AL/EQ-TR-1994-0032

AD-A283 250

ARMSTRONG LABORATORY

LEAK DETECTION BY ACOUSTIC EMISSIONS MONITORING: AN EXPERIMENTAL INVESTIGATION OF THE ACOUSTIC PROPERTIES OF LEAKS AND THE ATTENUATION CHARACTERISTICS OF SOIL

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94-25294

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May 1994

Final Technical Report for Period July 1987 - January 1988

94 8 11 005

AIR FORCE MATERIEL COMMAND
TYNDALL AIR FORCE BASE, FLORIDA 32403-5323

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
27 May 1994

3. REPORT TYPE AND DATES COVERED
Final; SBIR Phase 1; Jul 87 - Jan 88

4. TITLE AND SUBTITLE
Leak Detection by Acoustic Emissions Monitoring: An Experimental Investigation of the Acoustic Properties of Leaks and the Attenuation Characteristics of Soil

5. FUNDING NUMBERS
CF08635-87-C-0377
PE 65502F
JON 30550021

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10. SPONSORING/MONITORING AGENCY REPORT NUMBER
AL/EQ TR 1994-0032

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This study experimentally explored the conditions, equipment, and methodology necessary for the acoustic detection of small leaks of jet fuel (JP4) from underground storage tank (UST) systems. The study indicates that acoustic leak detection of very small leaks is feasible. In general, significant JP4 fuel leaks which occur across a 5 PSI (pounds per square inch) or greater pressure drop are acoustically active and can be detected with proper sensors and proper placement of sensors. The primary source of leak noise is turbulent flow through the leak orifice. At lower pressures, the leak flow becomes laminar, and the leak becomes virtually silent. With direct transducer contact on the pipe or tank wall and sufficient system pressure, leaks smaller than 0.1 GPH (gallons per hour) can be detected. Larger leaks can be detected through short distances in soil. However, sand, which is the most commonly used fill material for UST systems, provides significant acoustic attenuation. Consequently, waveguides must be used when monitoring distances exceeding about 1 foot of travel through sand. Sand acts to reduce background noise levels, providing an ideal environment for acoustic leak detection using sensors mounted directly on the pipe or tank wall.

14. SUBJECT TERMS
Leak detection; acoustics; underground storage tanks; pipelines; attenuation

15. NUMBER OF PAGES
99

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
U	U	U	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev 2-89)
Prescribed by ANSI Std 239-18

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PREFACE

This technical report was originally prepared by Eclectech, Inc., P.O. Box 177, 244 Bus Terminal Road, Oak Ridge, TN 37831-0177, under Contract Number F08635-87-C-0377 for the Air Force Engineering and Services Center. The work was accomplished as a SBIR Phase 1 effort, but the technical report was never published.

This report summarizes work accomplished between 6 July 1987 and 6 January 1988. Mr Hari B. Bindal was then the project manager.

Although the research is over 4 years old and the distribution limitation for SBIR has expired, the report is being published by this Directorate because of its interest to the DOD scientific and engineering community.

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SUMMARY

This study experimentally explored the conditions, equipment, and methodology necessary for the acoustic detection of small leaks of jet fuel (JP4) from underground storage tank (UST) systems. The work is based on an investigation, using modern, computer-based instrumentation and analysis techniques, of acoustic emissions due to water leaks and fuel leaks from 6-inch and 2-inch diameter pipes into a wide range of soil materials. The tests were conducted using a large "soil box." The soil box was equipped with a delivery system which allowed volumetrically measured delivery of fuel to a variety of underground leak conditions over a range of pressures. A number of fill materials, leak types, and acoustic sensing methods were examined. The fill materials included sand, gravel, clay, crushed rock, organic soil, and concrete. The leak types included pin hole leaks, leaks from threaded fittings, leaks from flanged joints, and leaks from hair-line cracks. Acoustic sensing methods included a variety of sensors ranging from custom-designed transducer/waveguide systems to commercially available transducers for leak detection. The sensors were examined for performance as both "through-soil" detectors and for use with direct pipe or tank wall contact.

The results from the study indicate that acoustic leak detection of very small leaks is feasible. In general, significant JP4 fuel leaks which occur across a 5 PSI (pounds per square inch) or greater pressure drop are acoustically active and can be detected with proper sensors and proper placement of sensors. The primary source of leak noise is turbulent flow through the leak orifice. At lower pressures, the leak flow becomes laminar, and the leak becomes virtually silent. With direct transducer contact on the pipe or tank wall and sufficient system pressure, leaks smaller than 0.1 GPH (gallons per hour) can be detected. Larger leaks can be detected through short distances in soil. However, sand, which is the most commonly used fill material for UST systems, provides significant acoustic attenuation. Consequently, waveguides must be used when monitoring distances exceed about 1 foot of travel through sand. Sand acts to reduce background noise levels, providing an ideal environment for acoustic leak detection using sensors mounted directly on the pipe or tank wall.

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TABLE OF CONTENTS

TABLE OF CONTENTS (CONCLUDED)

LIST OF FIGURES

LIST OF FIGURES (CONCLUDED)

LIST OF TABLES

GLOSSARY OF TERMINOLOGY

Accelerometer - A transducer designed to sense vibration in solids.

Acoustic Attenuation - Decrease in amplitude and energy content of sound as it travels. Usually expressed in units of decibels per unit length.

Acoustic Emission (AE) - Sound arising from material failure, leaks, friction, etc. Typically refers to ultrasonic sound.

Acoustic Impedance - A physical property of materials: the product of the material density and the speed of sound in the material.

A/D - Analog to digital converter; a device to convert a continuous voltage to a discrete binary representation. Speed of sampling is expressed as digitization rate or frequency representing the number of analog to digital conversions per second.

Celerity - In acoustics, the speed of sound in a material. Also referred to as the phase velocity.

FFT - Acronym for computer implementation of a discrete Fourier transform known as a Fast Fourier Transform. Used to examine frequency content of a time domain signal.

Harmonic - Frequencies evenly spaced above a fundamental natural resonance.

Hydrophone - Transducer which senses sound (vibrations) in water.

Impedance Mismatch - Occurs when two materials have different acoustic impedances. The sound is reflected according to the following equation:

$$Ar = Ai((Z2-Z1)/(Z2+Z1))$$

where Ar is the reflected amplitude, Ai is the incident amplitude, Z1 is the acoustic impedance of the first material, and Z2 is the acoustic impedance of the second material.

Phase Velocity - In acoustics, the speed of sound in a material. Refers to the velocity at which a phase of a sound wave, such as an amplitude peak, propagates. Synonymous with celerity.

Piezoelectric - Materials which when stressed acquire an electrical charge proportional to the stress. These materials are the basic element in most instrument-quality transducers.

Pink Noise - Sound having a constant intensity over a wide frequency range - a "real world" approximation to white noise.

Propagate - Travel, or progress, through a material.

Ray Tracing - A method for determining the path of high frequency sound through a material. For the method to be used, the sound must have much shorter wavelengths than the length of the path. Snell's Law applies at material discontinuities.

Resonance - In acoustics, the frequency or frequencies at which the ratio of internal sound intensity to excitation intensity is greatest. The acoustic resonance of any body is a function of its material properties and boundary conditions.

Spectral - Related to signal intensity represented as a function of frequency (as opposed to time).

Spectrum - A signal represented as a plot of intensity versus frequency.

Time Domain Signal - A signal represented as a plot of amplitude versus time.

Transducer - Device which transforms mechanical energy into electromagnetic energy.

Two-Phase Material- Heterogeneous substances having two components with different states of matter. Examples would be dry sand (gas-solid), cavitating flow (gas-liquid), or wet sand (liquid-solid).

Ultrasonic - Sound having a frequency content higher than the human ear can detect. Usually meant to describe sound above 20,000 Hz.

UST - Underground storage tank. Defined by the Environmental Protection Agency as a tank having at least 10 per cent of its volume, including associated piping, underground.

GLOSSARY OF TERMINOLOGY (CONCLUDED)

Waveguide - Long, slender, body fabricated from a homogeneous, isotropic, elastic material which is used to conduct acoustic energy with minimal energy loss.

White Noise - Ideally, sound having a constant intensity over an infinite frequency range.

SECTION I

INTRODUCTION

A. INTRODUCTORY REMARKS

Leakage from underground storage tank (UST) systems containing petroleum products has been identified as a serious environmental concern with the potential for severe economic impact, as well. The United States Environmental Protection Agency (EPA) has proposed regulations which would require extensive modifications to most existing UST systems if acceptable leak detection systems are not installed. In addition, the states of Florida, New York, and California have established specific regulations and leak detection requirements governing new UST system installations (1, 2, 3).

Few, if any, reliable methods have been found for underground leak detection with existing UST systems. The most common method, manual reconciliation of inventory, is based on crude, discrete measurements, often by untrained personnel. Consequently, the method is prone to human error. Leak detection by pressurizing the storage system for verification of the system's pressure boundaries and precision liquid level measurement techniques both require that the system be taken out of service during testing. Also, these methods detect leaks, but do not provide information on the location of leaks. Other, more automated, methods under investigation at this time include detection of fuel vapors in the soil, measurements of electrical resistance in soil, installation of double walled tanks with point level measuring devices in the bottom of the annular space, and acoustic monitoring for leak noise. The acoustic approach is attractive because it offers the potential for providing on-line leak monitoring and, in addition, can be used for locating suspected leaks.

B. OBJECTIVES

The overall purpose for this study was to determine the feasibility of using acoustic methods for detecting and locating leaks from UST systems. This purpose was addressed as four separate objectives, which are summarized below:

1. Determine the conditions under which JP4 fuel leaks produce acoustic emissions;

2. Determine the acoustic characteristics of JP4 fuel leaks from UST systems;

3. Measure and evaluate the acoustic transmission properties of fill materials commonly used at UST installations;

4. Investigate sensor designs and sensor placements for optimizing the capability for leak detection in UST systems.

C. BACKGROUND

The Federal Register for April 17, 1987, contains over 200 pages of discussion relating to the EPA's proposed rules for regulation of UST systems. For petroleum UST systems, the EPA has proposed that secondary containment with interstitial monitoring will not be necessary, but that "release detection must be instituted at all UST systems (1)." The EPA definition of a UST system includes the storage vessel and the associated underground piping, when more than 10 percent of the total volume is located below ground. The EPA has proposed that a 3 to 5 year time period should be allowed for installation of release detection equipment at existing UST systems.

The significance of the inclusion of associating piping in the definition of a UST system is made apparent when the proposal discusses the experience of Suffolk County, New York, where 6,200 inspections have been made since 1980:

> ...26 percent of the tank systems failed under the conditions of the test. When these failed systems were partially unearthed and investigated, the condition of non-tightness was discovered (by more than a 10 to 1 margin) to be primarily caused by loose fittings on top of the tank or faulty piping in need of repair or replacement (1).

In terms of leak detection methodology, the EPA has proposed that the regulations will be satisfied by any technology having equal or better performance than those suggested in the EPA proposal. Of the six methods mentioned in the proposal, the tank tightness technique appears to have the most stringent and easily measured performance standard, which is a sensitivity of 0.1 GPH. The EPA discussion states that the standard is only realizable in UST systems having capacities smaller than 12,000 gallons. However, National Fire Protection Association standards call for an even more stringent performance standard of 0.05 GPH leakage flow as a minimum sensitivity for testing of tightness in UST systems (4).

An annotated bibliography (5), included as Appendix A, provides additional background information on the application of acoustic techniques. The bibliography includes references describing acoustic leak monitoring in UST or similar systems (6, 7, 8, 9, 10, 11, 12, 13, 14, 15) and describing the application of transducers and waveguides to acoustic emissions monitoring in soils (16, 17, 18, 19, 20, 21).

D. SCOPE AND APPROACH

The appoach used in addressing the project's objectives was to examine experimentally the appropriate physical and acoustic phenomena in a test stand which was large enough to allow duplication of acoustic phenomena at a prototype scale. Although limitations imposed by size precluded testing of actual tank acoustics, it was possible to use prototype scale piping and pipe fittings and to determine the transmission qualities of soils over distances which eliminated acoustic boundary condition effects. Because the overall feasibility of acoustic undergound leak detection involves the relationships of substantially independent variables, the study was broken into the five distinct efforts described below:

1. A literature seach was conducted to provide additional information on current practice and research status;

2. A thorough examination was made of sound generated by leaks in piping and the pertinent sound generating characteristics of leaks;

3. Experiments were conducted to determine the acoustic properties of typical fill materials including sand, gravel, crushed rock, clay, humus, and concrete, with emphasis on frequency-dependent attentuation.

4. Alternative acoustic sensors and waveguides were designed, fabricated, and tested.

5. Constraints affecting leak detection were determined for a variety of leak and soil combinations.

E. OVERVIEW OF REPORT

A search of the relevant technical literature on leak detection by acoustic emissions monitoring was conducted, and an annotated bibliography was prepared (see Appendix A). The experimental investigations, described in this report, have provided information on several fundamental aspects of acoustic leak detection. The soil test facility and instrumentation used in this research are described in Section II. Section III discusses the generation of noise by leaks and describes results from a variety of tests with air leaks, water leaks, and fuel leaks. Section IV includes results from acoustic attenuation tests conducted with a variety of soil or fill materials, including sand, organic soil, concrete, pea gravel, crushed rock, and clay. Conclusions are provided in Section V. Recommendations for additional sensor development and for the design, prototype production, and field testing of a comprehensive system for underground leak detection are provided in Section VI.

SECTION II

DESCRIPTION OF TEST FACILITY AND INSTRUMENTATION

A. SOIL TEST FACILITY

A test facility for investigating acoustic properties of soil was designed and constructed for this study. The primary component of the facility is an acoustically isolated container, or "soil box," measuring 8 feet long by 4 feet wide by 4 feet deep. The soil box is shown in Figure 1. The container is isolated from ground-borne sound by pads consisting of alternate layers of acoustic felt and wood. The pads may be removed if the admission of ambient noise is desired. An infinite acoustic environment is simulated by lining the bottom and walls of the soil box with acoustically absorbent material so that reflections from the sides and bottom of the container are minimized. The soil box also provides a controlled containment, for disposal purposes, of soils contaminated by exposure to fuel leaks.

Hydraulic test equipment, also shown in Figure 1, includes a volumetric tank, fabricated from transparent acrylic plastic, for measuring leakage rates; two air tanks for pressurizing piping and controlling flow rate; delivery hoses suitable for use with petroleum products; and steel pipes and fittings for simulation of prototype leak conditions.

The test bed is located indoors so that soil conditions can be controlled. A wide range of ambient ground-borne noise conditions are present at the test site. Major noise sources include heavy machinery (printing presses) in the building, traffic noise from a major road about 400 feet distant, and air-borne noise from a "hard rock" band which occasionally practices in an adjoining office. Control over the ambient noise is exercised by conducting experiments either during the daytime or late at night.

B. INSTRUMENTATION

Both commercial and custom-designed acoustic instruments were used in the conduct of this study. The primary instrumentation consists of a high-speed (up to 25 MHz), two-channel, analog-to-digital converter with an arbitrary waveform generator controlled by an IBM-compatible microcomputer. Data acquisition and signal analysis software includes capabilities for Fast Fourier Transforms (FFTs) of single time records, FFT averaging, correlation of time domain waveforms, computation of frequency response (transfer) functions, time domain dT and dY

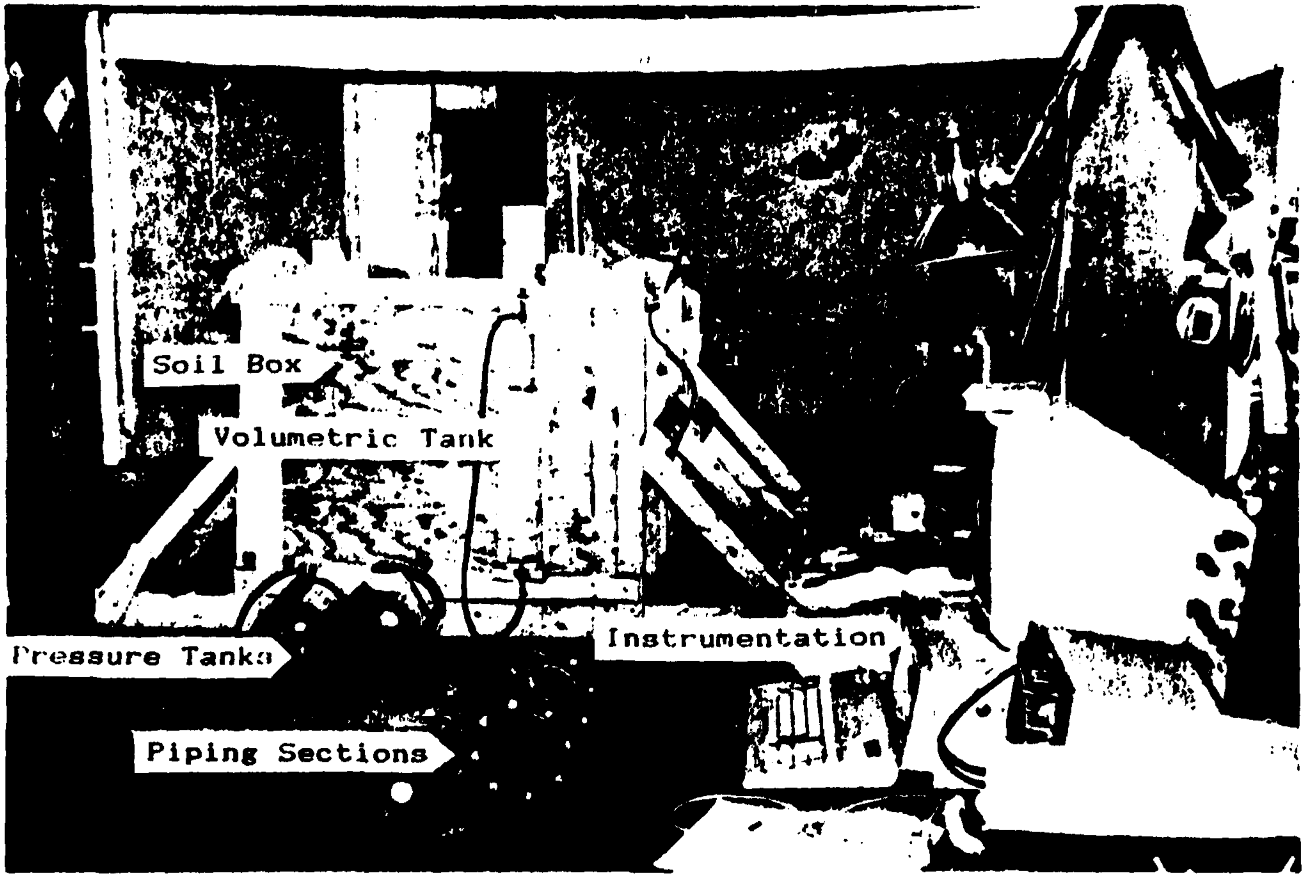


Figure 1. Soil Box and Instrumentation.

measurements, and acoustic emission event counting and rate determination. A 2 MHz function generator, a 20 MHz two channel analog oscilloscope, a pink noise generator, a 20 watt linear amplifier, an analog tape recorder, a broad-band sound level meter, and an optical microscope were also used in the study. Much of this instrumentation can be seen in Figure 1.

C. TRANSDUCERS

A wide range of transducer types were used and compared. The transducers and their specifications are shown in Table 1. The Realistic 33-1089 microphone was used as a microphone and, when protected with a thin, low impedance plastic film, as a hydrophone.

Several leak detection transducers, based on a sensitive, low-cost piezoelectric film, were designed, fabricated, and tested for this study. The Eclectech soil transducer, shown in Figure 2, includes piezoelectric film sensing elements surrounded by acoustic foam, an internal power supply, internal amplification, and a metal housing for noise reduction. An accelerometer/waveguide combination is also shown in Figure 2. Another transducer design, shown in Figure 3, consists of an integrated waveguide, transducer, and amplifier. Piezoelectric film is also used as the active transduction element in this design.

TABLE 1. SUMMARY OF TRANSDUCER TYPES AND SPECIFICATIONS.

