaches or modifications to the AE method, which are technically sound, may be substituted if technically verified, validated and documented.

3. This method does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the method's user to establish appropriate health and safety practices and determine the applicability of regulatory limitations prior to its use.

Method A: Ground-based noise logging for leak ***localization***

Leak noise can be acoustically localized by setting up a noise logging network on hydrants and/or valves, which is left overnight to monitor the flow, normally between 2 and 4 a.m. During this period, the constant sound of leak noise is most obvious when background noise is at its lowest level and pressure is at its highest. Noise level threshold and the consistency of any noise recorded are used to estimate the probability of there being a leak in pipes near the noise loggers. The area with the highest probability of a leak is thus identified for subsequent locating and pinpointing activities aimed at detecting the precise location of the leak.

Method B: Ground-based leak noise correlation (LNC) for leak ***locating*** and listening device for leak ***pinpointing***

The use of acoustic methods for leak noise detection enables water leaks to be identified even when there is no obvious evidence, such as water flowing on the street. Hydrants, valves, and utility pipes themselves all offer possible locations for the attachment of acoustic sensors to enable leak noises to be detected by a listening device. Since sound travels better via the pipe wall than through the soil, one should always listen at hydrants, valves, and on the pipe body, if accessible. As one approaches a leak, the sound gets progressively louder.

There are three main ground-based AE methods: namely, (1) signal attenuation-based source location, (2) leak noise correlation (LNC), and (3) listening devices. This specification focuses on the second and third methods due to their popularity and high effectiveness in densely populated urban environments. For LNC, microphones or acoustic sensors are placed in contact with the pipe at two or more points to record the sound emitted by a leak somewhere between them. The sound data is processed through a correlation algorithm that compares or correlates the two sound recordings to determine the difference in the times taken by the sound to travel from the leak point(s) to each of the sensors. Surveying the utility alignment then provides an accurate measurement of the distance between the sensors, and when combined with the comparative time information above can be used to locate the leak. For listening devices, they can be either mechanical or electronic, and they require a proficient operator to listen to the unique sound emitted by a leak.

Method C: In-line AE method for leak ***locating*** and ***pinpointing***

An increasingly popular method of AE leak detection involves the use of an in-line inspection tool as an alternative means of identifying minor leaks and seepage not detectable by method B. If AE sensors can be inserted into a pressurized water utility, then leaks can be detected following the same principles as methods A and B. Method C overcomes most of the limitations of ground-based AE methods, as listed in Section 'G'. The in-line AE tool may consist of an acoustic hydrophone, magnetometer, gyroscope and accelerometer, together with an internal power supply. The in-line AE tool, mounted within an appropriate water-proof and dust-proof housing, is conveyed through the utility, and is driven by the current flow without disrupting normal service. The quality of the in-line AE tool, the transport medium and the transmission velocity together determine the sensitivity (i.e. the lowest leak rate detectable by the device). To acquire an exact location for a leak within a utility, the in-line AE tool is driven by the current flow and chainage is measured by an odometer wheel or regular time tag or receiver on the ground. The start (insertion), intermediate (tracking) and end (extraction) nodes (e.g. air valves) must be geo-referenced with a GNSS (global navigation satellite system) or topographic survey.

B3 – Glossary

The following glossary is extracted from ASTM E1316-18a (2018), Section B Acoustic Emission.

Acoustic emission (AE)	The class of phenomena whereby transient stress/displacement waves are generated by the rapid release of energy from localized sources within a material, or the transient waves so generated.
Acoustic emission mechanism or acoustic emission source mechanism	A dynamic process or combination of processes occurring within a material, generating acoustic emission events. AE source mechanisms can be subdivided into several categories: material and mechanical, macroscopic and microscopic, primary and secondary.
Active source	One which exhibits increasing cumulative AE activity with increasing or constant stimulus.
Adaptive location	Source location by iterative use of simulated sources in combination with computed location.
Attenuation	The gradual loss of acoustic emission wave energy as a function of distance through absorption, scattering, diffraction and geometric spreading. Attenuation can be measured as the decrease in AE amplitude or another AE signal parameter per unit distance.
Average signal level	The rectified, time averaged AE logarithmic signal, measured on the AE amplitude logarithmic scale and reported in dB_{ae} units.
Dynamic range	The difference, in decibels, between the overload level and the minimum signal level (usually fixed by one or more of the noise levels, low-level distortion, interference, or resolution level) in a system or sensor.
Electronic listening device (ELD)	An Electronic Leak Detector (ELD) is the electronic version of mechanical listening device of leak noise. It consists of a ground microphone, a noise amplifier,

	headphones and frequency filters. The leak noise is amplified and transmitted electronically to either headphones, a loudspeaker or an indicating meter.
Event, acoustic emission (emission event)	An occurrence of a local material change or mechanical action resulting in acoustic emission.
Leak noise correlator (LNC)	A leak noise correlator is an electronic device for pinpointing leak(s) in pressurized water or gas lines. Typically, two or more microphones or acoustic sound sensors are placed in contact with the pipe at two or more access points. Between the contact points, the device records the sound emitted by a leak (e.g. a hissing noise) using the pipe as an acoustic waveguide.
Location, continuous AE signal	A method of location based on continuous AE signals, as opposed to hit or difference in arrival time location methods. This method is commonly used in leak location due to the presence of continuous emission. Some common types of continuous signal location methods include signal attenuation and correlation analysis methods: (a) *signal attenuation-based source location*, — a source location method that relies on the attenuation versus distance phenomenon of AE signals. By monitoring the AE signal magnitudes of the continuous signal at various points along the object, the source can be determined based on the highest magnitude or by interpolation or extrapolation of multiple readings; (b) *correlation-based source location,* — a source location method that compares the changing AE signal levels (usually waveform-based amplitude analysis) at two or more points surrounding the source and determines the time displacement of these signals. The time displacement data can be used with conventional hit-based location techniques to arrive at a solution for the source site.
Mechanical listening device (MLD)	A Mechanical Leak Detector (MLD) is a passive device similar to a doctor's stethoscope, which transfers the leak noise to the operator's ear directly through ground microphones.
Sensor, acoustic emission	A detection device, generally piezoelectric, that transforms the particle motion produced by an elastic wave into an electrical signal.
Signal, acoustic emission (emission signal)	An electrical signal obtained by detection of one or more acoustic emission events.
Signal amplitude, acoustic emission	The peak voltage of the largest excursion attained by the signal waveform from an emission event.
Signal strength	The measured area of the rectified AE signal with units proportional to volt-sec. The proportionality constant is specified by the AE instrument manufacturer.
Signature, acoustic emission (signature)	A characteristic set of reproducible attributes of acoustic emission signals associated with a specific test article as observed with a particular instrumentation system under specified test conditions.

