JOHN G. PARKER

ACOUSTIC DETECTION AND LOCATION OF LEAKS IN UNDERGROUND NATURAL GAS DISTRIBUTION LINES

Use of a Poisson distribution to project the rate of development of corrosion-induced leaks in underground natural gas distribution lines in future years leads to the expectation that the problem will increase significantly in magnitude. Results of a research program directed toward improving means of leak detection and location by using active acoustics as a diagnostic are described. Substantial agreement is demonstrated between calculations from theory and experimental data obtained using the APL experimental pipeline facility. The prospects that this approach will lead to future improvements in the reliability of leak detection are discussed.

> "In the main street, at the corner of the court, some labourers were repairing the gas-pipes, and had lighted a great fire in a brazier, round which a party of ragged men and boys were gathered, warming their hands and winking their eyes before the blaze in rapture."
>
> (Charles Dickens, *A Christmas Carol*)

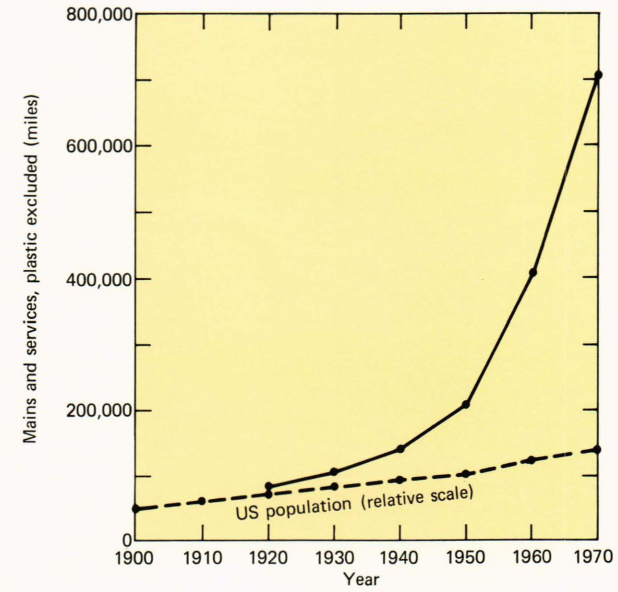

Fig. 1—The increase in mileage of underground natural gas mains and services from 1900 to 1970. Growth of the U.S. population during this period is also indicated.

CORROSION AS A FACTOR IN THE DEVELOPMENT OF LEAKS IN UNDERGROUND NATURAL GAS DISTRIBUTION LINES

Background

Growth of the natural gas distribution system in the United States over the period from 1900 to 1970 is documented in Fig. 1, in which the total existing line mileage, including mains/pipelines and service branches, is plotted at 10 year intervals.[1,2] For purposes of comparison, the relative U.S. population over this period has also been included.[3] Examination of the two sets of data indicates that from 1920 to 1940 the installed pipeline mileage grew slightly more rapidly than the population; however, after 1940 — and particularly after 1950 — the increase was extremely rapid, indicating a correspondingly large increase in per capita gas consumption.

Apparently no records of installed pipeline mileage prior to 1919 exist. However, several factors indicate that most of the pipelines existing at that time were put in place before 1900 and probably after 1880. One reason for this is the rapid rate of population increase during the late 1800's and a substantial leveling off after 1900 to the rate indicated in Fig. 1. Thus, in 1850, the U.S. population was approximately 23 million, increasing more than threefold to 76 million in 1900. It would seem logical to assume a corresponding increase in gas production and distribution. This is supported in an account describing the problem of leak detection and repair in the Wilmington, Del., area published in 1935.[4] In that article, the maximum age of the piping in the distribution system was estimated to be no more than 50 years, with an average age of 35 years, and with external corrosion the main cause of failure. A more complete survey of corrosion-induced pipeline leakage appears in Ref. 1 for the period 1880 to 1975. However, in that tabulation, only "reportable incidents" are included. These are defined as those that

1. Caused a death or personal injury requiring hospitalization,
2. Required the removal of any segment of pipeline from service,
3. Resulted in gas igniting, or
4. Caused an estimated property damage of $5000 or more.

These data are important because they provide a measure of what might be referred to as the potential for "high hazard" occurrences.

The most widely used pipeline material is steel, accounting for 854,000 miles of the total 1,054,000 miles of mains and services in place as of 1975. Excluding plastic, the next most common material is cast iron, which is used primarily in the older urban systems. Usage of plastic, introduced late in the decade 1961-1970, has continued to gain in popularity, with 94,000 miles in place in 1975, up from 33,000 miles in 1970. Figure 2 is a plot of average annual reportable incidents occurring during the period 1970 to 1975, displayed according to decade of installation, for cases in which external corrosion due to galvanic action was identified as the cause. Such incidents involve steel pipes almost exclusively. A distribution of pipeline mileage, excluding plastic, according to decade of installation is presented in Fig. 3.

Interpretation of Corrosion Statistics

Comparison of Figs. 2 and 3 shows a steadily rising trend in the number of repaired corrosion leaks that roughly parallels the increase in installed mileage through the end of 1950. During the period 1960 to 1975, however, the number of leaks dropped significantly from the peak of the 1951-60 decade. This departure is no doubt a consequence of the finite time required for electrochemical decomposition to bring about perforation of the pipe wall. From the data appearing in Figs. 2 and 3, it should be possible to provide a statistical basis for estimating the probability of a corrosion-related incident, depending on the length of the time the pipe has been buried. Thus, in Fig. 4, values of average annual corrosion incidents for each decade interval, normalized according to the corresponding pipeline mileage and referred to a scale in which one unit equals 1680 miles, are plotted against intervals installed prior to 1975. From this figure, the probability for leak occurrence is seen to rise steadily with increasing pipe age, ultimately reaching unity at 100 years. A reasonably good fit to these data (the solid curve) was obtained by summing a Poisson distribution,[5] with $\epsilon = 4$ and an interval width of 10 years, indicating the most probable age for leak development to be 30 to 40 years, consistent with the data presented in Ref. 4. The implication of this is that, on average, fully matured pipe (older than 50 years) will annually generate a reportable incident for each 1680 miles. Pipes buried 35 years will

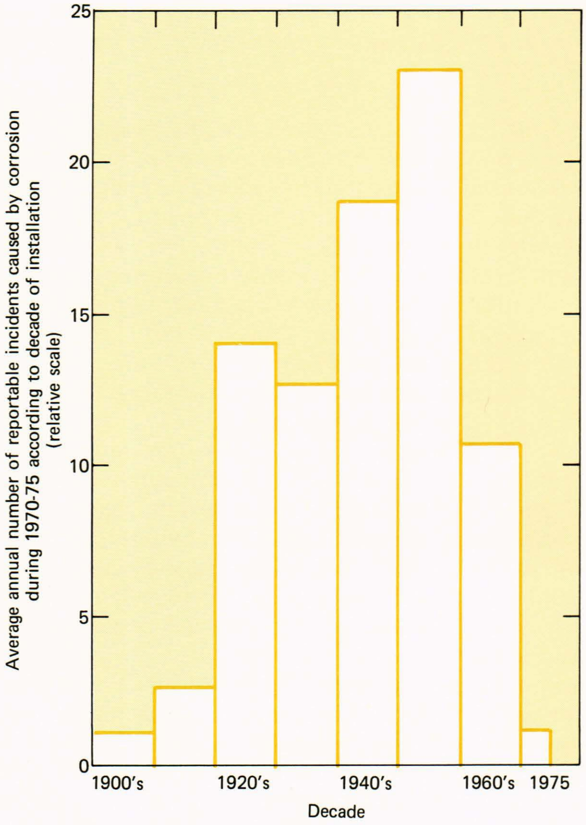

Fig. 2—The distribution of average annual reportable incidents caused by corrosion during 1970-75, according to the decade of installation.

