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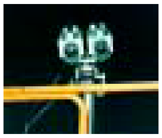
Detecting Leaks



in Plastic Pipes

Commercial leak-noise correlators were generally able to locate leaks in plastic pipe, but modifications could increases their effectiveness.

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

Water utilities commonly use acoustic equipment to locate leaks. Although acoustic equipment is generally considered satisfactory for metallic pipes, its application to plastic pipes could be problematic. This study found that leaks in plastic piped could be located using acoustic techniques; however, there were several difficulties. Professional leak detection teams using leak noise correlators rarely succeeded in locating leaks because the frequency range selected automatically by correlators (or manually by operators) was usually too high. The frequency content of leak signals from plastic pipes was mostly below 50 Hz. Listening devices were ineffective unless they were used very close to leaks. Acoustic leak detection methods can be made more effective by revising the automatic-mode algorithms of correlators, using finely tunable noise filters, and measuring leak signals with hydrophones or highly sensitive vibration sensors. Nonacoustic methods such as radar, thermography, and tracer gases, appear promising.

A large percentage of water is lost in many water distribution systems in transit from the treatment plant to the consumer. According to an inquiry made in 1991 by the International Water Supply Association (IWSA), the amount of lost or unaccounted-for water is typically 20 to 30 percent of total water production.[1] Some distribution systems, mostly older ones, may lose as much as 50 percent.[2] Unaccounted-for water is usually attributed to leakage, metering errors, or theft. According to the IWSA survey, the major cause is leakage.[1]

Leaks waste both a precious natural resource and money. The primary economic loss comes from 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 to foundations of roads and buildings. Leaky pipes also create a public health risk, because every leak is a potential entry point for contaminants if pressure should drop in the system.

Leak detection tests used an experimental water pipe at a facility constructed especially for this project. Use of this site eliminated the public health risk and inconvenience normally associated with such tests.

Leakage control programs

Economic constraints, over public health risk, and the need to conserve water motivate

widely used. Two components in any systematic leakage control program are water audits and leak detection surveys. Water audits account for water flow into and out of the distribution system (or parts of it),[3] and they help to identify parts of the distribution systems that have excessive leakage. However, they do not locate the leaks; that requires leak detection surveys, usually using acoustic equipment.

Leak detection equipment

Acoustic devices are the principal type of equipment used by the water industry to locate leaks in distribution systems. These include leak-noise correlators and simple devices to listen for the sound induced by water as it escapes from pipes under pressure.

Leak-noise correlators pinpoint leaks by measuring vibration or sound signals at two points that bracket the location of a suspected leak.

Listening devices. These include listening rods, acquaphones, and geophones (ground microphones). Listening devices may be either mechanical or electronic. They use sensitive mechanisms or materials such as piezoelectric elements to sense leak-induced sound and vibration. Modern electronic devices may use signal amplifiers and noise filters to make the leak signal stand out. The operation of listening devices is usually straightforward, but their effectiveness depends on the experience of the user. In leak surveys, rods and acquaphones are used to roughly identify leak locations by listening at all contact points within the distribution system (mainly at fire hydrants and valves). Leaks also can be pinpointed using noise correlators, which have become popular over the first decade

Leak-noise correlators. Leak-noise correlators are state-of-the-art portable computer based devices that can pinpoint leaks automatically. They work by measuring vibration or sound at two points that bracket the location of a suspected leak.

Vibration sensors (normally accelerometers) or alternatively hydrophones (underwater microphones) are attached to fire hydrants, valves, or any other points that contact water pipes. Vibration or sound signals are usually transmitted wirelessly from the sensors to the correlator. To pinpoint a suspected leak, a correlator first determines the time lag between 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

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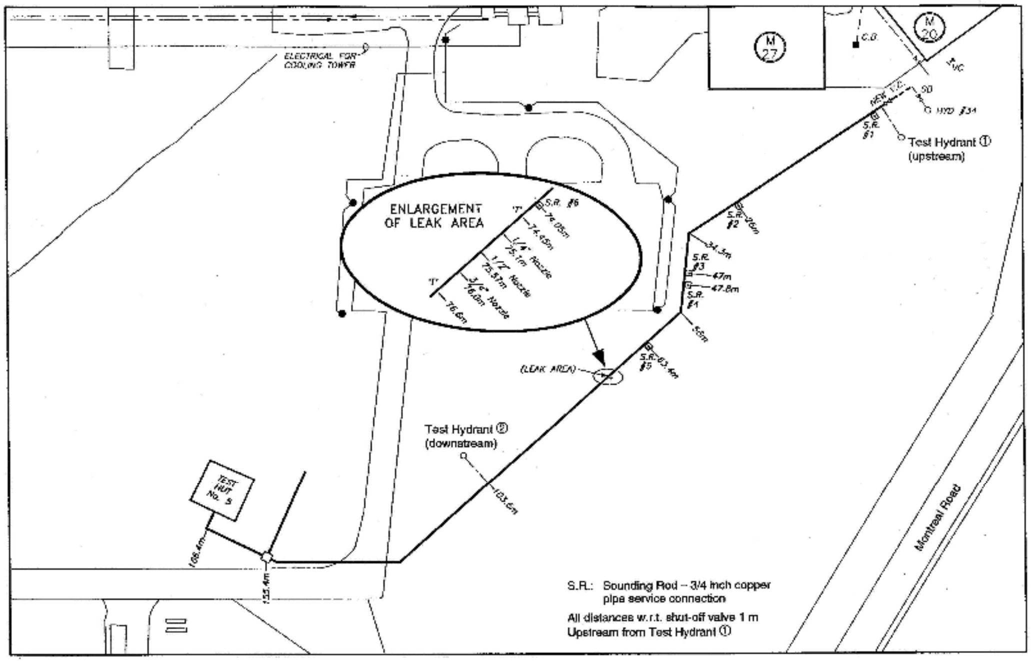
A full report of this project, Detecting Leaks in Plastic Water Distribution Pipes (90770), is available from the AWWA Bookstore (1-800-926-7337). Reports are free to AWWA Research Foundation subscribers by calling 303-347-6121.