Waveguide, acoustic emission	A device that couples elastic energy from a structure or other test object to a remotely mounted sensor during AE monitoring. An example of an acoustic emission waveguide would be a solid wire or rod that is coupled at one end to a monitored structure, and to a sensor at the other end.

B4 – Theories and Principles

B4,1 Method A: Ground-based noise logging for leak localization

Noise loggers record an amplitude distribution graph of acoustic levels in dB, in which the number of noise samples from each noise level reveal the consistency of the noise caused by any leak present. In the graphical record produced by a logger, a sharp peak and the lowest background noise level usually occur closest to a leak's location. Comparing the results of multiple noise loggers at minimum flow at 2-4 am can localize the suspected leak area and extent but exact pinpoint of leak requires the following Method B.

B4,2 Method B: Ground-based leak noise correlation (LNC) for leak locating and pinpointing

A leak noise correlator is an electronic device used for pinpointing leak(s) in pressurized water or gas lines. Typically, two or more microphones or acoustic sound sensors are placed in contact with the pipe at two or more access points. Between the contact points, the device records the sound emitted by a leak (e.g. a hissing noise) using the pipe as an acoustic waveguide. The sound data is processed in order to correlate the two recordings and thus determine the difference in time taken by the noise to travel from one sensor to the others. The distance between the sensors must be known in advance in order to estimate the leak point.

The cross-correlation signal of one continuous function, f, with another, g, is defined as:

$$(f * g)(t) = \int_{-\infty}^{\infty} f^*(\tau) g(t+\tau) d\tau \qquad \text{.......[1]}$$

where f^* is the complex conjugate of f; f and g are the two sound recordings of the noise produced by a leak. The time delay can be found by estimating the time offset at which the cross-correlation product *(f * g)(t)* reaches its maximum value. When more than two sensors are used, the correlation process can be conducted at multiple sensor stations. This approach is accurate as long as the sound of the leak received at each sensor is adequately similar over a period of time, e.g. a few minutes. After estimating the leak's time delay, leak noise correlators then require (1) the sound travel velocity and (2) the previously measured length between the two access points, as a basis for calculating the exact distance of the leak from the sensors. For (1), the velocity depends on the pipe's size and its material types, which are standard inputs in most LNC devices. For (2), it is necessary to determine the pipe's alignment using another method: for example, a pipe / cable locator, electromagnetic locating device or ground penetrating radar (GPR). Accurate leak locating and pinpointing can only occur with a high degree of confidence if these two types of information are available and can be successfully cross-correlated. Detail discussion of the mathematical expression of LNC is found in Muggleton and Brennan (2004), Gao et al. (2004) and Gao et al. (2005).

B4,3 Method C: In-line AE inspection method for leak locating and pinpointing

A leak inside a pressurized pipeline produces a specific acoustic signal. This acoustic signal is created when the pressurized product inside the pipeline escapes into the lower pressure atmosphere outside the pipe. As an in-line inspection tool traverses the pipeline, it continuously records all acoustic data in the pipeline, which is evaluated later to identify acoustic activity that may be associated with leaks. The device also reports the presence, approximate size, and location of leaks and gas pockets.

As the in-line inspection tool approaches a leak, the acoustic signal it detects increases in volume until it peaks as the tool passes the leak point, and then diminishes as the tool continues to move away from the leak.

B4,4 Accuracy

Table 1 recommends three quality levels: reliable, survey unreliable (SU) and survey not successful (SNS), with respective leak location accuracies according to survey methods B and C.

Table 1 Recommended accuracies and quality levels of leak localization, locating and pinpointing surveys using AE methods

Survey method [1]	Quality level	Horizontal locating and pinpointing accuracy[2]	Survey Condition
Method A: Noise logging	**Reliable**	NA	Utility alignment in record plan is required.
Method B: LNC and MLD/ELD	**Reliable I**: No leak	NA	Utility alignment and depth must be declared as 'reliable' according to NDTSID specification 1,1 PCL/EML (LSGI, 2019a) and/or 1,2 GPR (LSGI, 2019b)
	Reliable II: Leak	± 1.0 m or ± 0.5% of pipe distance between LNC sensors, whichever is greater at a limit agreed by the client and lab/survey company	Utility alignment and depth must be declared as 'reliable' according to NDTSID specification 1,1 PCL/EML (LSGI, 2019a) and or 1,2 GPR (LSGI, 2019b). Beyond the limit (e.g. 300m), the Signatory and the Survey Officer advise the accuracy level.
	Survey unreliable (SU)[3]	Undefined	(1) Limitations suggested in Section G, or (2) utility alignment is/are declared 'survey unreliable' or 'survey not successful'.
	Survey not successful (SNS)[4]	Undefined	Same as above.
Method C: In-line inspection	**Reliable I**: No leak	NA	Utility alignment and depth must be declared as 'reliable' according to NDTSID specification 1,1 PCL/EML (LSGI, 2019a) and/or 1,2 GPR (LSGI, 2019b)
	Reliable II: Leak	± 0,5m	(1) Utility alignment and depth must be declared as 'reliable' according to NDTSID specification 1,1 PCL/EML (LSGI, 2019a) and/or by 1,2 GPR (LSGI, 2019b), (2) a minimum flow velocity of 0.3 m/s exists on horizontal sections, (3) pipe internal diameter is 300mm or larger, (4) insertion valve access measures minimum 100mm, (5) working pressure is not less than 1 bar, and (6) leak rate is not less than 0.15 L/min.
	Survey unreliable[3]	Undefined	(1) Limitations suggested in Section G, or (2) utility alignment is declared 'survey unreliable' or 'survey not successful'.
	Survey not successful (SNS)[4]	Undefined	Same as above.