Manufacturer & Model	Type	Frequency Range	Peak F
PAC R-61	AE	30 - 650 KHz	100 KHz
PCB 308B-2	Accel.	10 Hz - 30+ KHz	30 KHz
Eclectech Soil	Soil	20 Hz - 2+ MHz	flat
Eclectech Integrated	Waveguide/ Transducer	20 Hz - 20+ KHz	5 KHz 10 KHz
Realistic 33-1089	Microphone/ Preamp	20 Hz - 22 KHz	flat
Realistic 33-2050	Microphone/ Level Meter	32 Hz - 10+ KHz	flat

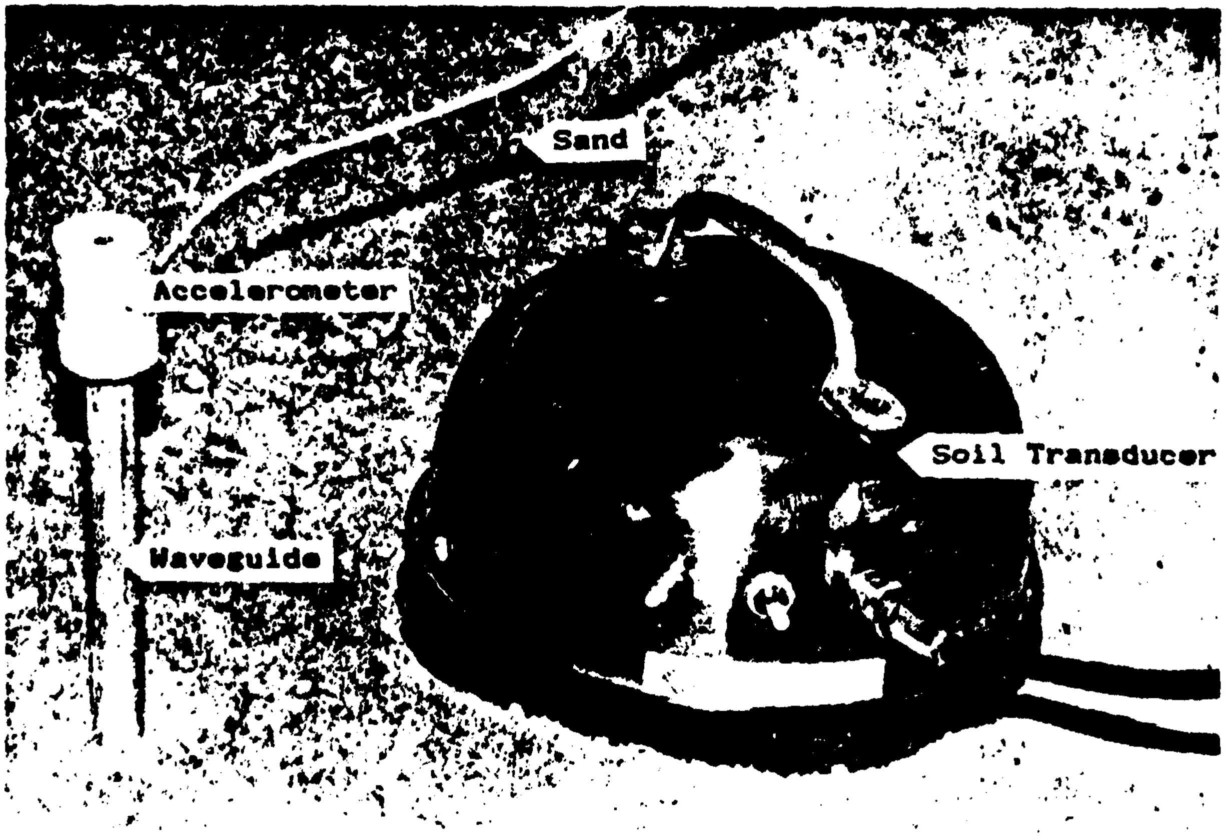
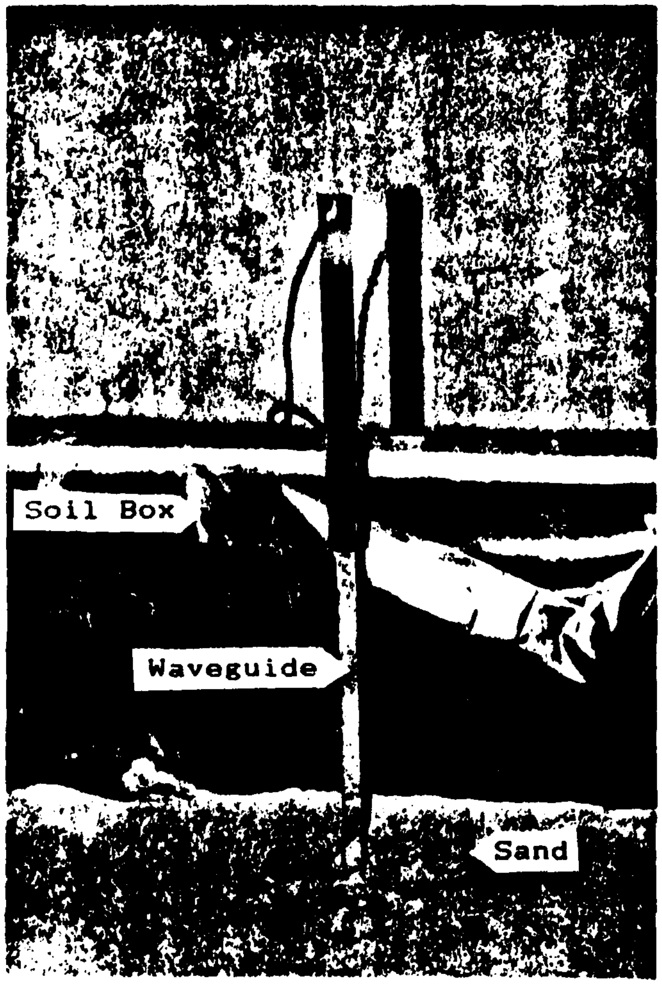
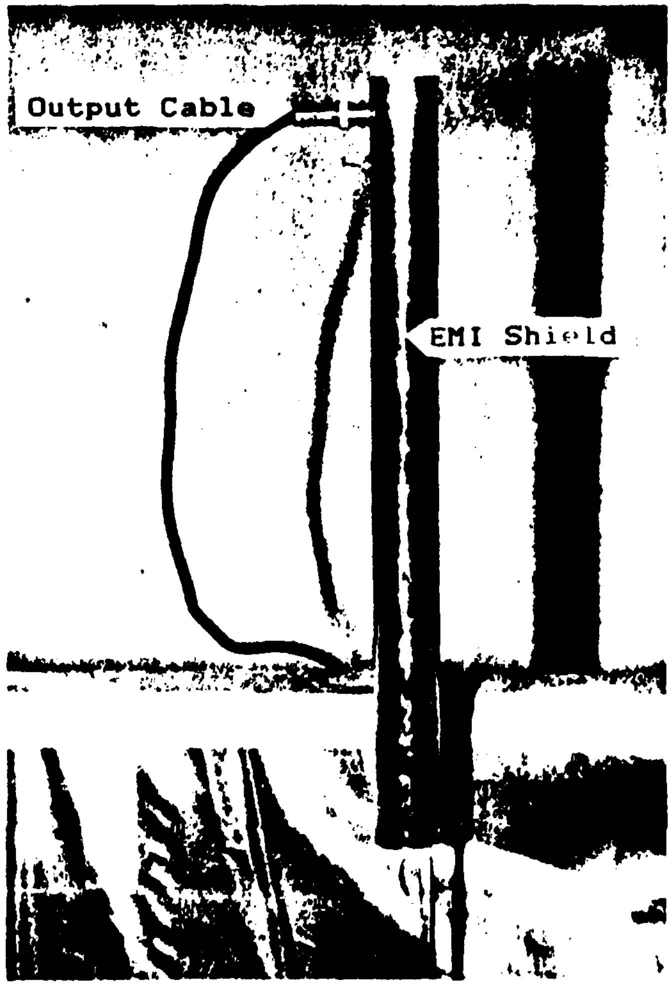


Figure 2. Eclectech Soil Transducer and Transducer/Waveguide.



Overall View



Detailed View

Figure 3. Eclectech Piezofilm Waveguide/Transducer.

SECTION III

LEAK CHARACTERIZATION AND TRANSDUCER EVALUATION

A. SUMMARY

A fundamental purpose for this phase of the investigations was to determine the influence of leak pressure, leak types, fluid types, and leak geometries on the characteristics of sound generated from leaks. Leak noise characteristics were examined in order to identify the practical applications and limitations of acoustics and acoustic emission technology for leak detection and monitoring. Test results strongly indicate that turbulent flow through the leak orifice or in the adjacent soil is a necessary and limiting condition for passive acoustic leak detection. Our data also indicates that the generation of leak noise depends on a complex acoustic system which includes the pipe geometry and exterior soil conditions in addition to the more conventional considerations of fluid dynamics in the leak orifice.

B. DESCRIPTION OF TESTS

Leak noise generation tests were conducted in the Eclectech facility during late evening hours to minimize the ambient noise level. Pressurized fuel or water was delivered to a 2-inch diameter Schedule 40 pipe or a 6-inch diameter Schedule 40 pipe (see Figure 4). The liquid delivery system included a clear plastic volumetric tank from which flow rate could be determined. Pressurization was either from the static head of the volumetric tank (for very low leak rates) or from an air tank (see Figure 1). Leak orifices were created in the pipe walls to represent conditions which would typically be found in the field. Each test began with a determination of the leak noise in air and a visual confirmation of the leak. Next, the pipe was buried in the soil box (typically in sand, the most common fill material). After the sand was uniformly packed about the pipe, the pipe was pressurized to about 30 PSI. The leak rate was noted and a digital recording of the leak noise was taken from the pipe wall with an accelerometer located near the leak. The pressure to the leak was then reduced by 10 PSI and the recording process was repeated. This cycle was repeated until the leak became undetectable. Pertinent leak dimensions are listed below in Table 2.

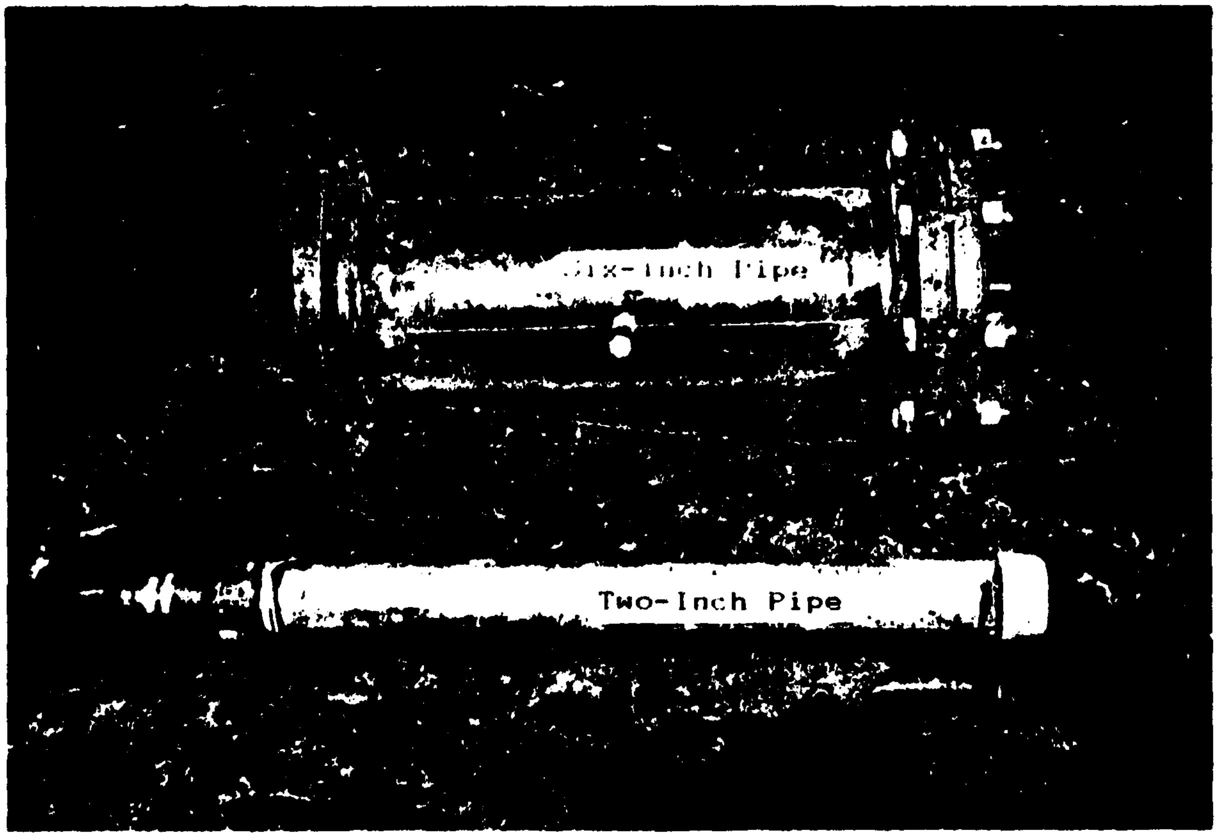


Figure 4. Two-Inch and Six-Inch Piping Sections for Leak Source Characterization.

TABLE 2. SUMMARY OF LEAK DIMENSIONS.

Leak Type	Wall Thickness (inches)	Major Length (inches)	Minor Length (inches)
Threaded (2")	n/a	<1	<.03
Pin Hole (2")	.16	.06	.06
Pin Hole (6")	.31	.06	.06
Flange (6")	n/a	<2	<.01
Crack (6")	.31	1.75	<.01

C. TEST RESULTS

The first, and most significant, result of our testing was verification that low pressure, single phase leaks are not acoustically active. Typically, fuel leaks into sand became inaudible at about 2 PSI across the leak. Although the point at which a leak became audible was found to be related to the leak velocity, the velocity itself was not consistent for constant pressures and leak orifice sizes. Leak velocities are an unknown quantity in the field, so the most valid predictor of leak audibility will be the system pressure, which is generally known or can easily be measured. The minimum pressure for an audible leak varied from about 2 PSI to 5 PSI. Therefore, passive acoustic leak detection appears to be only feasible in systems which operate under at least 5 PSI of positive pressure across the leak or which can be pressurized to this level for purposes of leak detection. The minimum leak rate which can be acoustically detected at these pressures is a function of the size of the leak orifice.

For small leaks with flow rates under 5-10 GPH, the leak history into the adjacent sand had a decided influence on the flow rate and the minimum pressure necessary for generation of leak noise. Typically, clean dry sand resulted in larger flow rates for a given system pressure than fuel- or water-soaked sand. If the leak history included a large flow rate (20 GPH or more) under significant pressure, the minimum audible pressure decreased and the flow rate increased. Post-test examinations of the sand adjacent to the leak site revealed that the larger leaks created voids in the sand at the leak site. This indicates that increased flow rates observed after a large leak are the result of an increased cross-sectional area of interstitial space available to the leak discharge, decreasing the pressure necessary to maintain a given flow rate. Maximum leak rates for an orifice occur, of course, when the discharge is into the air rather than into the soil. Table 3 lists the effects of soil types on the generation of sound by a leak discharge to the soil, compared to discharge into air.

TABLE 3. DRIVING PRESSURE FOR MINIMUM DETECTABLE FUEL LEAKS

Soil Type	Leak Type	Minimum Pressure for Leak Noise Generation
Air	pin hole	2 PSI
Air	threaded	2 PSI
Air	crack	2 PSI
Pea Gravel	pin hole	2 PSI
Sand (dry)	pin hole	2-4 PSI
Sand (wet)	pin hole	3-7 PSI
Sand (dry)	threaded	2-4 PSI
Clay (damp)	pin hole	2-7 PSI

The magnitude and frequency of leak noise, once turbulent flow was reached, depended on acoustic characteristics of the leaking system, not just on system pressure. With the 6 inch piping, all leak types gave a characteristic noise having a sharp peak at 5 KHz, as shown in Figure 5.

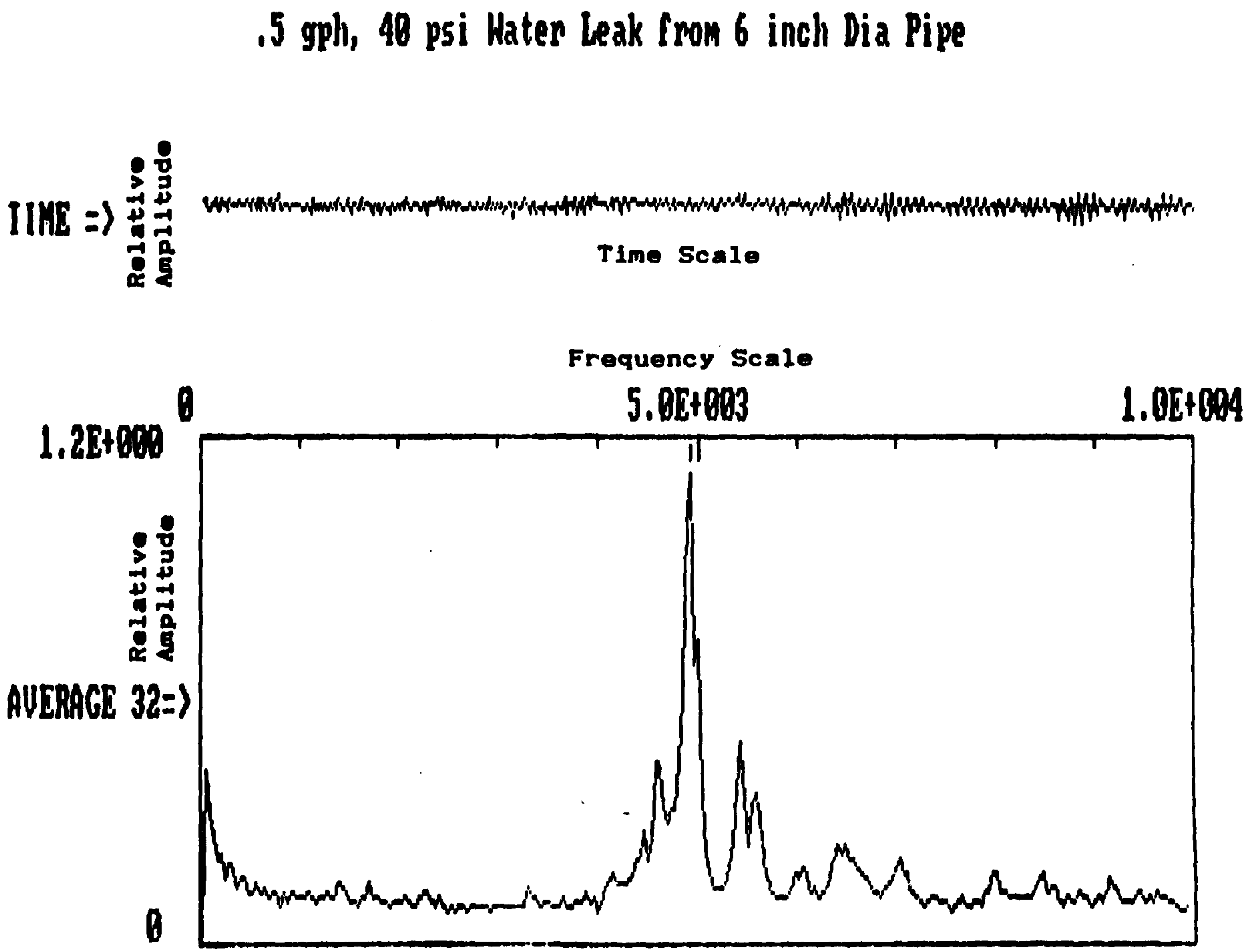


Figure 5. Frequency Spectrum for Leak Noise from Six-Inch Pipe.

Figure 5 is typical of the output from the microcomputer-based signal analysis used to characterize the acoustic characteristics of leaks and soil and to determine the sound transmission properties of soil. The upper trace displays the output signal from the transducer as a function of time. The lower trace presents the output from a Fast Fourier Transform (FFT) operation performed with 32 averages of the time varying signal from the transducer. The ordinate is the relative intensity of the signal from the transducer. The abscissa at any point in the lower trace is the frequency. The scale for the frequency axis is provided in scientific notation at the top of the lower trace. The time-domain data from Figure 5 indicates that the sound level was nearly uniform, and the spectral plot from the figure indicates that the bulk of the acoustic energy from this leak was centered at about 5 KHz.

Figure 6 is a frequency spectrum from the pipe caused by frictional excitation near the leak site. The 5 KHz peak in the leak noise is obviously a result of pipe resonance and not a characteristic of the leak noise. The resonance in question is just under the calculated first harmonic of both the longitudinal wall resonance and the circumferential wall resonance for the 18-inch pipe length between the flanges. This is based on a speed of sound in the pipe wall of 16,000 feet per second (ft/s), which is a good value for an extensional wave in steel. The 1,000 Hz peak is apparently a mechanical resonance in the pipe. The 2-inch pipe with threaded ends and unequal end conditions, rather than heavy identical flanges, did not exhibit an extensional mode resonance for the longitudinal direction. Figure 7 shows a spectrum measured when the 2-inch pipe was externally excited. Most of the leak spectra measured for the 2-inch pipe contain a peak near 500 Hz. The cause of this relatively low frequency peak is thought to be a bending mode in the pipe. The higher 1,600 Hz peak can be identified as a shear wave mode propagating in quarter wave lengths due to the unequal end conditions created by fittings at the pipe ends. The obvious conclusion that can be drawn from these figures is that leak noise radiated from a piping system will be modified by resonances in the pipe and pipe walls.

Figures 8 through 11 show typical spectra for water leaks at leak differentials of 5 PSI, 10 PSI, 20 PSI, and 30 PSI from a 1/16-inch pin hole in the 2-inch pipe. Similar resonant peaks occurred at each pressure. Also, amplitude did not increase significantly or consistently with pressure. This suggests, again, that a primary factor in the generation of leak noise, once turbulent flow is achieved, is the ability of broad band leak noise to drive the natural pipe resonances.