FIGURE 1 **Experimental leak detection facility**



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 than listening devices do. The introduction of these devices in the early 1980s substantially improved the art of pinpointing leaks.

Problem statement

Existing acoustic methods and equipment are generally considered by most professional users to be effective for metal pipes.[4-6] However, a similar effectiveness is not well established for plastic pipes, and most leak detection professionals are skeptical about locating leaks accurately in them.

The acoustical characteristics of leak signals in plastic and metal pipes differ substantially. Plastic pipes are quieter and do not transmit sound or vibration as efficiently as metal ones. Existing acoustic leak detection equipment was developed mainly with metal piped in mind. Consequently, the normal problems of using acoustic equipment with metal, e.g., interfering traffic signals and attenuation of leak signals along pipes, are most detrimental in plastic pipes.

The lack of information about the effectiveness of acoustic equipment in locating leaks in plastic pipe is alarming in view of the which the equipment is based rather than comparing devices produced by different manufacturers. increasing worldwide use of plastic in water distribution systems. This prompted a research project to address the issue. The project was funded by the AWWA Research Foundation and carried out by the National Research Council (NRC) of Canada. The objectives of the project, the research approach, and its major findings are presented in this article.

Research Objectives

The objective of this research was to determine how well acoustic leak detection equipment, in particular leak-noise correlators, located leaks in plastic pipes. The research evaluated the methods on Components of the project were (1) a survey of leak detection equipment, (2) characterization of leak signals in plastic pipes, (3) identification of needed improvements to existing equipment and methods, and (4) evaluation of the potential of technologies used in other industries.

Research method

Many field tests were performed under controlled conditions at an experimental leak detection facility on the campus of the NRC in Ottawa, Can. Experienced leak detection teams from utilities and service companies in Canada and the United States evaluated commonly used listening devices and leak-noise correlators in blind tests. Simulated leaks were sought without prior knowledge of their location. Leaks of several types were produced at various rates and pipe pressures.

In addition to the blind tests, the research team performed extensive parametric tests. Those tests evaluated the effect of several parameters on the accuracy with which the cross-correlation method pinpointed leaks, and they identified optimum instrumentation and signal-processing parameters. The parametric tests were performed using a state-of-the-art vibration measurement an 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 – the signals' 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 the signals' acoustical characteristics.

Finally, the possibility of using other, nonacoustic technologies to find leaks was evaluated. Experienced operators used ground-penetrating radar, thermography, and tracer gas to locate leaks at the NRC site.

Experimental leak detection facility

Site description. Leak detection tests used an experimental water pipe at a facility constructed especially for the project. Use of this site eliminated the public health risk and inconvenience normally associated with such tests in a public water distribution system. Moreover, equipment could be tested under controlled and repeatable conditions – an essential provision of this study.

The experimental site had an underground polyvinyl chloride (PVC) test pipe connected to the NRC's water distribution network. The pipe is 150 mm (6 in.) in diameter and 200 m (652 ft) long and is buried 2.4 m (7.87 ft) deep. The soil type is soft silty clay. Construction of the facility included setup of several access points to the test pipe, simulation of leaks, installation of a backflow preventer, and arrangements for varying the pipe pressure and measuring the flow rate of leaks (Figure 1).

Access points. Several contact points that allowed access to the test pipe were installed for attaching leak sensors. Two fire hydrants were placed about 103 m (338 ft) apart, a spacing similar to that typically found between hydrants in urban areas. Six additional contact points, in the form of typical 19-mm (0.75-in.) copper service connections, were placed between the two fire hydrants. The copper pipes were connected to the test pipe by saddle-type couplings and were bent vertically and extended above the ground surface by about 0.5 m (1.6 ft.).

Thermography techniques detect thermal infrared radiation and display it as visible images. This thermographic survey was conducted with the camera system focused directly on the ground surface above a similated leak.

Two service connections were located < 1 m (3.3 ft) apart across a joint of the test PVC pipe. The connections 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 caused by water usage at residential services.

Simulated leaks. Service connection leaks, a joint leak, and a longitudinal crack leak were simulated in the test pipe. These leaks were created in a segment of the test pipe that was situated asymmetrically between the two fire hydrants (Figure 2). Control valves allowed each simulated leak to be opened individually at the desired flow rate. Unfortunately, the pipe segment with the crack leak collapsed soon after the soil was replaced.

Backflow prevention. The risk of water backflow from the test pipe to the NRC water network (in case upstream pressure suddenly dropped) was minimized by installing a double-check backflow preventer at the upstream end of the test pipe.