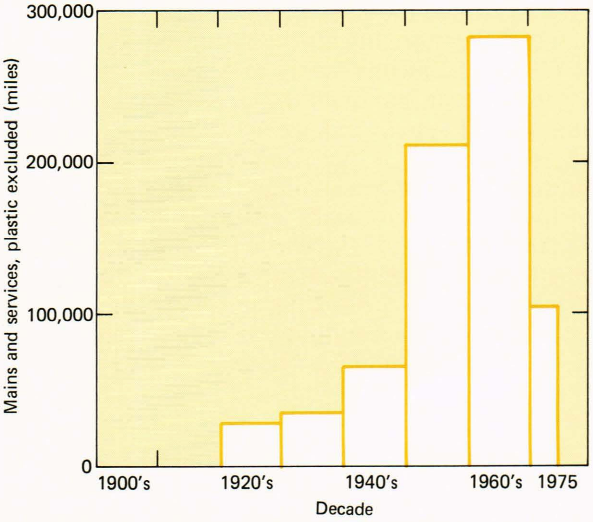

Fig. 3—Distribution of the mileage of mains and services (plastic excluded), according to the decade of installation.

contribute at half that rate while for pipes in the ground only 10 years the rate drops to one-tenth of maximum.

Analysis of data obtained for the totality of cases in which corrosion-induced leaking occurred[6] indicates a statistical distribution essentially the same as that used to interpret the reportable incident data. The only difference is that now the unit of distance involved in normalization drops from 1680 to 0.80 miles. This means that for a fully matured pipe, the expectation is that a leak will appear annually every 0.80 mile. It is clear that a "high hazard" corrosion-generated leak is a relatively rare event, amounting to only one out of every 2000 occurrences. This, interestingly enough, is in accord with results presented in Ref. 6. However, the fact that such high hazard events are distributed with the same relative statistical probability as those of more benign character has to be regarded as significant. One obvious interpretation is that a leak that under most circumstances would be routine may be transformed into one of high hazard by appropriate external conditions. A striking example consistent with this view appears in a recent bulletin released by the National Transportation Safety Board[7] describing an explosion and fire that destroyed five buildings in London, Ky., in which the cause was identified as ignition of natural gas that had leaked from a corrosion hole in a nearly 50-year-old pipe when the gas company made a quick, one-step increase in pressure. In addition to the safety aspects of the leakage problem, as reflected in the reportable incident data, a very important additional factor involves economic considerations centered around the value of the gas lost.

One of the more interesting results emerging from the Office of Pipeline Safety data analysis presented in Ref. 6 is that, although the larger utilities conduct some sort of system leakage survey at regular intervals, the practice is far from universal. A further significant finding presented in this document is that the total number of leaks repaired increased from 533,000 in 1971 to 749,000 in 1975, an increase of roughly 50%, which, extrapolated to the decade 1971-80, suggests a doubling in this period, consistent with a recent account of leak repair experience of the Baltimore Gas and Electric Co.[8]

Future Projections

A prerequisite to the meaningful forecasting of future events is a reduction of past behavioral patterns to some physically realistic statistical basis. The probability function appearing in Fig. 4 would seem to provide an acceptable basis in this regard. As pointed out in the earlier discussion, the distribution of leaks according to pipe age, both in the overall and high hazard categories, appears to be consistent with this observation, with only the scale factor being different. Accordingly, this analytical description may be applied in both cases as a virtual time machine with which one can project backward as well as forward in time. In Fig. 5, the total annual number of estimated leaks is plotted as a function of year during the period from 1950 to 2025, normalized to unity in

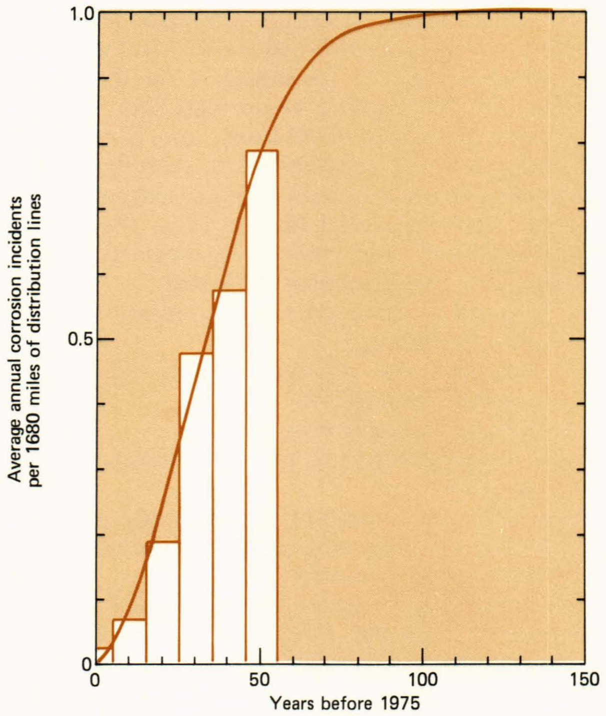

Fig. 4—The average annual number of normalized corrosion incidents according to years installed prior to 1975. The curve through the data was calculated assuming that the leak probability follows a Poisson distribution.

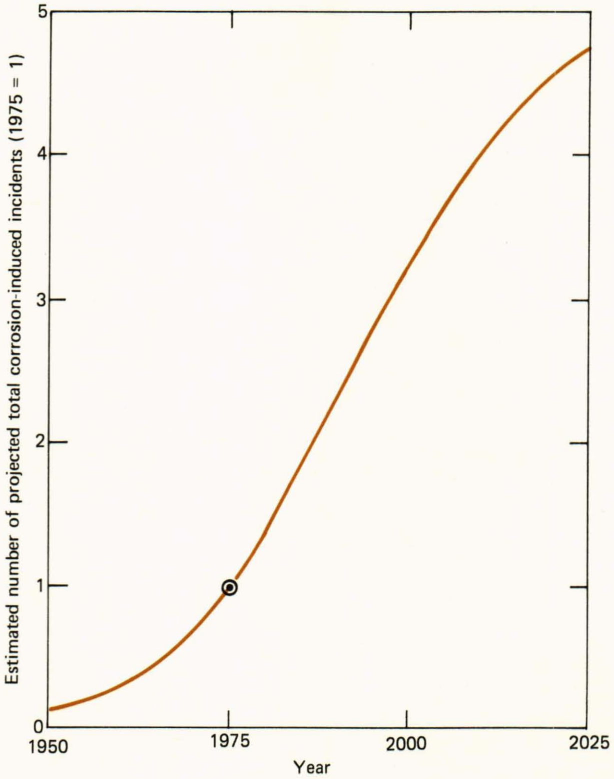

Fig. 5—The relative number of corrosion-induced incidents projected to the year 2025. The 1975 value is taken as unity.