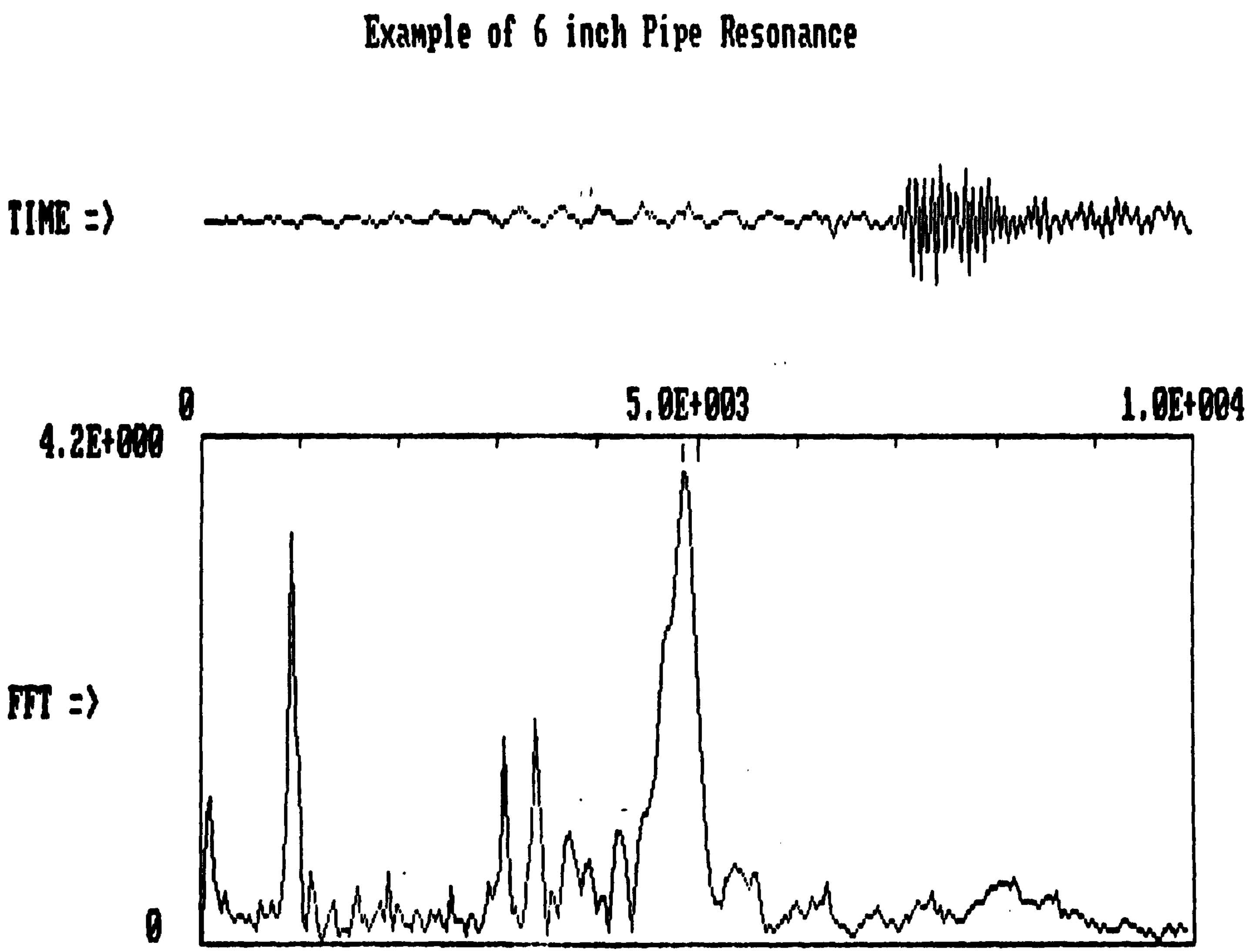


Figure 6. Frequency Spectrum for Frictional Excitation of Six-Inch Pipe.

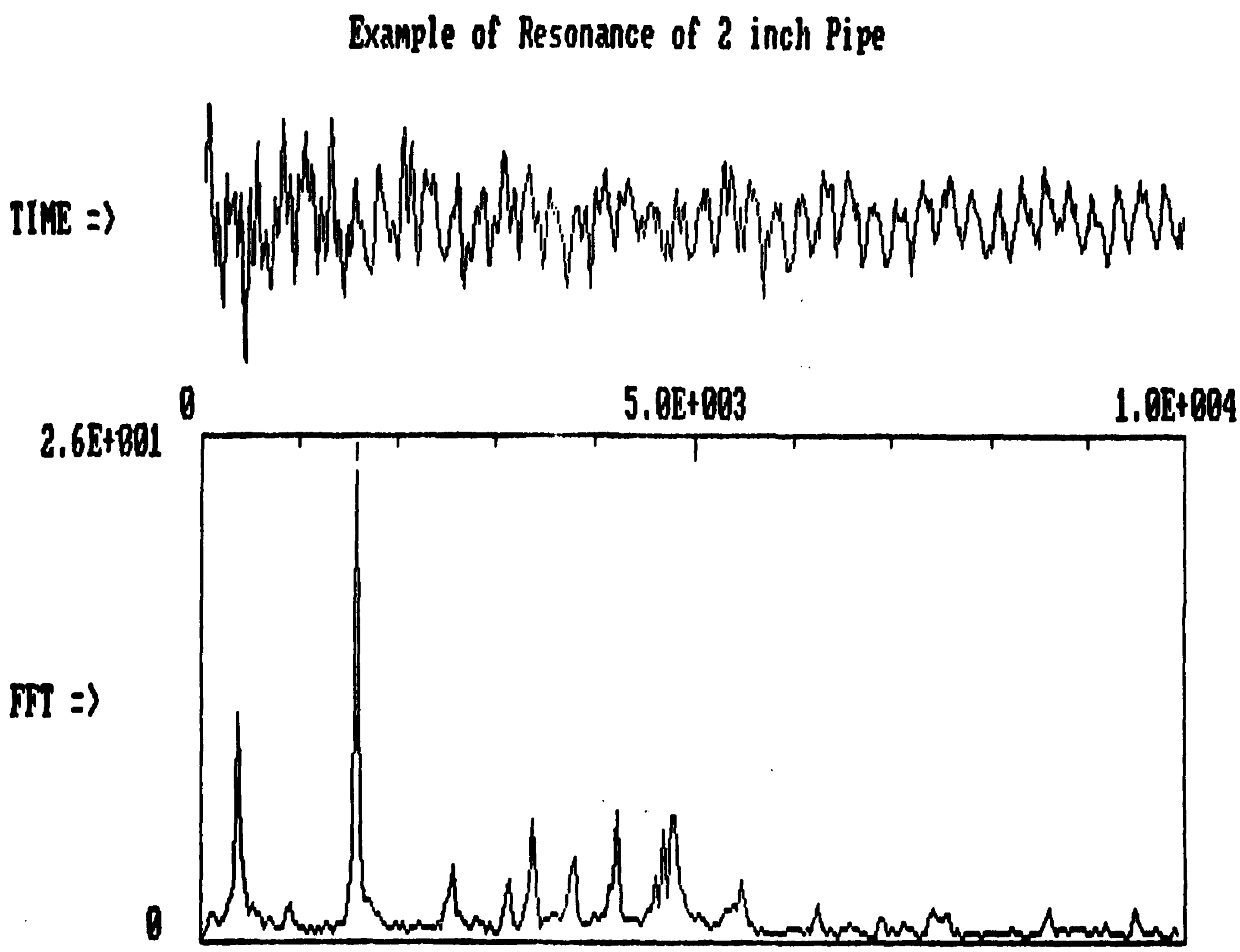


Figure 7. Frequency Spectrum for External Excitation of Two-Inch Pipe.

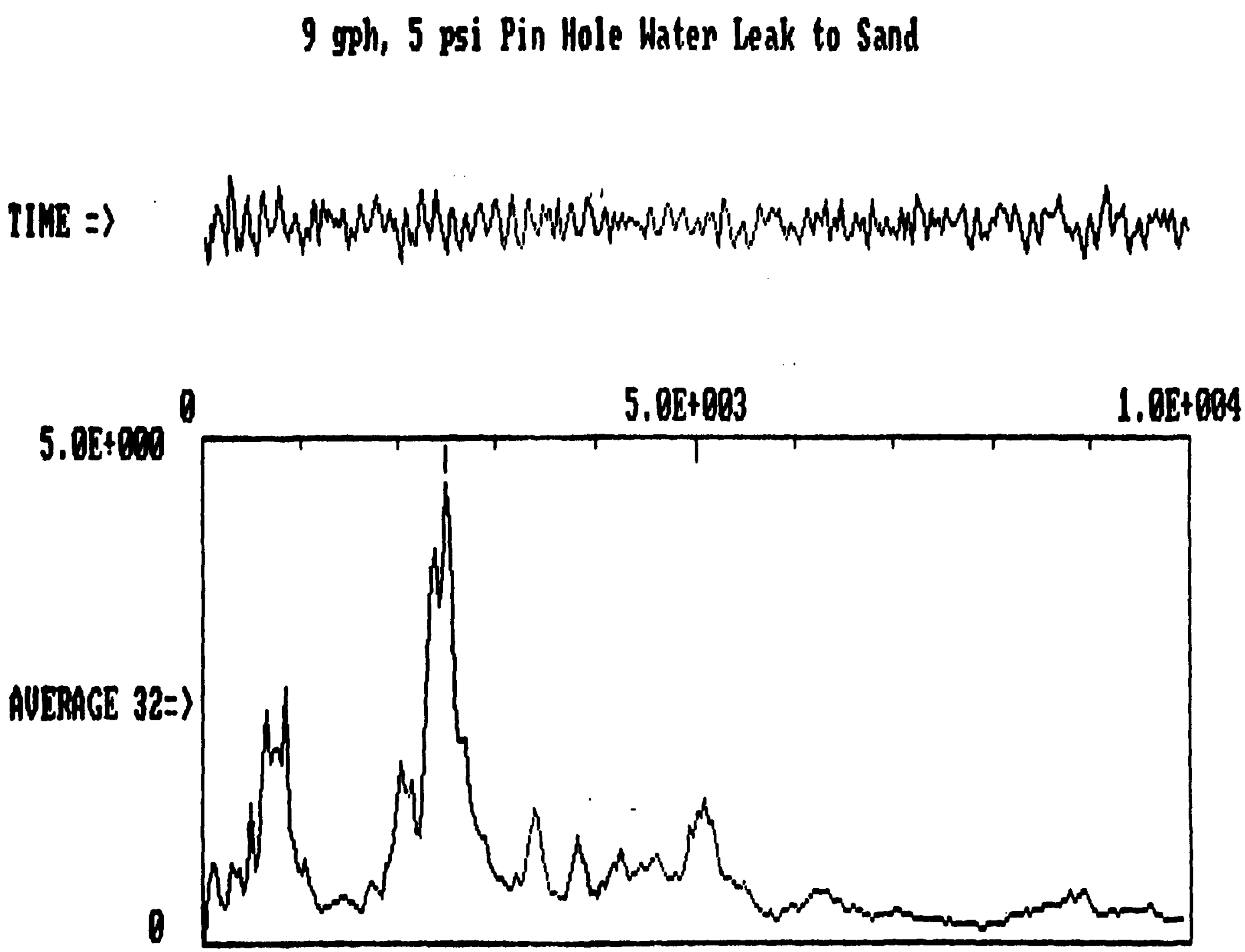


Figure 6. Frequency Spectrum for Pin Hole Water Leak to Sand, Two-Inch Pipe at 5 PSI.

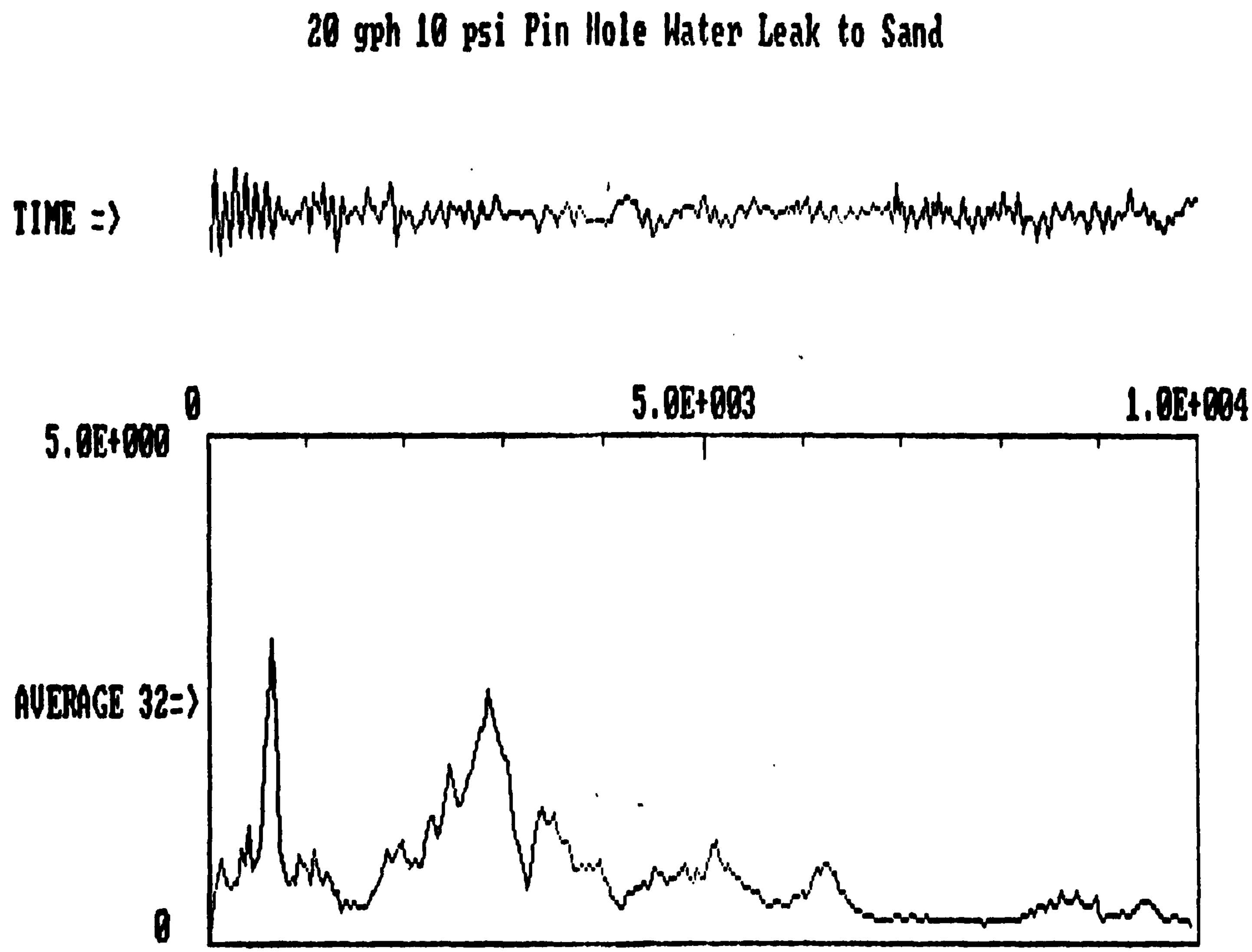


Figure 9. Frequency Spectrum for Pin Hole Water Leak to Sand, Two-Inch Pipe at 10 PSI.

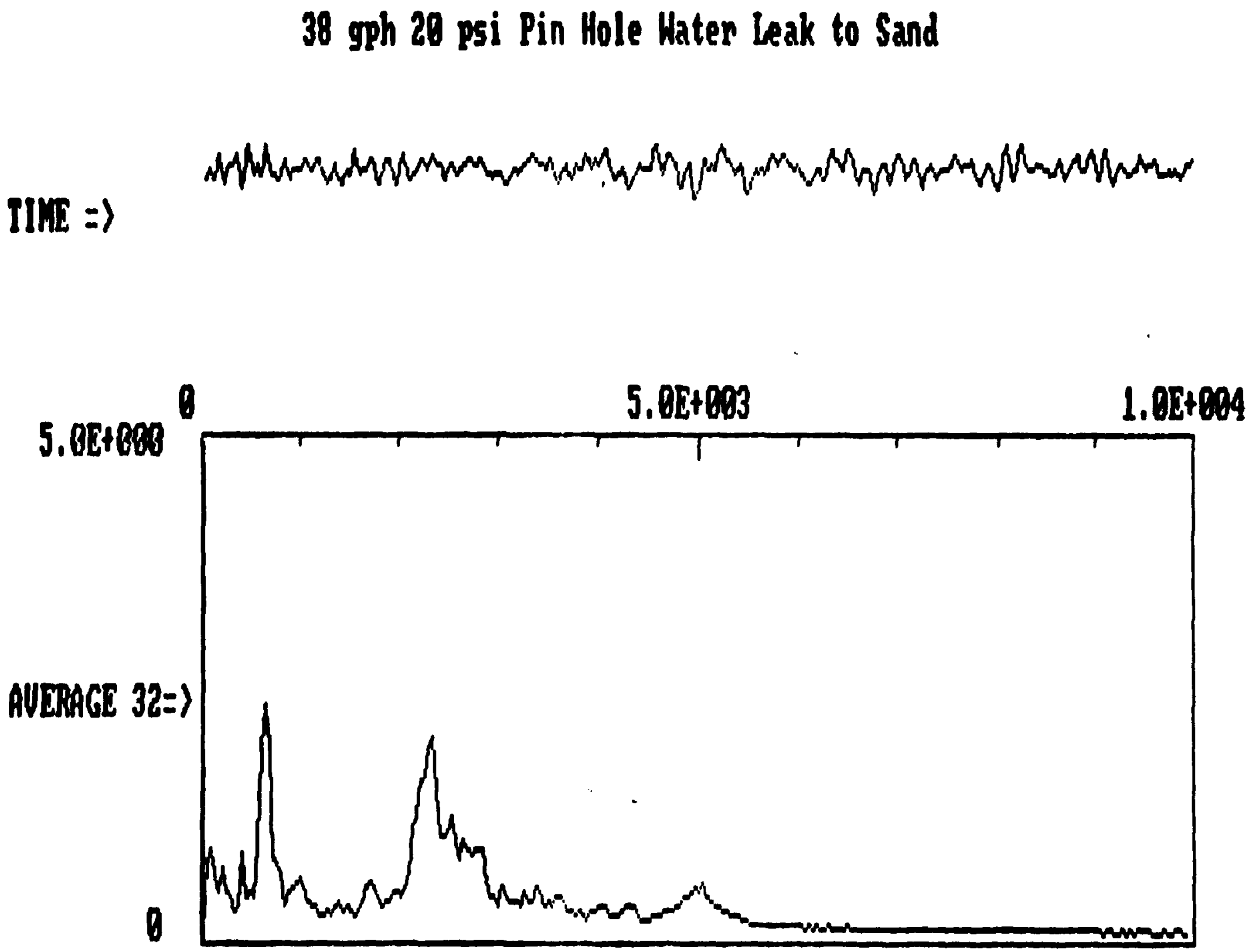


Figure 10. Frequency Spectrum for Pin Hole Water Leak to Sand, Two-Inch Pipe at 20 PSI.

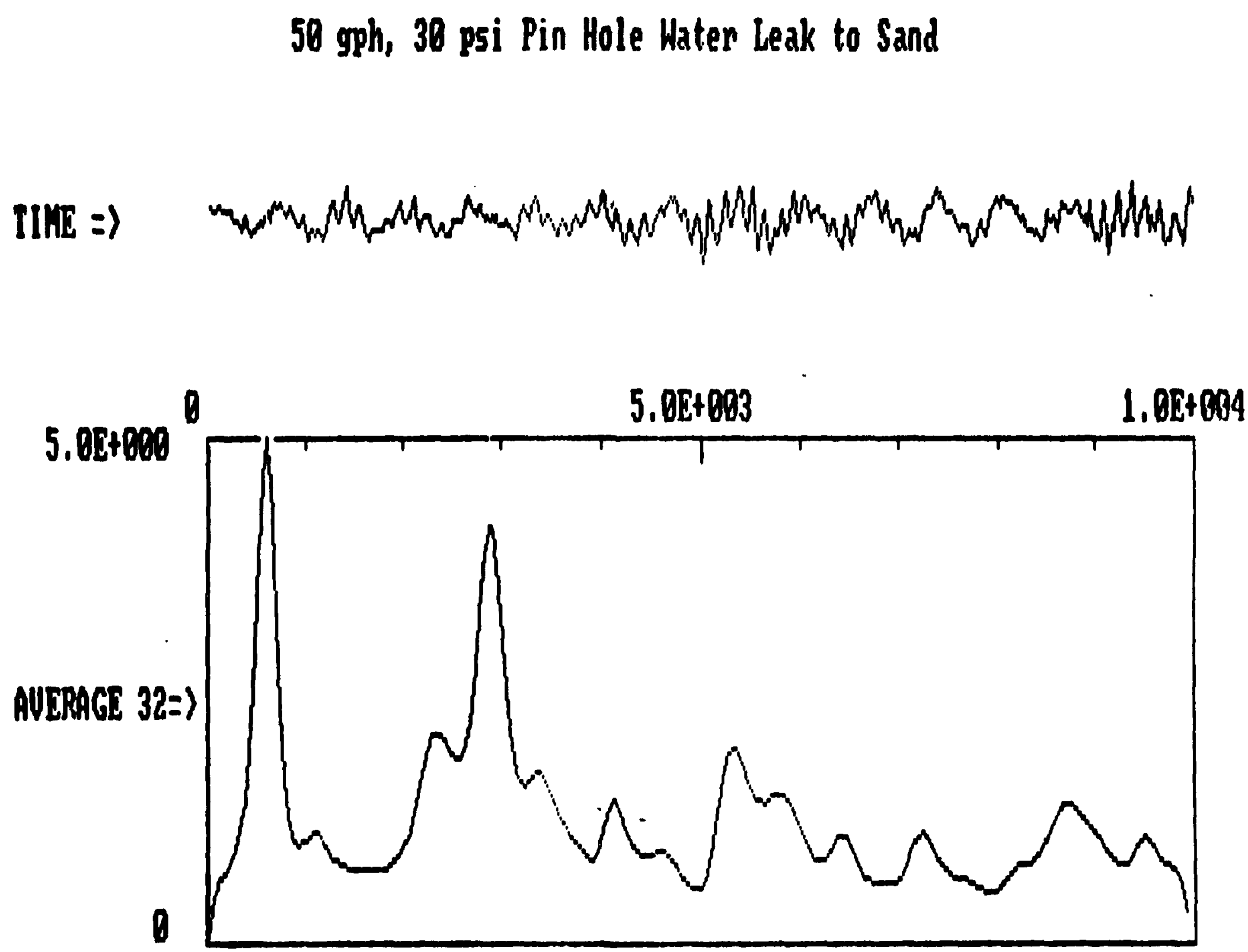


Figure 11. Frequency Spectrum for Pin Hole Water Leak to Sand, Two-Inch Pipe at 30 PSI.