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

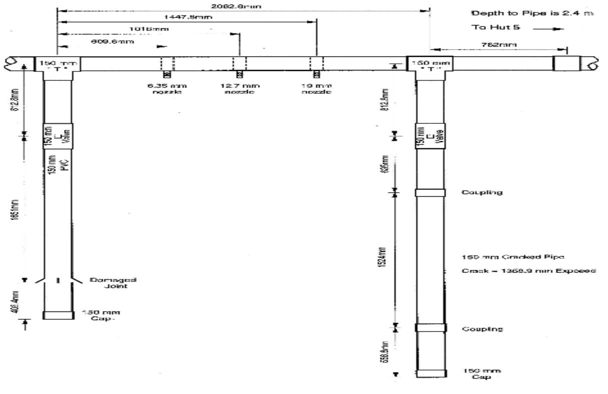
Blind leak detection tests

Description of tests. Blind leak detection test evaluated 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 the tests. Only one leak detection team at a time was present at the site.

Teams attempted to located simulated leaks without knowing their location. After each team finished, the locations of leaks were revealed, and the team's results were evaluated. If a team had been unsuccessful, then team members were given an opportunity to adjust their equipment and try a second time. Before this second round, researchers recommended appropriate settings for measuring and processing leak signals.

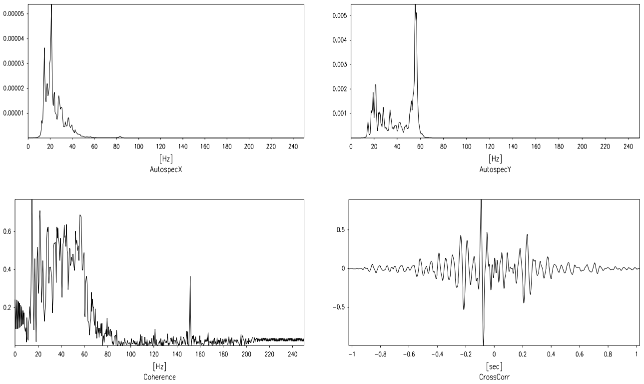
The blind tests emphasized use of leak-noise correlators. Only after leak location tests using correlators were completed did teams listen for leak noises with electronic or mechanical listening rods and ground microphones. Teams were not allowed to inspect the site before completing the correlation tests. This procedure is contrary to usual practice, but it ensured that the teams did not figure out the location of the leaks prematurely.

FIGURE 2 **Construction drawing, plan, view, of simulated leaks**



Leak detection equipment. The listening devices and leak-noise correlators were of four makes. Leak-noise correlators used by most teams were equipped with accelerometers and hydrophones and could filter noise and amplify signals. Most correlators could be used either in automatic or manual mode. In automatic mode, signal-conditioning parameters such as cutoff frequencies of high- and low-pass filters and amplification settings were automatically selected by the correlator, depending on the characteristics of the leak signals. In manual mode, the operator decided these settings depending on past experience and site conditions.

FIGURE 3 **Leak signals measured by hydrophone**



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

Test procedure. Teams using correlators sought several leak types at various leak-flow rates and pipe pressures. They had to first 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, the teams tried to locate an underground leak simulated by opening a 6.4-mm (0.25-in.) nozzle at several flow rates of 2 – 20 L/min (0.53-5.3 gpm). Finally, the teams tried to locate the simulated joint leak. If the joint leak 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 leak. In some cases, as suggested by a team, interference from the ticking sound of water meters was also simulated by intermittently tapping with screwdriver on a service connection pipe located 10 m (32.8 ft) from the leak.

All blind tests for each leak flow rate were first performed at a pipe pressure of about 345 kPa (50 psi). If the leak was not located, then tests were not attempted at a lower pressure. Tests also started with higher flow rates and, similarly, if a leak was not found at a given flow rate, then tests were not attempted at lower rates.

Most team members were skeptical about locating leaks in plastic pipes by corrleating leak signals measured with vibration sensors (accelerometers); they favoured measuring leak signals with hydrophones. For this study they were urged to use both types of sensors. Every team wanted to know if it could attach sensors to valve chambers because of the belief that better leak signals would obtained directly from the pipe. Initially, correlator tests were carried out with accelerometers (having magnetic bases) attached to the underground shutoff valves of fire hydrants 1 and 2 (Figure 1). Teams were urged by researchers 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. The tests took place in late summer or in early fall when topsoil was not frozen.

Results and observations. Only one team located all simulated leaks in the first round of tests. “Locate” is used here to mean that teams obtained a cross-correlation function that had a distinct peak. In a second round, after being advised by researchers to use lower filter settings (include lower frequencies in the analysis), three other teams detected simulated leaks.