1975. In making this calculation, the distribution of pipeline mileage as a function of decade of installation was taken to be that appearing in Fig. 3, with the restriction that no additional mileage was installed after 1975. Furthermore, only steel pipeline was considered, so that the projection appearing in Fig. 5 applies solely to corrosion incidents.

Referring to Fig. 5, we see that the number of leaks increased by a factor of five, from 0.2 unit in 1950 to 1.0 in 1975, and is expected to increase to 3.6 by the year 2000 and ultimately to 4.7 by 2025. Obviously, ratios are not always the most meaningful indicator. This is made clear by noting that in 1985 the increase in annual number of leaks systemwide over 1975 will be the same as the total increase over the 25-year period from 1951 to 1975 and that similar increases will appear well into the next century. The economic significance of this is somewhat alarming. According to Ref. 6, the total number of corrosion leaks repaired in the system amounted to 300,000, which (applying an average cost of \$300 per repair) cost approximately \$100 million. By 1985, this number will increase to \$200 million without inflation, or more realistically, to \$300-400 million with inflation. Thus, by the year 2000, the expectation is that the cost of repairing corrosion-induced leakage will be close to a billion dollars. This, unfortunately, is not the only economic factor to be considered, because the value of the gas lost must also be included, particularly in view of the trend of price per thousand cubic feet, which increased from an average retail level of \$0.70 in 1970 to \$2.80 in 1980, with additional future rises expected.

Similar expectations apply to the future increase in "high hazard" incidents, which are projected to increase by a factor of roughly four by the year 2000 and five by 2025. Using the scale factor developed earlier, this means that for a utility with 7000 miles of distribution lines, about four major incidents will occur annually by the year 2000, whereas the expectation in 1975 is perhaps one per year or less. The economic importance of these events cannot be ignored; although they are relatively infrequent, the cost per event is clearly several orders of magnitude higher than the cost of a routine leak repair. Moreover, the indirect cost resulting from adverse consumer reaction should not be underestimated.

HISTORICAL OVERVIEW OF ACOUSTIC LEAK DETECTION TECHNIQUES

A brief historical search indicates that the first attempts to develop improved methods for leak detection using acoustic techniques appeared in the 1930's. It was in that decade that three publications[9-11] appeared in addition to Ref. 4. In accord with the statistical picture developed above, pipes installed during the late 1880's would have already attained by then the 30 to 40 years of age required for the appearance of significant leakage. Further interest in the problem did not appear until approximately 20 years later.[12,13] As in the earlier work, the effort was confined to a listening or passive approach.

The first systematic attempt to develop an improved means of leak detection combining both active and passive approaches was initiated late in 1950 and continued through 1965. That effort was supported by the American Gas Association (AGA) with the technical work being carried out at the Institute of Gas Technology (IGT). A record of progress in developing an operational system is contained in two publications.[14,15] Reference 15 is particularly significant because it presents a summary of the results of extensive field testing involving six major gas utilities. One noteworthy statement appearing in this summary has to do with difficulties involved in transfer of technology to operating people who were largely unskilled in the use of the electronic instrumentation employed. This same point was raised earlier[11] in efforts to use a geophone for leak detection: "Thus far the best results have been obtained from operators who have had some college training along engineering lines." Although some success in leak location using the IGT approach was achieved, the system was not considered to be sufficiently reliable for an effort to be made to replace the time-honored technique of "barholing." Analysis of the results of the extensive field measurements data indicated that the main problem was the unpredictable performance of the system, coupled with an inability to predict quantitatively the chance of success or failure in a given situation.

THE APL PROGRAM

Thus in May 1975, a research program was initiated at APL at the request of the AGA to investigate, from a fundamental point of view, factors of importance in the operation of an acoustic leak detection system. This program was funded through May 1978 by AGA and from that time through December 1979 by the recently formed Gas Research Institute. A general discussion of the physically important results emerging from this work is presented in the following account. A comprehensive review of the overall program, along with details of the experimental and theoretical methods developed and results obtained, appears in a recent publication.[16]

The stated objective of the APL program, from its inception, has been to undertake the necessary fundamental research (both theoretical and experimental) to identify factors of major importance in the operation of a system of active acoustic leak detection and then to investigate in detail the interrelation of these factors. Such a program would provide a systematic basis on which to optimize the effectiveness of the system as a whole. Reasons for considering only an active method are partially evident in the previous discussion of the various passive techniques used earlier, combined with the results of controlled experiments carried out at APL in which the spectrum of noise emitted by a 1/64-inch orifice located approximately 2 feet below ground level was recorded as a function of supply pressure by an accelerometer located on the surface directly overhead. Although elevated levels are apparent when the supply pressure was increased from atmospheric pressure to approximately 2 atmospheres overpressure, there is no recognizable change in the spectral pattern or signature that could be used to categorize the output *a priori* as resulting from the presence of a leak, in addition to the background spectrum. This is true even though the measurements were carried out at a relatively isolated location where the ambient noise was minimal. Use of a listening technique is thus complicated by the following dilemma. If one couples a sensor (such as a microphone) to the gas inside the pipe,(4,9-13) leak-generated noise is clearly audible because the magnitude of ambient noise in the external soil is rendered negligible by high transmission loss through the pipe walls. However, precise determination of leak location is impossible without entry into the pipe using a system described in Ref. 12; this is not practical for a line with numerous changes of direction, bends, etc., which is generally the case. On the other hand, if one uses detectors external to the pipe (e.g., a movable accelerometer located on the surface), the level of ambient soilborne interference is large, and the magnitude of the leak-generated signal is small as a result of relatively poor coupling to the soil.

All of these considerations contributed to the final decision to confine the approach to the use of an active diagnostic. The essential gain to be achieved by use of an active acoustic system is that, through the use of correlation, a large improvement in the ratio of an acoustic signal, S_A, to noise, N, may be achieved. In general, the detector provides a total signal

$$S_D = S_A + N, \tag{1}$$

in which the acoustic signal frequency, f, is known exactly. However, the phase is not; i.e.,

$$S_A = A_1 \cos(\omega t + \phi_1), \tag{2}$$

where $\omega = 2\pi f$. The signal or voltage used to excite the acoustic signal is

$$S_E = A_0 \cos(\omega t + \phi_0). \tag{3}$$

Correlation, C, of S_E with S_D operationally involves summing the product $S_E S_D$ over a time interval, T, and then averaging the result. Thus

$$\begin{aligned} C &= \int_0^T \frac{S_E(t) S_D(t)\,dt}{T} \\ &= \frac{A_1 A_0 \int_0^T \cos(\omega t + \phi_1)\cos(\omega t + \phi_0)\,dt}{T} \\ &\quad + A_0 \frac{\int_0^T N(t)\cos(\omega t + \phi_0)\,dt}{T}\,. \end{aligned} \tag{4}$$

Since $N(t)$ has its origin in sources both seismic and electronic in nature that differ from S_E in an unpredictable fashion, the second term on the right side of Eq. 4 tends to zero as T steadily increases, leaving only the first term, which may be integrated to give

$$C = \tfrac{1}{2} A_1 A_0 \cos(\phi_1 - \phi_0), \tag{5}$$

independent of T. Thus, the longer the integrating time, the higher the signal-to-noise ratio (S/N) of the processed signal, with the result that signals with very small initial S_A/N can be detected easily.

