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NRCC-43058

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A version of this document is published in / Une version de ce document se trouve dans:
Seminars on Water & Sewer Infrastructure Systems: Challenges and Solutions, Ottawa, Ontario, April 27, 2000, pp. 249-270

LEAK DETECTION METHODS FOR PLASTIC WATER DISTRIBUTION PIPES

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Abstract

Acoustic leak detection methods, in particular leak noise correlators, were studied to determine their effectiveness for locating leaks in plastic water distribution pipes. Also the potential of three alternative non-acoustic methods was evaluated. The study involved field tests at an experimental leak detection facility where several leak types could be simulated under controlled conditions, e.g., flow rate and pipe pressure. Blind tests were performed in collaboration with professional leak detection teams to evaluate commonly used procedures and equipment. Extensive parametric tests were also performed by the research team using a modern vibration measurement and analysis system. The characteristics of leak signals and the effect of several parameters on the accuracy of the cross-correlation method were evaluated. The study demonstrated that leaks in plastic pipes can be located using acoustic equipment – however, it is recommended that several modifications be made to equipment and field procedures to improve their effectiveness. Non-acoustic methods were found promising.

1. Introduction

In many water distribution systems a significant percentage of water is lost while in transit from treatment plants to consumers. According to an inquiry made in 1991 by the International Water Supply Association (IWSA), the amount of lost or "unaccounted for" water is typically in the range of 20 to 30% of production[1]. In the case of some systems, mostly older ones, the percentage of lost water could be as high as 50%.[2] Unaccounted for water is usually attributed to several causes including leakage, metering errors, and theft– according to the IWSA survey, leakage is the major cause.

Water leakage is a costly problem – not only in terms of wasting a precious natural resource but also in economic terms. The primary economic loss due to leakage is the cost of raw water, its treatment, and transportation. Leakage inevitably also results in secondary economic loss in the form of damage to the pipe network itself, e.g., erosion of pipe bedding and major pipe breaks, and in the form of damage to foundations of roads and buildings. Besides the environmental and economic losses caused by leakage, leaky pipes create a public health risk as every leak is a potential entry point for contaminants if a pressure drop occurs in the system.

Economic pressure, concern over public health risk and simply the need to conserve water motivate water system operators to implement leakage control programs. Significant efforts were made in the past to develop such programs, and as a result procedures for systematic water loss control programs are now well established and widely used. There are two major steps in any systematic leakage control program. These are: (i) water audits, and (ii) leak detection surveys. Water audits involve detailed accounting of water flow into and out of the distribution system or parts of it. The American Water Works Association manual "Water Audits and Leak Detection" provides detailed procedures for water audits[3]. The audits help to identify parts of the distribution system that have excessive leakage and hence they are an important part of any effective leakage control program. Unfortunately, however, they do not provide information about the location of leaks. In order to locate leaks in areas that have been identified by water audits as suffering from leakage, leak detection surveys must be undertaken.

In leak surveys, the water distribution system is systematically checked for leaks by using acoustic equipment which detects the sound or vibration induced by water as it escapes from pipes under pressure. Acoustic equipment is the main type of leak detection equipment used by the water industry. Locating leaks using acoustic equipment normally consist of two phases. In the first phase, an initial survey is conducted by listening for leak sounds using for example listening rods or aquaphones on all accessible contact points with the distribution system sucg as fire hydrants, valves, etc. Suspect leak locations found in this phase are noted for more accurate determination in the second phase in which leaks are pinpointed by using geophones (or ground microphones) to listen for leak sounds on the ground directly above the pipe at very close intervals, e.g., every 1 m (3.3 ft); or by using leak noise correlators.

Listening devices utilize sensitive mechanisms or materials, e.g., piezo-electric elements, for sensing leak-induced sound and vibration. They could be either of the mechanical or electronic type. Modern electronic devices may include signal amplifiers and noise filters which could be very helpful in adverse environments. The use of listening devices is usually straight forward but their effectiveness depends on the experience of the user. Leak noise correlators, on the other hand, are state-of-the-art portable computer-based devices which can locate leaks automatically. They work by measuring vibration or sound signals at two points that bracket the location of a suspected leak. Vibration sensors (normally accelerometers) are attached to fire hydrants, valves or any other contact points with water pipes. Alternatively, hydrophones (or underwater microphones) can be used. These are inserted into fire hydrants through modified hydrant caps. Vibration or sound signals are usually transmitted from the sensors to the correlator via wireless radio transmitters. In order to pinpoint a suspected leak, noise correlators first determine the time lag between the measured leak signals by calculating the cross-correlation function. The location of the leak relative to one of the measurement points is then easily calculated by the correlator based on a simple algebraic relationship between the time lag, distance between the measurement points, and sound propagation velocity in the pipe. Normally, leak noise correlators are more efficient and yield more accurate results compared to listening devices. Since the introduction of these devices in the early 1980s, they have significantly improved the "*art*" of pinpointing leaks. Several makes of acoustic leak detection equipment are now commercially available – a list of manufacturers is provided in Table 1.

The effectiveness of existing acoustic methods and equipment has been demonstrated extensively in the past, see for example references 4-6. Generally, acoustic methods are considered to be satisfactory by most professional users. This is only the case, however, where these methods are used for metallic pipes. For plastic pipes, the effectiveness of existing equipment is not well established or documented and most leak detection professionals are skeptical about locating leaks accurately. Existing acoustic leak detection equipment was developed mainly with metallic pipes in mind, but the acoustical characteristics of leak signals in plastic and metallic pipes differ significantly. Plastic pipes are "quieter" and do not transmit sound or vibration as efficiently as metallic ones. Consequently, problems that are normally encountered with locating leaks with acoustic equipment, e.g., interfering traffic signals, and attenuation of leak signals along pipes, are more detrimental in the case of plastic pipes.

The lack of information about the effectiveness of acoustic leak detection equipment for plastic pipes is alarming in view of the increasing world-wide use of these pipes in water distribution systems. This has prompted a research project to address this issue. The project was undertaken jointly by the American Water Works Association Research Foundation and the National Research Council of Canada. The objectives of the project, the research approach and its major findings are presented here*.

2. Research objectives

The main objective of the research project was to investigate the effectiveness of acoustic leak detection equipment, in particular leak noise correlators, for locating leaks in plastic pipes. Emphasis was placed on evaluating the methods on which the equipment, not on comparing different equipment makes. Objectives of the research also included:

- Survey of leak-detection equipment,
- Characterization of leak signals in plastic pipes,
- Identification of necessary improvements to existing equipment and methods, and
- Evaluation of the potential of technologies from other industries.

3. Research approach

The research involved extensive field tests that were performed under controlled conditions at a specially constructed experimental leak-detection facility at the campus of the National Research Council (NRC) in Ottawa, Canada. Evaluation of commonly used acoustic leak detection equipment was performed by inviting several experienced leak-detection teams from utilities and service companies in Canada and the United States to participate in "blind" leak-detection tests at the NRC site. Equipment used by the teams included listening devices and leak noise correlators. The tests involved locating simulated leaks at the experimental site without having prior knowledge about their actual location. Leaks included different types at various flow rates and pipe pressures.

In addition to the blind tests, extensive parametric tests were carried out by the research team. The purpose was to evaluate the effect of several parameters on the accuracy of pin-pointing leaks using the cross-correlation method, and to identify optimum instrumentation and signal processing parameters. The parametric tests were performed using a state-of-the-art vibration measurement and analysis system. Parameters included in the investigation were related to site conditions, instrumentation, and signal processing and analysis. Acoustical characteristics of leak signals were also investigated. These included frequency content, attenuation rate, and variation of propagation velocity with frequency (or dispersion). Leak signals were measured during both winter and summer to evaluate the effect of frozen soil on their acoustical characteristics.

Finally, the potential of locating leaks using alternative non-acoustic technologies was evaluated by inviting experienced users of selected methods to apply them for locating leaks at the NRC site. The potential of the following three methods was evaluated: ground-penetrating radar, thermography, and tracer gas.

4. Experimental leak detection facility

Site description. Leak detection tests in this project were carried out at a facility constructed especially for the project in an experimental waterline site at the campus of the National Research Council (NRC) in Ottawa, Canada. Use of this site for carrying out leak detection tests eliminated public health risk and inconvenience normally associated with such tests at actual water distribution systems. Also, the experimental facility made it possible to perform the tests under controlled and repeatable conditions. This was essential for this study.

The experimental site has an underground PVC test pipe connected to NRC's water distribution network. The pipe is 150 mm (6 in.) in diameter, 200 m (652 ft) in length, and is buried at a depth of 2.4 m (7.87 ft). Soil type at the site is soft silty clay. Construction of the facility involved the following: (i) setup of several access points to the tests pipe, (ii) simulation of leaks, (iii) installation of a back-flow preventor, and (iv) arrangements for varying pipe pressure and measuring the flow rate of leaks. A plan of the test site is shown in Figure 1.

Access points. Several contact or access points to the test pipe were installed for attaching leak sensors. These

* A full report on this project "Leak detection methods for plastic water distribution pipes" will be available in Spring 1999 from the AWWA Bookstore [toll-free telephone No. (800)-926-7337]. It is free to AWWA Research Foundation subscribers [telephone No. (303) 347-6121].

included two fire hydrants installed about 103 m (338 ft) apart – a spacing close to that between hydrants in urban areas. Six additional contact points with the pipe were also introduced between the two fire hydrants. These were in the form of typical 19 mm (¾ in.) copper service connections. The copper pipes were connected to the test pipe via saddle-type couplings and were bent vertically and extended above the ground surface by about 0.5 m (1.6 ft). Two service connections were located less than 1 m apart across a joint of the test PVC pipe. These were used to measure leak signal attenuation across the joint. In addition to providing contact with the test pipe, service connections were used to simulate interfering noise due to water usage at residential services.

Simulated leaks. Service connection leaks, a joint leak, and a crack leak were simulated in the test pipe. These were created in a segment of the test pipe that was situated asymmetrically between the two fire hydrants. Construction details of the leaks and a photo of the area where they were located are shown in Figure 2. Each simulated leak can be opened individually and at the desired flow rate by turning appropriate control valves. Photos of the three simulated leak types are shown in Figure 3. The area where leaks were created was back-filled with the native clay soil at the site. Unfortunately, the pipe segment with the crack leak collapsed soon after the ground was reinstated.

Back-flow prevention. The risk of water back-flow from the test pipe to the NRC water network (in case upstream pressure suddenly drops) was minimized by installing a double-check back-flow preventor at the upstream end of the test pipe.