Figures 12 through 15 show typical spectra for fuel leaks at leak differentials of 5 PSI, 10 PSI, 20 PSI, and 30 PSI from a 1/16-inch pin hole in the 2-inch pipe. By comparison with the corresponding figures for water leaks, volumetric leak rates are higher in each case for fuel than for water. At lower leak pressures (and, consequently, lower flow rates), the characteristics of the spectra are quite similar for fuel leaks and water leaks. At 20 and 30 PSI, a dramatic difference occurs. The bulk of the energy now appears below 2,000 Hz. The time trace for the 30 PSI leak shows that the signal was so strong that the sampling electronics were over-ranged. The sudden appearance of such high levels of energy indicated that a fundamental change had taken place in the leak dynamics. Subsequent tests indicated that this was due to fuel vaporization occurring at the leak orifice.

D. COMPARISON OF TRANSDUCER TYPES

The final acoustic tests with actual leaks involved a comparison of transducer types. Figure 16 presents a frequency spectrum for data taken with the commercial acoustic emission transducer. (Note that the frequency scale in Figure 16 is from 0 to 100 KHz.) This spectrum demonstrates that the transducer was insensitive to sound below 20 KHz. Because the energy content of fuel leaks is typically below 5 KHz, this type of transducer is inappropriate for use in detecting low pressure fuel leaks.

Figure 17 shows the results obtained through one foot of sand with the Eclectech soil microphone. This was the only transducer tested that could detect leak noise through sand without a waveguide. Figure 18 presents a plot of leak noise detected with the Eclectech integrated transducer/waveguide with one foot of sand between the leak site and the waveguide. The small peak near 6,000 Hz coincides with a calculated acoustic resonance of the waveguide. Although this device does not require direct contact with a piping system or tank, direct contact is best for optimal performance. The transducer-waveguide combination can be reproduced at about 1/3 of the cost of an accelerometer, and it also has directional sensitivity, which could be important for determining leak location.

Finally, Figure 19 shows a plot of data obtained from a water leak of 0.1 GPH, detected with an accelerometer mounted directly on the pipe wall and the leak discharging to air. This was the smallest leak rate detected acoustically. The leak differential, however, was 50 PSI.

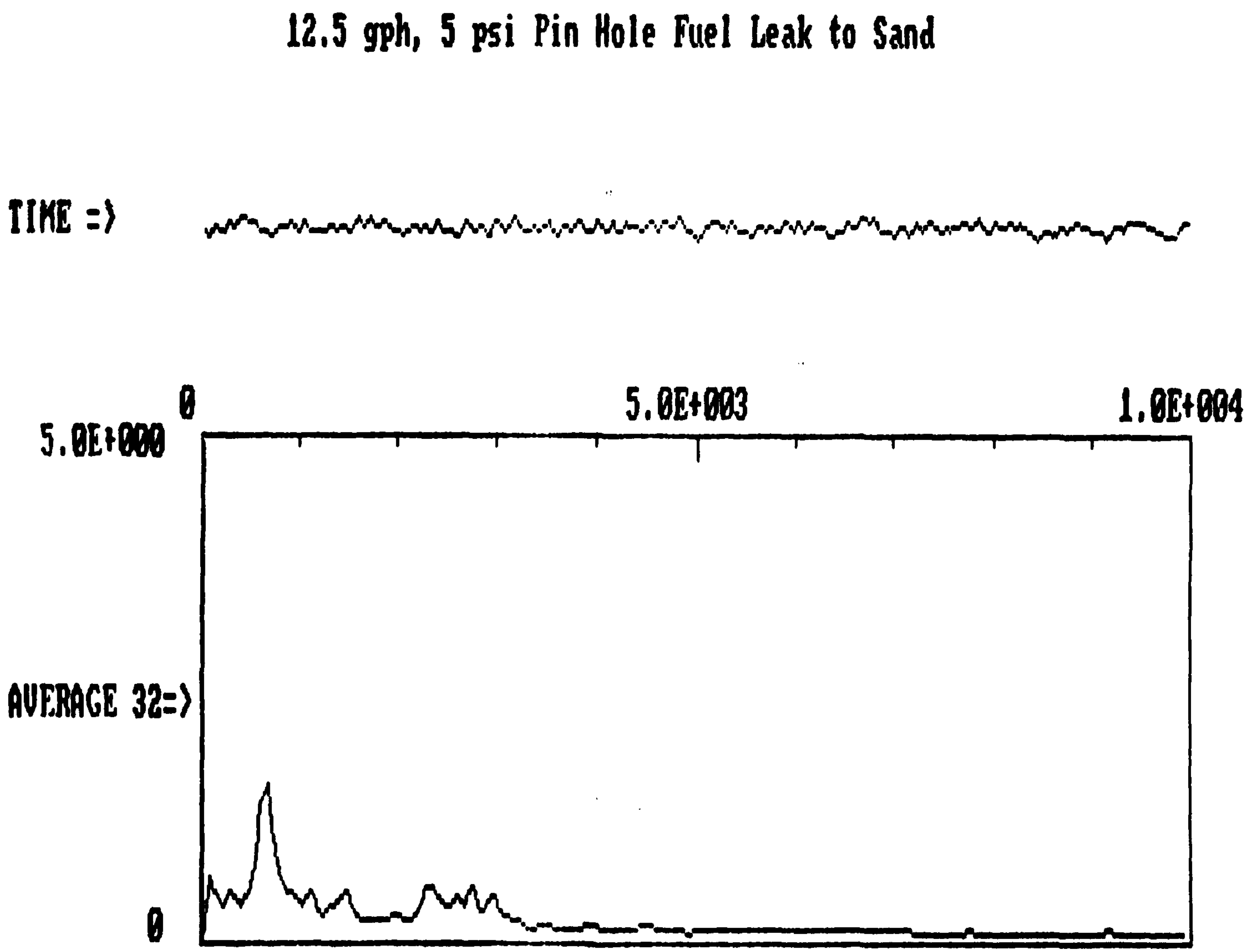


Figure 12. Frequency Spectrum for Pin Hole Fuel Leak to Sand, Two-Inch Pipe at 5 PSI.

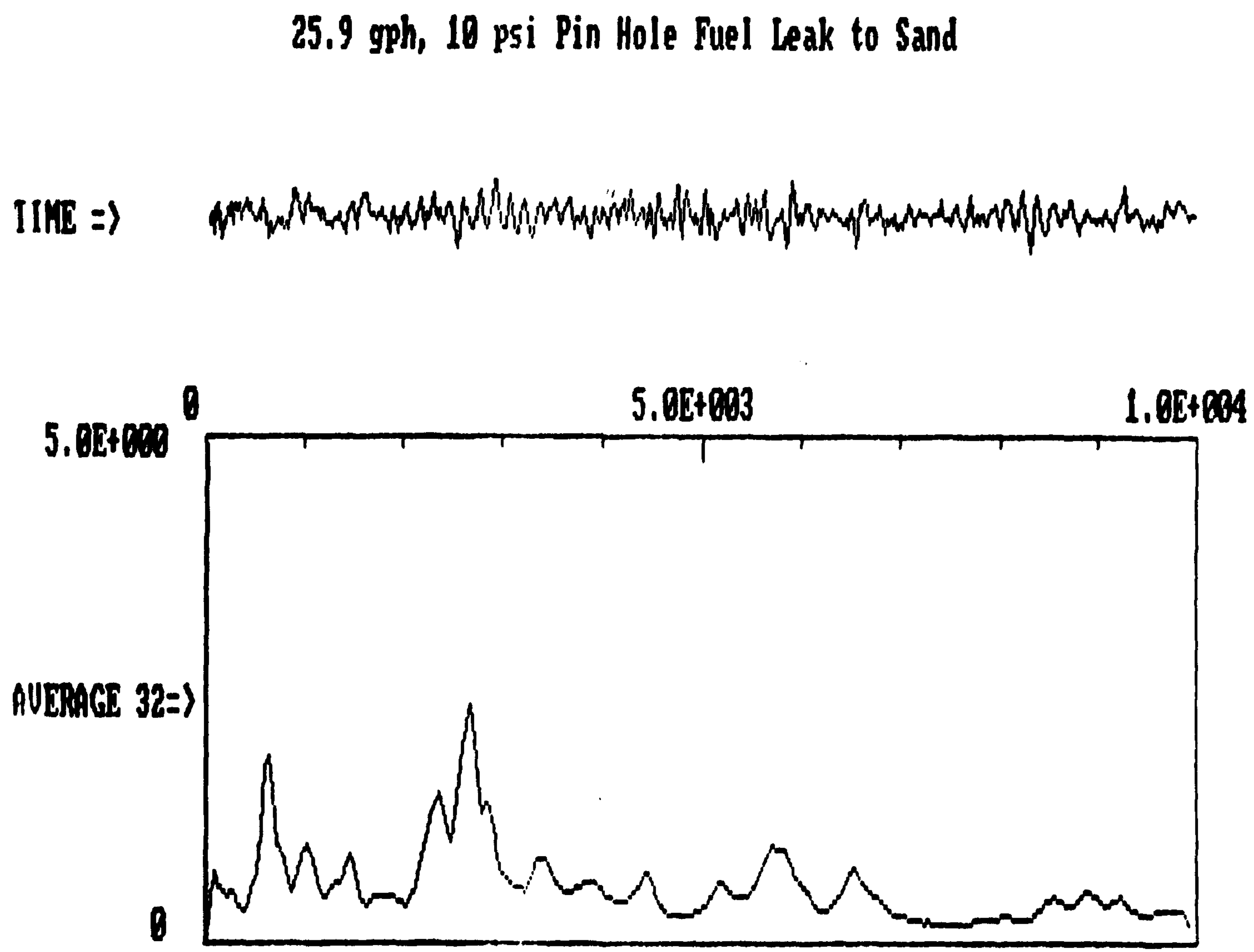


Figure 13. Frequency Spectrum for Pin Hole Fuel Leak to Sand, Two-Inch Pipe at 10 PSI.

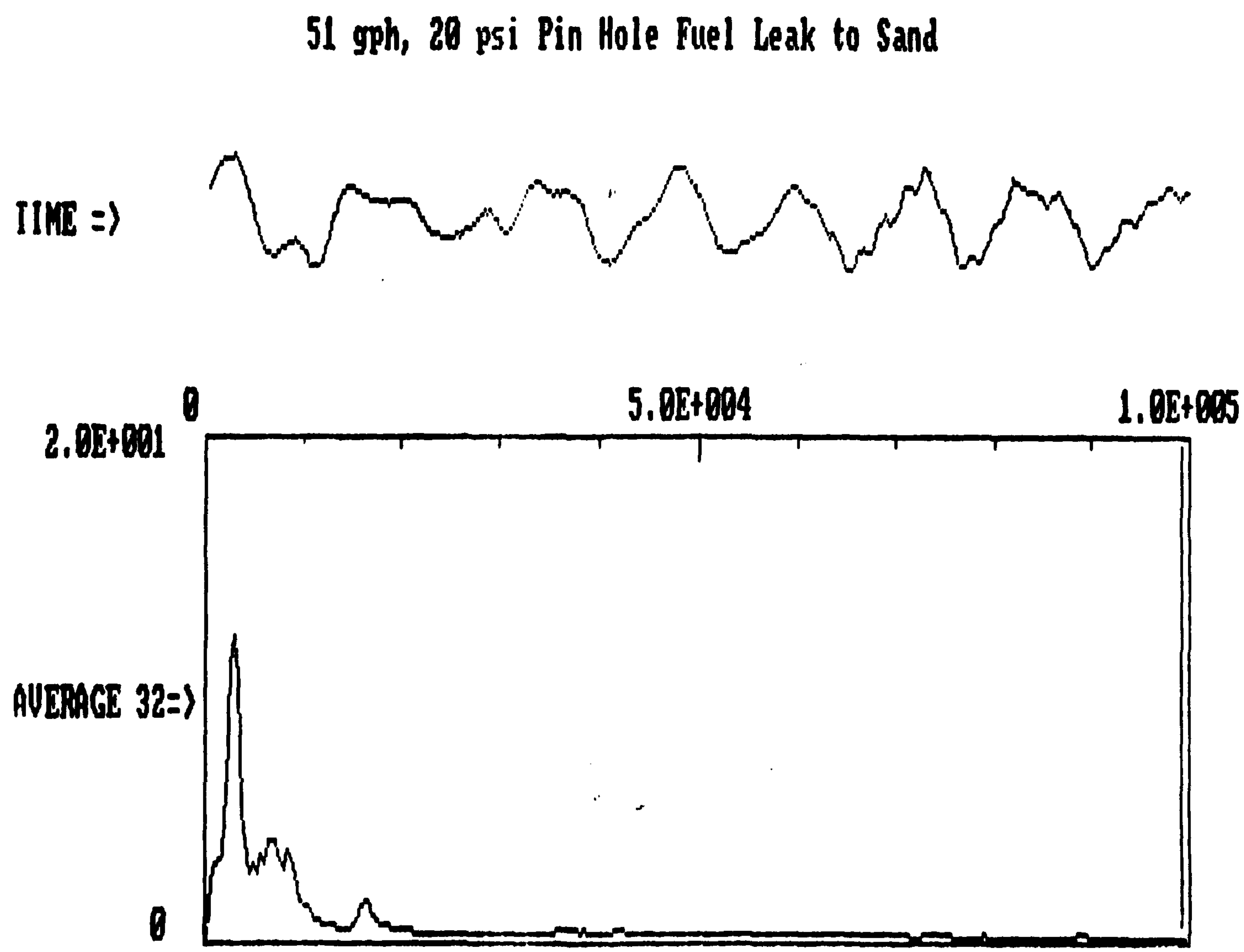


Figure 14. Frequency Spectrum for Pin Hole Fuel Leak to Sand, Two-Inch Pipe at 20 PSI.

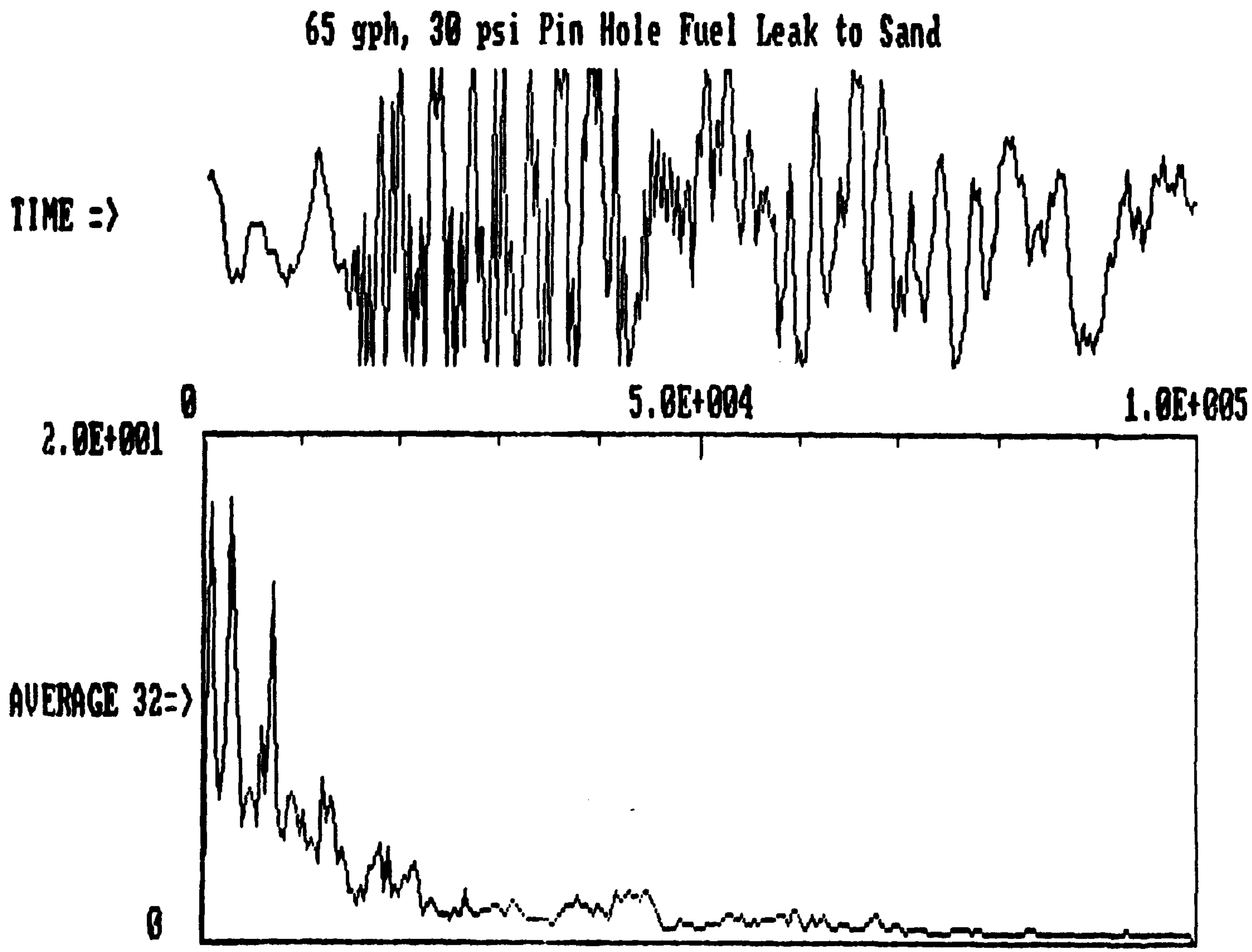


Figure 15. Frequency Spectrum for Pin Hole Fuel Leak to Sand, Two-Inch Pipe at 30 PSI.

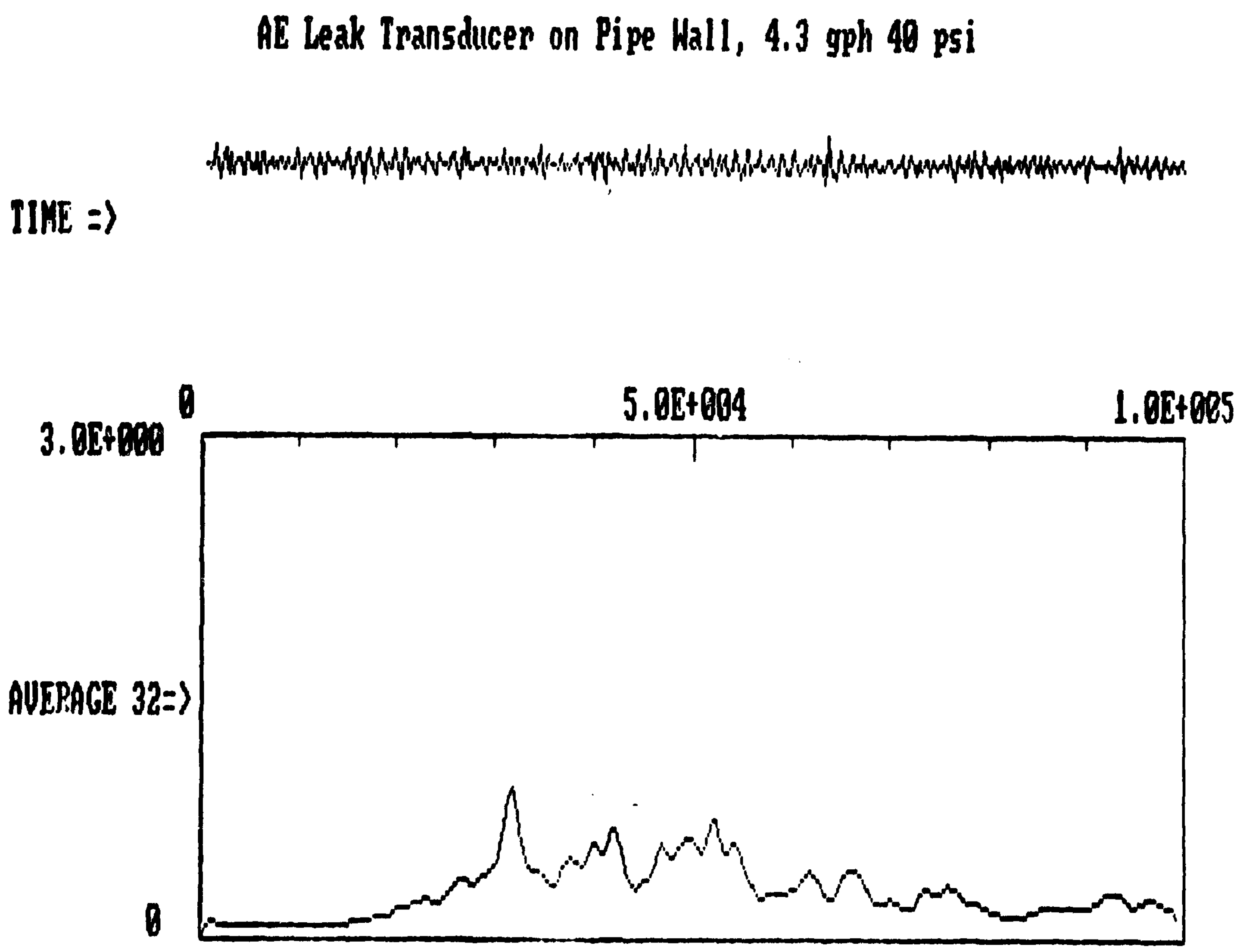


Figure 16. Frequency Spectrum for Leak Noise at Pipe Wall, Commercial AE Transducer.