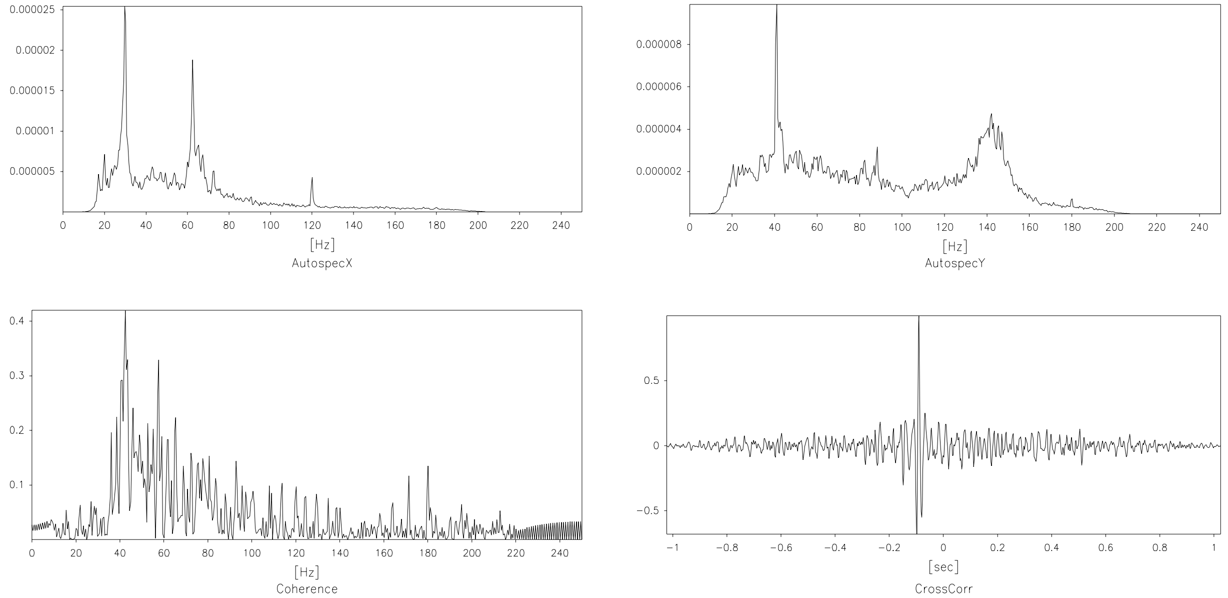
The calculated location of the leak, however was rarely accurate and was up to 5 m (16 ft) in error. This error was due to the discrepancy between the sound propagation velocity used in correlators and the actual sound velocity in the test pipe. After the velocity of leak signals in the test pipe was measured and that velocity was used in the correlators, leaks could be pinpointed to about 1 m (3.3 ft). This accuracy, which is well within the reach of a small excavator’s shovel, is normally considered sufficient.

Other findings of the blind tests are as follows.

- Leak-noise correlators, when operated in commonly used automatic mode, rarely located leaks because the correlator usually selected an inappropriate filter setting
- In general, operators shifted filter setting for leak signals into a higher range when no definite peak was observed in the cross-correlation function. Rather, low filter settings are needed for plastic pipes.
- Vibration sensors located only large leaks (generally > 20 L/min or 5.3 gpm). Hydrophones were needed to locate small leaks (joint leak at 6 L/min [1.6 gpm]).
- Leaks were located even in the presence of simulated noise of water meters or noise from water flow at residential services.
- Damaged sensors, especially hydrophones, seemed to be quite common. Two teams used damaged equipment (they were not aware of the problem). Researchers also found damaged sensors in loaned commercial equipment.
- Operators using headsets attached to leak-noise correlators were not able to hear leak sounds. According to popular wisdom, if no nose is heard, then no leak should exist. Operators where then extremely surprised to be able to locate leaks using the cross-correlation of leak sounds that they could not hear. Leaks signals in plastic pipes, however were dominated by low-frequency components (<50 Hz) to which the human ear is not sensitive.
- Listening devices were not effective unless they were attached to access points that were close to the leak – roughly within 5 m (16.4 ft).

In the tracer gas method, a portable gas sensor is used to detect nontoxic gas as it escaped through leaks in the pipe and rises through the surrounding soil to the ground surface

FIGURE 4 **Leak signals measured by accelerometer**



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

Parametric leak detection test.

Description of tests. More than 200 parametric tests were performed 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 optimum instrument and signal-processing settings. This information in turn helped to identify ways to improve methods and equipment used to detect leaks in plastic pipes. The parametric tests followed the procedure 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. Leak signals were measured using vibration sensors (piezoelectric acceleration sensors and seismometers) having a sensitivity of 1 and 50 V/g, in which g is the unit of gravitational acceleration equal to 9.8 m/s^2 (32.15 fps). Hydrophones having a sensitivity of 44.7 V/bar (1 bar = 100 kPa or 14.5 psi) were also used. The signals from the sensors were amplified as necessary and transmitted to the recording system using either cables or a homemade wireless system having a flat frequency response in the range 0-200 Hz. At the receiving end, the signals were filtered as necessary and then acquired and analyzed on site using a two-channel spectral analyzer. This system was convenient for checking and analyzing leak signals quickly but did not allow the analysis parameters to be changed after the signals were acquired. Thus, the signals were also recorded simultaneously using a two-channel digital tape recorder having a 16-bit resolution. For 5 min, leak signals were recorded "as is" (with no conditioning, i.e., before passing through filters and amplifiers.)

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

Digitized leak signals were analyzed using digital-filtering and spectral analysis software on a personal computer. The signals were first digitally filtered as necessary using high- and low-pass filters of the fourth-order Butterworth type. Spectral analysis was then performed on the filtered signals to obtain the autospectra of the leak signals, the coherence function, and the cross-correlation function. Parameters used in the spectral analysis were as follows: 1,204-point fast Fourier transform, rectangular 512-point force window, 50 percent window overlap, and power spectrum averaging with 64 averages.