Remarks:
[1] Definitions of the survey methods are described in Section B4.
[2] Accuracy levels may possibly be affected at locations of reinforced concrete with dense rebar mesh, or locations where underground utilities (e.g. in urban or rural areas) are densely populated. The accuracy level for utilities not fulfilling the conditions (e.g. non-metallic utility) shall be advised by the Signatory and Survey Officer (Section C), and shall be subject to agreement in the contract between the clients and the Signatory.
[3] No accuracy shall be given if 'survey unreliable' (SU) is reported and the reasons for this result shall refer to the limitations listed in Section G.
[4] No accuracy shall be given if 'survey not successful' (SNS) is reported and the reasons for this result shall refer to the limitations listed in Section G.

C – Qualified Personnel

C1 – Personnel

The Signatories and Survey Officers for acoustic emission method for leak detection in pressurized water-carrying utilities shall meet the personal requirements in Sections C2 and C3 below, respectively.

C2 – Signatory

C2,1 A **Signatory** of a report shall either have:

(i) a Bachelor of Science (e.g. Geomatics / Land Surveying) or Engineering (e.g. Civil / Electrical / Materials / Mechanical / Gas / Industrial) degree with specialization in underground-utility (UU) survey or a Bachelor of Science (e.g. Geomatics / Land Surveying) degree with not at less than 200 contact hours of BSc/BEng's UU training plus final year project, provided by a recognized tertiary institution plus at least ***three*** years of technical and managerial experience of underground utilities, within which a period of two years is substantially[1] related to the subject matter in this specification, or

(ii) a valid certificate or diploma[2] of specialization in leak detection issued by a recognized organization operating under international standards or qualifications framework level 4 plus at least ***five*** years of technical and managerial experience of underground utilities, within which three years are substantially related to the subject matter in this specification, or

(iii) at least a higher certificate or diploma issued by a recognized technical institute or an equivalent qualification in a relevant discipline, with at least ***seven*** years of direct technical and managerial experience, within which five years are directly related to the subject matter in this specification, plus relevant training courses[2] covering the content in this specification.

[1] Direct technical and managerial involvement in 10 test/survey reports for methods A and B, and 3 test/survey reports for method C in different contracts/works orders.
[2] A typical certificate/diploma shall include all aspects covered in this specification.

C3 – Survey Officer

C3,1 A **Survey Officer** shall normally be supervised by a Signatory having the necessary qualifications, experience and technical knowledge. A Survey Officer shall either have:

(i) a higher diploma or above (e.g. Geomatics/Land Surveying) or an engineering higher diploma or above (e.g. Civil / Electrical/Materials / Mechanical / Gas / Industrial) with not less than 75 contact hours of UU training provided by a recognized tertiary institution, plus at least ***one*** year of on-the-job experience substantially[3] related to the subject matter in this specification, or

(ii) a valid certificate or diploma[4] of specialization in leak detection issued by a recognized organization operating under international standards or qualifications framework level 3 plus at least ***two*** years of substantial on-the-job experience[3] related to the subject matter in this specification, or

(iii) at least a higher certificate or diploma issued by a recognized technical institute or an equivalent qualification in a relevant discipline, plus at least ***three*** years of substantial on-the-job experience[3] related to the subject matter in this specification, plus relevant training courses covering the content in this specification[4], or

(iv) at least ***eight*** years of substantial on-the-job experience[3] related to the subject matter in this specification.

[3] On-the-job direct involvement in 10 test/survey reports for method A and B, and 3 test/survey reports for method C in different contracts/works orders; and also self-proof of at least 10 successful leak points for method B and C.
[4] A typical certificate/diploma shall include all hands-on aspects covered in this specification.

D – Instrumentation

The instrumentation components (hardware and software) used shall conform to EN 13477-1 and EN 13477-2 (ISO 18081, Section 7). The optimum frequency range for leak detection depends very much on the application, the fluid type, pressure difference at the leak, the leak rate, and the sensor to source distance, as well as other factors, and shall normally be below **5000Hz**. As a rule of thumb, the preferred frequency range used for detection of leaks in high-pressure pipes is higher than that used for low-pressure pipe leaks.

Passive sensors and sensors with an integral pre-amplifier of suitable bandwidth are both available. Sensors with built-in electronics are less susceptible to electromagnetic disturbance due to the elimination of a sensor-to-pre-amplifier cable. An acoustic-emission leak detection instrument designed for portable use usually contains one or several channels. The choice of a portable device is generally based on several factors, such as cost, test duration, potential hazards involved and availability of external power (e.g. mechanical or electronic listening device). Single-channel systems are usually used for a point-by-point search mode, with the sensor being moved to accessible points of interest along the utility. Multi-channel systems are mainly used for utilities where the sensor positions are fixed to continuously monitor and localize (e.g. noise loggers), locate (e.g. leak noise correlator and inline AE) and pinpoint (e.g. ELD/MLD) leaks.

If the sensor is to be installed in a potentially explosive atmosphere, the sensor shall be safe and should usually be ATEX conformant in accordance with the classified hazard at the location where it is to be used. Reference should be made to the requirements of EN 60079-0, EN 60079-11 and EN 60079-14 for explosion-proof installations. If the sensor is to be immersed in a liquid, the sensor's IP-code (defined in EN 60529) shall be specified to at least IP68. The sensor and other immersed accessories shall be guaranteed watertight for the maximum possible pressure of the liquid.