The next major issue in formulating the program was to decide exactly what is meant by a leak. It is clear that a hole in the pipe wall by itself is not sufficient. The final definition adopted was that a leak must be responsible for loss of gas from the distribution system and as such must consist of a leak path extending to the surface in addition to a pipe-wall perforation. A hole newly developed as a consequence of a relatively long period of external corrosion may ultimately develop into a leak as an external path develops slowly in response to either the increase in pressure in the surrounding soil caused by the gas pressure buildup, or (more suddenly) to soil movement caused by nearby excavation or freeze – thaw and wet – dry cycles accompanying seasonal weather change.

Viewed in general terms, the technique of active acoustic leak detection involves remote excitation of the gas contained within a buried pipeline network in the form of pressure oscillations that propagate throughout the system. This alternating gas pressure is coupled to the external soil medium either indirectly through radial displacement of the pipe walls in the case of an unperforated pipe or directly through any existing holes in the pipe walls. This acoustoelastic coupling results in the excitation of radiation in the form of both compressional and shear waves. Reflection of these elastic waves from the surface gives rise to displacements that may be detected by means of conventional accelerometers or optically by using laser interferometry. The problem thus posed is this: given knowledge of such surface displacements, what can be deduced as to the condition of the pipeline beneath?

All information gained involves transmission through the intervening soil medium. Thus it is clear that meaningful interpretation of surface displacement measurements must involve a full and fundamental understanding of the characteristics of this medium. Much information exists in the literature regarding compressional and shear wave propagation at low frequencies (less than 100 hertz) involved in seismic exploration of regions ranging to depths of hundreds of feet below the earth surface. However, data applying to the layer within 10 feet of the surface, characterized by rather loosely compacted soil, are rather sparse and highly variable.

For example, although individual measurements of compressional and shear velocities in both sandy and clay soils are reported both *in situ* and in the laboratory, there exists no case in which both shear and compressional wave velocities have been measured simultaneously. Moreover, the matter of attenuation is even less well understood. The question as to the relative magnitudes of shear and compressional wave propagational losses and their possible interrelationship is a virtually unexplored area.

DEVELOPMENT OF THE PROGRAM

In order to achieve a sense of realism, it was required that an underground pipeline of the proper age, size, material of construction, and burial depth be located and used as the central laboratory. Fortunately, an abandoned water line was located on APL property that had the desired characteristics: 25 years old, 2 inch ID × 2⅜ inch OD steel at a depth of 30 to 36 inches. This line is indicated in schematic form in Fig. 6, zigzagging its way from well house 8 to well house 7, a total distance of approximately 1000 feet. The point of initiation of the acoustic signal is well house 8, with a horn driver of the type used in public address systems as the means of excitation. Power to the driver is fed from a trailer located approximately 150 feet along the line toward well house 7, as indicated in Fig. 6.

Operationally, the research plan, which combined a program of experimental measurement with a parallel theoretical effort, proceeded in three discrete phases. In the first, the characteristic behavior of earth-surface displacement generated by excitation of acoustic waves within the buried pipe in the absence of a hole was investigated in detail, using both pulsed and continuous-wave (CW) methods. The second phase involved an investigation of the effect of introducing a rather large hole in the top of the pipe. In the third, the effect of an external leak path coupled to the pipe interior through a relatively small hole was examined.

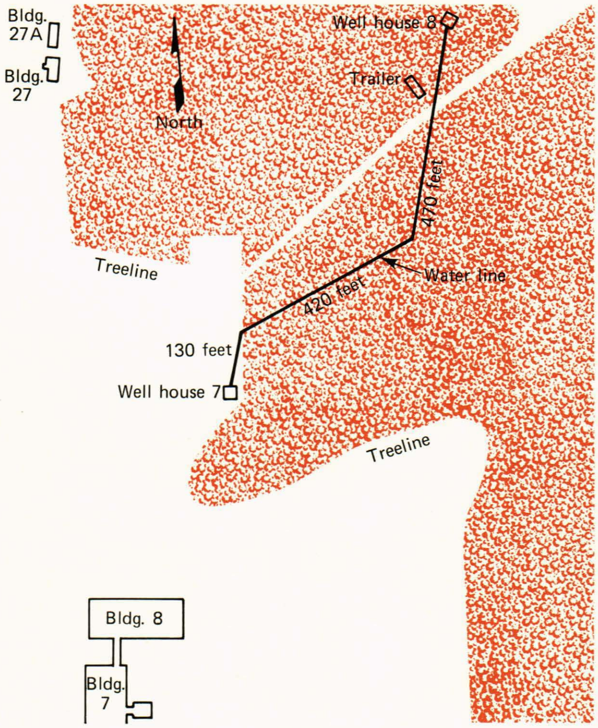

Fig. 6—A schematic representation of the APL experimental pipeline facility. The acoustic driver is located in well house 8, and associated instrumentation is in the trailer.

Phase I (Pulse)

Initial exploratory measurements indicated that sizable accelerometer outputs accompany excitation of the acoustic driver and that these signals originate from the buried pipe. It was recognized at the outset that two possible propagation paths existed, one provided by the gas within the pipe (which in the experiments described here was air), and the second consisting of the steel walls of the pipe. The most direct way to resolve this uncertainty was to time the arrival of a short pulse excited by the driver and thus determine the velocity of propagation. For air at a temperature of 20°C, the velocity is of the order of 1140 feet per second (ft/s)—340 meters per second—and for steel, it is much higher—16,000 ft/s. Thus, with the accelerometer located 122 feet from the source, a pulse in the form of a one-cycle sinusoid, 1.67 milliseconds (ms) in duration, was initiated by the driver. The resultant accelerometer output consisted only of a single event,[17] a pulse that arrived after a delay of 113 ms and persisted for an interval of approximately 20 ms. From this, the propagation velocity is determined to be 1080 ft/s, which is approximately the value expected for air. The pulse lengthening has been observed on numerous subsequent occasions and is probably due to a damped oscillation of the accelerometer mass against the soil compliance.