Pressure variation and flow rate measurement. A manifold consisting of a pressure reducing valve (PRV), a low-flow meter (LFM), a pressure gauge, and a double-check back-flow preventor was installed at the upstream end of the test pipe. Pressure could be set at any level in the range from 139 to 414 kPa (20 to 60 psi). Flow rates ranging from 0.9 to 27 *l*/min. (0.25 to 7 gpm) could be measured at an accuracy of ±5 %.

5. Blind leak detection tests

Description of Tests. The purpose of these tests was to evaluate the effectiveness of commonly used acoustic equipment. Five professional leak detection teams from utilities and service companies in Canada and the United States took part in blind leak detection tests at the NRC facility. The tests were scheduled so that only one leak detection team was present at the site at a time.

Participating teams were asked to locate simulated leaks at the NRC site without having prior information about their location. After the completion of leak location by each team, leak locations were revealed and the results were evaluated. If a team was not successful in locating a particular leak, team members were given a second opportunity to fine-tune their equipment to determine "what it takes" to locate leaks that had initially gone undetected. Also, advise was made in the second round by the researchers to the teams regarding appropriate settings for measurement and processing of leak signals.

Emphasis in the blind tests was placed on locating simulated leaks using leak noise correlators. The participating teams were allowed to listen for leak sounds with electronic or mechanical listening rods and ground microphones only after leak location tests using correlators were completed. Also they were not allowed to visually survey the site before completing the correlation tests. This is contrary to usual leak detection procedures, but it was necessary to ensure that the teams did not know the location of the leaks prematurely and hence to avoid any potential bias in results obtained with leak noise correlators.

Leak detection equipment. The equipment used by each team included listening devices and leak noise correlators which were of four different makes. Leak noise correlators used by most participating teams were equipped with both accelerometers and hydrophones and had signal conditioning capabilities, e.g., noise filtering and signal amplification. Most correlators could be used either in automatic or manual mode. In automatic mode, signal conditioning parameters such as cut-off frequencies of high and low pass filters and amplification settings are automatically selected by the correlator depending on the characteristics of leak signals. In manual mode, however, the operator makes these settings depending on past experience and site conditions.

Test procedure. Leak location tests using correlators were performed for different leak types at various leak flow rates and pipe pressures. Participating teams had first to locate a visible above-ground leak simulated by fully opening a petcock attached to a service connection – the flow rate was about 17 *l*/min (4.49 gpm). Following this preliminary test, they had to locate an underground leak simulated by opening a 6.4 mm (¼ in.) nozzle at several flow rates between 2 to 20 *l*/min. (0.53 to 5.3 gpm). Finally, the teams had to locate the simulated joint leak. In the case of the joint leak, if it was located successfully, the test was repeated in the presence of a simulated interference caused by water consumption at residential connections. The interference was created by opening a garden hose attached to a service connection located at about 10 m (32.8 ft) from the joint leak. In some cases also, as was suggested by a participating team, interference due to the ticking sound of water meters was simulated by intermittently tapping with a screw driver on a service connection pipe located at 10 m (32.8 ft) from the leak.

All blind tests were first performed at a pipe pressure of about 345 kPa (50 psi) for each selected leak flow rate. If the leak could not be located successfully, tests were not attempted at a lower pressure. Also tests were performed by starting with higher flow rates. If leak location could not be determined successfully at a given flow rate, tests were not attempted at lower rates.

Most participating team members were skeptical about locating leaks in plastic pipes by correlating leak signals measured with vibration sensors (accelerometers) – they favored measuring leak signals with hydrophones. For this study, however, they were urged to use both types of sensors. All teams, with no exception, wanted to know if they could have access to valve chambers since they believed that "better" leak signals would be obtained by attaching vibration sensors directly to the pipe. Initially, correlator tests were carried out with accelerometers (having magnetic bases) attached to the underground shut-off valves of fire hydrants 1 and 2, seen in Figure 1. Participating teams were urged by the research team to repeat the tests but with accelerometers attached to the top surface of pressurized fire hydrants. Leak correlation tests were also carried out with hydrophones connected to the two fire hydrants at the site.

Findings. Initially, most participating teams were not able to locate the simulated leaks successfully – only one team succeeded. In a second round, and after being advised by the research team to use lower filter settings, i.e., include lower frequency components in the analysis, three other teams succeeded in detecting simulated leaks. However, the calculated location of the leak was not accurate in most cases – it was up to 5 m (16 ft) in error. This was found to be due to the discrepancy between the sound propagation velocity used in the correlators and the actual sound velocity in the test pipe. When the velocity of leak signals in the test pipe was measured and used in the correlators, leaks could be pinpointed with an accuracy of about ±1 m (±3.3 ft). Other findings of the blind tests were as follows:

- Leak noise correlators, when operated in commonly used automatic mode, rarely succeeded in locating leaks. An inappropriate filter setting was usually selected by the correlator.
- In general, operators had the tendency to shift filter settings for leak signals into a higher range when no definite peak was observed in the cross-correlation function. As seen further on, however, low filter settings are needed for plastic pipes.
- Vibration sensors were only effective in locating large leaks (generally greater than 20 *l*/min. or 5.3 gpm). Hydrophones had to be used to locate small leaks, e.g., joint leak at 6 *l*/min. (1.6 gpm).
- Leaks could be located successfully even in the presence of simulated noise of water meters or noise due to water flow at residential services.
- Out-of-order sensors, especially hydrophones, seem to be a common problem – it was encountered with equipment used by two participating teams (they were not aware of the problem) and with commercial equipment used by the research team.
- Operators were not able to hear leak sounds using headsets attached to leak noise correlators. They were extremely surprised, therefore, when they were able to successfully locate leaks using the cross-correlation of leak sounds that they could not hear. According to popular wisdom, they believed that "if no noise is heard, there should be no leak." Leak signals in plastic pipes, however, were found to be dominated by low-frequency components (below 50 Hz) for which the human hearing is not sensitive.
- Listening devices were not effective unless they were attached to access points that were very close to the leak source – roughly within 5 m (16.4 ft).

6. Parametric leak detection tests

Description of tests. Extensive parametric tests were carried out by the research team to evaluate the effect of various parameters on the accuracy of the cross-correlation method for locating leaks. This information was needed to identify suitable field procedures, and to determine optimum settings for instrumentation and signal processing parameters. This in turn helped to identify necessary improvements to leak detection methods and equipment to increase their effectiveness for plastic pipes. More than 200 parametric tests were performed at the NRC experimental site. The tests were carried out in the usual manner used for the cross-correlation method. Leak signals were measured at two points that bracketed a leak and then they were conditioned as necessary and cross-correlated.

Measurement System. The tests were carried out using a laboratory-grade measurement and analysis system, shown in Figure 4. Leak signals were measured using vibration sensors including piezoelectric acceleration sensors and seismometers having a sensitivity of 1 and 50 volts/g**, respectively. Hydrophones having a sensitivity of 44.7 volts/bar*** were also used. The signals from the sensors were amplified as necessary and transmitted to the recording system using either cables or a home-made wireless system having a flat frequency response in the range from DC to 2000 Hz. At the receiving end, the signals were filtered as necessary and then acquired and analyzed on-site using a 2-channel spectral analyzer. This system proved to be convenient for checking and analyzing leak signals quickly but offered no flexibility in terms of changing the analysis parameters after the signals were acquired. Therefore, the signals were also recorded simultaneously using a 2-channel digital tape recorder having a 16-bit resolution. Leak signals were recorded "as is" with no conditioning, i.e., before passing through filters and amplifiers, for a duration of 5 minutes.

Digitally recorded leak signals were played back off-site in analog form and acquired using a PC-based data acquisition as follows. The signals were first passed through anti-aliasing filters with cut-off frequency set at 200 Hz. Then, a 66-second segment of each signal was digitized at a sampling frequency of 500 samples/second and stored on the hard disk of the PC.

Analysis of leak signals.. Digitized leak signals was analyzed using a digital filtering and spectral analysis software on a PC. The signals were first digitally filtered as necessary using high and low-pass filters of the 4^{th} order Butterworth type. Spectral analysis was then performed on the filtered signals to obtain the auto spectra of the leak signals, the coherence function, and the cross-correlation function. Parameters used in the spectral analysis were as follows: 1024-point fast Fourier transform (FFT), rectangular 512-point force window, 50% window overlap, and power-spectrum averaging with 64 averages.

** g is unit of gravitational acceleration equal to 9.8 m/sec^2 (32.15 ft/sec^2)
*** bar is the c.g.s. unit of atmospheric pressure equal to 100 kPa (14.5 psi)

Test parameters. These included parameters related to signal processing and analysis such as cross-correlation type, signal length and number of averages, and cut-off frequencies of high and low-pass filters. Filter cut-off frequencies were set from 0 to 100 Hz for high-pass filters and from 45 to 200 Hz for low-pass filters.

Test parameters also included those related to the instrumentation used, e.g., sensor type, sensor attachment, and signal transmission. Identical tests were performed with three different types of sensors: hydrophones, accelerometers, and seismometers. Hydrophones were always attached to the two fire hydrants at the NRC site. Accelerometers were attached to underground shut-off valves near the fire hydrants. Tests were carried out with the accelerometers attached to both drained and fully pressurized fire hydrants. Tests were also performed with mismatched sensors, i.e., a hydrophone attached to one fire hydrant and an accelerometer attached to another.

Furthermore, several site parameters were investigated. These included leak type, position, and flow rate; pipe pressure, and interference noise from residential services and leaky hydrants. Leak types included a leak from a damaged joint, service connection leak simulated by opening an underground ¼ inch nozzle, and a leak simulated by opening an above-ground petcock attached to a service connection.