D1 – Ground-based AE

D1,1 Noise logger

Noise loggers are simple instruments that measure noise continuously over a specified period of time. On some instruments, the noise event over time can be shown numerically or graphically for each channel and can be compared against static or computed alarm levels so when a specific threshold is met an alarm may be automatically triggered. The necessary signal parameters can be acquired and recorded continuously or periodically. The duration of the acquisition period shall be determined based on consideration of the values and fluctuation of the background noise measurements.

D1,2 Leak noise correlator (LNC)

Sensors: The acoustic emission sensors are generally piezoelectric devices and shall be mounted on accessible parts of the utility to ensure proper signal coupling. For buried utilities, the normal frequency range for cross-correlation leak detection and location shall be below **5000Hz**. Higher frequencies can be used to achieve greater discrimination between leak noise and airborne or mechanical background noise.

Amplifiers: Amplifiers / preamplifiers shall have sufficient gain or dynamic range, or both, to allow the signal processing equipment to detect the level of acoustic background noise in the pressurized system. The sensor / amplifier bandwidth shall be selected to minimize background noise.

Signal Processor: The signal processor measures the root mean square (RMS) level, the acoustic emission signal power, the average signal level, and may include a leak location processor to compute the source location from signal levels and attenuation data.

The LNC shall have, but not be limited to, the following functions and capabilities (Guideline on Leak Detection on Underground Communal Service of Housing Estates, Appendix A Section A): (1) a survey range of not less than 1000 metres; (2) the capability of measuring a minimum of 4 different combinations of pipe diameters and pipe materials in a single measurement; and (3) optimal radio transmission capabilities at 500 to 1000 metres in favourable condition.

D1,3 Listening device

A Mechanical Leak Detector (MLD) is a passive device similar to a doctor's stethoscope, which transfers the leak noise to the operator's ear directly through ground microphones. An Electronic Leak Detector (ELD) consists of a ground microphone, a noise amplifier, headphones and frequency filters. The leak noise is amplified and transmitted electronically to either headphones, a loudspeaker or an indicating meter. Unwanted noises can be removed by electronic frequency filters. An ELD must cover a frequency range of between 100 to 3000 Hz in order to achieve successful filtering of other noises.

D2 – In-line AE Method

The in-line inspection tool shall have, but not be limited to, the following functions and capabilities:

- Use as a tethered or non-tethered in-line inspection tool.
- The capability to be inserted into a pressurized utility without de-pressurizing for minor leak and seepage cases not detectable by method B LNC and MLD/ELD.
- The capability of collecting and presenting data in such a way that leaks can be categorized as being of small, medium and large size.
- A suitability for use with various pipe materials including, but not limited to, pre-stressed concrete cylinder pipe (PCCP), reinforced concrete cylinder pipe (RCCP), asbestos cement (AC) pipe, polyvinyl chloride (PVC), high density polyethylene (HDPE), glass reinforced polymer (GRP), steel, cast iron, and ductile iron pipe.

D3 – Equipment Calibration

The calibration process shall comply with the requirements of ISO/IEC 17025:2017 and shall be conducted by a calibration body. The requirements for equipment calibration/verification intervals for LNC and pipe's in-line inspection tool are provided in Table 2.

Table 2 Specific Calibration / Verification Requirements

Type of equipment	Maximum period between successive calibration / verification	Calibration / verification procedure or guidance documents and equipment requirements
Noise logger (method A)	5 years (calibration)	Calibration shall be conducted by a competent calibration body as defined in HOKLAS Supplementary Criteria No. 2 or manufacturer.
	1 year (verification of sound level)	At least five artificial audible sound files shall be used for system verification by attaching the device to a microphone for sound transmission. Deviation of dB level between the measured and known values shall be within the manufacturer's recommended tolerance levels.
Leak noise correlator (method B)	5 years (calibration)	Calibration shall be conducted by a competent calibration body as defined in HOKLAS Supplementary Criteria No. 2 or manufacturer.
	1 year (verification of sound level and time delay)	(1) Sound level: same verification procedure as used for the noise logger. (2) Time delay: At least five artificial audible sound files with different types and sizes of pipe materials shall be used for system verification by attaching at least one pair of sensors to detect a leak's noise with sound sources of known time delay on each sensor. Deviation of dB levels between the measured and known values shall be within the manufacturer's recommended tolerance levels.
Mechanical listening device (method B)	1 year (verification)	An artificial audible sound shall be used for system verification by attaching the listening device to any object that can transmit sound, such as a water tap. The personnel shall listen to the sound transmitted to the earphone in order to verify that the transmitting path in the listening device is in good and intact condition.
Electronic listening device (method B)	1 year (verification of sound level)	Sound level: same verification procedure as used for the noise logger.
In-line AE method (method C)	5 years (calibration)	Calibration shall be conducted by a competent calibration body as defined in HOKLAS Supplementary Criteria No. 2 or manufacturer.
	1 year (verification)	Sound level: same verification procedure as used for the noise logger.

E – General Testing and Survey Procedure

The AE signals from waves caused by a fluid leak are usually continuously superimposed by transients reflecting the nature of the fluid dynamics, leak path, structural response and wave propagation path in the water-carrying utility. In general, none of the testing / survey strategies yields highly accurate locational information, but for industrial applications even an approximate location can be highly economical when compared to the bill paid for non-revenue water. The AE methods are divided into ground-based and in-line types of survey.

E1 – Method A: Ground-based Noise Logging

The instrumentation detailed in Section D shall be used. The following general procedures shall be followed by the crew led by the Survey Officer.