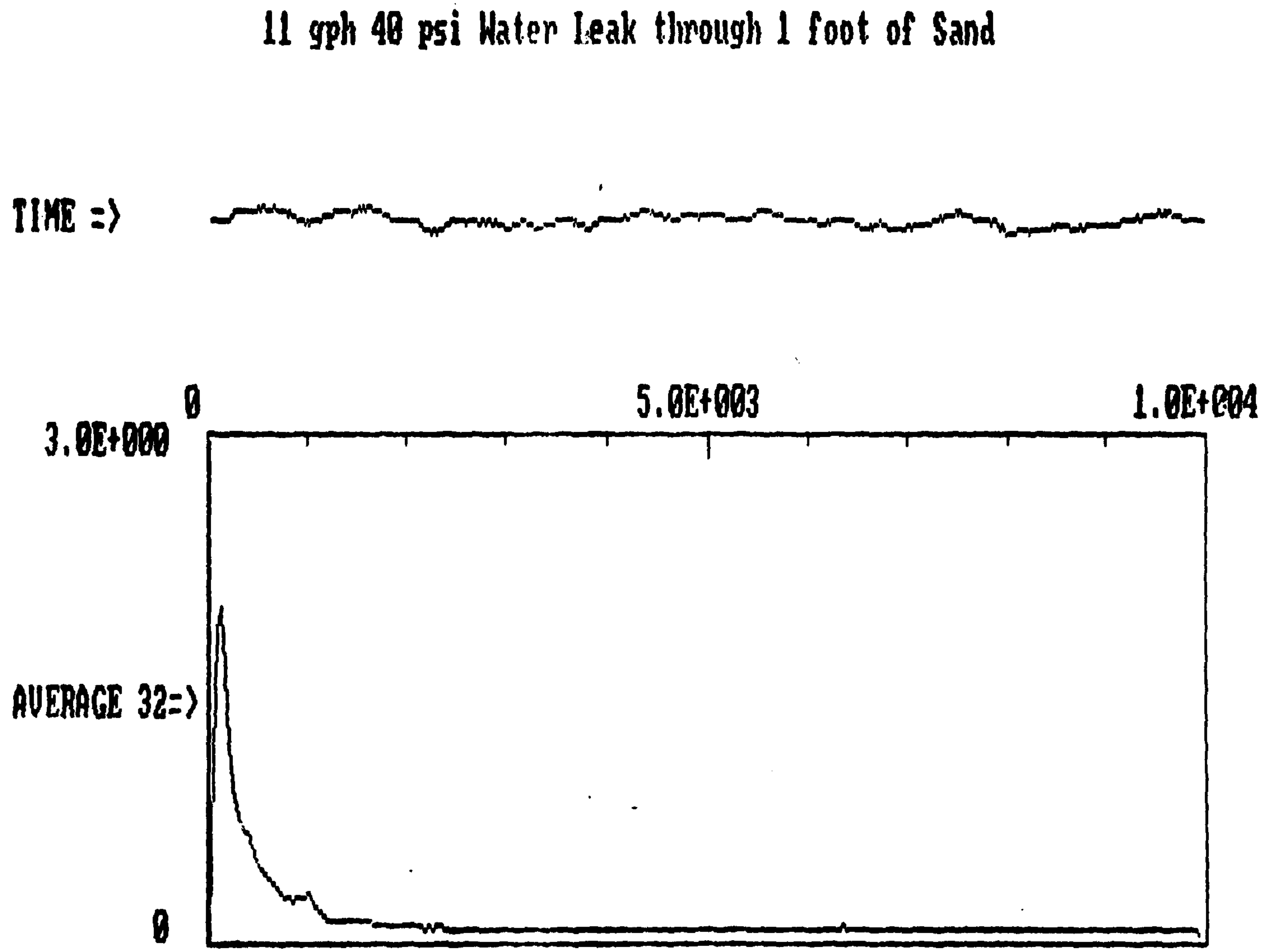


Figure 17. Frequency Spectrum for Leak Noise Through Sand, Eclectech Soil Transducer.

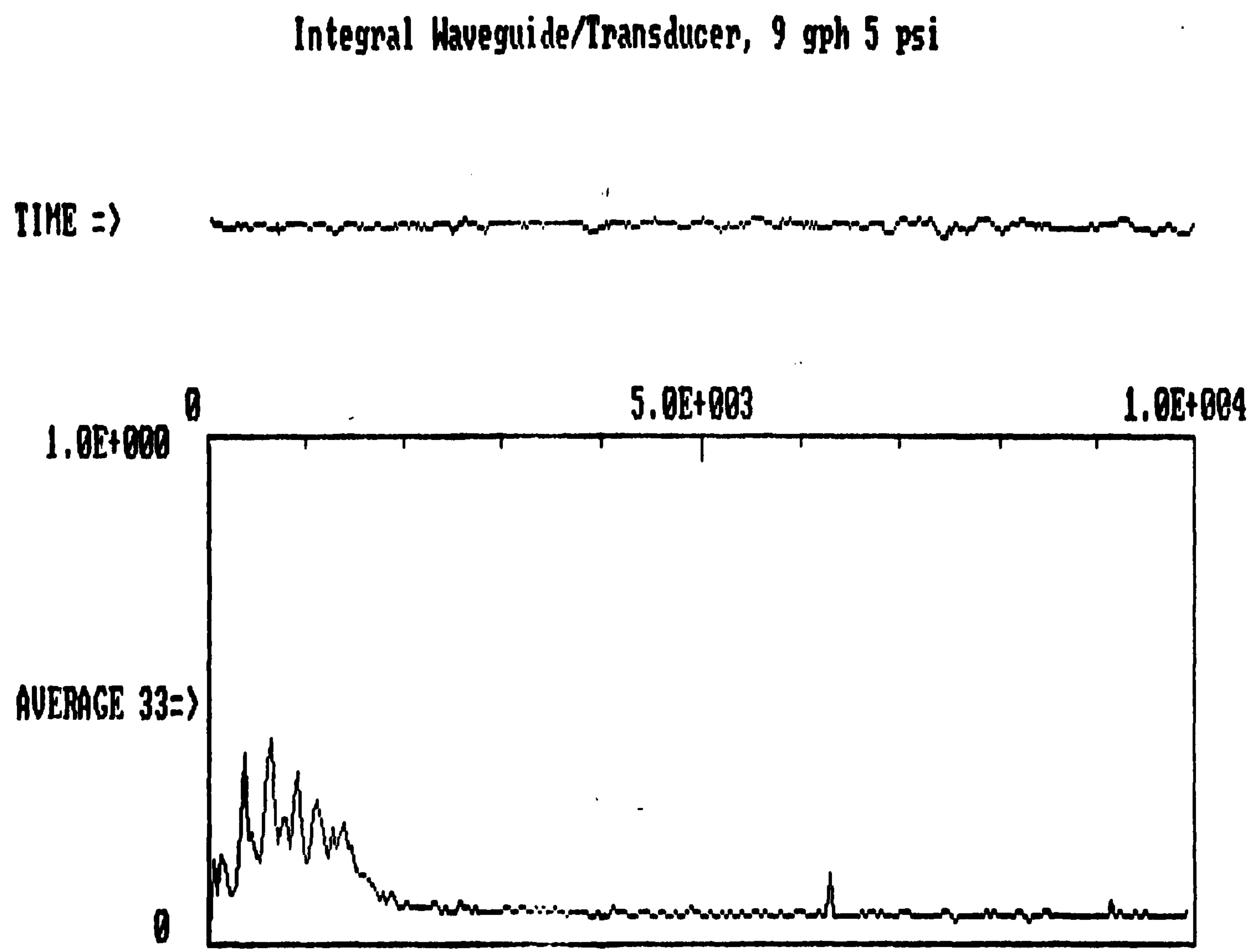


Figure 18. Frequency Spectrum for Leak Noise Through Sand, Eclectech Piezofilm Transducer/Waveguide.

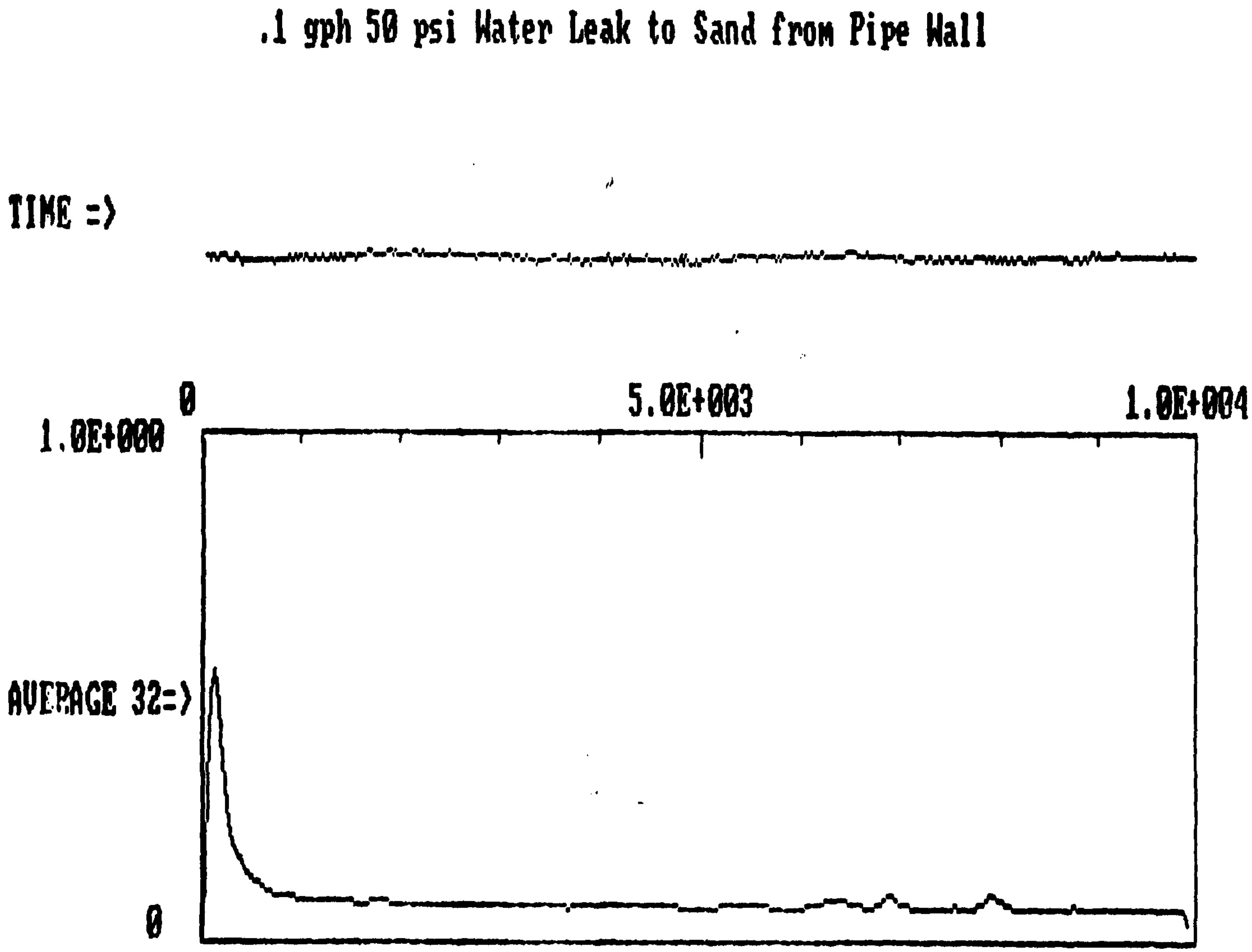


Figure 19. Frequency Spectrum for Minimum Detectable Water Leak, Pipe Wall Accelerometer.

E. CONCLUSIONS FROM LEAK CHARACTERIZATION TESTS

The preceding sections have discussed instrumentation, methodology, and results from experiments conducted to characterize the generation of noise from pipe leaks. Important results are summarized below:

1. Passive acoustic leak detection will be most successful with leak differential pressures of 5 PSI or more.

2. Direct transducer contact or waveguides contacting the pipe surface are necessary for acoustic leak detection in sand, clay, and organic soils. With gravels and concrete, direct contact is preferable but not necessary (see Section IV).

3. Through-soil acoustic devices will only be useful for locating rather than detecting leaks. Through-soil devices should not be used as a primary means of leak detection due to the high attenuation in most soils.

4. Pipe wall resonances heavily contribute to leak noise. Field tests are needed to characterize natural acoustic frequencies of typical pipe and storage tank installations. With this information, waveguides and transducers can be selected to offer optimal performance.

5. Leak noises were easily detected in the presence of very high air-borne noise levels because of the extreme attenuation of the noise in sand. In UST installations where sand is used as the backfill material, soil-borne background noise should not be a problem. An assessment of background noise levels can, and should, be made as part of any test procedure.

6. Large tanks were not examined in this study. Preliminary data obtained from a 55 gallon drum containing water confirms that fluid level as well as soil contact area will affect tank acoustics. Field tests on prototype scale tanks, however, are necessary for a complete evaluation of acoustic leak detection in tanks. It is probable that hydrophone sensors placed in the liquid will provide the most cost effective and sensitive method of detecting leaks in large storage tanks. The previous conclusions pertaining to minimum pressures necessary for generation of detectable leak noises apply to tanks as well as piping.

SECTION IV

ACOUSTIC ATTENUATION IN SOIL

A. FUNDAMENTAL BACKGROUND INFORMATION

The following paragraphs present a brief discussion of the various mechanisms for the attenuation of sound and their application to soil acoustics. These mechanisms include absorption, impedance mismatch, spreading, scattering, and mode conversion.

Absorption is the conversion of phased, directional acoustic energy into heat and other disorganized forms of kinetic energy. Sound attenuation can occur due to impedance mismatch as acoustic energy is reflected at surfaces formed by dissimilar materials. Impedance mismatch is the basis for ultrasonic inspection techniques (reflection from air or vacuum pockets in the metal) and is also responsible for the bulk of attenuation in two phase materials such as soils.

Spreading refers to a decrease in energy due to the geometry of the path. A wave with a pure point source in an infinite environment will have a spherical configuration and will decrease in amplitude with the inverse of the distance. (Power obeys the inverse square rule.) This is independent of absorption. Usually, sound sources are not point sources and are directional. The higher the frequency of the sound, the more directional it tends to become. Further, most environments are confined, so that sound is reflected back from the confining surfaces. Thus, in a rod with a diameter much smaller than the wavelength of the sound, spreading can be neglected. In bodies much larger than the wavelength, it must be considered.

High frequency sound is highly directional, and ray tracing techniques can be used to determine paths of propagation in simple geometries. However, impedance mismatches with rough surfaces can cause scattering in multiple directions. This phenomenon is commonly seen in cast metals. Sound is attenuated by spreading and energy loss in the reflective mechanism. When the medium of transmission is a solid, mode conversion also occurs. A longitudinal wave incident at an angle (other than normal) on a plane surface will reflect as both a longitudinal and a polarized shear wave. A vertical shear wave will reflect as both a longitudinal wave and a vertical shear wave. Only a horizontal shear wave or a longitudinal wave having normal incidence will reflect without conversion of some energy into another wave mode. These mechanisms can result in dispersion of acoustic energy in both space and time. Other attenuating mechanisms include high levels of fluid viscosity, multiple material resonances, and dynamic changes in material properties such as those seen in the presence of shock wave fronts.

B. OVERVIEW OF ACOUSTIC TESTS IN SOIL

Tests were conducted to determine the acoustic properties of selected soil materials and concrete. The soil materials tested included sand, organic soil, pea gravel, crushed rock, and clay. For these tests, the primary emphasis was placed on sand, which is the most commonly used backfill material for underground storage tanks.

The soil characterization tests consisted of an initial determination of dry bulk density and physical composition. The dry bulk density was determined by weighing a known volume of the soil material. A microscopic examination of the subject material was conducted with an optical microscope to estimate characteristics, such as particle size range and dimensions of interstitial spaces. The soil material was then exposed to both fuel and water, and absorption traits were noted. Finally, the basic acoustic properties of attenuation and phase velocity were measured.

Soil properties are rarely uniform, even when samples are acquired from a single, well-defined location. Soil bulk density, for example, is dependent on the degree of compaction as well as the particle density. Clay may exhibit a bulk specific gravity of only 1.25 or less if it is loosely compacted, for example. When tightly compressed, the same sample may exhibit a bulk specific gravity approaching 2.0. Although we have tested at prototype scales in order to obtain data typical of field conditions, our results are specific to a limited range of conditions and materials. Therefore, results should be considered as an indicative subset of the soil properties which can occur in the field, rather than as a set of values which can be precisely applied to any field condition. The results from the soil characterization tests are presented below for each of the tested soil materials.

C. ACOUSTIC TESTS WITH SAND

The sand which was used in the study had particle sizes ranging from 0.005 mm to over 2.0 mm in diameter. The average particle size was on the order of 0.3 mm in diameter and would be classified as a "medium" sand by the U.S. Department of Agriculture. The bulk specific gravity was approximately 1.5. The individual particles were irregular in shape with rough, fractured surfaces. The particles were uniformly translucent with the light amber to white color typical of quartz. Just under 45% of the bulk volume consisted of interstitial space, based on the volume of water absorbed by the dry material. The longest free paths in the interstitial spaces were typically less than 0.5 mm in length, with a non-uniform cross section.

Both water and fuel were observed to replace air in the interstitial spaces of sand. Typically, the sand was less absorbent to fuel than to water. Water absorption was about 45% of the volume of the sand. Fuel absorption was about 25% of the volume of the sand. This difference appears to be a function of interstitial dimensions. The fuel did not penetrate into the smaller spaces as a consequence of higher surface tensions and vapor pressures than are present with water.

The drainage of water and fuel from the sand were also markedly different. Water tended to leave the interstitial space under the effect of gravity in a matter of hours. The fuel, on the other hand, left an oily deposit on the surface of individual grains and tended to remain in the smaller interstitial spaces. The fuel "contamination" can apparently persist for periods of months, as fuel can still be observed in sand which was exposed to fuel at the beginning of this study. (This has negative implications for leak detection systems which use devices that measure fuel vapor concentrations in soils.)

Tests were conducted to characterize acoustic attenuation in uncompacted, compacted, and water-saturated sand. A 1.5 inch diameter high-frequency, high-fidelity loudspeaker was used in conjunction with a signal generator as sound source. The speaker's plastic cone was placed in direct contact with the sand. The projection axis of the speaker was placed 5 inches below the surface of the sand and oriented to emit horizontally along the soil box's long (8 foot) axis. The speaker was driven with single-frequency sinusoids ranging from 500 Hz to 20 KHz. A waveguide consisting of a 1/2 inch diameter aluminum rod was placed vertically in the sand three inches from the face of the speaker. A commercially available piezoelectric transducer (PCB 308B-2) having flat response characteristics below 10 KHz was mounted on the aluminum rod. Readings were taken from the transducer at each test frequency to verify the speaker's fidelity and to obtain baseline readings. A second identical waveguide and transducer were located 15 inches from the front of the speaker. Readings at intervals of 500 Hz were taken from both locations and compared. A commercial sound-level meter was used to ensure that the speaker output remained constant for each frequency throughout the test. The results from the tests, expressed as a percentage of signal amplitude remaining after transmission and as a coefficient of attenuation, are given in

Table 4. Table 4 compares results for dry uncompacted sand and saturated sand. Table 5 compares results for uncompacted and compacted dry sand with compacted wet sand. (For comparison purposes, it should be noted that the Eclectech soil transducer was able to detect the acoustic signal to 5,000 Hz in dry uncompacted sand at the same distance from the source).

TABLE 4. ATTENUATION RESULTS FOR DRY AND WET SAND.

Frequency	Uncompacted Dry Sand		Uncompacted Wet Sand	
(Hz)	(% baseline)	(dB/ft)	(% baseline)	(dB/ft)
500	34	9.3	68	3.3
1,000	14	17.2	49	6.2
2,000	11	19.2	11	19.2
2,500	near ambient		10	20.0
3,000	ambient		ambient	

TABLE 5. ADDITIONAL ATTENUATION RESULTS FOR SAND.