Results and observations. Typical autospectra, coherence and crosscorrelation functions are shown in Figures 5 for leak signals measured with hydrophones and accelerometers, respectively. The frequency characteristics of leak signals will be presented in the next section but attention is drawn here to the dominant low-frequency content of leak signals. Regarding the cross-correlation function, it is interesting to note that the correlation of leak signals measured with accelerometers produces a more pronounced peak than that obtained with hydrophones. This is so in spite of the fact that that the coherence function between accelerometer signals is much poorer than that between hydrophone-measured leak signals. An explanation for this contradiction is perhaps that acceleration signals are dominated by incoherent noise which was easily diminished by spectral averaging. The main findings and observations of the parametric tests are as follows:

- All simulated leaks could be located using either accelerometers or hydrophones. Accelerometers having a sensitivity of only 1 volts/g were as effective as hydrophones having a sensitivity of 44.7 volts/bar. This was not the case for accelerometers used by professional teams in the blind leak tests.
- For hydrophones, a definite cross-correlation peak was obtained when leak signals were high-pass filtered at 10 to 15 Hz. A definite peak could not always be obtained at lower frequency settings – most likely due to the inclusion of dominant low-frequency ambient noise at the pipe resonance frequencies. Low-pass filters could be set at frequencies as low as 45 Hz. Little was usually gained by including higher frequencies. Results for various cutoff frequencies are shown in Figure 6.
- No filtering was required for leak signals measured with accelerometers, but it was frequently necessary to remove low-frequency drift using high-pass filters set at 5 Hz or lower. Low-pass filters could be set as low as 100 Hz. Unlike the case for hydrophones, including high-frequency components was helpful. Results for various filter cutoff frequencies are shown in Figure 7.
- Peaks of cross-correlation functions obtained at high pipe pressures were more definite than peaks obtained at low pressures. Also, the higher the flow rate of the leak, the more definite the peak of the cross-correlation function.
- No leaks whatsoever could be located by attaching accelerometers to drained fire hydrants, even when very sensitive sensors were used. Fire hydrants had to be pressurized to successfully locate the leaks.
- Attaching accelerometers to pressurized fire hydrants led to more definite cross-correlation peaks than attaching them to underground shut-off valves.
- Attaching sensors to "leaky" fire hydrants, e.g., simulated by loosening hydrant caps, did not influence the accuracy of leak location. Also, leaks were located successfully even when noise due to water flow at residential services was present.
- Minimum detectable flow rate for simulated service connection leaks was between 1.6 and 3 l/min. (0.42 to 0.8 gpm) when hydrophones were used and between 4.5 and 6 l/min. (1.2 to 1.6 gpm) when accelerometers were used.
- Relatively small leaks could be accurately located even with mismatched sensors, i.e., an accelerometer on one fire hydrant and a hydrophone on another.

7. Acoustical characteristics of leak signals

Acoustical characteristics of leak signals were evaluated for various leak signals measured under controlled conditions at the NRC experimental leak detection facility. The following acoustical characteristics were evaluated:

- Frequency content of sound or vibration signals as a function of sensor attachment, leak type, flow rate, pipe pressure and season,
- Attenuation rate, i.e., amplitude loss per unit distance, and
- Variation of propagation velocity with frequency.

Information about these characteristics is needed for the selection of appropriate instrumentation, and the design of appropriate measurement and analysis procedures. Leak signals were measured and analysed using the system described earlier for the parametric leak tests. Signal processing parameters were also the same as those used with the parametric tests except that a hanning window was used in Fourier transforms instead of a rectangular force window. The main findings of the investigation are as follows[7]:

- Most of the frequency content of measured leak signals was below 50 Hz. Signal amplitudes at higher frequencies were very small.
- There was no significant difference between the frequency content of signals induced by different leak types, e.g., joint versus service connection leaks.

- In the very low frequency range, below approximately 5 Hz, leak signals were dominated by ambient noise at peaks corresponding to the longitudinal resonance frequencies of the test pipe.
- The effect of season on the frequency content of leak signals was significant. Leak signals measured in winter, while the top 1 m (3.3 ft) of soil was frozen, had significantly less high-frequency components than signals measured in summer.
- The amplitude of leak signals diminished rapidly with distance at a rate of roughly 0.25 dB/m. The attenuation rate in winter was significantly higher.
- Attenuation of leak signals across pipe joints was insignificant.
- The propagation velocity of leak signals was identical for both hydrophone and accelerometer-measured signals.
- The propagation velocity measured in winter was about 7% higher than that measured in summer possibly due to the higher water density and stiffer pipe wall at lower water temperatures in winter.
- The propagation velocity of leak signals was independent of frequency over the frequency range of interest.
- The propagation velocity of leak signals varied insignificantly with pipe pressure over the range between 172 to 414 kPa (25 and 60 psi).

8. Alternative leak detection methods

The potential for locating leaks in plastic pipes by alternative non-acoustic technologies developed by other industries was evaluated in a manner similar to that used for the blind tests described earlier for acoustic methods. Experienced users of selected alternative technologies applied them under controlled conditions at the NRC experimental leak detection facility. The following three methods were evaluated: ground-penetrating radar, thermography, and tracer gas. In their present form, these methods are more complex and time-consuming to perform than acoustic ones. Therefore, teams using alternative methods were informed about the location of the leaks in order to allow them more time to experiment with the various parameters that affect the performance of their methods. This was more helpful in evaluating the potential of the methods than scanning the entire length of the test pipe according to normal leak detection practice. The tests carried out with the selected methods were exploratory and hence limited in scope, but they yielded valuable information about the potential of the methods. A brief overview of alternative methods, description of tests, and findings are presented next.

Ground-Penetrating Radar. This method could in principle be used to locate leaks in water pipes by either detecting underground voids created by leaking water as it circulates near the pipe or by detecting anomalies in the pipe depth as measured by radar. Saturation of soil by leaking water slows down radar waves – thus making the pipe appear deeper than it should be. Ground-penetrating radar (GPR) is similar in principle to seismic and sonar techniques. It works by transmitting a short duration pulse of high-frequency electromagnetic energy into the ground by means of a transmitting antenna. The transmitted pulse signal is partially reflected back to the ground surface by buried objects or voids in the ground or by boundaries between soil layers that have different dielectric properties. Reflected radar signals are captured by a receiving antenna and then digitized and stored for processing. Time traces of radar signals captured along the surface of the ground are normally displayed vertically (side by side) to form a vertical cross-section of the ground with position being along the horizontal axis and time (or depth if the velocity in the ground is known) along the vertical axis. Reflection patterns in the resulting radar images are then used to delineate information about buried objects.

The GPR survey at the NRC experimental leak detection site was performed using the pulseEKKO 100 radar system equipped with 200, 100, and 50 MHz antennas. A leak was simulated by opening a 6.4 mm (¼ in.) underground nozzle for about 4 hours prior to the survey. The leak was left open during the survey. A 10 by 40 m (32.8 by 131.2 ft) survey grid was marked on the ground surface, as shown in Figure 8, and covered a large area above the leak and further away from it. Grid lines were spaced at 5 m intervals in both the east-west and south-north directions which were perpendicular and parallel to the pipe, respectively. Radar data were acquired along all gridlines. On-site review of radar images indicated that all antennas exhibited strong signal attenuation with depth. Only, the 100 MHz antenna provided both sufficient penetration depth and resolution of features in the top 2 to 3 m (6.6 to 10 ft).

Radar images are shown in Figure 9 for survey lines perpendicular and parallel to the test pipe. The point reflector seen near the center of the images in Figures 9a and 9b is believed to be the water pipe. It appears at a depth of about 2 m (6.6 ft) rather than the pipe's actual 2.4 m (7.9 ft) depth – perhaps due to an inaccuracy of the measured radar velocity[8]. It can be noticed that the pipe appears slightly deeper in the radar image taken above the leak area than in the one taken away from it. This perhaps could be an indication of a slow-down in the radar wave due to the saturation of the soil near the leak.

The radar image in Figure 9c reveals changes in both reflection pattern and signal frequency[8]. This also indicates that the radar wave is slowing down over the leak area likely due to saturation of the soil by the leaking water. However, it might be argued that the anomalies are caused by soil disturbance from construction activities undertaken to create the leaks. At the test site, soil type is mainly soft clay. Therefore, this uncertainty could not be resolved as the clay soil has a high natural moisture content. A velocity decrease due to water saturation would perhaps be more apparent in sandy soils for which the boundary between saturated and unsaturated parts is well-defined which in turn would produce a strong radar signal reflection. This has yet to be demonstrated.

Finally, careful inspection of the radar images did not reveal any anomalies that indicate the presence of voids due to the turbulent circulation of leaking water. The soft clay soil at the test site does not seem to be favorable to the formation of such voids. These difficulties may not be encountered at sites having other types of soil, especially sandy ones. This also remains to be demonstrated in the future.

Thermography. This method involves the detection and display of infrared (IR) radiation in the form of visible images. Thermography could be suitable for leak detection if the surface temperature of the ground is affected by leaking water. Depending on the temperature of water relative to surrounding soil, the ground surface area above a leak may appear cooler or warmer than surrounding areas. This thermal effect could take place if there is a significant heat transfer between leaking water and surface soil. If the water is much cooler than the surface of the ground (which is the case in summer), sufficient heat may be transferred from the surface of the ground to create a cool surface spot. If on the other hand, leaking water is warmer than surface soil (which is the case in winter), a warm surface spot might appear as a result of heat transfer to the surface soil.

The thermographic survey at the NRC experimental leak site was performed using an AGEMA 900 infrared camera system. This system has a high level of accuracy and can resolve absolute temperatures to within ±0.1 °C (±0.18 °F) and relative temperatures to within ±0.04 °C (±0.072 °F). Photos of the infrared camera system as set up in the field are shown in Figure 10. To aid in the positioning of the scanners and the analysis of the infrared images, five small aluminum markers were used to identify the four corners and the center of a rectangular area above the leak. Also, the test pipe was marked by placing wooden sticks horizontally on the ground surface directly above the pipe. An aerial view and an infrared image of the test site are shown in Figure 11. The aluminum markers show up in the infrared image as prominent cold spots because on cloudless nights the sky acts as a huge heat sink that can cool surfaces below the temperature of ambient air.

The thermographic survey was performed during a cloudless night in the Fall of 1997. Infrared cameras were focused directly on the leak area above the pipe and thermographic images were captured over the span of a few hours. The first image was captured prior to opening any leaks. Subsequent images were captured during the buildup of water that was leaking at a rate of about 20 l/min. (5.3 gpm) from a 6.4 mm (¼ in.) underground nozzle. Images were captured at roughly 30 minutes intervals.

The captured infrared images of the leak area displayed unexpected conflicting trends. Generally, however, the leak area was seen clearly as a warm spot in all the images taken in the survey (see Figure 11). The night-time release of thermal energy stored during the day by water-saturated soil above the leak seems to be a major contributor to the warming of the ground surface.

Based on the limited survey performed in this project, it appears that thermography could be used as a method for leak detection in water distribution systems especially as an initial survey tool. However, several issues remain to be resolved. First, it could not be stated with certainty in this study whether the heat transferred directly from the warm leaking water to the surface soil was also an important contributing factor. This needs to be further investigated as it could have implications regarding the most appropriate time of the night for thermographic surveys. Second, thermographic surveys should also be investigated under other seasonal conditions, e.g., in summer. Other issues that need also further investigation include the effect of ambient conditions, e.g., sky cover and relative humidity, thermal noise (especially in urban settings), and ground cover.

Tracer gas. This method works simply by isolating a suspected leak zone, de-watering the pipe and then pressurizing it with a mixture of air and tracer gas. The most commonly used tracer gases are helium and hydrogen – both are nontoxic. Under pressure, the tracer gas escapes through leaks in the pipe and rises through the surrounding soil to the ground surface. The location of the leak is determined by scanning the ground surface with a portable gas sensor.