Theory indicates propagation of the acoustic wave in the gas within the pipe with phase velocity c_0 to be accompanied by compressional and shear waves, propagating at velocities α and β, respectively, in the surrounding earth medium at angles θ_c and θ_s with respect to the pipe axis, as indicated in Fig. 7. Thus,

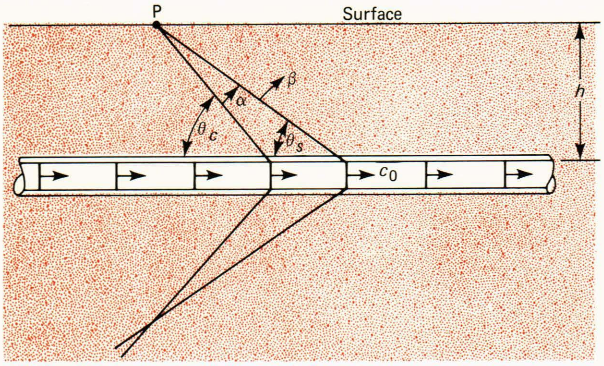

Fig. 7—A diagram showing elastic wave propagation in the earth accompanying the passage of an acoustic wave in the gas within a buried pipe. The compressional wave velocity in the surrounding earth is designated as α and that of the shear wave velocity as β.

for example, when the soil-borne compressional wave arrives at point P on the surface, the wave front within the gas has passed beyond by a distance

$$\delta_c = h \cot \theta_c, \tag{6}$$

where θ_c is given by

$$\theta_c = \sin^{-1}(\alpha / c_0). \tag{7}$$

For the shear wave propagating with a slower velocity, δ is larger and thus the first arrival will be the compressional wave. If P is located at distance ℓ from the acoustic source, the total time required for the disturbance to arrive at P is

$$t_A = \frac{\ell + \delta_c}{c_0} = \frac{\ell}{c_0} + h\left[\left(\frac{1}{\alpha}\right)^2 - \left(\frac{1}{c_0}\right)^2\right]^{1/2}. \tag{8}$$

Substitution of the numbers appearing above gives $\ell / c_0 = 107$ ms, which is significantly less than the 113 ms observed. The difference obviously is due to the time required to travel the additional distances δ_c which, taking $h = 30$ inches, leads to $\alpha = 390$ ft/s (which, in view of the obvious uncertainty in estimating the arrival time, has to be regarded as approximate).

In order to establish more accurately the propagation velocity within the soil, a series of similar measurements was carried out in which different source accelerometer separations were used; the results appear in Fig. 8. The corresponding arrival times, t_A, including that given above, are summarized in Fig. 9. A least-squares linear fit to the data gives

$$t_A \text{ (milliseconds)} = 7.03 + 0.8672\,\ell, \tag{9}$$

with a probable error in intercept of 1.75 and 0.0153 in slope. Using these values, we thus determine that $c_0 = 1153$ ft/s and $\alpha = 357$ ft/s.

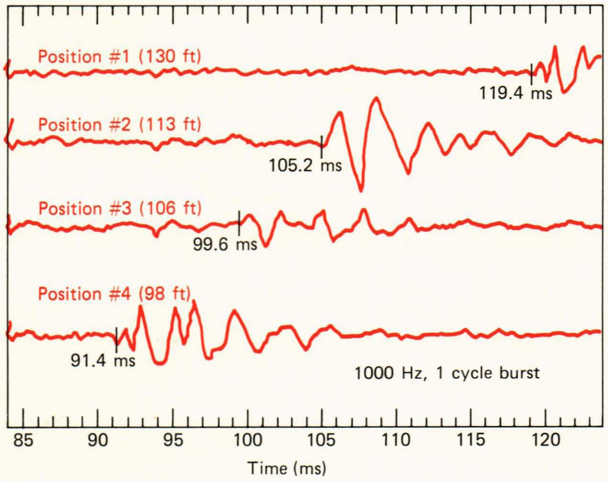

Fig. 8—The response of a surface-mounted accelerometer to one cycle of a sinusoid of period 1 ms excited by the driver. The signal arrival time is clearly dependent on the distance between the source and the accelerometer separation.

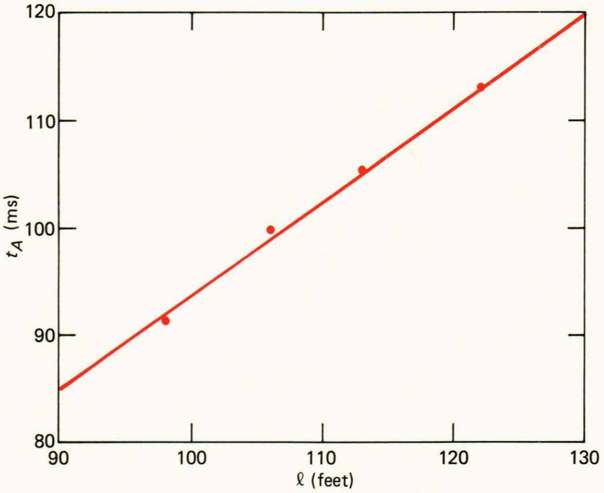

Fig. 9—The dependence of arrival time indicated in Fig. 8 on source–accelerometer separation. The straight line represents a least-squares linear fit to the data.

One interesting feature of the data appearing in Fig. 8 is the rather erratic trace-to-trace variation in the amplitude of the received signals. A similar spatial fluctuation in measured levels of surface acceleration was also experienced in carrying out a subsequent series of CW measurements. Data in the latter case were characterized by variations that were particularly pronounced at high frequencies to the extent that, at some locations, there was virtually no signal. After considering numerous possibilities, it was decided that the existence of these variations could only be accounted for by the presence of large rocks between the pipe and surface that at high frequencies could produce a substantial screening, while at low frequencies sufficient diffraction occurred to moderate the screening significantly. This conclusion was confirmed in subsequent excavation by correlating the positions of large rocks and boulders as they were unearthed with the observed pattern of surface displacement variation.

Phase I (Continuous Wave)

The first sequence of CW measurements involved a determination of the dependence of earth-surface acceleration on frequency at a point directly over the pipe and approximately 120 feet from the source. In carrying out these measurements, the level of current into the driver was adjusted at each frequency to provide a constant sound-pressure level as recorded by the monitoring microphone. This level was arbitrarily set at 2×10^4 dynes per square centimeter, which corresponds to a driver acoustic output of approximately 10 watts. A typical run involved recording microphone output as a function of frequency. A series of peaks and dips superposed on a generally decreasing output was observed (Fig. 10) as the frequency was increased in successive steps from 200 to 2000 hertz. Reduction in average signal level with increasing frequency is a consequence of three major factors: (a) loss in propagation through the gas