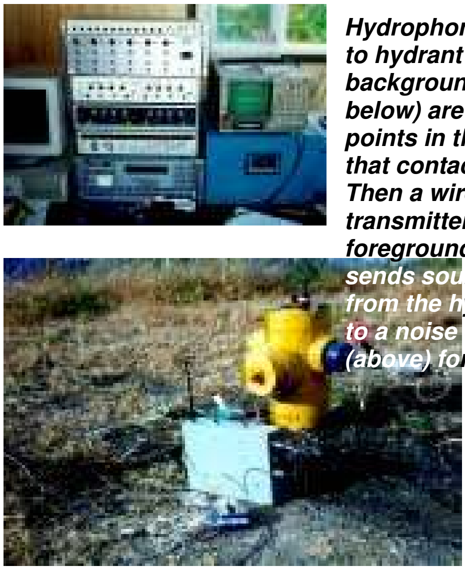
Test parameters. The parameters of interest were aspects of signal processing and analysis – cross-correlation type, signal length and number of averages, and cutoff frequencies of high- and low-pass filters. Filter cutoff frequencies were set from 0 to 100 Hz for high-pass filters and from 45 to 200 Hz for low-pass filters.

Test parameters also included those related to the instruments used – the sensor type, sensor attachment, and signal transmission. Identical tests were performed with three types of sensors – hydrophones, accelerometers, and seismometer. Hydrophones were always attached to the two fire hydrants at the fire hydrant site. Accelerometers were attached to underground shutoff valves near the fire hydrant as well as to 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 – a hydrophone attached to one fire hydrant and an accelerometer attached to another.

Furthermore, several parameters of the leaks themselves were investigates – leak type, positions and flow rate; pipe pressure; and interference noise from residential services and leaky hydrants. The target leaks were from a damaged joint, from a service connection (simulated by opening an underground 6.4-mm [0.25-in] nozzle), and from a leak simulated by opening an aboveground petcock attached to a service connection.

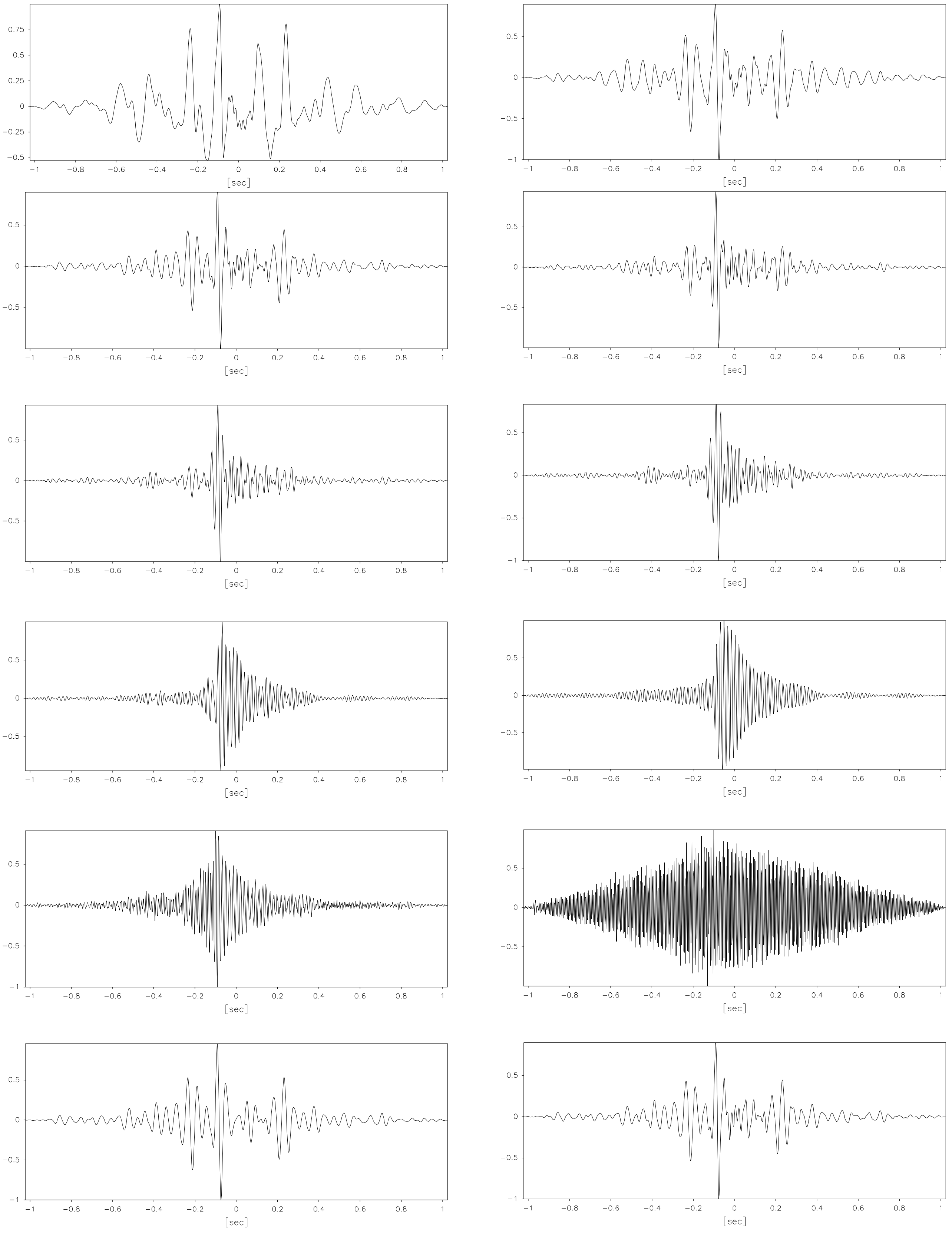
Results and observations. Typical autospectra, coherence, and cross-correlation functions are shown for leak signals measured with hydrophones (Figure 3) and accelerometers (Figure 4), respectively. Low frequencies dominated the leak signals. The correlation of leak signals measured with accelerometers produced a more pronounced peak than that obtained with hydrophones. This was true in spite of the facts that the coherence function between accelerometer-measured leak signals was poorer than that between hydrophone–measured signals. This contradiction may perhaps be explained by the wider frequency range of acceleration signals and if these signals were dominated by incoherent noise that was easily diminished by spectral averaging. The main findings and observations of the parametric tests are as follows.