The tracer gas method is mainly used by the telecommunication industry for leak detection and maintenance of pressurized telephone cables. Its use by the water industry for leak detection in distribution pipes is very limited, mainly due to the requirement for pipe de-watering. Therefore, the focus of tests performed in this project was to evaluate the potential of using the tracer gas method for detecting leaks in "live" water pipes, i.e., without de-watering.

Tracer gas tests at the NRC leak detection site were performed using a hydrogen leak detection system manufactured by Sensistor AB of Linköping, Sweden. A mixture of about 4% hydrogen and 96% nitrogen is normally used in the hydrogen leak detection method (or for short H_2 method). Hydrogen-nitrogen mixtures are non-flammable if the percentage of hydrogen in the mixture is less than 5.7%. A standard 43-litre gas bottle was used for the tests (gas cost is between 40 to 60 Canadian dollars). The hydrogen gas mixture was injected into the test pipe at the upstream fire hydrant. The gas injection setup, shown in Figure 12, consisted of the following components: pressure regulator, flow-meter, and a standard oxygen hose that was attached to a fire hydrant cap having a 19 mm (¾ in.) adapter.

Initially, about 1000 standard litres of hydrogen gas mixture were injected into the pipe. The gas was detected above the leak location 1.5 h after being injected into the pipe. However, the signal emitted by the hydrogen sensor was weak and diminished rapidly with distance from the location of the leak. An additional 1750 standard litres of hydrogen gas mixture were injected. About 1 h later, the signal became significantly stronger – definitely indicating the presence of hydrogen that escaped through the leak. However, hydrogen could not be detected at a radius greater than approximately 1 m (3.3 ft) from the leak location.

The soil surface at the test site was exposed and thus it may not representative of conditions at actual sites. Water pipes are usually installed under roads and this may either delay or hinder the surfacing of hydrogen. However, the fact that the hydrogen did penetrate more than 2 m (6.6 ft) of clay backfill at the test site is very promising. It's very likely that it will penetrate typical pavements especially when using gas sensing probes equipped with vacuum pumps to help force the gas out – but this remains to be demonstrated. The fact that hydrogen could be detected only within a short radius from the leak is a mixed blessing as leaks could be located accurately, but also they could be missed if the gas scanning is not performed directly above the pipe or if the resolution of the survey is too coarse.

For the survey performed in this project, hydrogen surfaced after about 1.5 h of being injected into the pipe. Usually, the time it takes the gas to surface can not be predicted precisely – it depends on soil type and depth, as well as the type and thickness of the road or sidewalk construction materials[9].

A concern that could be raised regarding the use of the tracer gas method on live water pipes is that it may not be effective due to the belief that the gas is likely to be trapped near the ceiling of the pipe. Based on the limited survey performed in this study, it appears that this may not necessarily be the case. The simulated leak was at the 3 o'clock position; nonetheless, the H_2 method was able to detect it. There should not be a problem also for leaks at lower positions, e.g., bottom of pipe, especially if the pressure in the pipe is high[9]. At high pressures, sufficient gas is dissolved in the water as opposed to being suspended in the form of small bubbles when the pressure is low. Dissolved gas has access to any leak opening and is released once under a pressure lower than that inside the pipe. The boundary between low and high pressure is roughly at 310 kPa (45 psi). The higher the pressure, the greater the amount of dissolved gas (2% standard volume of gas is dissolved per 310 kPa or 45 psi of pipe pressure). The amount of gas needed in the tests carried out in this study was relatively small. However, in actual situations it might be necessary to inject large amount of gas continuously especially for pipes with high flow rates.

Finally, it should be mentioned that tracer gas that remains trapped inside the pipe might lead to a water redness problem if pressure in the pipe drops suddenly by a significant amount[9]. A pressure drop releases dissolved gas as bubbles which in turn could disturb the debris in the pipe.

9. Conclusions and recommendations

Commercial modern leak noise correlators were generally found to be capable of locating leaks in plastic water distribution pipes. Based on the findings of this study, however, several improvements could be incorporated into existing equipment and field procedures to increase their effectiveness. Improvements for equipment may include the revision of automatic mode algorithms, use of higher sensitivity sensors especially in the case of accelerometers, verification of propagation velocities for various pipe types and sizes, procedures to verify proper functioning of sensors, very low-frequency capability of wireless transmission / receiving systems, flexible high and low-pass filter settings (e.g., finer steps and lower limits), optional display of time histories and frequency spectra of leak signals.

On the other hand, improvements of field procedures for locating leaks by correlating leak signals may include the use of low-frequency components, on-site measurement of leak signal propagation velocity, verification of proper functioning of sensors, use of hydrophones, and attachment of vibration sensors to pressurized fire hydrants rather than shut-off valves when sufficiently sensitive sensors are available. In the case of the 150 mm (6 in.) PVC test pipe used in this study, the optimum frequency range for correlating leak signals was between 15 and 100 Hz. However, the low-frequency limit may need to be increased or decreased slightly depending on the pipe size and type as well as site conditions.

Finally, initial leak surveys that are normally carried out using listening devices only at access points with distribution pipes may not be effective in detecting leaks due to the high attenuation rate of leak signals in plastic pipes. High resolution surveys using ground microphones may need to be performed instead, but these are time consuming. Thermography and (or) ground-penetrating radar showed promise and could provide efficient tools for initial leak surveys – therefore, it is recommended that their potential be further investigated. The tracer gas method was found to be effective but time-consuming and hence impractical for routine leak locating – however, it could be helpful where other methods fail.

Acknowledgements

This project was funded jointly by the American Water Works Association Research Foundation and the National Research Council of Canada. In-kind support was provided by the Regional Municipality of Ottawa-Carleton and the Louisville Water Company.

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9. Sensistor AB. *The H2 Method for Locating Leaks in Buried Water Pipes*. Application Note, Sensistor AB, P.O. Box 76, 581 02 Linköping, Sweden (1997).

Table 1
List of manufacturers of acoustic leak detection equipment

	Product type		Contact information		
Company name	Correlator	Listening devices	Address	Telephone	Fax
Biwater Spectrascan	√	√	24/25 Hussar Court, Westside View Waterlooville, Hampshire P07 7SQ England	+44 1705 230640	+44 1705 230526
Dantec Measurement Technology A/S	√	√	Tonsbakken 16-18 P.O. Box 121 DK-2740 Skovlunde DENMARK	+45 44 92 36 10 or in USA: +1 201 512 0037	+45 42 84 61 36 or in USA: +1 201 512 0120
Fisher Research Laboratory		√	200 West Willmott Road Los Banos, CA 93635 USA	+1 209 826 3292	+1 209 826 0416
Flow Metrix Inc.	√		P.O. Box 157 Lincoln, MA 01773 USA	+1 800 517 4737	
Fluid Conservation Systems	√	√	2001 Ford Circle, Suite F Milford, Ohio 45150 USA	+1 513 831 9335	+1 513 831 9336
Fuji Tecom	√	√	1-11 Izumi-cho Kanda, Chiyoda-ku Tokyo JAPAN	+81 3 3862 3196 or in USA (Subsurface Leak Detection Inc.): +1 408 249 4673	+81 3 3862 3196 or in USA (Subsurface Leak Detection Inc.): +1 408 249 9653
Goldak / UDSEC		√	P.O. Box 1988 Glendale, CA 91209 USA	+1 818 240 2666	
Gutermann Messtechnik	√	√	Alte Landstrasse 116 CH-8702 Zollikon SWITZERLAND	+41 1 391 31 13 or in North America: +1 403 287 1550	+41 1 391 30 90 or in North America: +1 403 287 1550
Heath Consultants		√	2085 Piper Lane London, Ontario N5V 3S5 CANADA	+1 519 659 1144	+1 519 453 2182
Joseph G. Pollard Co.		√	200 Atlantic Avenue New Hyde Park, NY 11040 USA	+1 516 748 0842	+1 516 294 6898
Metravib Fluide - Silic 2C	√	√	1, rue des vergers 69760 Limonest FRANCE	+33 4 78 64 97 12	+33 4 78 64 97 48
Metrotech		√	488 Tasman Drive Sunnyvale, CA 94089 USA	+1 408 734 1400	+1 408 734 1415
Palmer Environmental	√	√	Ty Coch House Llantarnam Park Way Cwmbran Gwent NP44 3AW England	+44 1633 489479	+44 1633 877857
Primayer Limited	√		2, The Spinney, Parklands Business Park, Denmead, Hampshire, PO7 6AR England	+44 1705 252228 or in USA (Schonstedt Instrument Company): +1 703 471 1050	+44 1705 252235 or in USA (Schonstedt Instrument Company): +1 703 471 1795

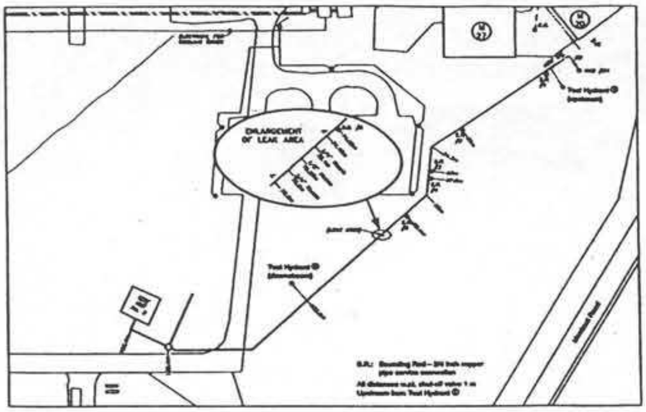
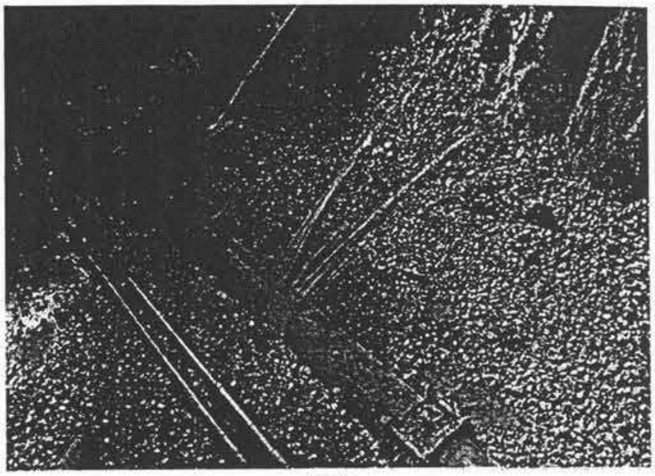
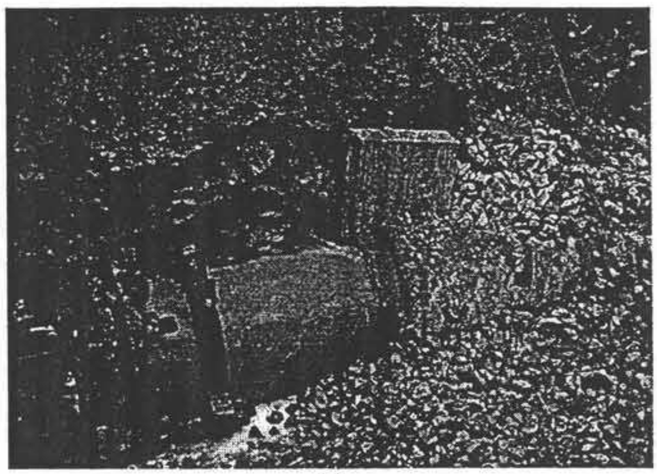