Frequency	Uncompacted Dry		Compacted Dry		Compacted Wet	
(Hz)	(%base)	(dB/ft)	(%base)	(dB/ft)	(%base)	(dB/ft)
500	34	9.3	-	-	-	-
750	19	14.5	22	13.1	25	12.0
1000	14	17.2	08	21.6	23	12.9
1500	12	18.4	17	15.5	45	7.4
2000	11	19.2	24	12.4	39	8.2
2500	ambient		28	11.1	28	11.1
3000	ambient		7	23.5	ambient	

As expected, attenuation of sound in sand was significant and frequency dependent. The unexpected decreases in attenuation with increasing frequency observed in compacted sand appear to be the result of multiple wave celerities in the material. Local maxima of acoustic energy move in frequency and location with changes in moisture content and state of compaction. Other observed properties include pronounced scattering, anisotropic absorption, and a nonlinear response of attenuation to surface loading (both heavy loading and light loading increase attenuation.) The most obvious implication of the data is that more than a few feet of sand will effectively absorb all leak noise from small, high-pressure leaks, which typically emit the bulk of their acoustic energy above 1,000 Hz.

The importance of selecting an appropriate transducer for the detection of sound in sand can not be overemphasized. Microphones, which are intended for use in air, and accelerometers, including AE transducers which are intended for use directly attached to solids, do not couple efficiently with sand. The Eclectech soil transducer gave the best performance of the transducers tested due to its low acoustic impedance and relatively large active surface area. Accelerometers can also be used with sand if waveguides are employed to increase the effective contact area. Table 6 compares the relative efficiency of various transducers/waveguides for use with sand. The tests were conducted with a 1,000 Hz sound source through 1 foot of dry uncompacted sand. The microphone was also tested in damp compacted sand to show the effects of moisture (or fuel) on interstitial, air-borne sound. A commercial accelerometer (PC 308B-2) was used for evaluation of waveguide types.

A variety of test methods were attempted to determine the celerity (wave speed) of sound in sand. The method which proved most satisfactory was the most basic: time of flight over a known distance for an impulse signal. Identical accelerometers were buried under 6 inches of sand one foot apart. An impulse signal was then introduced to the sand through an aluminum rod located 7 inches from the transducer serving as the trigger for the electronics. The time differences between similar portions of the measured waveforms at the two transducers were measured to determine the wave celerities. Figure 20 is typical of the time traces made to determine celerity. Table presents the celerity results calculated from the recorded data. Multiple celerities were observed. The most significant fact is that in the case of fuel-dampened sand, the C2 and C3 celerities are close enough together that over short distances the sand will appear to have a single celerity. It should be noted that the C1 celerity calculated from the high-frequency, low-amplitude incidence of the wave front is consistent with sound speeds in

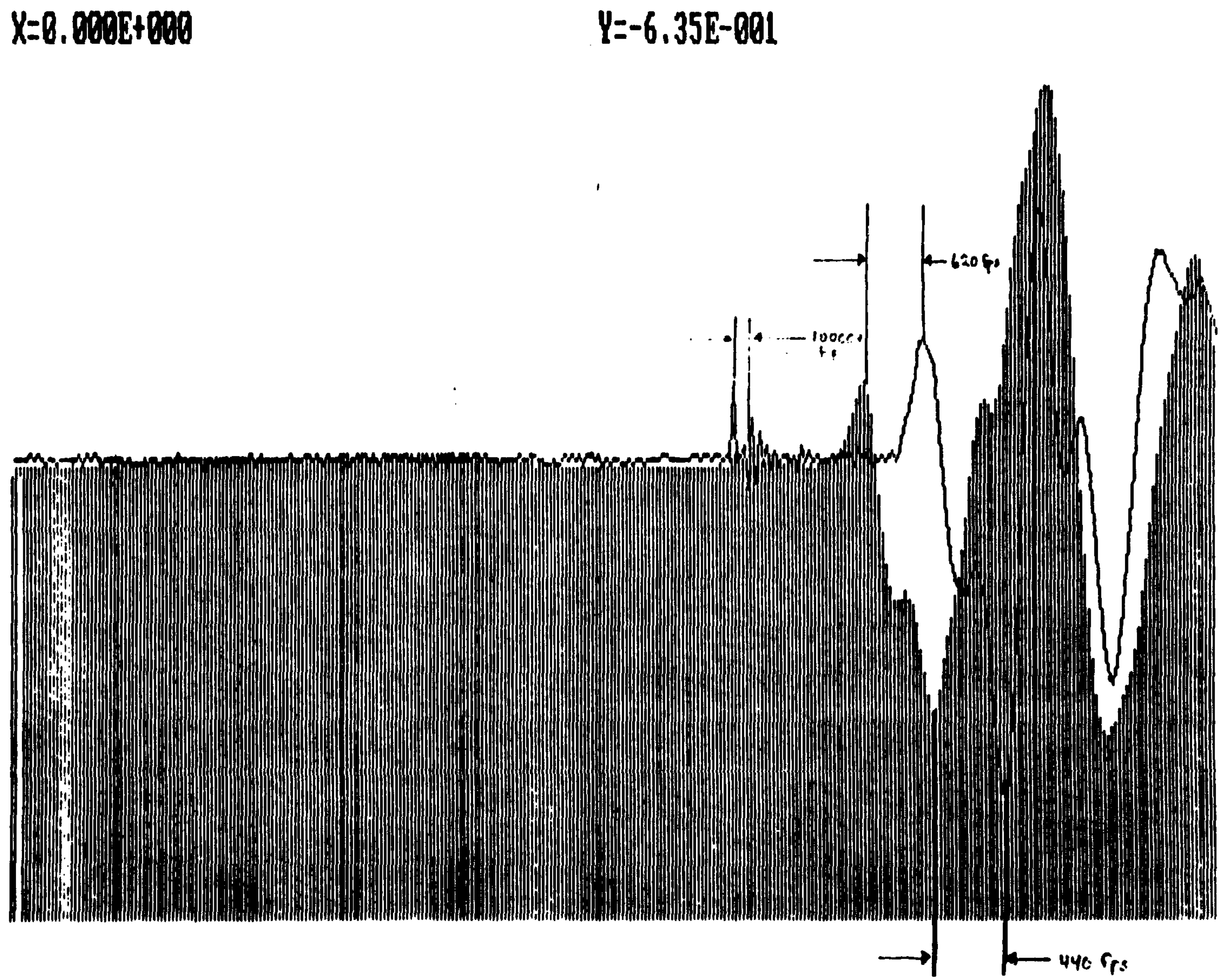


Figure 20. Typical Time-Domain Data for Determining Celerity.

solid materials rather than in two-phase materials. The attenuation of this high velocity mode is extreme, and it does not contribute significantly to the spectral data.

TABLE 6. RELATIVE EFFICIENCIES FOR TRANSDUCERS AND WAVEGUIDES.

Waveguide Type	Relative Efficiency (%)
Eclectech Soil Transducer	100
1/2" dia. aluminum rod	50
3/4" dia. steel tube	49
3/8" dia. steel rod	35
1/8" by 1" rect. steel blade (directionally sensitive)	13 (normal)
1/8" by 1" rect. steel blade	4 (oblique)
1-3/4" PVC tube	7
microphone (dry sand)	5
(damp sand)	(no signal)
3-3/4"x1/32" diaphragm (buried)	3
3/4" steel rod	(no signal)

TABLE 7. MEASURED CELERITIES IN SAND.

Sand Condition	Measured Celerities		
	C1 (ft/s)	C2 (ft/s)	C3 (ft/s)
Dry, uncompacted	10,000+	620	440
Water-Dampened	10,000+	606	520
Fuel-Dampened	10,000+	510	490

The spectral influences of sand on sound were also determined. These tests consisted of introducing a broad band 1 KHz to 10 KHz sound into dry, wet, and fuel-soaked sand. The signal source in this case closely simulates that of a 10 psi pinhole fuel leak (see Section III). A plate-mounted accelerometer, placed six inches from the sound source, was used to receive the transmitted sound. A 16,000 point digital record was made of the signal at a sampling rate of 20 KHz. Thirty-two consecutive 512 point FFTs were then averaged to obtain the spectral content of signal. Figures 21, 22, and 23 present data typical of these tests for dry, water-saturated, and fuel-saturated sand, respectively. Each sand condition returns a unique spectral pattern, presumably due to changes in the interstitial spaces. Figures 24 and 25 present similar data for water- and fuel-saturated sand with the transducer only 3 inches from a 500 Hz to 5 KHz sound source.

A general "rule of thumb" for identifying the spectrum for a signal which has traveled through fuel-soaked sand is that individual peaks appear to be somewhat more sharply defined than will be the case for equivalent transmissions through dry or water-soaked sand. This is consistent with a material having a single mode of propagation. In fact, in the case of Figure 23, a fundamental frequency can be observed near 2,000 Hz with higher harmonics occurring at 4,000 Hz and 6,000 Hz. No acoustic emissions were observed from fuel-sand interactions other than from turbulent flow.

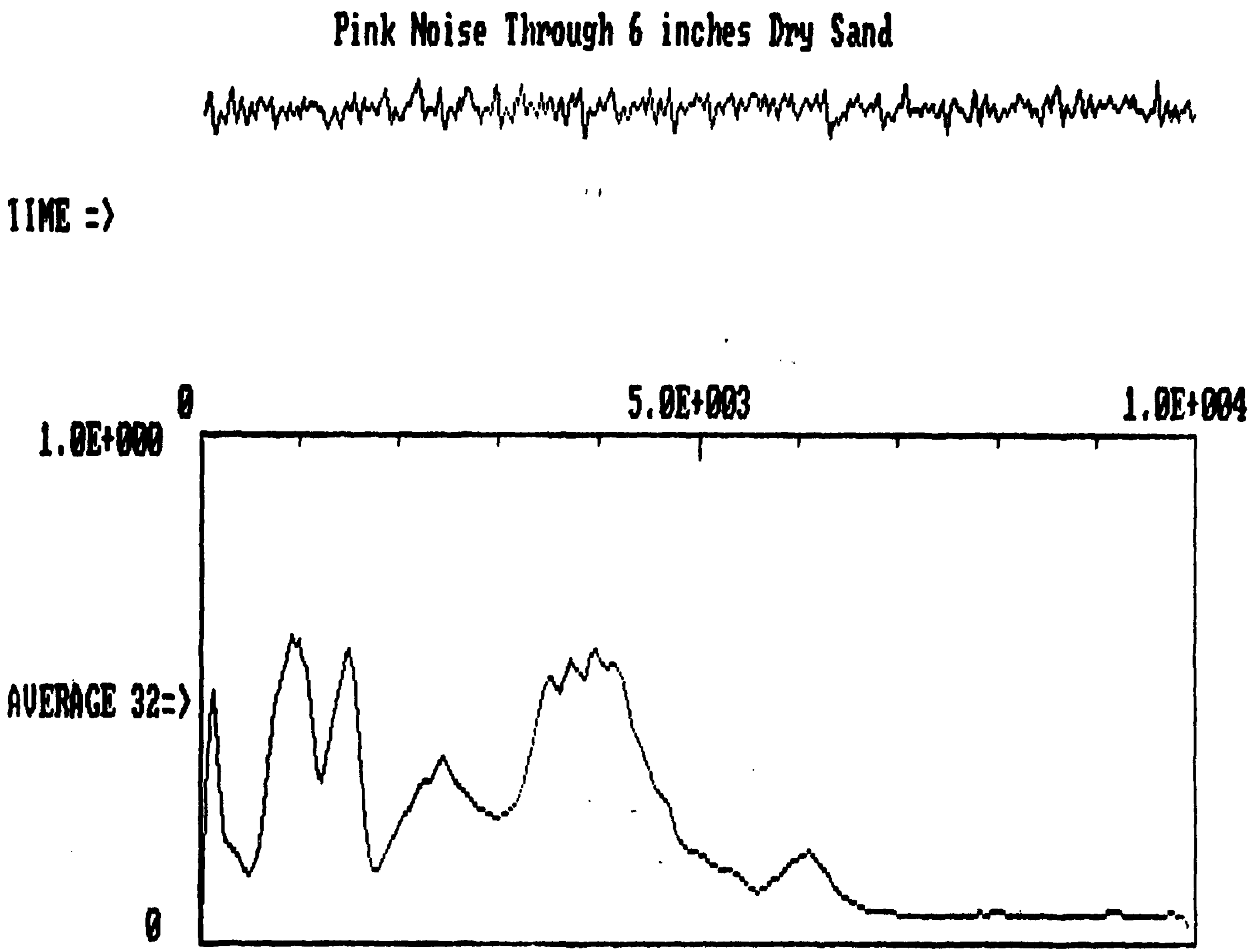


Figure 21. Attenuation of Pink Noise Through Six Inches of Dry Sand.

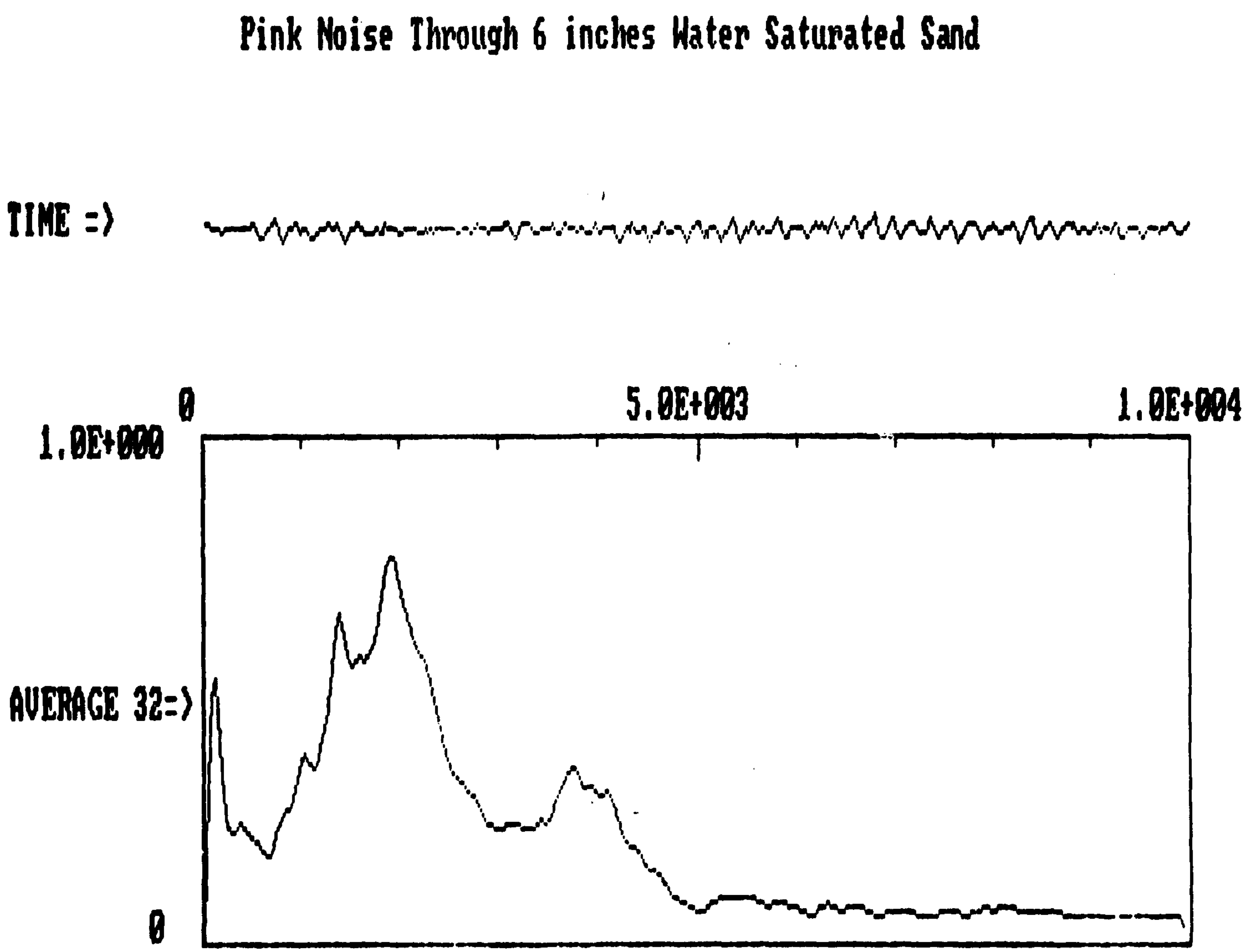


Figure 22. Attenuation of Pink Noise Through Six Inches of Water-Saturated Sand.

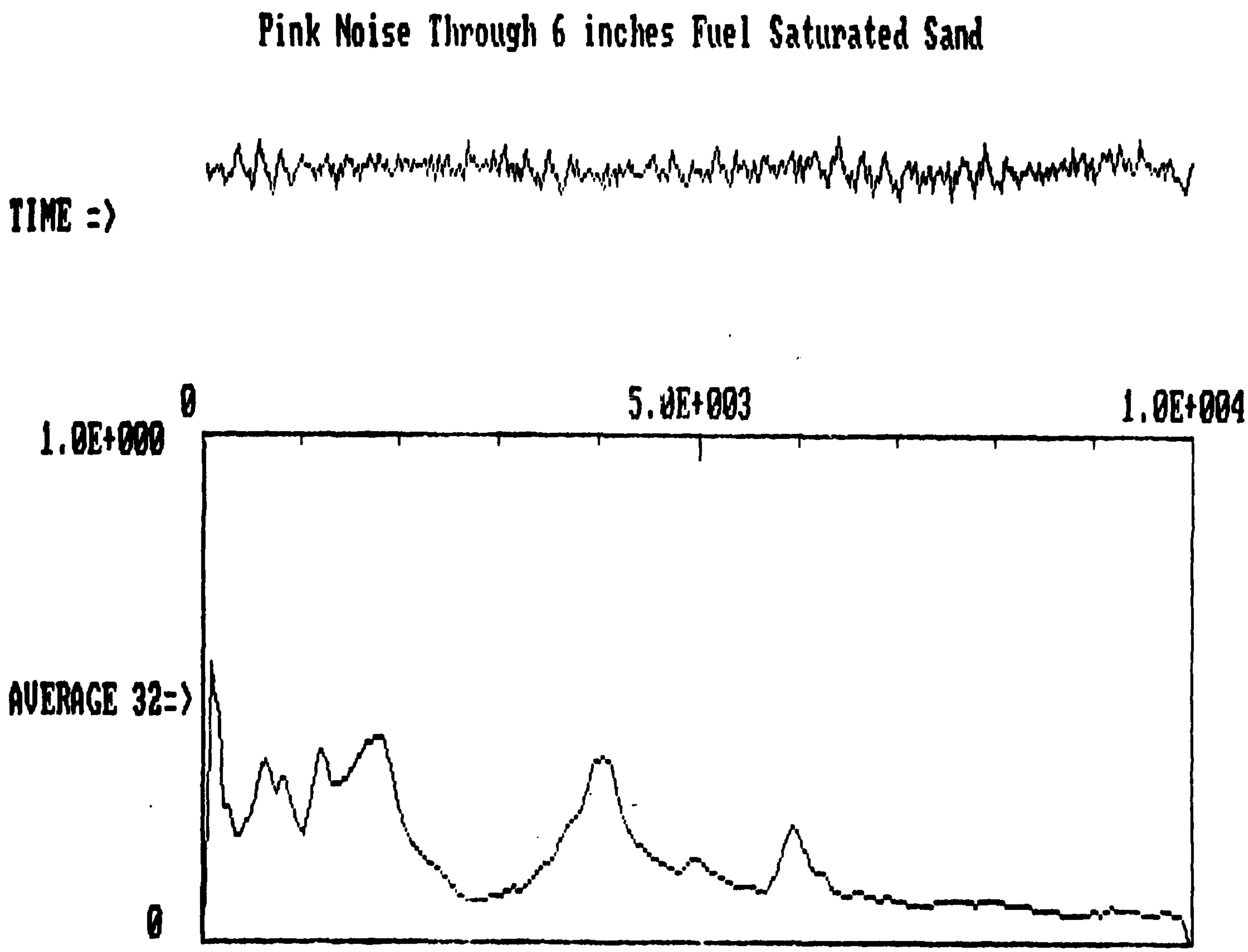


Figure 23. Attenuation of Pink Noise Through Six Inches of Fuel-Saturated Sand.