Table 3 Survey procedures for ground-based AE (noise logging)

Procedures	Actions
(a) Tracing utility alignment and connected ground features	1. Map all ground features connected to the target utility and the utility alignment according to NDTSID Specification 1,1 PCL/EML (LSGI, 2019a) and/or 1,2 GPR (LSGI, 2019b). A test using PCL/EML and/or GPR shall be conducted by a testing laboratory accredited by HKAS or its MRA partners, and the results obtained by PCL/EML and/or GPR shall be reported in an endorsed test report. 2. Measure the distance among the sensors by taking into account the horizontal and vertical bends.
(b) On-site observation	1. Observe visible leaks in valves and any potential seepage adjacent to the site, and record the extent of monitoring, for example, entire volume of pressure boundary or weld areas only. 2. Review the operational schedule to identify all potential sources of extraneous acoustic noise such as nozzle-plug movement, pump vibration, valve stroking, personnel movement, fluid flow, and turbulence. Such sources may require acoustic isolation or control so that they do not mask relevant leak emission noise within the utility being examined. Uncontrolled generation of acoustic interference by conditions such as rain, sleet, hail, sand, wind (for unprotected vessels), chipping, or grinding, shall be avoided and minimized by acoustic isolation. A record shall be made of such sources if the noise cannot be removed.
(c) Mounting and coupling the sensors on features connected to the utility	Fasten the sensors by metallic clamps or by bonding to the pipe's fittings, such as air valves, using a suitable adhesive coupling agent. Record and report the method of mounting and coupling. Mark the locations of the sensors on the survey plan in procedure (a). The separation distance between sensors shall in general not be larger than 100m, unless connection points within 100m are not available.
(d) Measurement	Conduct night flow survey between 2 to 4 am. Continuously or periodically record the noise level at a frequency suggested by the manufacturer or requested by the client. The pressure and / or other significant parameters should be recorded to allow correlation with logged noise.
(e) Recording	1. Analyse the results according to the theory and principles in Section B4. 2. When an increase in noise level attributed to a leak has been detected, conduct further surveys using leak noise correlation and listening devices, and / or an in-

line inspection tool for leak locating and pinpointing subject to agreement by the client.

3. Give reasons if, despite the best efforts of the site crew, the survey of any particular utility is declared as 'survey unreliable (SU)'. One or more of the reasons in Section G 'Limitations' shall be listed.
4. Give reasons if, despite the best efforts of the site crew, the survey of any particular utility is declared as 'survey not successful (SNS)'. One or more of the reasons in Section G 'Limitations' shall be listed.

E2 – Method B: Ground-based LNC and Listening Device

The instrumentation detailed in Section D shall be used. The following general procedures shall be followed by the crew led by the Survey Officer.

Table 4 Survey procedures for ground-based AE (leak noise correlation)

Procedures	Actions
(a) Tracing utility alignment and connected ground features	1. Map all ground features connected to the target utility and the utility alignment according to NDTSID Specification 1,1 PCL/EML (LSGI, 2019a) and/or 1,2 GPR (LSGI, 2019b). A test using PCL/EML and/or GPR shall be conducted by a testing laboratory accredited by HKAS or its MRA partners, and the results obtained by PCL/EML and/or GPR shall be reported in an endorsed test report. 2. Measure the distance between the sensors by taking into account the horizontal and vertical bends.
(b) On-site observation	1. Observe visible leaks in valves and any potential seepage adjacent to the site, and record the extent of monitoring, for example, entire volume of pressure boundary, weld areas only, etc. 2. Clean the hydrants, valves, and pipe body with suspected leak, and listen at these exposed features, if accessible, by electronic and / or mechanical listening devices. 3. Review the operating schedule to identify all potential sources of extraneous acoustic noise such as nozzle-plug movement, pump vibration, valve stroking, personnel movement, fluid flow, and turbulence. Such sources may require acoustic isolation or control so that they do not mask relevant leak emission noise within the utility being examined. Uncontrolled generation of acoustic interference by conditions such as rain, sleet, hail, sand, wind (for unprotected vessels), chipping, or grinding, shall be evaluated and its effect minimized by acoustic isolation. A record shall be made of such sources if they cannot be removed.
(c) Mounting and coupling the sensors on features connected to the utility	Attach the sensors in direct contact with the pipe fittings such as air valves. Mark the locations of the sensors on the survey plan in procedure (a). For a temporary installation on a ferromagnetic connection, a magnetic holder is preferred. The durability, consistency, and chemical composition of the coupling agent shall comply with the manufacturer's recommendations. The method of mounting and coupling shall be recorded and reported.
(d) Measurement	1. Apply a minimum of two acoustic sensors to the target utility, and input the pipe material, length and diameter for estimation of the acoustic wave velocity. Provide a more accurate measurement of acoustic velocity and wave attenuation using a third sensor, if available and necessary.

	2. For survey with one pair of sensors, swap the sensors and repeat the measurement. For a survey with more than one pair of sensors, the sensor swap is not required. 3. Change the positions of the sensors to repeat the survey for every measurement in the following cases: (i) If the leak is located outside the length of pipe between the sensors, then the transit time from the leak to the nearest sensor is ignored. The result will suggest that the leak is located at the sensor nearest to it, which is known as "out-of-bracket". In such cases, the affected sensors must be moved further away to the closest access connecting to the pipe. (ii) If there is a leak on a branch pipe, the peak noise will appear at the branching point. It is then necessary to move one sensor or add another sensor to the connecting pipe and repeat the measurement. (iii) If the noise sources are close to the sensors, they may not be able to detect the leak source accurately. In this case, the affected sensor must be moved further away from the noise source. (iv) When two correlation sensors are put along a water pipe which does not have a point of continuous sound source, the sensors will only pick up ambient noises and results in a peak/leak at the centre of the pipe section in the correlation graph, which is known as centre correlation. 4. If possible, pressurize the utility up to a predefined level (often the service pressure) and then start the measurement. Evaluate the result only after applying filters suggested by the manufacturer and obtaining high confidence of the coherence spectrum. 5. For every survey, record the plot of the coherence spectrum and the cross-correlation function, including the cross-correlation factor.
(e) Pinpointing and recording	1. Analyse the results according to the theory and principles in Section B4. 2. Record the survey mode for locating suspected leaks. Geo-reference each suspected leak point using a total station or other surveying methods referenced to local control points. 3. Confirm the leak point by listening to the leak with an electronic listening device or mechanical listening device. 4. Mark the location with spray paint or another means when a genuine signal is detected. 5. Give reasons if, despite the best efforts of the site crew, the survey of any particular utility is declared as 'survey unreliable (SU)'. One or more of the reasons in Section G 'Limitations' shall be listed. 6. Give reasons if, despite the best efforts of the site crew, the survey of any particular utility is declared as 'survey not successful (SNS)'. One or more of the reasons in Section G 'Limitations' shall be listed.