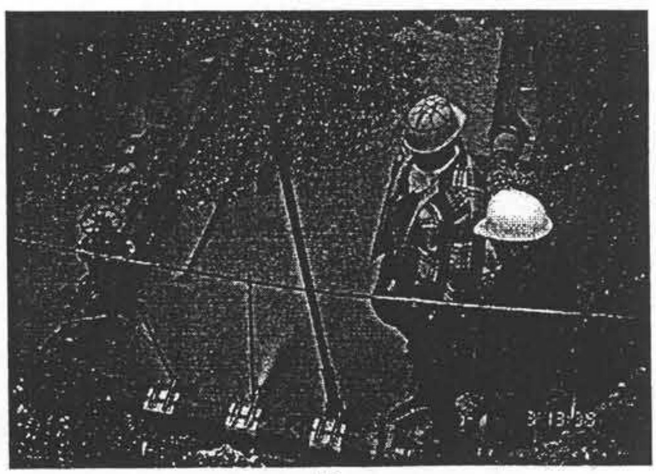
Figure 1 Plan of experimental leak detection facility



(a)



(b)



(c)

Figure 3 Simulated leaks at experimental site: (a) crack leak, (b) joint leak, and (c) service connection leak

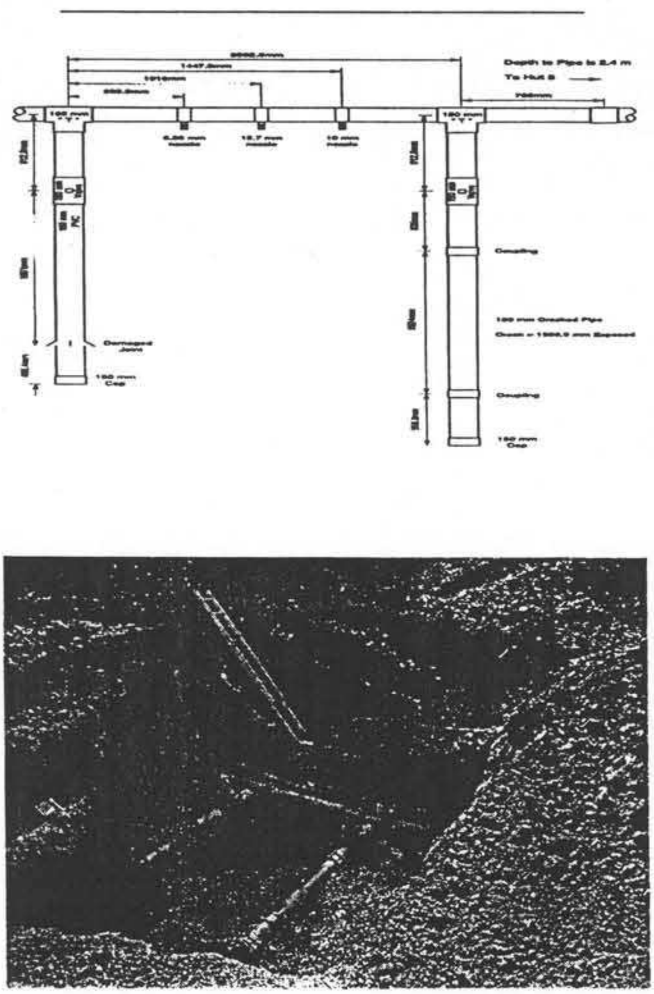


Figure 2 Construction details and photo of simulated leaks

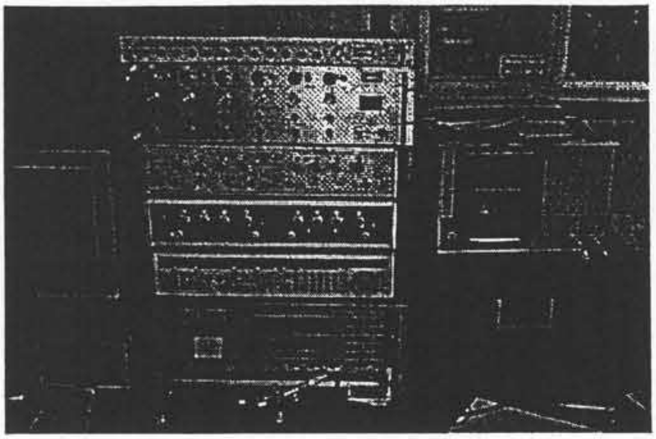


Figure 4a Vibration measurement and analysis system

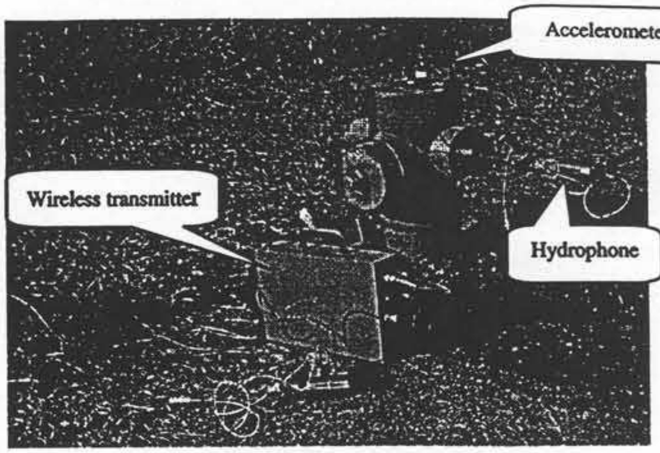
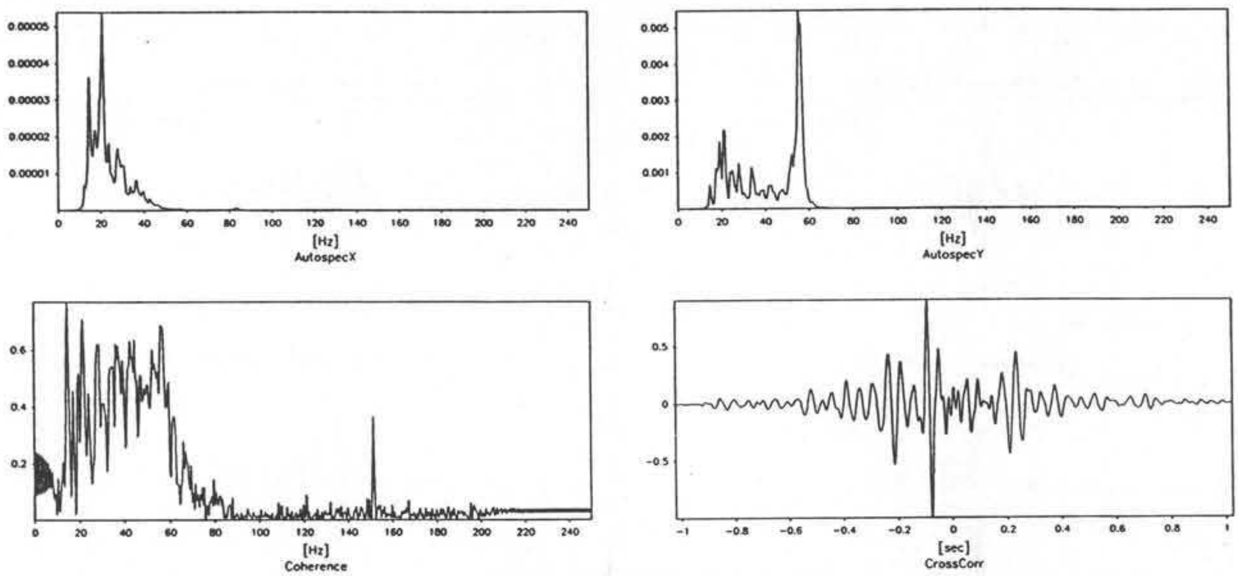
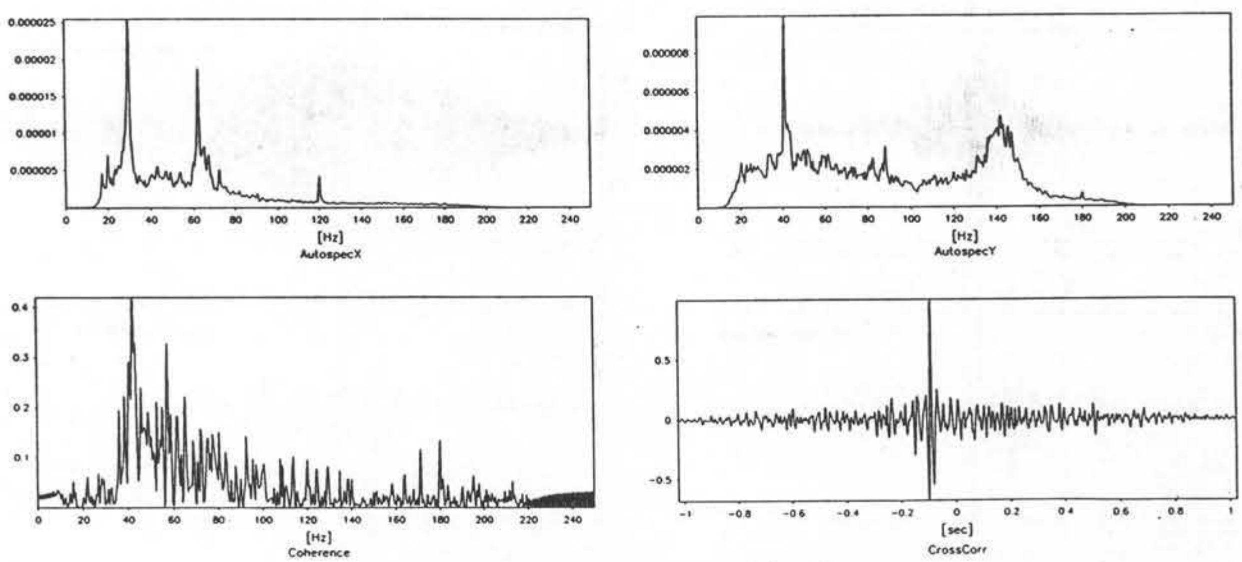