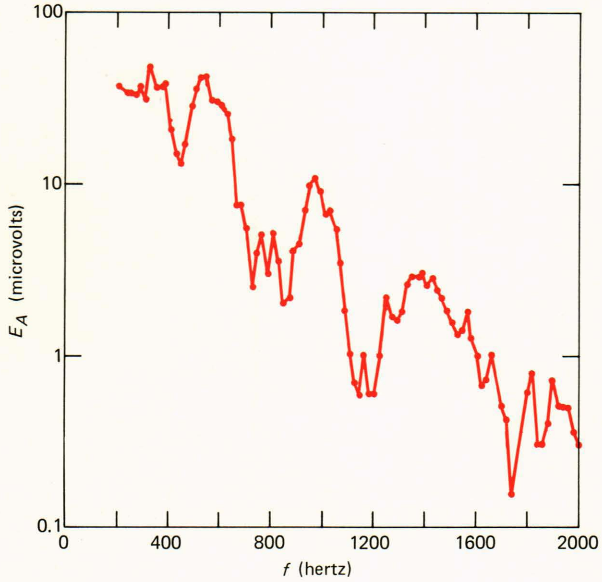

Fig. 10—Dependence of the accelerometer output on the frequency for a source – detector separation of approximately 120 feet. The peaks and dips evident in the figure are caused by interference between the compressional and shear components of the acoustically induced elastic wave radiation from the pipe wall. This radiation is from an unperforated section of pipe and presents a coherent background interfering with leak-related signals.

within the pipe resulting from interaction with the walls; (b) loss in propagation through the soil from pipe depth to the surface; and (c) mechanical loading of the earth by the accelerometer.

The series of peaks and dips results from the fact that both compressional and shear waves are generated by pipe wall displacement accompanying the internal acoustic pressure oscillations in the air within the pipe. Generation of compressional waves is a direct consequence of pipe wall radial displacement, which causes the contacting soil to be alternately compressed and expanded. Excitation of shear waves, on the other hand, is due to two simultaneous effects. The first is caused by the couple established in the soil by the combined action of soil compression at an acoustic maximum and the accompanying expansion at the minimum located at a distance of a half wavelength (in the gas). The second source of shear excitation is apparent if one takes into account the longitudinal displacement of the pipe walls accompanying radial expansion and contraction. A section of pipe undergoing outward radial exapansion is subjected to an axial strain, the magnitude of which depends on the Poisson ratio for the particular material. Expressed simply, there will be a longitudinal wall displacement toward an internal acoustic pressure maximum and associated pipe wall circumferential stretch and, conversely, away from a minimum. This action is indicated schematically in Fig. 11.

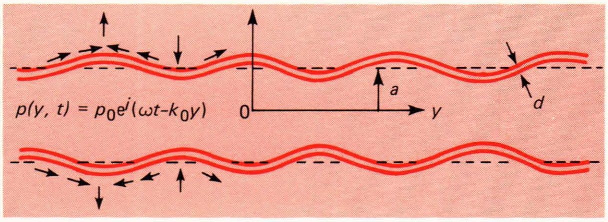

Fig. 11 — Schematic representation of the radial and longitudinal displacement of the pipe wall generated by internal acoustic-pressure variation.

Application of theory indicates the amplitudes of the radiated compressional and shear waves to be comparable. In view of the fact that shear wave propagation is considerably slower than compression, this leads to the prediction that the resultant earth-surface displacement should exhibit a variation with changing frequency as the two components are alternately in and out of phase with each other. A further consequence of this difference in propagation velocities is that the angle at which the respective waves approach the surface will be different, with the angle of incidence of the slower shear wave lying closer to the normal, as shown in Fig. 7.

A final series of measurements involved an investigation of the variation of signal level produced by positioning the accelerometer at various surface points along a path transverse to the pipe axis. A rather sharp maximum was observed at a point directly above the pipe, as indicated in Fig. 12, suggesting that measurements of this type would be quite useful in determining pipe location in any field application.

Phase I Summary—It has been established that a sizable surface displacement results from the remote acoustic excitation of the gas within an unperforated underground pipe and that the propagation path involves only the gas within the pipe and surrounding soil, with the effect of any coupling to the pipe walls being negligible. Propagation in the soil caused by this pipe "wall radiation" involves both compressional and shear waves of comparable amplitude traveling in unison with the wave front existing in the pipe interior. A consequence of the slowness of the

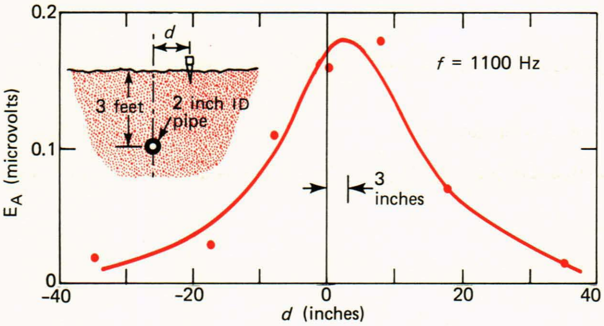

Fig. 12 — Plot of accelerometer output versus transverse distance from a point assumed to be directly above the pipe axis. The maximum in the curve averaged through the data indicates that the pipe axis is shifted 3 inches to the right, in agreement with the results of subsequent excavation.

shear waves relative to compression is that the two components interfere, producing rather large variations in surface displacement as the frequency is varied. The presence of inhomogeneities in the soil in the form of large rocks was found to be important in screening the surface from radiation below. The existence of wall radiation clearly provides an obstacle to the detection of signals generated at holes in the piping. However, on the positive side, it is clear that this provides a means of pipe location under certain circumstances, although it can present problems (e.g., under paving).

Phase II

The next step in the research plan was to investigate the characteristics of radiation produced by acoustoelastic coupling from within the pipe through a hole to the surrounding soil medium. In order that this radiation be of sufficient magnitude to exceed the level of wall radiation, it was clear that a rather large hole was necessary. Ultimately, a ¾-inch hole diameter was decided upon as being the maximum possible size without impairing the structural integrity of the pipe. To provide a test medium of reasonable homogeneity to avoid the problems described above, a 35-foot section of the pipe near well house 8 was excavated and then backfilled with 70 tons of sand. This excavation, displayed schematically in Fig. 13, was 6 feet in width and 6 feet in depth, with the pipe running approximately through the center (i.e., 3 feet below the surface). Attainment of free-field conditions was ensured by the existence of relatively large attenuation, which reduced reflections from the sand-clay soil boundaries to negligible levels.

Preliminary measurements obtained in July 1977 before and after drilling the hole indicated substantial elevation in surface displacement at points directly above the hole. However, it was recognized that these results could only be regarded as tentative until the sand had a chance to settle and become thoroughly compacted. Most of the effort in late 1977 and early 1978 was directed toward the development of a rapid-scan minicomputer-based data acquisition and analysis system. Development of this system was necessitated by the long period of time required in manual data-taking (which amounted to more than an hour per location). This obviously precluded the possibility of conducting either an areal or linear survey. The effort culminated successfully with the first detailed surface survey over the pipe carried out in June 1978. With the data acquisition time reduced to 2 to 3 minutes per point, the time required to survey 30 points at 1-foot separation amounted to approximately 2 hours. In developing the rapid-scan system, it was decided to provide a capacity not only for amplitude movement but also for phase (more specifically, differential phase).