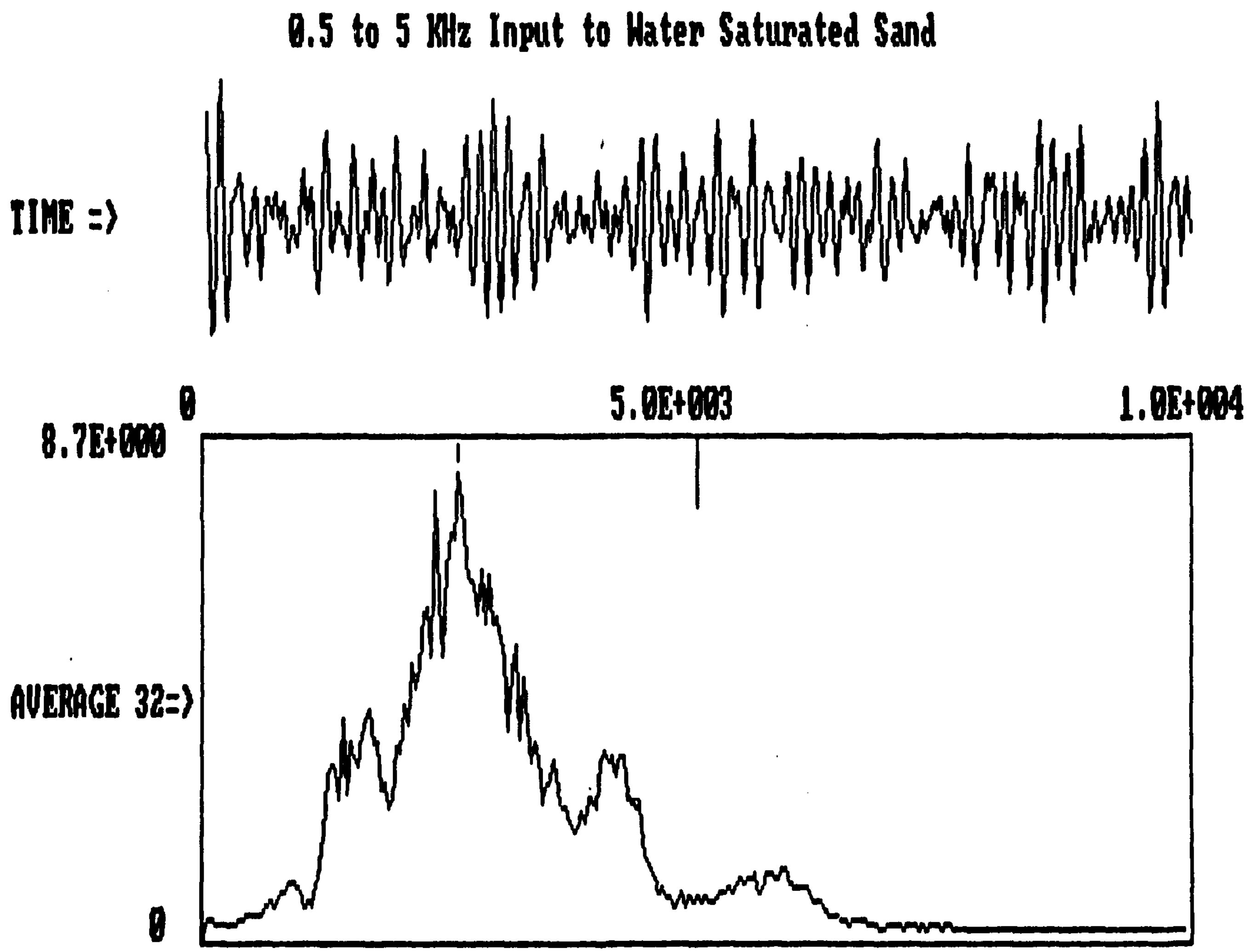


Figure 24. Attenuation of Pink Noise Through Three Inches of Water-Saturated Sand.

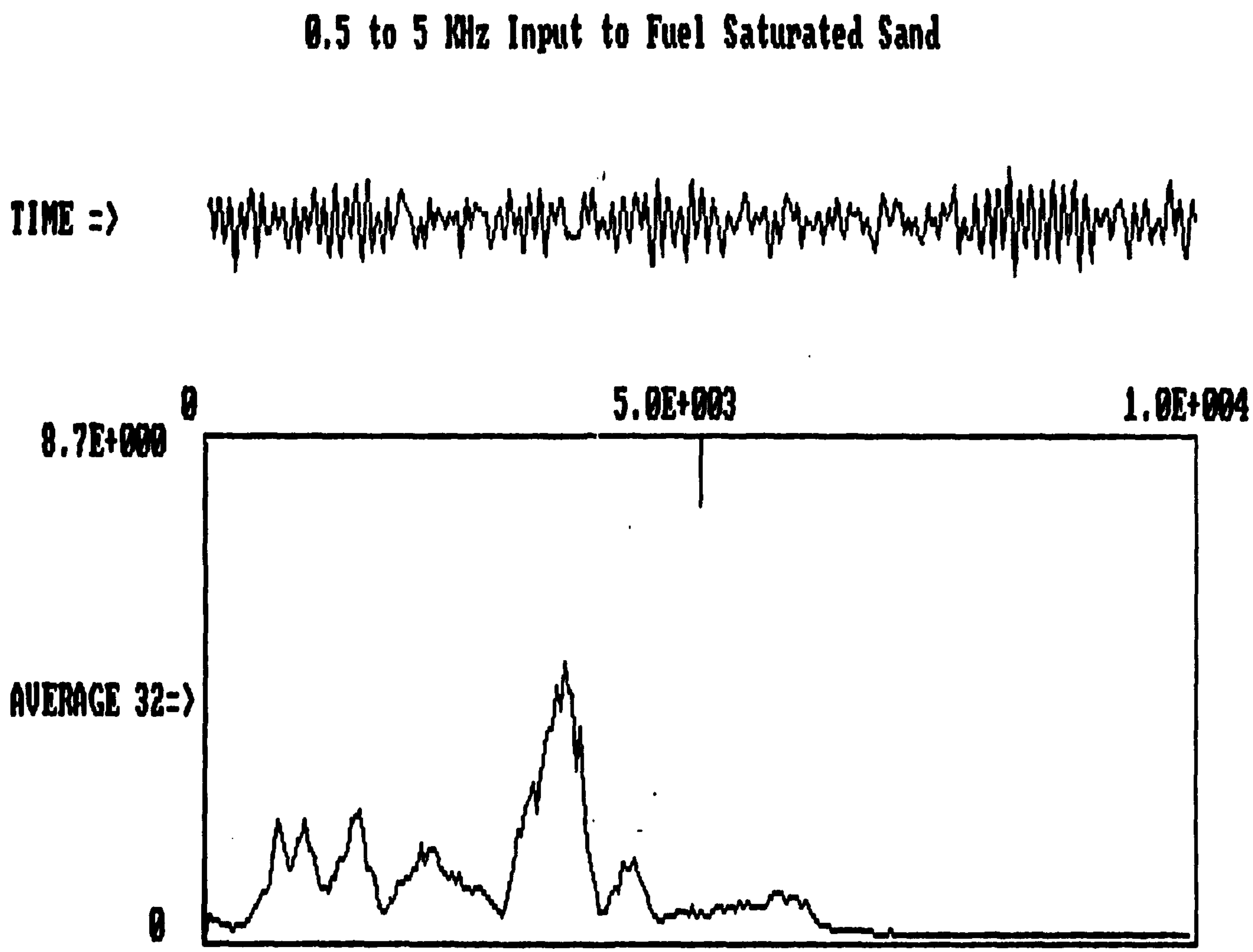


Figure 25. Attenuation of Pink Noise Through Three Inches of Fuel-Saturated Sand.

D. ACOUSTIC TESTS WITH CLAY

The clay used in the study was obtained from an excavation site in Oak Ridge, Tennessee. The clay, when obtained, was in the form of compressed, dry blocks. It was characterized as having minimum particle sizes below the optical resolution of a 150X magnification microscope. The maximum particle sizes varied, but typically the particles were inclusions of quartz or limestone with average diameters on the order of 0.05 mm. The average bulk specific density was about 1.3. The microscopic appearance was of a heterogeneous material with inclusions of both translucent and opaque particles in a reddish-brown matrix. Although the dry clay could absorb up to 50% of its volume in water, no acoustically significant interstitial free paths could be microscopically observed.

A marked difference was observed between the short term absorption rates for water and fuel in clay. When clay was exposed to water, the material rapidly absorbed the liquid and became fluidized in a matter of minutes. Fuel, on the other hand, was not rapidly absorbed by clay. For fuel, a maximum volumetric absorption ratio of less than 20% was observed after two hours of immersion. Although clay drains more slowly than sand, small (100 cc) amounts of saturated clay will dry in about 48 hours when exposed to air at ambient temperatures. Fuel-soaked clay appears to remain "contaminated" for much longer periods of time.

Dry clay, when initially exposed to either fuel or water, is acoustically active. The emissions, however, only occur for the first few minutes of exposure in water or fuel. Clay which was already damp or fuel-soaked was acoustically inactive when exposed to additional fuel or water.

Dry, compressed clay displays wavespeeds near 10,000 ft/s. The mean attenuation in dry clay is approximately 3-4 dB per foot at 5,000 Hz. The material is anisotropic and these figures will vary over different wave paths. Fluidized (water-soaked) clay appears opaque to sound with the transducers which were available. However, more work in the area of transducers and couplants is needed before a conclusion can be reached. Whole, continuous clay which has been soaked in fuel from a dry state has acoustic properties similar to those of dry clay. Dry, loose clay is extremely attenuating, with losses exceeding 50 dB per foot at 2,000 Hz. For all practical purposes it can be regarded as a barrier to leak noise.

Clay presents a real challenge with respect to the choice of an appropriate transducer. Piezoelectric transducers with hard shoes are only appropriate for use with hard, dry clay.

Soil microphones, such as the Eclectech piezofilm transducer, or waveguide-mounted piezoelectric transducers are the best choice for discontinuous damp or dry clay. The choice of a transducer for fluidized clay remains a problem for future research.

E. ACOUSTIC TESTS WITH PEA GRAVEL

The pea gravel used in our tests had particle diameters ranging from 3.0 mm to over 1.3 cm. The particles were of a widely divergent composition with both opaque and translucent particles suggesting the presence of quartz and granite. The gravel had generally smooth particle surfaces with rounded edges in a variety of geometries. The bulk specific gravity was 1.5. Roughly 50% of the bulk volume was interstitial spaces, based on the filling of these spaces with water. Free paths in the interstitial spaces were observed, with major lengths approaching 3.0 cm. Both fuel and water readily filled the interstitial spaces. Drainage of bulk fluid in both cases was rapid. The fuel, however, coated the individual pebbles.

The pea gravel was acoustically inactive in the presence of both fuel and water. However significant levels of flow noise were developed when fluids were poured through the gravel. Sound attenuation values for pea gravel were similar to those which are presented below for crushed rock. The dominant acoustic path through the material was the air space, with little sound being transmitted through the solids. Wave celerity was about 947 ft/s, which is under the speed of sound in air. The difference is probably due to the lack of a linear free air space through the gravel. For all practical purposes, including transducer selection, pea gravel can be thought of as free air space if it is not immersed.

F. ACOUSTIC TESTS WITH CRUSHED ROCK

The crushed rock which was tested had highly irregular particle shapes with sharp, rough edges. The surfaces of the particles at 50X magnification were dull and fractured with inclusions of translucent materials in an opaque, grey matrix. The larger particles had major dimensions of about 3 cm. The smallest particles had major dimensions of 0.6 cm. Particles smaller than this tended to slip into the interstitial spaces and fall, collecting at the bottom of the outdoor test bed. Due to the large range of rock sizes and shapes, free paths with dimensions well over 5 cm were observed in the interstitial spaces. The bulk specific gravity was about 1.5 with significant variations among small samples. The interstitial space was determined to be 55% to 60% of the total volume with significant variations existing among small samples.

The crushed rock filled and drained rapidly with either fuel or water. There were no significant differences in the volumetric determinations of interstitial space for fuel compared to water. The fuel, however, tended to remain in the cracks of the fractured surfaces and on the surfaces themselves as a thin film weeks after the rock was exposed to the fuel.

No acoustic emissions were observed as a result of fuel-rock interactions. However, significant levels of flow noise developed when fuel was poured through the crushed rock. The level of flow noise tended to be slightly above that seen in the pea gravel for equivalent flow rates.

Table 8 gives sound levels of pink noise (500 Hz to 5,000 Hz) in crushed rock from 1 to 5 feet. It was noted that over short distances (less than 6 inches) sound levels were actually much higher in the interstitial spaces of crushed rock for a given source than for the same source at equivalent distances in free air. This is a result of the 3 dB increase in sound pressures which typically occur in air at rigid surfaces and the 40% reduction in free space relative to open air. Beyond 6 inches, the interstitial spaces begin to act as a series of resonant air columns leading to significant attenuation of high frequency sound.

TABLE 8.- ATTENUATION OF SOUND WITH DISTANCE IN CRUSHED ROCK.

Distance (feet)	Sound Level Through Gravel (dB)
1	99
2	88
3	83.5
4	79
5	79

Figures 26 and 27 contrast the propagation of a 1,000 to 10,000 Hz pink noise through 6 inches of air compared to 6 inches of crushed rock. A broad band (20 Hz to 22 KHz) microphone was used as the sensing transducer for these tests. The crushed rock acts as an acoustic low pass filter,

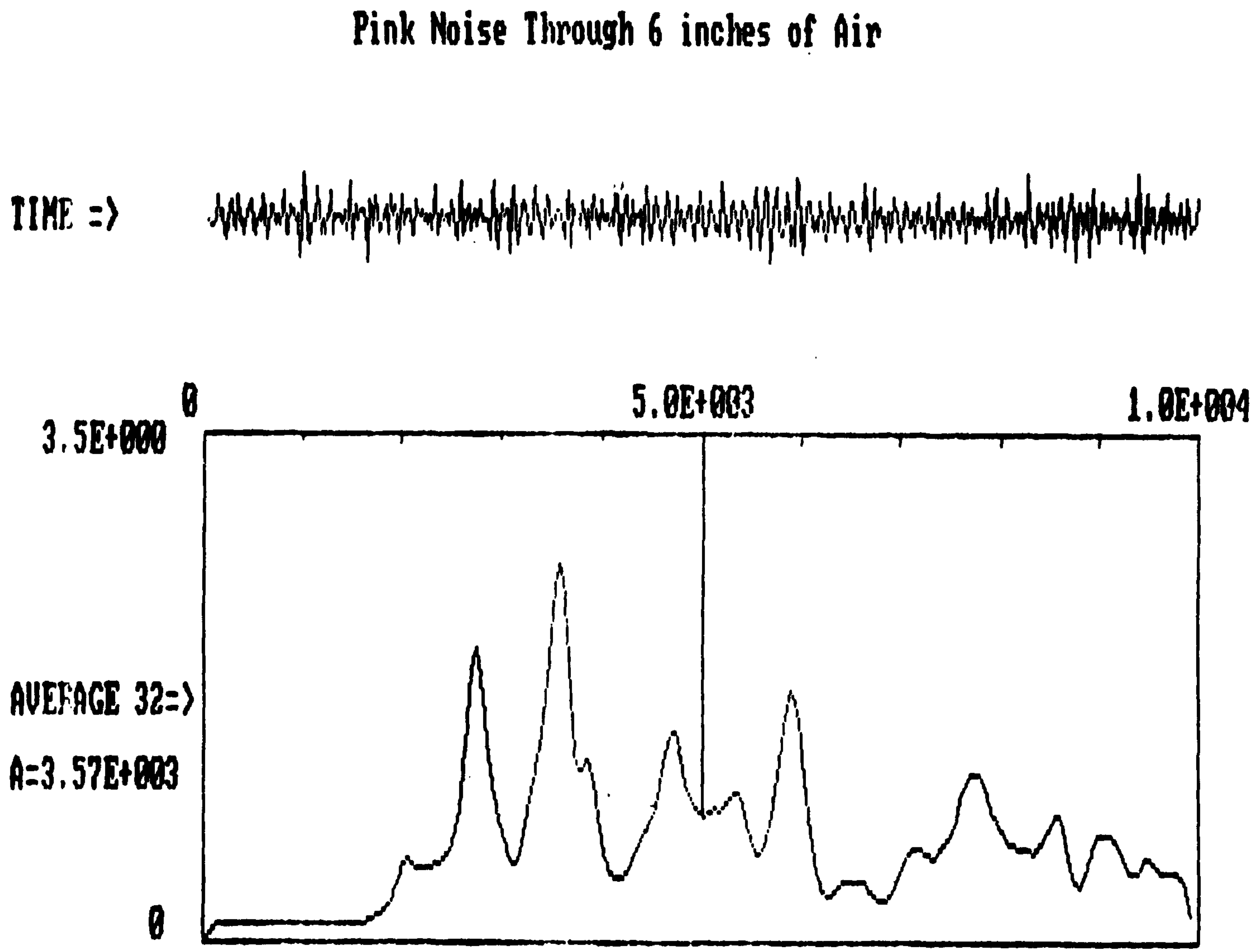


Figure 26. Attenuation of Pink Noise in Air.

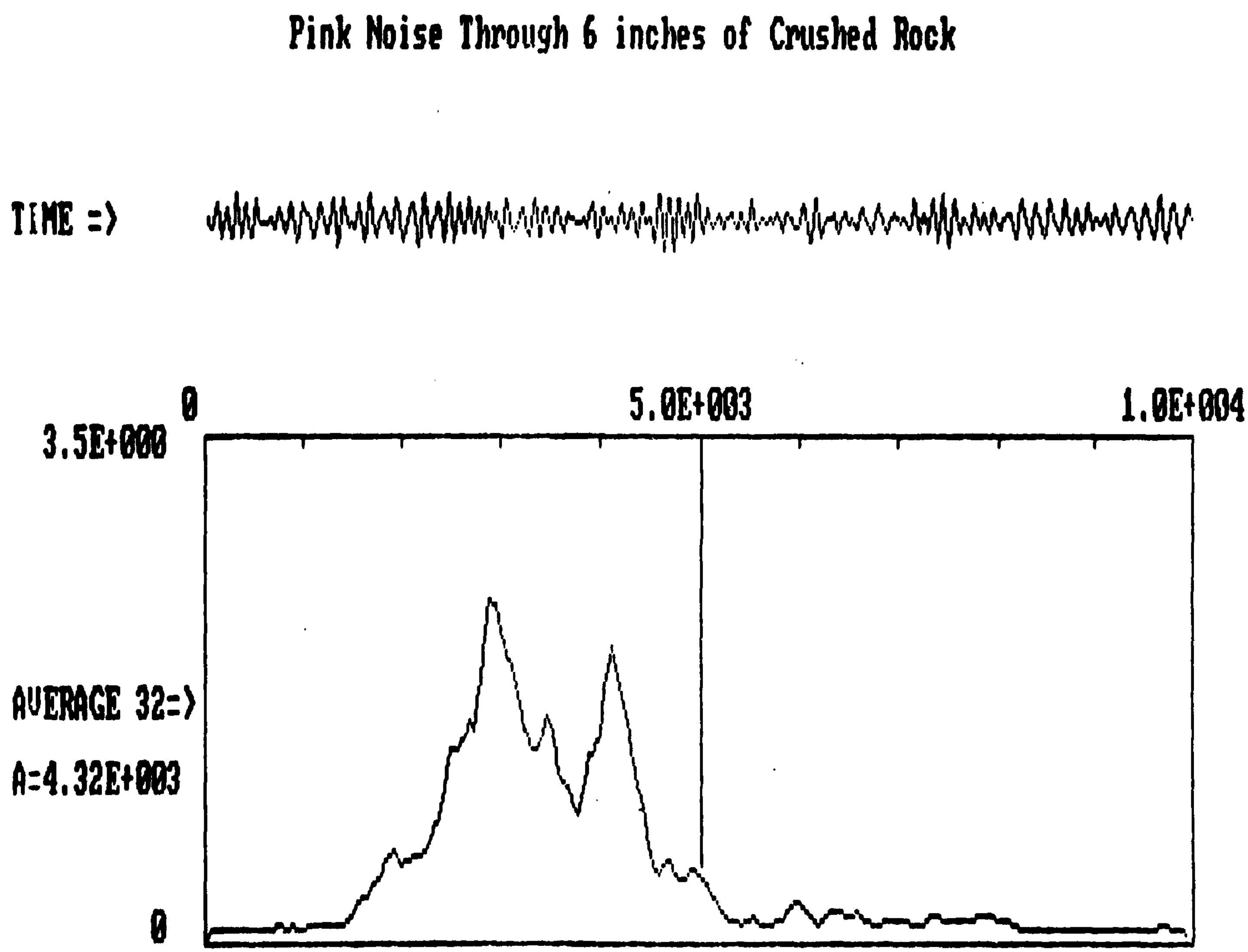


Figure 27. Attenuation of Pink Noise in Crushed Rock.

effectively removing the energy content above 5,000 Hz. In addition, the crushed rock apparently has marginally increased the average energy level below 5,000 Hz. The mean frequency of the acoustic energy after passing through the crushed rock is about 3,500 Hz. This frequency suggests that the natural resonances of the longer free air columns in the interstitial spaces have been excited. (The calculated free-free resonance for a 4.5 cm air column, for example, is 3,550 Hz.)

G. ACOUSTIC TESTS WITH ORGANIC SOIL

The content of organic soils varies widely, and each type will have significant and possibly unique acoustic and absorption properties. Consequently, we have limited our testing to measuring sound attenuation in a single sandy loam. Figures 28, 29, and 30 compare a pink noise signal after propagation through one and six inches of dry organic soil and six inches of water-saturated organic soil, respectively. The figures demonstrate extreme, frequency-dependent attenuation. The organic soil can be viewed as essentially opaque to high frequency leak noise. No acoustic emissions were detected from organic soil-fuel interaction.

H. ACOUSTIC TESTS WITH CONCRETE

Acoustic testing of concrete was also limited, because its acoustic properties are well-known from the technical literature. The tests which were conducted verified that concrete is a good conductor of sound throughout the audible range. However, above 30 KHz, attenuation in concrete becomes severe, suggesting that commercial acoustic emission leak transducers are a poor choice for monitoring leak noise through concrete.