E3 – Method C: In-line AE Method

The instrumentation detailed in Section D shall be used. The following general procedures shall be followed by the crew led by the Survey Officer.

Table 5 Survey procedures for in-line AE inspection

Procedures	Actions
(a) Tracing utility alignment and connected ground features	1. Map all ground features connected to the target utility and the utility alignment according to NDTSID Specification 1,1 PCL/EML (LSGI, 2019a) and/or 1,2 GPR (LSGI, 2019b). A test using PCL/EML and/or GPR shall be conducted by a testing laboratory accredited by HKAS or its MRA partners, and the results obtained by PCL/EML and/or GPR shall be reported in an endorsed test report. 2. Measure the distance among the sensors by taking into account the horizontal and vertical bends.
(b) On-site observation	- Perform site visit prior to in-line AE tool inspection at potential insertion/ extraction points of the target utility to ensure: 1. Riser and tap size with isolation valve is large enough for the insertion of the tool; 2. Isolation valve is operational; 3. There is sufficient overhead clearance and radial clearance from the middle of the isolation valve and riser. - Non-tethered in-line tool inspection procedure at extraction point: 1. Check the flow and pressure of the target utility to ensure that they are within the tool's mechanical tolerance; 2. Assemble the extraction tool and then bolt to the isolation valve; 3. Open the isolation valve slowly and confirm that all of the insertion tool's seals are preventing water from leaking; 4. Deploy the extraction tool into the pipeline. - Non-tethered in-line tool inspection procedure at insertion point: 5. Switch on the in-line tool and verify the functionality of the electronics; 6. Assemble the insertion tool and then bolt to the isolation valve; 7. Open the isolation valve slowly and confirm that all of the insertion tool's seals are preventing water from leaking; 8. Deploy in-line inspection tool into the flow and then retract the insertion tool; 9. Close the isolation valve; 10. Track the in-line inspection tool along the pipeline with tracking sensors; 11. Retract the extraction tool when the in-line inspection tool has reached its extraction point; 12. Close the isolation valve. - Tethered in-line tool inspection procedure: 1. Check the flow and pressure of the target utility to ensure that they are within the tool's mechanical tolerance; 2. Assemble the tethered in-line tool and then bolt to the isolation valve; 3. Open the isolation valve slowly and confirm that all of the insertion tool's seals are preventing water from leaking; 4. Deploy the in-line inspection tool into the flow while unreeling from the cable drum;

	5. Track the in-line inspection tool along the pipeline in real-time using the above ground locator; 6. Conduct real-time location of leaks / air pockets / other features of interest during inspection; 7. Retract the in-line inspection tool at the insertion point by reeling in the cable drum; 8. Close the isolation valve.
(c) Mounting and coupling the tracking sensors on features connected to the utility	Tracking sensors have to be mounted prior to non-tethered in-line tool inspection using following steps: 1. Remove any coating on the pipe before attaching the tracking sensors; 2. Glue the tracking sensors at the insertion / extraction points and other tracking points on the exterior of the uncoated riser.
(d) Measurement	For non-tethered in-line inspection tools, the acoustic data and magnetometer data are continuously collected. For tethered in-line inspection tools, the acoustic data and underwater visual images are continuously collected.
(f) Pinpointing and recording	1. Analyse the results according to the theory and principles in Section B4. 2. Record the survey mode used for locating suspected leaks. Geo-reference each suspected leak point using a total station or other surveying methods referenced to local control points. 3. Mark the location using spray paint or another means when a genuine signal is detected. 4. Give reasons if, despite the best efforts of the site crew, the survey of any particular utility is declared as 'survey unreliable (SU)'. One or more of the reasons in Section G 'Limitations' shall be listed. 5. Give reasons if, despite the best efforts of the site crew, the survey of any particular utility is declared as 'survey not successful (SNS)'. One or more of the reasons in Section G 'Limitations' shall be listed.

E4 – Leak Validation (Optional)

E4,1 On-site (during test) and off-site (post analysis)

For spot measurements with portable one-channel systems, leak indications shall be verified by measurements around the estimated leak location (e.g. at valves upstream and downstream). By using this approach, external noise can be recognized and distinguished from relevant signals. For other applications, the validation of a leak may be performed by monitoring the AE signals during pressure increase. Also, location graphs may show the suspected position. By evaluation of other AE features (e.g. duration, counts and rise time), the localization process can be improved and any noise sources identified can be easily distinguished from the real leak source. Following acquisition, further analysis, such as filtering out noise signals, produces a clearer view of the located leak.

E4,2 Correlation with pressure

The increased pressure difference caused by a leaking orifice also increases the AE signals produced. The acquired ASL / RMS values will be increased only above a certain minimum differential pressure level. For burst emission application, there is also a pressure limit, which has to be exceeded before the AE signals can be detected. This pressure limit depends on the size of the orifice, the viscosity of the test fluid and the distance of the AE sensors from the orifice.