- Accelerometers having a sensitivity of only 1 V/*g* were as effective as hydrophones having a sensitivity of 44.7 V/bar (1 bar = 100 = kPa or 14.5 psi). Such was not the case for accelerometers used by the professional teams in the blind tests of for accelerometers of commercial correlators used in the blind tests, most likely because of the insufficient sensitivity.
- Hydrophones produced a definite cross-correlation peak when leak signals were high-pass-filtered at 10-15 Hz. A definite peak could not always be obtained at lower frequency setting, most likely because of the inclusion of dominant low-frequency components at the pipe resonance frequencies (Figure 5). Low-pass filters could be set at frequencies as low as 45 Hz. Usually little was gained by including higher frequencies (Figure 5)
- No filtering was required for leak signals measured with accelerometers, but it was commonly 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.[8]
- 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 were located by attaching accelerometer to drained fire hydrants, even when sensors were used. Fire hydrants had to be pressurized to provide useful signals.
- Accelerometers attached to pressurized fire hydrants led to more clearly defined cross-correlation peaks than those attached to underground shut-off valves.
- Attaching sensors to leaky fire hydrants (simulated) by loosening hydrant caps), did not influence the accuracy of leak location. Leaks were located even when noise from water flow at residential services was present.
- Minimum detectable flow rate for simulated service connection leak was 1.6 – 3 L/min (0.42-0.8 gpm) when hydrophones were used and 4.5 – 6 L/min (1.2 – 1.6 gpm) when accelerometer were used.
- Relatively small leaks could be accurately located even with mismatched sensors (an accelerometer on one fire hydrant and a hydrophone on another).



Hydrophones (attached to hydrant in background of photo below) are attached to points in the system, that contact pipes. Then a wireless transmitter (case in foreground at left) sends sound signals from the hydrophone to a noise correlator (above) for analysis.

FIGURE 5 **Effect of filter cutoff frequencies on cross-correlation of leak signals measured by hydrophones**



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

Acoustical characteristics of leak signals

Acoustical characteristics of leak signals were measured under controlled conditions. 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 (amplitude loss per unit distance); and variation of propagation velocity with frequency. These characteristics must be known in order to select appropriate measurement and analysis procedures.

Analysis of signals. Leak signals were measured and analyzed 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 the hanning window was used in Fourier transforms instead of rectangular force window. Reference 7 contains full details of the results summarized here.

Results and observations.

Frequency. The main findings with respect to frequency are summarized here.

- Most of the frequency content of measured leak signals was <50 Hz. Signal amplitudes at higher frequencies were small.
- The frequency content of signals induced by several leak typed (e.g., joint versus service connection leaks) were essentially the same.
- In the very-low-frequency range, below approximately 5 Hz, leak signals were dominated by noise at peaks corresponding to the longitudinal resonance frequencies of the pipe.
- The frequency content of leak signals varies seasonally. Leak signals measured in winter while the top 1m (3.3 ft) of soil was frozen had many fewer high-frequency components than did signals measured in summer.

Attenuation. The main findings regarding attenuation are summarized here.

- The amplitude of leak signals diminished rapidly with distance at a rate of roughly 0.25 dB/m in mild weather; rates were much higher in winter.
- Attenuation of leak signals across pipe joints was insignificant.

Propagation velocity. The main findings with respect to propagation velocity are summarized here.