Figure 4b Leak sensors



(a) Hydrophone-measured signals



(b) Accelerometer-measured signals

Figure 5 Typical auto-spectra, coherence, and cross-correlation functions (joint leak at 50 psi pressure, signals band-pass filtered between from 5 to 200 Hz)

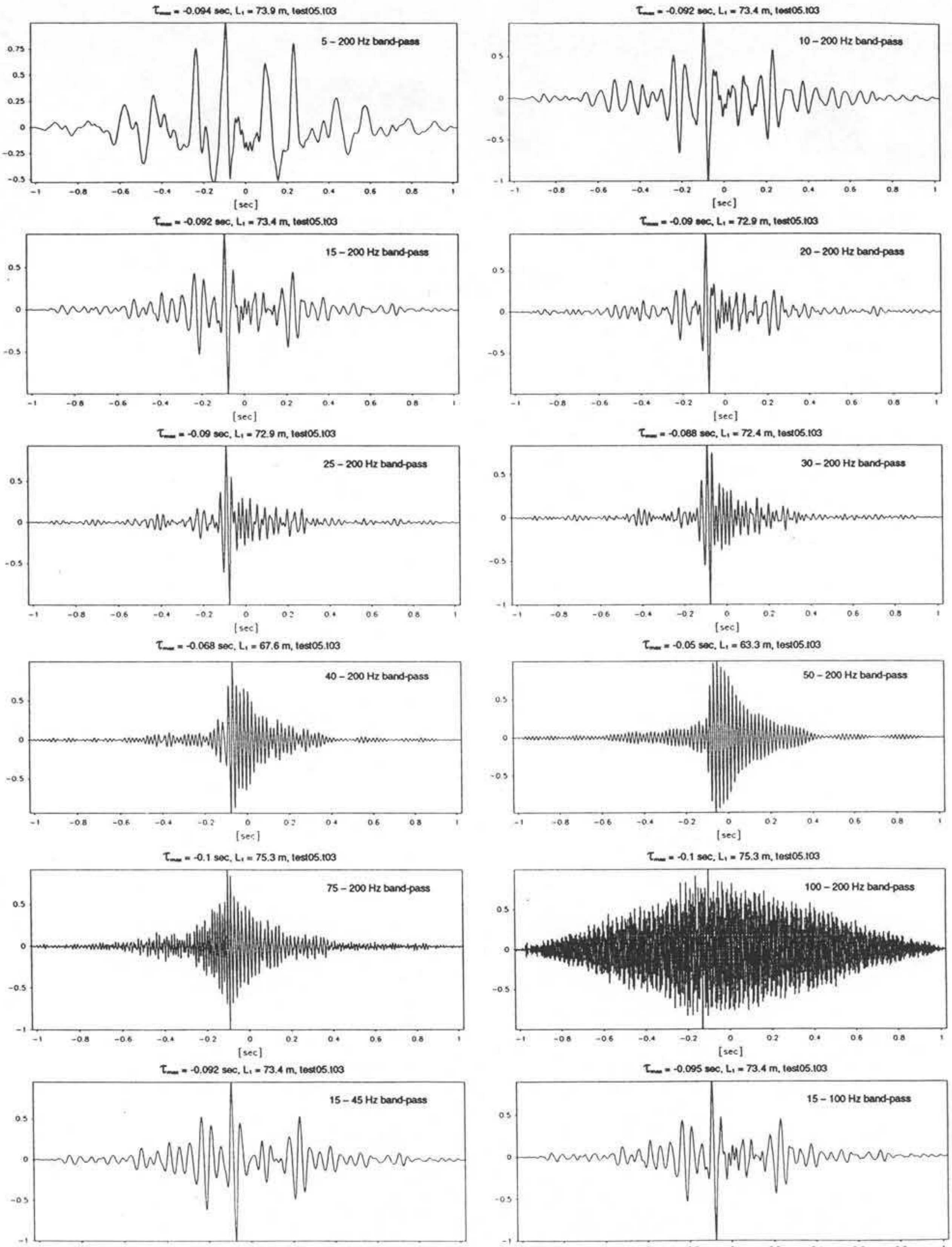


Figure 6 Effect of filter cutoff frequencies on cross-correlation of hydrophone-measured signals

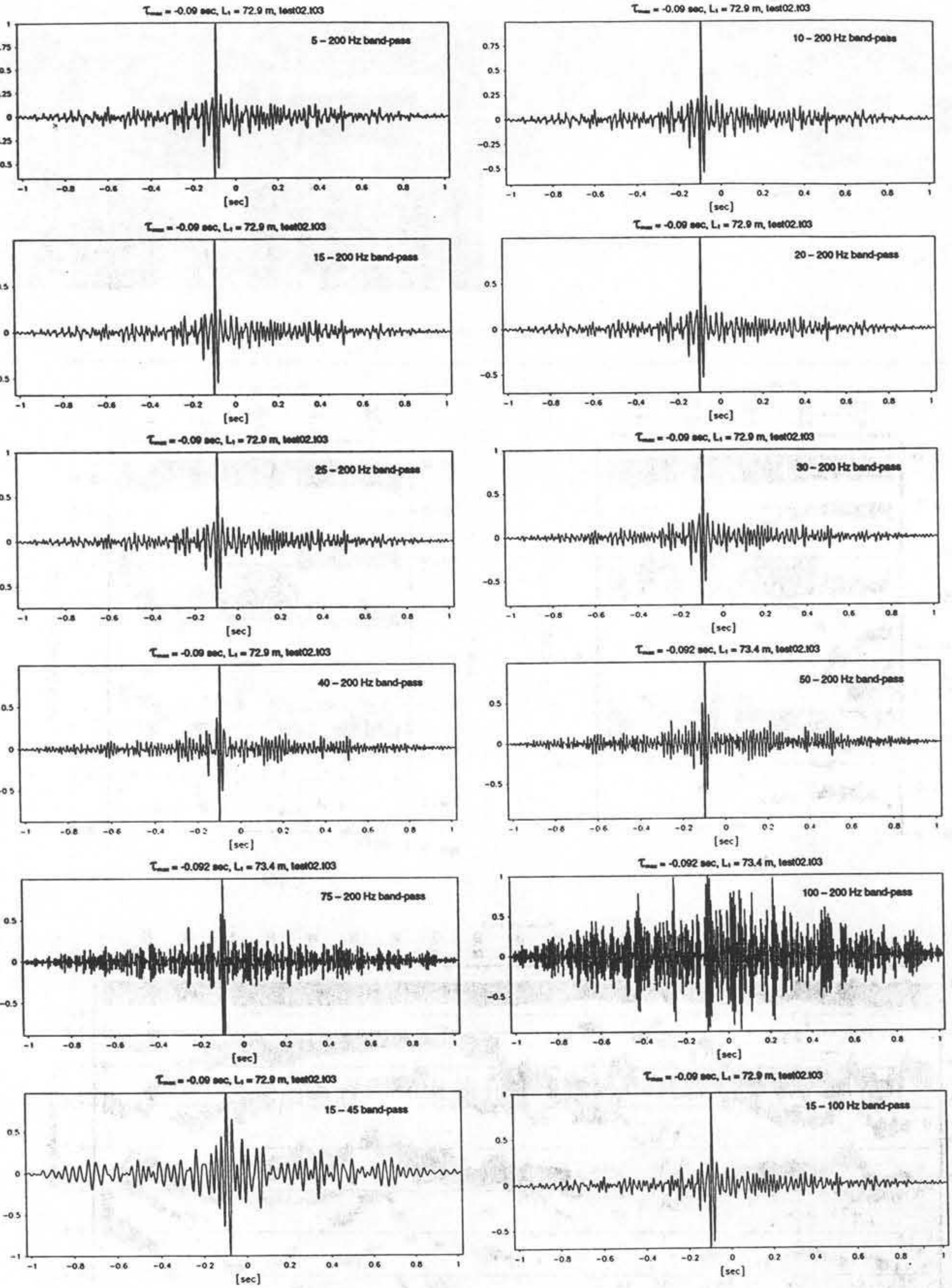


Figure 7 Effect of filter cuttoff frequencies on cross-correlation of accelerometer-measured signals