One of the interesting aspects of phase data is the fact that, since other long transmission paths are involved, large differences exist in the relative phase of detector and driver. This, of course, is caused by the correspondingly large propagation time. Thus, in the pulse measurements described earlier for which a source-detector separation of 122 feet was used, the arrival time, t_A, amounted to 113 ms. The phase of the delayed arrival relative to that at the point of excitation is $\phi = 2\pi f t_A$ expressed in radians. Clearly, large total phase magnitudes are involved, e.g., for frequency $f = 1000$ hertz, $\phi = 226$ radians or 40,680 degrees. Differential phase

$$\frac{d\phi}{df} = 2\pi t_A, \tag{10}$$

on the other hand, being the phase shift per unit change in frequency, amounts to 0.226π or 41 degrees. Determination of differential phase was found to be a very useful means for deciding whether electrical interference was adversely affecting accelerometer output because, for such interference, the corresponding phase shift was extremely small.

Frequency-dependent phase shifts may also appear in other parts (driver, pipeline, soil, accelerometer) of the overall acoustic detection electronics system. In the pipeline-soil system, excluding the large shift caused by propagation delay, phase shifts resulting from loss-related dispersion effects in the gas and earth will be present. Accelerometer response and mechanical coupling to the earth will also produce phase shifts, as will the subsequent electronic detection and amplification system. However, the change in phase per unit change in frequency, $d\phi/df$, will be very small in these cases. This leads to a very interesting and intriguing conclusion: the only way in which $d\phi/df$ can be affected is through the presence of signals that are delayed by relatively long propagation times.

In carrying out the survey described above, measurements of accelerometer output directly above the pipeline, with the output of the acoustic driver held at a fixed level, were obtained over the frequency range from 1 to 2 kilohertz and recorded on either tape or flexible disk. These measurements were confined entirely to the sand-filled section of the pipeline

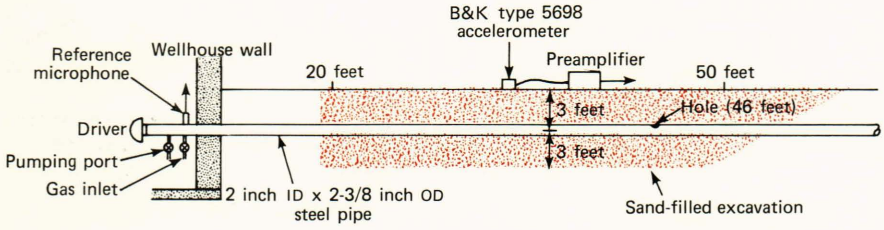

Fig. 13—Schematic diagram of the sand-filled excavation used in carrying out surface accelerometer surveys, indicating the relative positions of the acoustic driver and the reference microphone. The hole, located 46 feet from the microphone, was involved in the data discussed in the text.

and were repeated at separations of 1 foot over the interval of 20 to 50 feet from the monitoring microphone. As indicated earlier, both amplitude and differential phase data were recorded.

Values of amplitude data averaged over the entire frequency band are plotted in Fig. 14 as a function of distance from the monitoring microphone. Increases in these values above the average wall radiation level (5 to 10 microvolts) are apparent over the interval 28 to 34 feet and also 43 to 49 feet. Since the hole is located at 46 feet, the latter interval is expected; however, the former is not. It is clear from this figure that if amplitude data were the sole criterion for determining the leak location, a significant false alarm problem would exist.

Figure 15 contains a plot of differential phase, $d\phi/df$, similarly frequency averaged, again plotted as a function of reference microphone – accelerometer separation. Also superimposed on this plot as a dashed curve are the corresponding values of averaged amplitude data. The line drawn through the data is described by

$$\frac{d\phi}{df} = 2.40 + 0.318\,\ell, \tag{11}$$

expressed in degrees/hertz with ℓ in feet. To facilitate comparison with the pulse arrival time data appearing in Fig. 9, we modify Eq. 11, using Eq. 10, to read

$$t_A = 6.67 + 0.8833\,\ell, \tag{12}$$

expressed in milliseconds, which is close to the results summarized in Eq. 9.

Examination of Fig. 15 indicates two locations where the dependence of $d\phi/df$ on ℓ departs significantly from the linear behavior characteristic of wall radiation. The first, in the 20 to 24 foot range, probably results from propagational effects occurring at the interface of the undisturbed clay and sand-filled regions. The second is observed to coincide approximately with the position of the hole at 46 feet; however, it is obvious that the deviation is not symmetrical about this point. Reasons for the lack of symmetry are discussed in Ref. 16.

It is important to note that in the 28 to 34 foot interval, where significantly elevated amplitude levels were observed, there is no significant phase anomaly. Conversely, in the 20 to 24 foot region, there exists a phase anomaly but no unusual amplitude variation. Thus, coincidence of both amplitude and phase anomaly appears to be a useful criterion for reliable hole location.

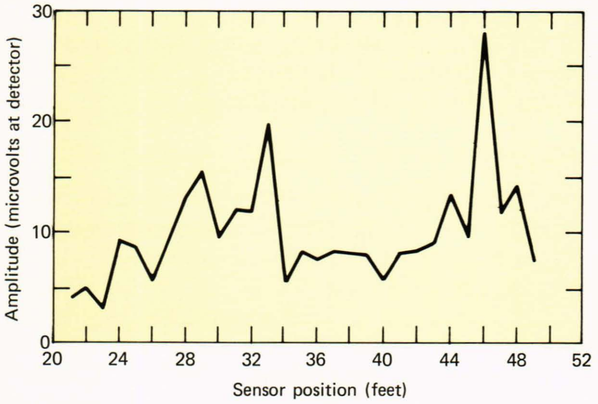

Fig. 14—The variation of frequency-averaged accelerometer output as a function of distance from the reference microphone.

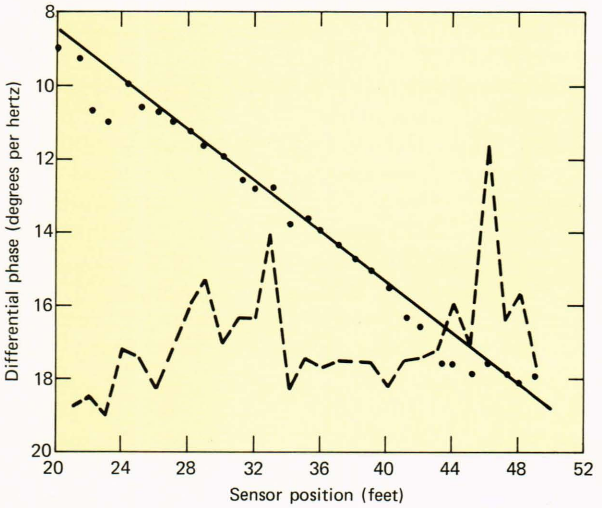

Fig. 15—The averaged differential phase, $d\phi/df$, plotted as a function of distance from the reference microphone.