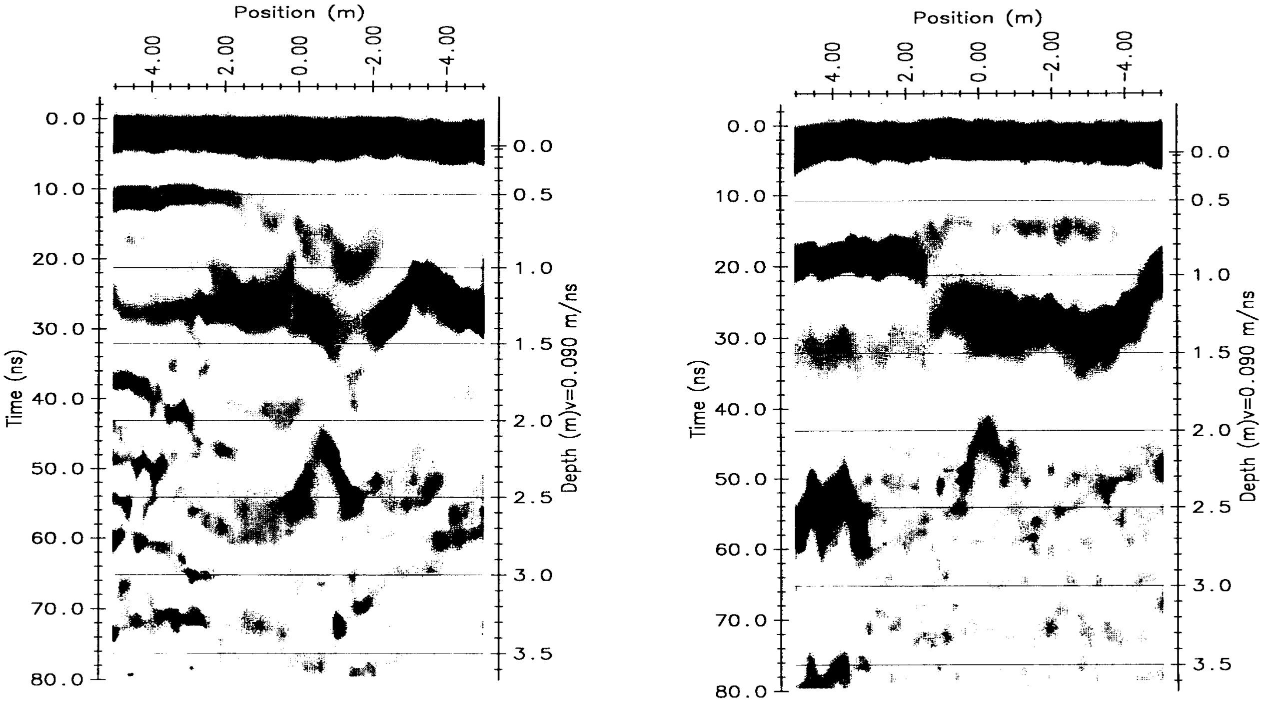
- The propagation velocity of leak signals was identical for both hydrophone- and accelerometer-measured signals.
- The propagation velocity measured during winter was about 7 percent higher than that measured during summer, possibly because water has a higher density and pipe walls are stiffer at lower winter temperatures.
- 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 in the range 172-414 kPa (25-60 psi).

Ground-penetrating radar could, in principle, be used to detect leaks in water pipes by detecting underground voids created by leaking water as it circulates near the pipe of by detecting anomalies in the pipe depth as measured by radar.

The finding of low-frequency and narrow-band frequency leak signals in plastic pipes highlights the need for low-frequency and finely tunable filters that can capture the important frequency components of leak signals. The attenuation rate found here was higher than that for metal pipes of comparable size by a factor of at least five. This high attenuation rate makes it necessary in most cases to use hydrophones or highly sensitive vibration sensors. It makes it necessary to also use a small spacing between sensors. The higher attenuation rate found in winter while topsoil was frozen aggravates this situation, and thus even smaller spacing between sensors may be needed.

The attenuation rate reported here applies to leak signals measured by both hydrophones and accelerometers, although in this study hydrophones were used to measure the rate. This might seem surprising because of the common belief that hydrophones measure vibrations propagating in the water core (or column) whereas accelerometers measure vibrations propagating in the pipe wall that may be attenuated across mechanical joints. In reality, however, vibrations induced by leaks do not travel separately in the water core and pipe wall. Rather, the propagation modes in both are coupled, especially at the low frequencies that dominate in platic pipes. A confirmation of this study is that the wave-propagation velocity obtained in this study was the same for both hydrophone- and accelerometer-measured leak signals.

FIGURE 6 **Radar images in the vicinity of and away from leak**



Radar images: (a) along line perpendicular to pipe and directly above leak location, and (b) along line perpendicular to pipe and 20 m away from leak location.

Alternative leak detection methods

The potential for using nonacoustic technologies developed by other industries – ground-penetrating radar, thermography, and tracer gas – to locate leaks in plastic pipes was also investigated. Tests of these methods were exploratory and thus limited in scope, but they yielded valuable information about their potential.

Ground-penetrating radar. This method could, in principle, be used to locate leaks in water pipes by detecting either underground voids created by leaking water as it circulates near the pipe or by detecting anomalies in the pipe depth as measured by radar. Soil that is saturated by leaking water slows down radar waves and makes the pipe appear deeper than it should be. Ground-penetrating radar (GPR) is similar in principle to seismic and ultrasound techniques. A transmitting antenna sends a short-duration pulse of high-frequency electromagnetic energy into the ground. The pulse 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 receiving antenna. The ground's interior is scanned with radar waves in a manner similar to that of ultrasound to obtain cross-sectional images.

The GPR survey used a commercial radar system* equipped with 200-, 100-, and 50-MHz antennas. Only the 100-MHz antenna provided both sufficient penetration depth and resolution of features in the top 2-3m (6.6-10 ft) of soil at the test site. A leak was simulated by opening a 6.4-mm (0.25-in.) underground nozzle for about 4 h before the survey and leaving it open during the survey. The area surveyed above the leak was 10 x 40 m (32.8 x 131.2 ft) and survey lines were spaced at 5-m intervals.