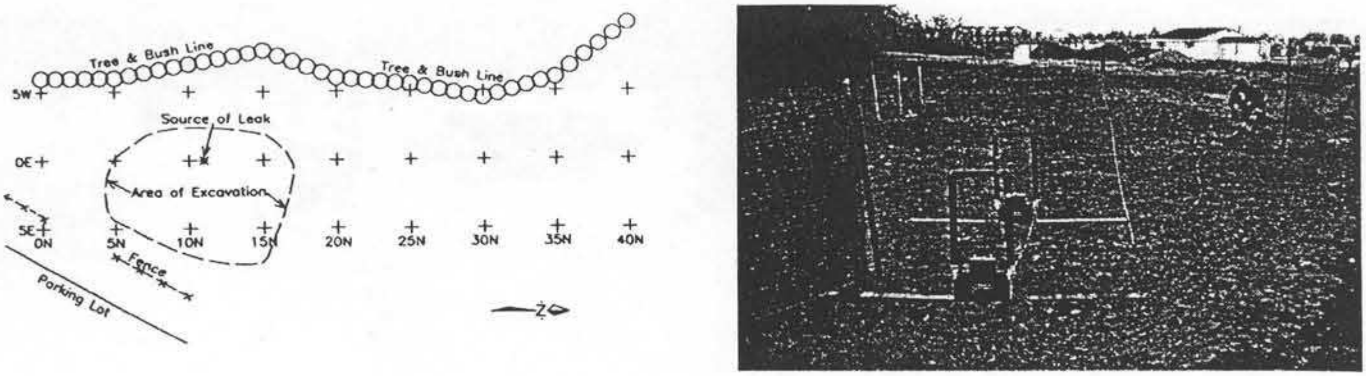


Figure 8 Grid used in radar survey and photo of radar antenna

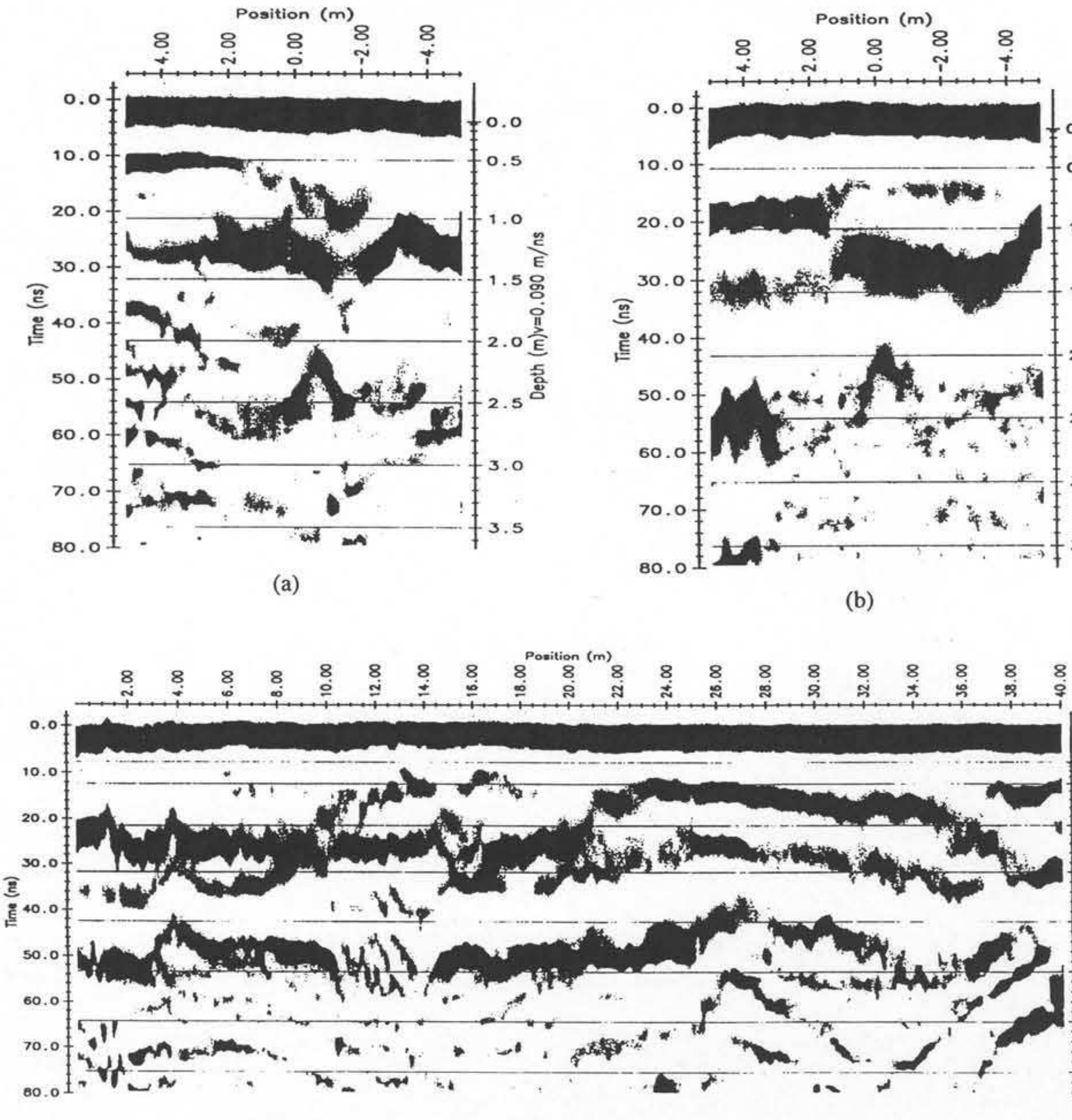


Figure 9 Radar images: (a) along line perpendicular to pipe and above leak location, (b) along line perpendicular to pipe and 20 m away from leak location, (c) along parallel line and above pipe

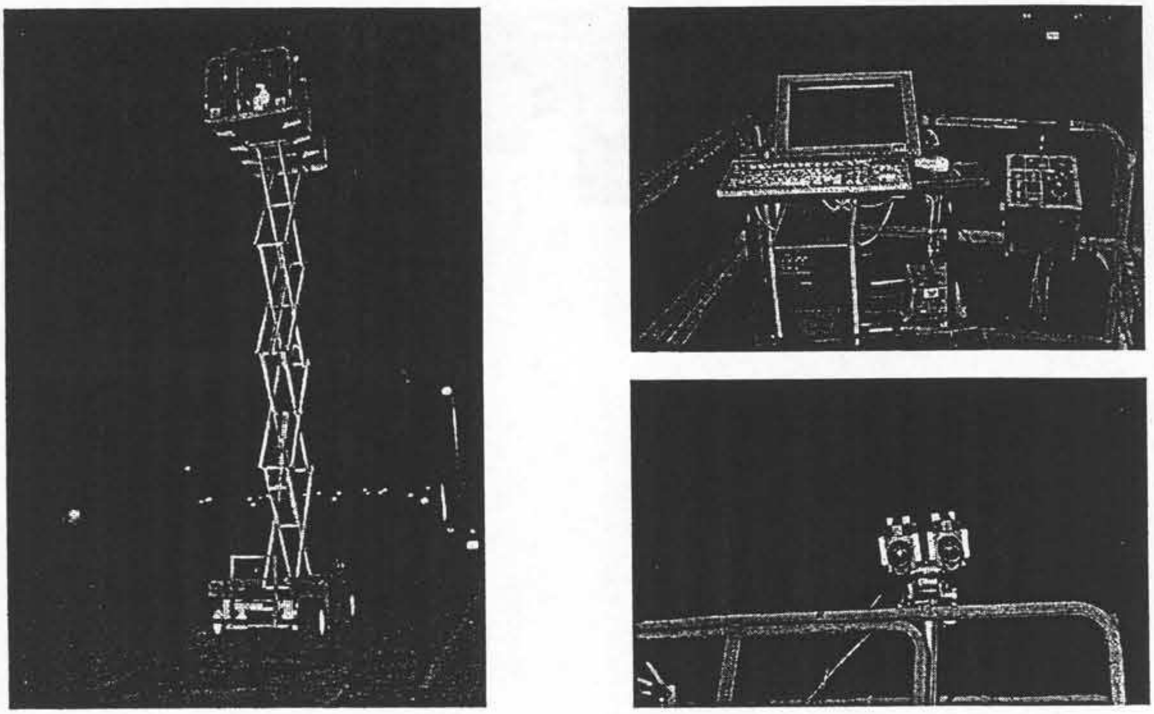


Figure 10 Set up of thermography system at experimental site

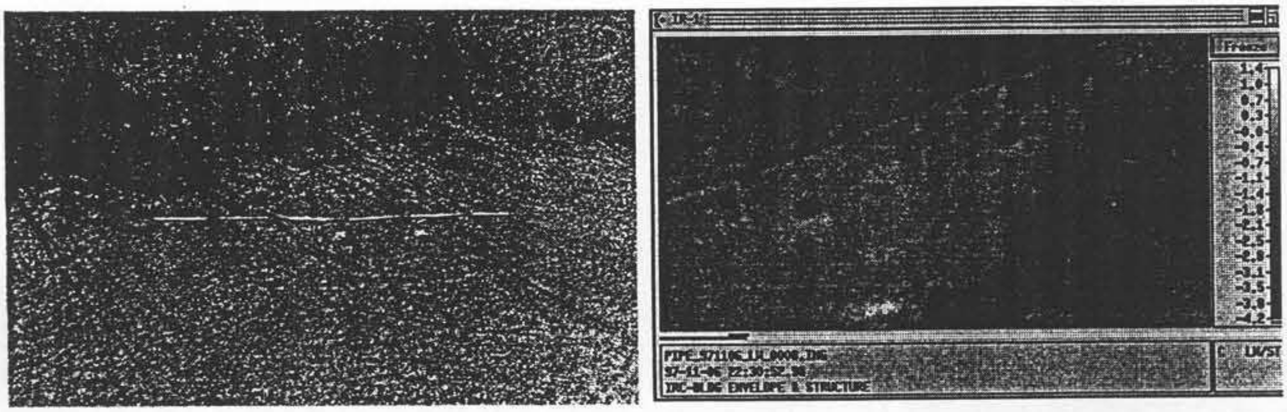


Figure 11 Aerial photo and corresponding infra-red image of simulated leak

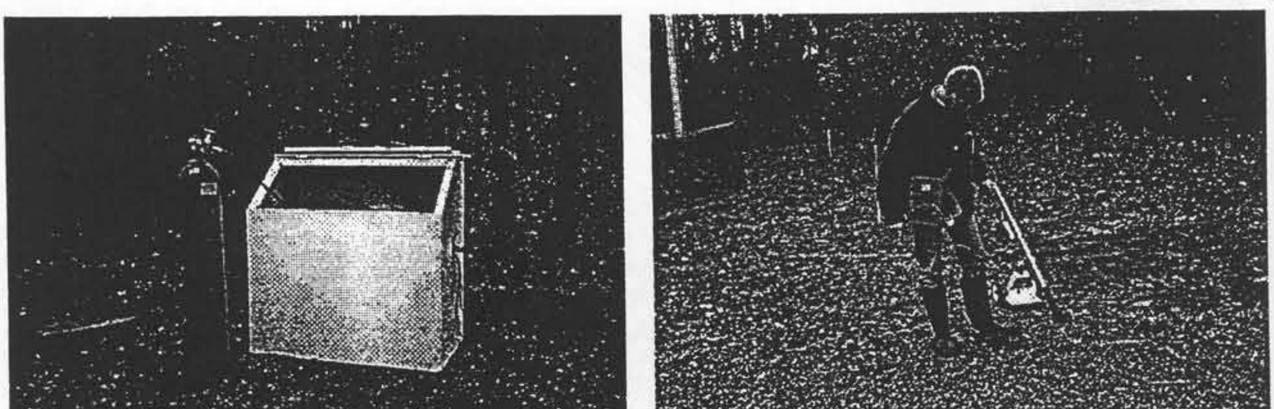


Figure 12 Field setup of the Hydrogen tracer gas system

National Research Council Canada / Conseil national de recherches Canada

Effectiveness of Leak Detection Methods for Plastic Pipes

Osama Hunaidi, Wing Chu, Alex Wang, & Wei Guan

Canada

Lost or "Unaccounted-for" Water

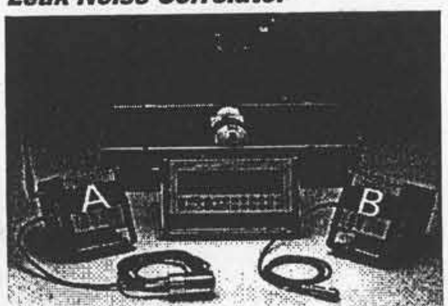
- Fact: Percentage of lost water is typically 20 - 30 %
- Causes: Leaks, breaks, metering errors, public consumption, and theft
- Consequences: Economic loss, damage to network, risk of contamination