E4,3 Rejection of false indications

In the case of a leak test, where the sensor can be placed close to the likely leak, the utility has to be tested on minimum and maximum pressure, in order to identify any possible external noise and to compare the two signals. If noise appears during AE acquisition as a result of persistent external noise, then multi-channel systems may identify it by means of the location process. Noise caused by sand or soil hitting the exposed part of a buried pipeline, or drops (condensation) falling from a tank roof, or operating noise next to a leaking valve, may all produce false indications that can be located in the same way as a leak.

F – Reporting

F1 Findings and Survey Drawings

The report's findings shall be clearly provided in survey drawing(s) of the suspected leak point(s), if any, underground utility alignments and associated ground features (connected by the traced points) marked on site following NDTSID Specification 1,1 PCL/EML (LSGI, 2019a) and/or NDTSID Specification 1,2 GPR (LSGI, 2019b). The leak points shall be identified as one of the following leak types:

- Barrel leak: a leak located on the barrel of a pipe section, indicating a reduction in pipe integrity.
- Joint leak: a leak located in a pipe joint.
- Feature leak: an acoustic signature of a leak near a known feature identified in a utility survey, indicating either the presence of a real leak near the feature (e.g. air valve) or that the feature itself emits an acoustic signature resembling a leak (e.g. a partially closed valve).
- Unknown: none of the above.

Also, the following points concerning the findings and survey drawings shall be followed:

(a) The investigation results of leak detection survey (layout plan only) shall be plotted at a 1:100 scale or another scale agreed with the client.
(b) In the drawing, the location(s) of suspected leak(s), if any, shall be connected to identified utility alignments, ground features such as valves, and roads and buildings contained in location plans. All reported coordinates and levels must be referenced to the HK80 Datum and the Hong Kong Principal Datum respectively. (The coordinates for Northings and Eastings are presented as 8*****.***, 8*****.***, relative to the HK80 Datum. Normally, "All levels are referred to HKPD" and must be present in the survey plan).
(c) When any suspected leak(s) is / are detected but not up to the accuracies listed in the category 'Reliable' in Table 1, they shall be declared as "survey unreliable (SU)" on the drawing, and the basis for that declaration shall be reported according to one or more of the reasons in the survey conditions in Table 1 and Section G 'Limitations'.
(d) When reasons exist that prevent successful completion of the survey (e.g. site constraints), the survey shall be declared as "survey not successful (SNS)" in Table 1, subject to agreement with the client, and the reasons for the 'SNS' status shall be reported according to one or more of the reasons in Section G 'Limitations'.
(e) For submissions in CAD and GIS formats, reference should be respectively made to the requirements in Computer-Aided-Drafting Standard for Works Projects (CSWP) Version 1.03.00 (2007) and Geographic Information System (GIS) Specifications for Engineering Surveys of Highway Department (2015).

F2 Test Report

The report shall include, but not be limited to, the following sections:

- Introduction and background.
- Site areas, boundary and methods of geo-referencing of all collected data.
- Site conditions.
- Theories and principles (Section B4).
- General test / survey procedures (Section E) and site-specific procedures.
- Instrumentation (Section D).
- Summary of findings of leak localization, pinpointing and locating with geo-referenced locations for every suspected leak, leak type (barrel, valve, joint) and supporting evidence such as survey drawing(s) of the target pressurized water pipe within the site area as part of the test report according to NDTSID Specification 1,1 PCL/EML (LSGI, 2019a) and/or NDTSID Specification 1,2 GPR (LSGI, 2019b).
- Limitations (Section G).
- Conclusions.
- Site photos in an Appendix.
- Record drawings of utilities within the site area.

F3 Fingerprint Database for Noise Logging, LNC and In-line AE Method

Each lab / survey company shall establish their own leak detection fingerprint database for manual or automatic matching of field data from noise logging, LNC and in-line inspection tool surveys. The basic fingerprints must include, but not be limited to, leak localization using noise logging for the following three leak types in various combinations of pipe diameters, materials and lengths:

- Barrel leak: a leak located on the barrel of a pipe section, indicating a reduction in pipe integrity.
- Joint leak: a leak located in a pipe joint.
- Feature leak: an acoustic signature of a leak near a known feature identified in a utility survey, indicating either the presence of a real leak near the feature (e.g. air valve) or that the feature itself emits an acoustic signature resembling a leak (e.g. a partially closed valve).

G – Limitations

A utilities detection survey shall be declared ‘survey unreliable (SU)’ and / or ‘survey not successful (SNS)’ according to the following examples. The lab / survey company shall expand the list as an in-house procedure, if necessary.

Table 6 Limitations of noise logging and leak noise correlation survey

Limitations	Examples	Reasons of declaring ‘Survey Unreliable’	Reasons of declaring ‘Survey not successful’
A. Utility alignment tracing	All limitations in specification 1,1 PCL/EML apply in this specification because an unreliable or unsuccessful UU survey could result in inaccurate distance measurements along the UU. To recap, those limitations are: coupling effects of nearby utilities, record drawings, lack of closed loop for signal	Refer to recommended quality levels and accuracies in NDTSID specification 1,1 PCL/EML (LSGI, 2019a) and / or 1,2 GPR (LSGI, 2019b)	