Radar images are shown in Figure 6 for two survey lines perpendicular to the test pipe – one line of which was directly above the leak and the other 20 m (66 ft) away. The point reflector seen as an inverted parabola near the center of both images is believed to be the water pipe. The pipe appears slightly deeper in the radar image taken above the leak area than in the one taken away from it. This deeper apparent depth on the radar image could indicate radar waves slowed by saturated soil near the leak.

No anomalies were found in the radar images that indicated voids produced by the turbulent circulation of leaking water.[8] Voids may not form easily in the soft clay soil at the test site, but they may form more easily at the other sites underlain by other types of soil such as sandy ones.

Thermography. Thermography techniques detect thermal infrared radiation (IR) and display its visible images. In an infrared radiation image, the ground surface above a leak may appear cooler or warmer than the surface farther away from it. This temperature difference may reflect differences in the temperature of leaking water and the overlying soil; considerable heat may be transferred between leaking water and surface soil. Also, soil close to the leak becomes saturated by leaking water, which may change its thermal characteristics and make it a more effective heat sink relative to dry soil away from the leak.

A thermographic survey of the leak site used in a high-resolution commercial infrared camera system[*] The survey was performed during a cloudless night in the fall. The camera system was focused directly on the ground surface above a simulated leak. The first image was captured before opening the leak. Subsequent images were captured during the buildup of water leaking at a rate of about 20 L/min (5.3 gpm) from a 6.4-mm (0.25-in) underground nozzle. Images were captured at roughly 30-min intervals for a few hours.

The captured infrared images of the leak area displayed unexpected conflicting trends.[8]Generally, however, the leak area was seen clearly as a warm spot in all images taken in the survey. The nighttime release of the thermal energy stored during the day by water-saturated soil above the leak was believed to be a major contributor to the warming of the ground surface.[8]

Thermography and ground-penetrating radar showed promise as tools for initial leak surveys.

This limited survey suggested that thermography could be used in an initial survey for leaks. However, several issues remain to be investigated: the most appropriate survey time, the effect of season, and the effect of ambient conditions such as thermal noise (in urban settings), cloud cover, and relative humidity.

Tracer gas. To use the tracer gas method, a suspected leak zone must be isolated, and the pipe must first be dewatered and pressurized with a mixture of air and nontoxic tracer gas such as helium or hydrogen. The tracer gas escapes through leaks in the pipe and rises through the surrounding soil to the ground surface where it can be detected with a portable gas sensor. The telecommunication industry uses this method to locate leaks in pressurized telephone cables. Use of this method by the water industry is limited because pipes must first be dewatered. Thus, this study evaluated the method's ability to detect leaks in pipes while they carried water.

Tracer gas tests used a commercial hydrogen leak detection system.[*9] In this system a hydrogen nitrogen mixture is used (the percentage of hydrogen in the mixture is < 5.7 percent so that is nonflammable). The gas mixture was injected into the test pipe at the upstream fire hydrant. The gas injection setup consisted of a pressure regulator, flowmeter, and a standard oxygen hose that was attached to a fire hydrant cap having a 19-mm (0.75-in.) adapter.

Initially, about 1,000 standard L (140 gal) of hydrogen gas was injected into the pipe. The gas was detected above the leak location 1.5 h later, but the signal emitted by the hydrogen sensor was weak. An additional 1,750 standard L (245 gal) of gas was injected, and 1 h later the signal became much stronger and definitely indicated a leak.[8] However, the leaking hydrogen gas could not be detected at a radius greater than approximately 1m (3.3 ft) from the leak location. This small radius is a mixed blessing – leaks could be pinpointed with this method, but they could also be missed easily if scanning for the gas is not performed directly above the pipe of if the resolution of the survey is too coarse. The fact that hydrogen penetrated more than 2 m (6.6 ft) of clay black-fill at the test site is promising. It's also likely that the gas will penetrate typical pavement layers above pipes in urban areas, especially if gas-sensing probes are equipped force the gas out. This speculation remains to be demonstrated. The time needed for the gas to surface is relatively long, which may make the method impractical for routine leak surveys or pinpointing.

It might be a concern that gas could be trapped near the ceiling of water-filled pipes (and thus could not escape if leaks are not near the top of the pipe). The simulated leak in the test pipe was at the 3 o'clock position; nonetheless, the method was able to detect it. Leaks at lower positions (the bottom of a pipe)[9] should also be detectable, especially if pipe pressure is high, but this speculation also remains to be demonstrated.

Conclusions and recommendations

Commercial modern leak-noise correlators were generally able to locate leaks in plastic water distribution pipes. Based on the findings of this study, however, several modifications would increase their effectiveness: 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, procedure to verify proper functioning of sensors, very-low-frequency capability of wireless transmission and 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.

Other modifications regarding field procedures may improve the chances of locating leaks with correlators, such as 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 15-100 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, leak surveys that initially use listening devices only at fire hydrants, valves, or other contact points with pipes may not be effective in detecting leaks because of the high attenuation rate of leak signals in plastic pipes. High-resolution surveys using ground microphones may be needed instead, but such surveys are time-consuming. Thermography and ground-penetrating radar showed promise as tools for initial leak surveys. It is recommended that their potential be further investigated. The tracer gas method was effective but time-consuming. It may be impractical for routine surveys or pinpointing of leaks, but it could be effective where other methods fail.

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