Phase II Summary—It is clear that detection of holes in underground piping using an active acoustic approach cannot rely simply on a measurement of the amplitude of surface displacement. In the case investigated here, the usefulness of differential phase as a means of rejecting false amplitude indications is apparent. An impressive feature of the data is the importance of wall radiation, even in the case of the rather large ¾-inch diameter hole used. Directly above the hole, the level of surface displacement exceeds the average value caused by wall radiation by roughly a factor of four. Since theory indicates that the level of radiation from a hole varies as the cube of the hole radius, this means that the wall radiation is essentially equal to that from a ½-inch diameter hole. Thus, unless some means to discriminate against wall radiation is developed, an active acoustic system of leak detection is only capable of sensing the presence of relatively large holes in the pipe walls. It is obvious from Fig. 7 that a detector that could sense only signals incident normally to the surface would possess the characteristic required for the elimination of wall radiation. One possible method of achieving such directionality is by using an array of transducers wherein the output of each individual element may be electronically phased to produce the desired angular sensitivity. Preliminary attempts using such an approach have been initiated from which it is clear that the problem is not nearly as straightforward as in the simple acoustic case in which shear is absent and only pressure waves need be considered.

Phase III

The objective of this series of experiments was to carefully measure the earth surface displacement that accompanies radiation from a simulated leak path and, in particular, to compare the experimental values with calculation from theory. To simplify such comparison, a vertical orientation of the leak path was chosen. The simulation was achieved through use of a section of soft ⅛-inch ID × 3/16-inch OD Tygon tubing, 2 feet in length, that was fitted over a tapered nipple extending from a specially machined plug threaded into the ¾-inch diameter hole used previously (Fig. 16). Because the pipe depth was 3 feet, the top of the leak path was 1 foot below the sand surface. This was necessary to ensure that signals reaching the accelerometer were propagated through the sand and not through the atmosphere.

Frequency dependence of the accelerometer output directly above the leak path is shown as the solid curve in Fig. 17 and also at a point displaced 5 feet toward the driver (broken line), sufficiently far removed that only wall radiation is important. One striking feature of the data obtained directly above the leak path is the appearance of a series of peaks separated by approximately 300 hertz that are most pronounced at lower frequencies and that substantially exceed the level of wall radiation. These peaks are caused by resonant excitation of the leak path at frequencies for which coupling to the acoustic pressure field in the main pipe is maximal. Values of accelerometer output calculated from theory appear as the dash-dot curve in Fig. 17. It is clear from this comparison that, over the entire frequency interval investigated, theory and experiment are in good agreement.

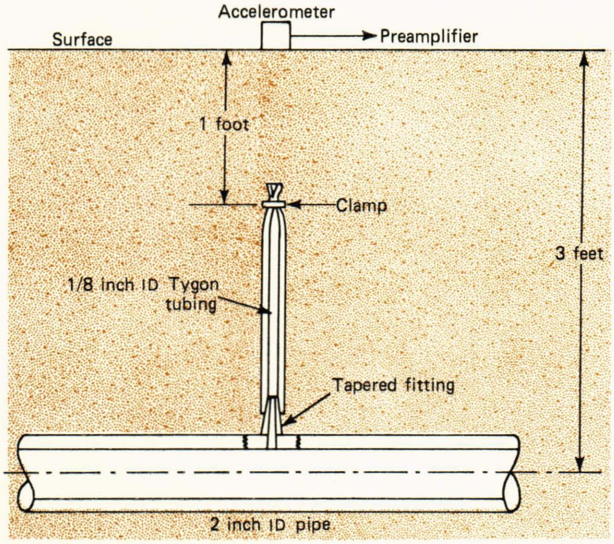

Fig. 16—Diagram of the experimental arrangement used in simulating the effect of acoustic coupling into an external leak path through a relatively small hole in the pipe wall. The simulated leak path consists of Tygon tubing, 2 feet in length, fitted over a tapered fitting screwed into the top of the pipe.

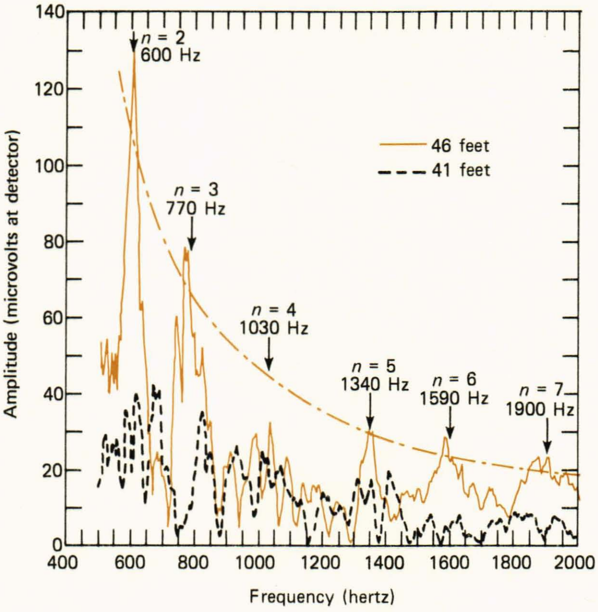

Fig. 17—The dependence of accelerometer output on frequency at a point directly above the vertically oriented leak path and at a point 5 feet away, far enough removed so that only wall radiation is significant. The values of the accelerometer output calculated from theory for each of the successive quarter-wave resonances in the external path fall on the indicated curve.

Phase III Summary—It is clear that leak path radiation provides an indication of the presence of holes in the pipe that could not be detected by radiation from the hole by itself. The investigation described in the preceding section indicates the level of radiation measured directly above a ¾-inch diameter hole to be approximately four times the average wall radiation level. Since the amplitude of hole radiation scales as the cube of the hole radius, this means that the level of radiation from a ⅛-inch diameter hole would amount to approximately 2% of the level of wall radiation. However, the experimental fact is that, through coupling of acoustic energy into an external leak path, the resultant radiation, particularly under conditions of resonance, may greatly exceed wall radiation. In a certain sense the leak path may be considered an acoustic antenna.

CONCLUSION

Considerable progress has been made in establishing a fundamental basis for assessing the effectiveness of an operational leak detection and location system using active acoustics as a diagnostic. Most importantly, the general agreement experienced between calculation based on the theory developed and the experimental data obtained serves as validation of the underlying fundamental hypothesis in which it is assumed that soil is basically a tractable elastic medium and as such is amenable to quantitative description using established elasticity theory. The theory developed is a hybrid that describes the coupling of acoustic waves propagating in the pipe interior with the elastic compressional and shear wave radiating into the external soil medium.

The research has matured to the point where it is now meaningful to draw on theory developed to provide a reliable guide in the formulation of the direction of future research. To date, all the experimental measurements have been confined to the case of a free earth surface. It is obvious that a practical system of leak detection must be able to handle those cases in which an overlayer exists in the form of reinforced concrete or asphalt. Thus, high on the list of priorities for future research is the problem of pavement, a matter that should first be attacked theoretically and only later through a program of directed experimental measurements.

It is hoped that ultimately the results of the research described in this article will be translated into reality in the form of an operational system permitting more rapid and reliable means of leak detection and location. In the course of this work, it has become evident that the problem is far from routine and that much more research remains to be carried out. Results obtained to date are encouraging indeed, inspiring confidence that the ultimate attainment of the goals established initially is a real possibility.

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