	propagation, depth range limits, site constraints, pipe size restrictions, material, under construction.		
B. Flow pressure	Reaching the flow pressure threshold is a primary factor affecting leak detection. Leak detection is flow pressure-dependent when a leak can only be localized and pinpointed once a pressure threshold is reached. It therefore follows that AE waves emitted by a leak yield characteristic frequency spectra as a function of pressure difference, the frequency response of the sensors, the shape of the leak path, and extent of the leak.	Applicable	Applicable
C. Changes in wave characteristics in the utilities' acoustic waveguide governed by materials, size and distance	AE signals are the response of a sensor to sound waves generated and guided by the complex solid media between the soil, utilities and any leak because of the ability of the utility to resist acoustic shear force. Therefore, the common modes of wave transmission, reflection and refraction will apply, leading to attenuation and changes to the direction of the acoustic wave's propagation in the waveguide, and also contributing to the form of the detected signal in the following ways: 1. Distance ranging First, multiple reflected and refracted ray-paths diffract acoustic wave propagation between the sensors, resulting in limitations to distance ranging. Second, acoustic attenuation governs the maximum sensor spacing that is acceptable for effective leak detection. The practical sensor distance can be up to 500 m. However, while sound attenuation for most liquids is low, the working distance might still be reduced to just 100 m to 200 m depending on the acoustic impedance of the different pipe material, pipe diameter and the required sensitivity. 2. Noise Sources of noise reduce the resolution and sensitivity of leak detection. There are two types of noise falling within the frequency range of leak localization and pinpointing systems. The first is feature noise, which can be subdivided as follows: (1) mechanical or electrical, such as turbulent flow or cavitation of the internal fluid or product flow noise; (2) geometrically-induced reflections, such as those caused by valves, nozzles, man-ways, and lap joints; and (3) attenuation of acoustic waves and possible multiple wave-paths between source and sensor locations, caused for example by coating, wrapping and insulation materials . The second is environmental noise, such as that caused by weather conditions, road traffic, railways, planes or birds. 3. Acoustic wave velocity estimation (only in LNC) An inaccurate velocity estimation due to unexpected changes, for example material types and sizes, will affect the accuracy of LNC results.	Applicable	Applicable

D. Out of bracket, leak too close to the sensor and / or a branch, centre correlation	Leak detection is unreliable or a leak is still not detectable even after moving the sensors, due to the three cases suggested in Table 4d.	Applicable	Applicable
E. Plastic pipe	Low frequency leak noise predominates as high frequencies are attenuated rapidly, and in general narrow-band (Gao et al. 2004).	Applicable	Applicable

Table 7 Limitations of in-line AE Methods

Limitations		Examples	Reasons of declaring 'Survey Unreliable'	Reasons of declaring 'Survey not successful'
A. Utility alignment tracing		All limitations in specification 1,1 PCL/EML apply in this specification because an unreliable or unsuccessful UU survey could result in inaccurate distance measurements along the UU. To recap, those limitations are: coupling effects of nearby utilities, record drawings, lack of closed loop for signal propagation, depth range limits, site constraints, pipe size restrictions, material, under construction.	Refer to NDTSID Specification 1,1 PCL/EML	
B. Loss of in-line inspection tool due to	1. Flow rate higher than expected	The in-line tool gets ahead of the tracking crew, causing: - a reduction in the accuracy of leak location - confusion during the inspection concerning the tool's exact location - an inability to time lateral closures effectively	Applicable	Applicable
		Retrieval setup malfunctions: - tool is not caught at the extraction point - difficulty in recovering the retrieval setup (bent) after the tool is caught	Not applicable	Applicable
	2. Tracking device stops working	The in-line inspection tool becomes temporarily lost and causes: - confusion during the inspection - a reduction in the accuracy of leak location - an inability to time lateral closures effectively	Applicable	Applicable

3.	Unchartered connections and / or valve not fully closed or left open	Inspection will be stopped as the tool: - becomes stuck in a valve - travels down an unchartered open lateral (which may cause damage to pumps and block smaller pipelines or fire hydrants)	Not applicable	Applicable

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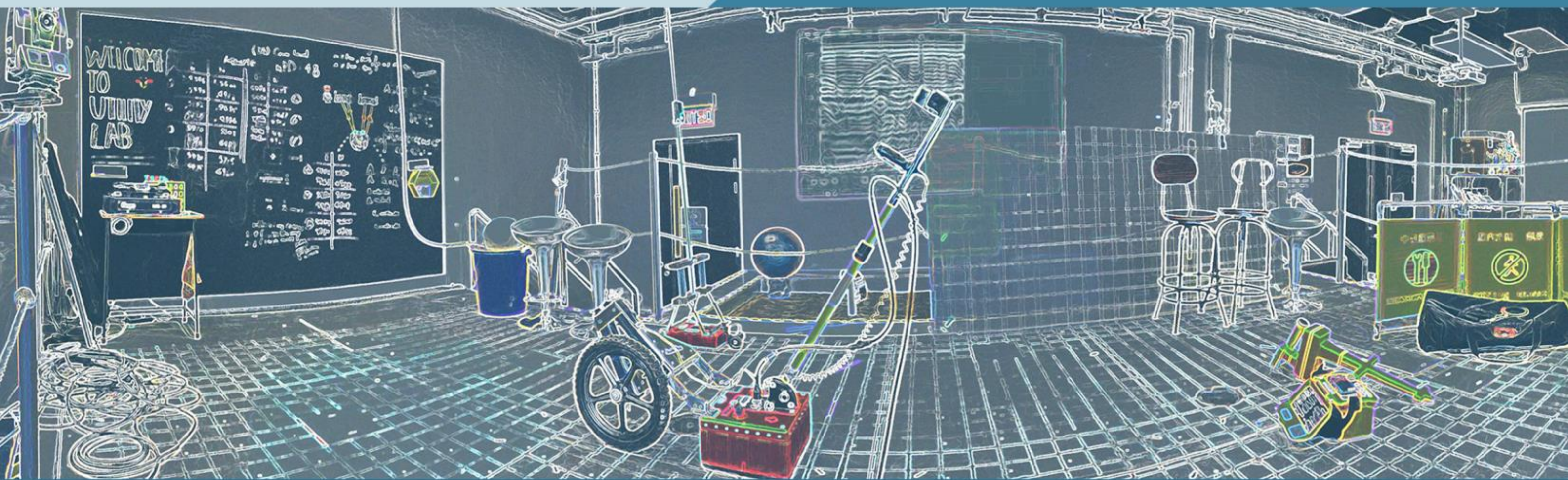

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