NRC·CNRC

Listening Devices

NRC·CNRC

Leak Noise Correlator



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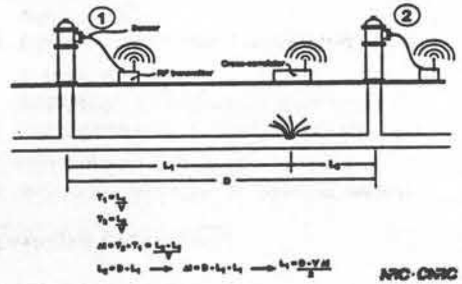
Field Setup of Cross-Correlation Method



NRC·CNRC

Cross-Correlation Type

- Time Domain

$$C_{12}(\tau)=\int_{-\infty}^{\infty} f_1(t)f_2(t+\tau)dt$$

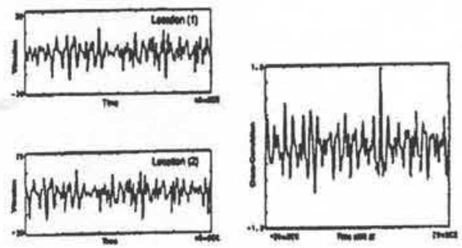
- Frequency Domain

$$C_{12}(\tau)=\frac{1}{2\pi}\int_{-\infty}^{\infty} E_{12}(\omega)e^{i\omega\tau}d\omega, \text{ where}$$

$$E_{12}(\omega)=F_1^*(\omega)F_2(\omega)$$

NRC·CNRC

Cross-Correlation Example



NRC·CNRC

Problem Statement

- Existing acoustic equipment mainly developed for metallic pipes
- Effectiveness of equipment not established or documented for plastic pipes
- Use of plastic pipes becoming widespread

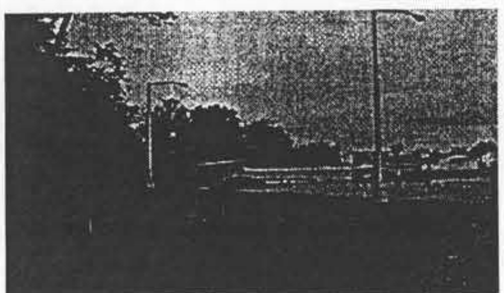
NRC·CNRC

Research Objectives

- Investigation of the effectiveness of acoustic methods
- Identification of necessary methods and equipment improvements
- Assessment of alternative non-acoustic technologies (e.g., radar, tracer gas, thermography)

NRC·CNRC

Experimental Leak Detection Site



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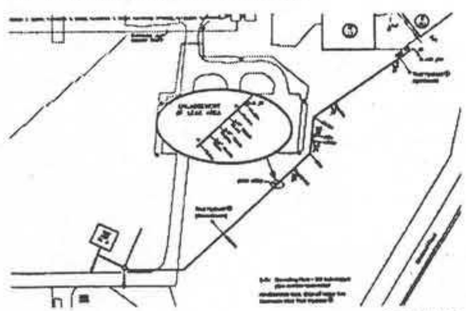
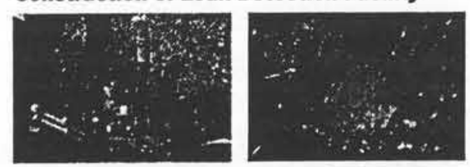
Plan of Leak Detection Site



NRC·CNRC

Construction of Leak Detection Facility



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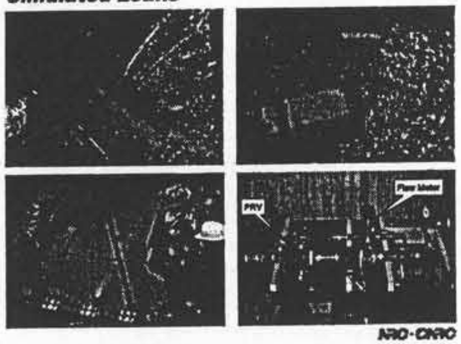
Simulated Leaks



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Evaluation of Acoustic Equipment

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Blind Leak Tests - Findings

- ❑ Most teams unable to locate leaks using leak correlators
- ❑ Tendency to move filters to higher settings when no leaks are found
- ❑ Correlators operated in automatic mode did not succeed - inappropriate frequency range was selected

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Blind Leak Tests - Findings (cont'd)

- ❑ Most teams located leaks when advised to use low filter settings
- ❑ Leak location not accurate (up to 5 m error) due to erroneous velocity
- ❑ Vibration sensors worked only for large leaks; hydrophones worked for all leaks

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Blind Leak Tests - Findings (cont'd)

- ❑ Leak sounds could not be heard with headsets attached to correlators - operators surprised when leaks were located
- ❑ Listening equipment not effective unless very close to leak - less than 5 m

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Parametric Leak Tests

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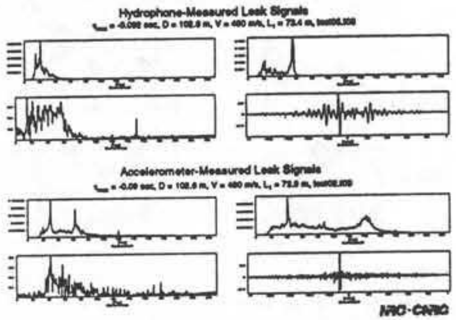
Typical Spectral Analysis Results

Leak: joint; Flow-rate: 6 l/min; Pressure: 50 psi, 15-200 Hz Band-pass



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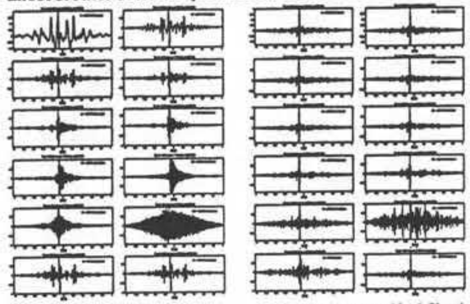
Effect of Filter Cutoff Frequencies on Cross-Correlation Results



Hydrophone-measured Leak Signals

Accelerometer-measured Leak Signals

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Recommendations

- ❑ **Equipment**
  - revision of automatic mode algorithms
  - higher sensitivity sensors
  - sensor self-test capability
  - low-frequency response
  - flexible filtering capability
  - time history and frequency spectra

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Recommendations (cont'd)

- ❑ **Field procedures**
  - focus on low-frequency components
  - on-site measurement of sound propagation velocity
  - verification of sensor operation
  - mounting of sensors on pressurized fire hydrants

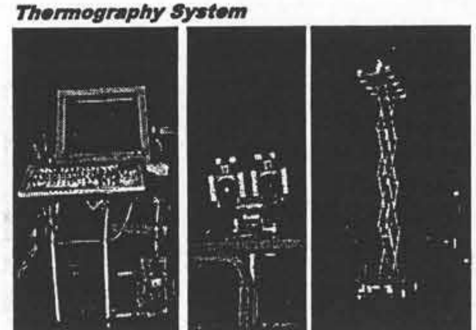
NRC·CNRC

Promising Non-Acoustic Methods

- ❑ Tracer gas
- ❑ Thermography
- ❑ Ground-Penetrating-Radar

NRC·CNRC

Thermography System



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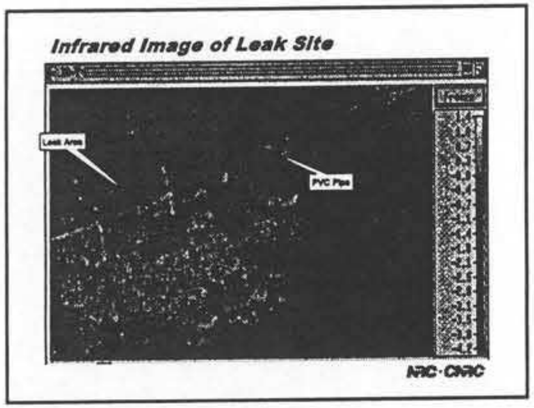

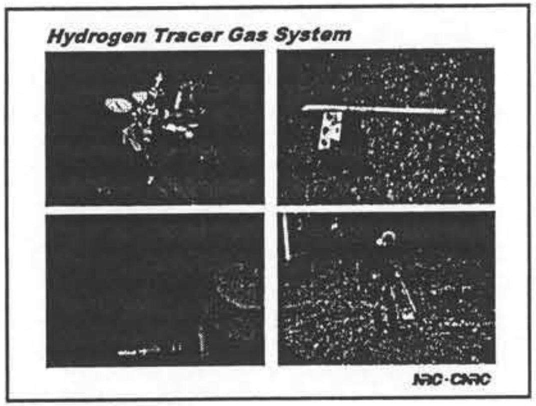

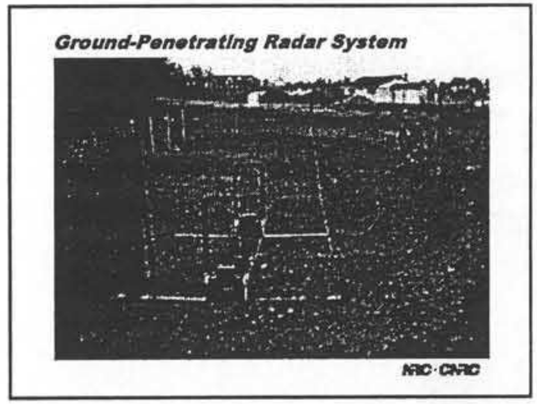

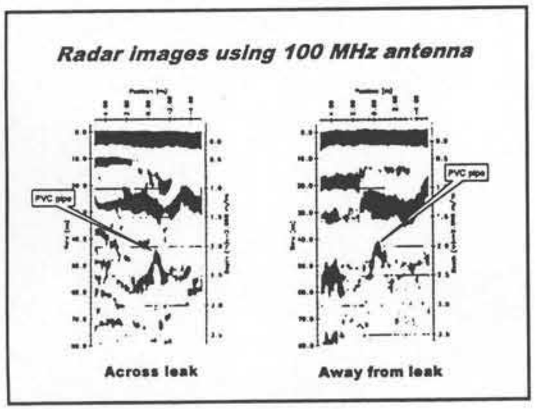

Participating Organizations

- AWWA Research Foundation
- National Research Council Canada
- Regional Municipality of Ottawa-Carleton (Ontario)
- Louisville Water Company (Kentucky)

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