Wavespeeds in concrete were measured by mounting two accelerometers two feet apart on a concrete slab and exciting the concrete with a broadband impact noise source about two feet from the "trigger" transducer. Both correlation functions and manual measurements of "time-of-flight" indicated phase velocities from 13,000 to 14,000 ft/s. Figure 31 presents a typical correlation plot.

Acoustic detection of leaks from piping embedded in concrete is possible throughout the audible range. However, if the piping is not in contact with the concrete, air gaps will form a very effective acoustic barrier between the source (pipe borne sound) and the concrete. The impedance mismatch across such an air barrier is such that virtually no sound will pass to the concrete.

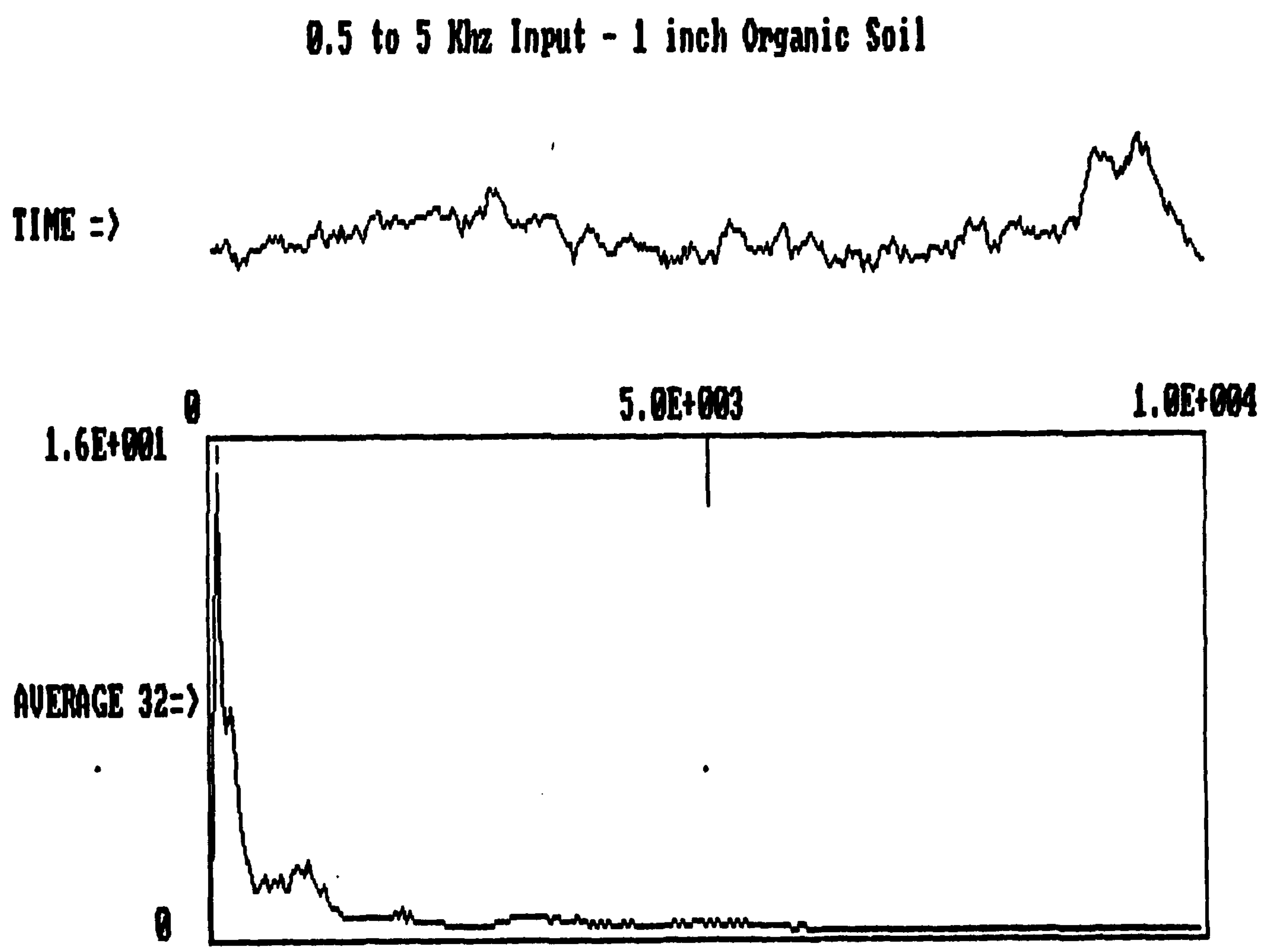


Figure 28. Attenuation of Pink Noise Through One Inch of Organic Soil.

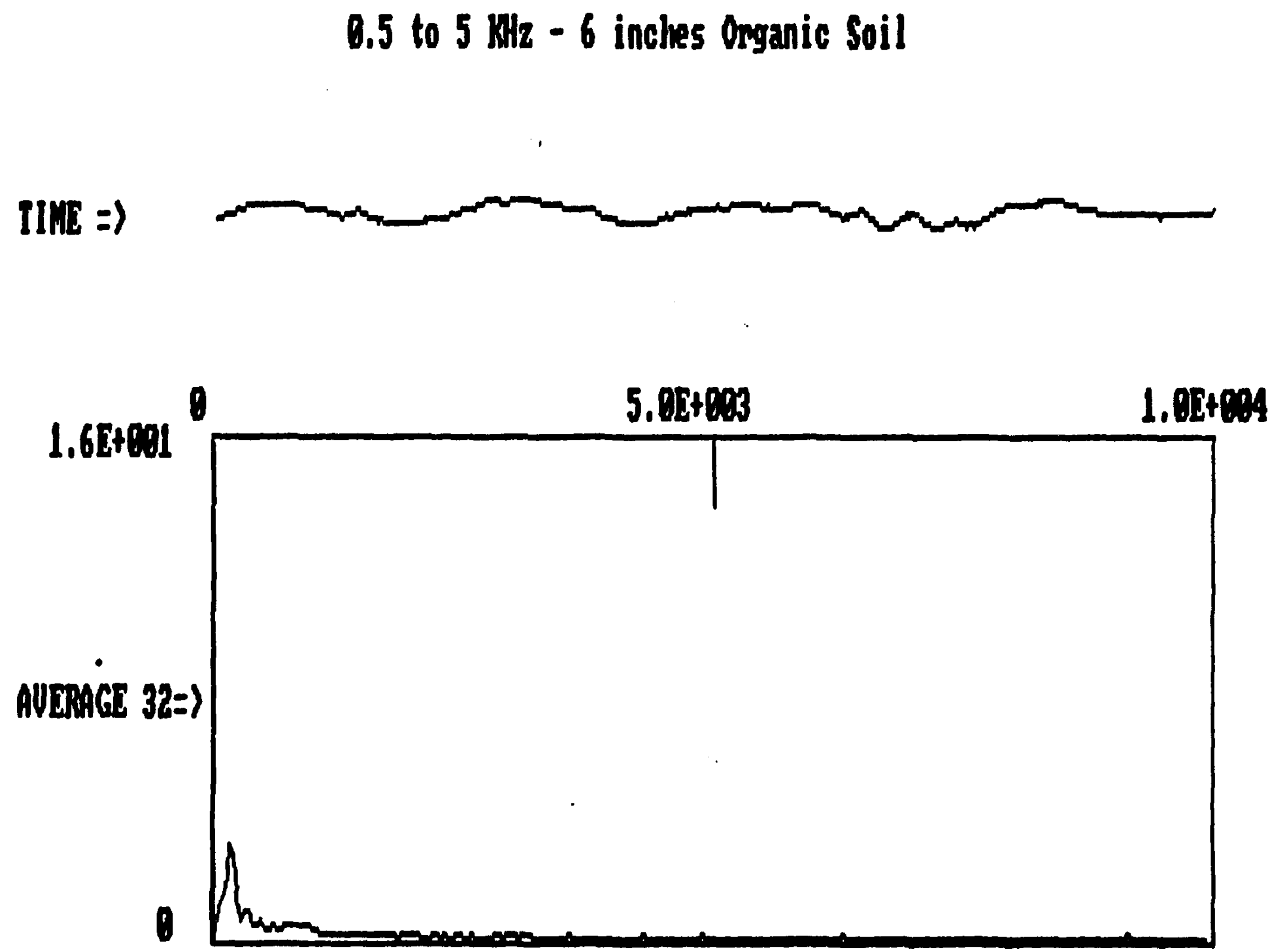


Figure 29. Attenuation of Pink Noise Through Six Inches of Organic Soil.

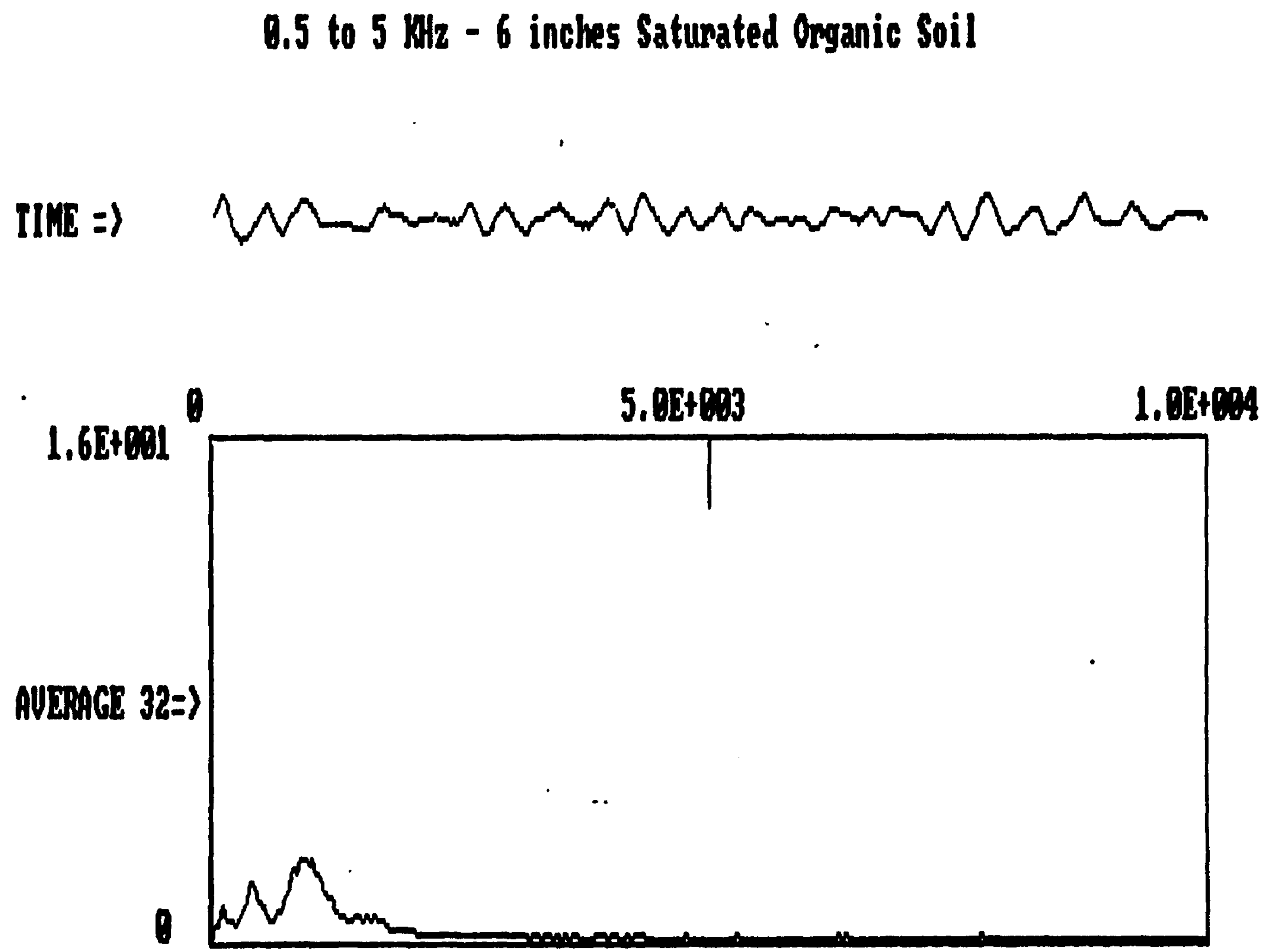


Figure 30. Attenuation of Pink Noise Through Six Inches of Water-Saturated Organic Soil.

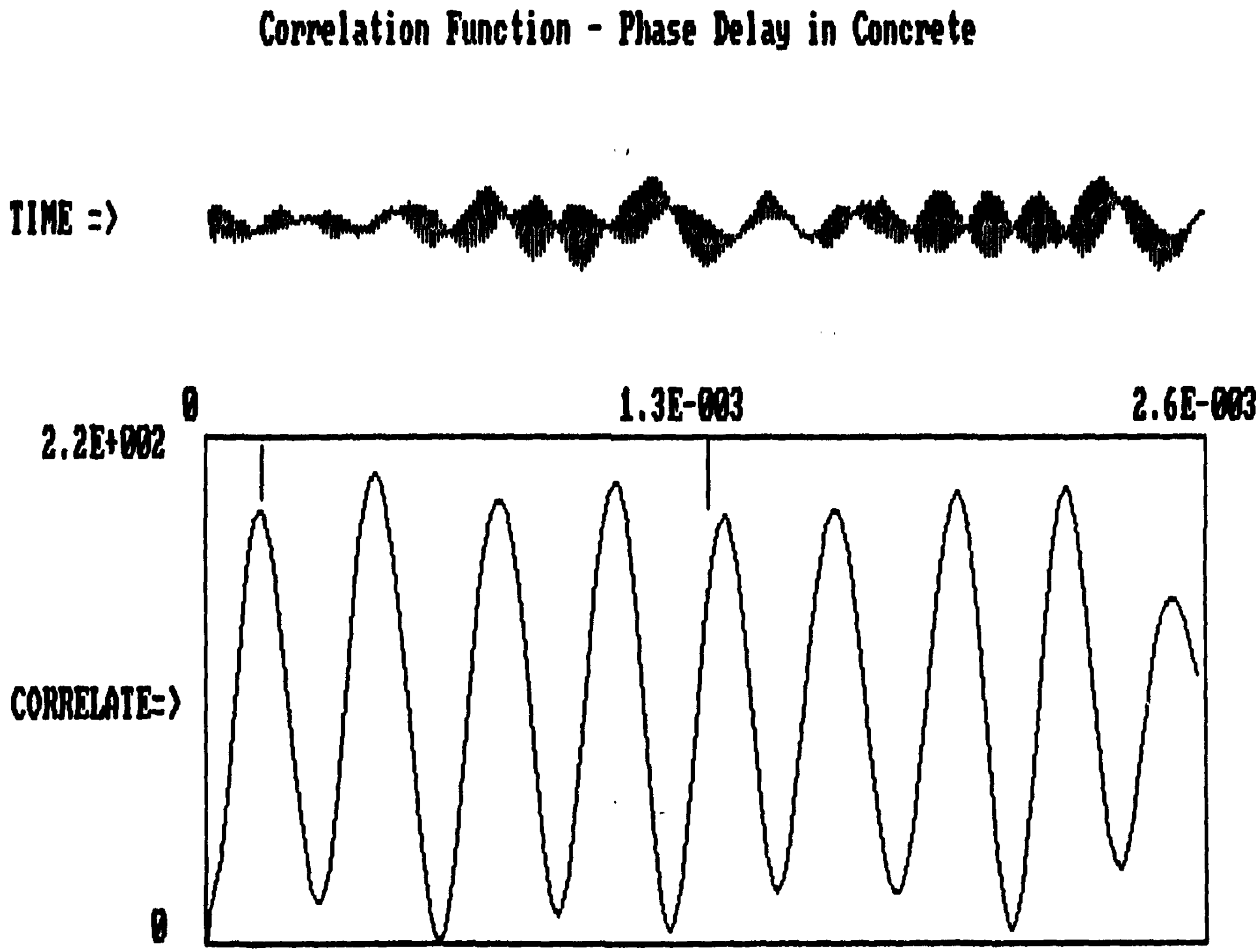


Figure 31. Correlation Function for Wave Transmission in Concrete Slab.

I. CONCLUSIONS FROM ACOUSTIC TESTS WITH SOILS

Most of the tested soil materials exhibited strong attenuation of sound in the 500 Hz to 50 KHz frequency range, which covers the range in which most pressurized leaks generate sound. Without exception, the soil materials are two-phase materials having a solid phase (the soil particles) and a fluid phase (the liquid or gas in the interstitial spaces). The loss of sound energy across such two phase interfaces will be on the order of 99% for an air-solid interface and on the order of 80% or more for a water-solid interface. Hundreds of such interfaces must be crossed per foot of propagation. Lower frequencies propagate more effectively in two-phase materials because of their greater displacements and lower particle velocities. Small gaps may be closed in the compressive half-cycle and more time is available for passage of fluids through restrictive passages, thereby allowing propagation of the pressure differentials. At high frequencies, particle displacements are small and velocities are high. Individual solid particles become disconnected resonant bodies with the more compressible fluid elements acting as localized spring elements rather than as a continuous medium.

If either the fluid or the solid phase is continuous, or nearly so, free paths without impedance mismatches will exist and the two-phase material will take on the acoustic properties of the dominant phase. This can be readily seen by contrasting dry compressed clay and crushed rock. Although both roughly consist of 50% interstitial space and 50% solid material by volume, the clay has a nearly continuous solid content with very small interstitial dimensions. The crushed rock, on the other hand, has a continuous interstitial space. Clay has the acoustic properties of a solid, while crushed rock has the acoustic properties of the fluid in the interstitial space. In the case of sand and organic soils, neither phase is continuous, all possible acoustic paths are across phase boundaries, and extreme attenuation results.

From the standpoint of acoustic leak detection through soil, little can be done to affect these acoustic properties, except by creating a continuous path with a waveguide. However, knowledge of the acoustic properties of soils can be used for monitoring at appropriate frequencies with appropriate transducer types when waveguides are not practical. Table 9 lists soils and soil conditions with suggested monitoring frequencies and transducer types for optimal acoustic performance.

TABLE 9. SUMMARY OF RECOMMENDED MONITORING RANGES AND TRANSDUCER TYPES.

SOIL TYPE	CONDITION	FREQUENCY RANGE	TRANSDUCER
Concrete	All	100 Hz-30 KHz	Accelerometer (10-20 KHz res)
Clay	Dry-comp Fuel-comp	100 Hz-30 KHz	Accelerometer (10-20 KHz res)
	Dry-loose	100 Hz-2 KHz	Piezofilm Soil (or waveguide)
	Damp-loose	100 Hz-2 KHz	Piezofilm Soil (or waveguide)
	Fluidized	?	?
Organic	All	100 Hz-2 KHz	Piezofilm Soil (or waveguide)
Sand	All	100 Hz-5 KHz	Piezofilm Soil (or waveguide)
Pea Gravel	Dry	100 Hz-5 KHz	Microphone
	Immersed	100 Hz-2 KHz	Hydrophone
Crushed Rock	Dry	100 Hz-5 KHz	Microphone
	Immersed	100 Hz-2 KHz	Hydrophone

SECTION V

SUMMARY OF RESULTS AND CONCLUSIONS

A. INTRODUCTORY REMARKS

The four primary objectives for this research were provided under "Objectives" on page 2. The following sections summarize the findings of this research with respect to the stated objectives.

B. OBJECTIVE 1

The first objective was to determine the conditions under which JP4 fuel leaks produce acoustic emissions. The JP4 fuel leaks produced acoustic emissions when differential pressures across the leak orifice were in excess of 5 PSI. This differential pressure was sufficient to produce acoustic emissions with all leak orifices tested that flowed at ambient pressures. Intermittent leaks, such as leaks from threaded and flanged pipe fittings, which only flowed at higher pressures would, of course, not be acoustically active at the low pressure. Such intermittent leaks will require higher test pressures. The minimum EPA criteria for volumetric testing, 0.1 GPH, can be met for low pressure, "in-service" leaks. A more detailed discussion of these findings is presented in Section III.

C. OBJECTIVE 2

The second objective was to determine the acoustic characteristics of JP4 fuel leaks from UST systems. The sound produced by all tested JP4 leaks was influenced by the pipe wall geometry. The dominant characteristics in spectra for leaks of JP4 were below 5,000 Hz. Water leaks contained spectra similar to JP4. Only air leaks had much higher frequency contents. Commercial high-frequency leak detection equipment is not suitable for use in detecting low-pressure leaks. A more detailed discussion of these findings is presented in Section III.

D. OBJECTIVE 3

The third objective was to measure and evaluate the acoustic transmission properties of fill materials commonly used at UST installations. Fill materials such as sand and organic soil are acoustically opaque and do not conduct leak noise. Only very large leaks may be detected through more than a foot of these soil materials. Other materials, such as pea gravel and crushed rock, have large interstitial air spaces which transmit leak sound as well, or better, than free air. A more detailed discussion of these findings is presented in Section IV.

E. OBJECTIVE 4

The fourth objective was to investigate sensor designs and sensor placements for optimizing the capability for leak detection in UST systems. For underground piping, direct transducer or waveguide contact with the pipe wall provides optimal results. Over short distances (less than one to two feet) in sand and humus, piezofilm soil transducers are capable of detecting leak noise. In general, detection of leaks through soil should only be used for determining leak location. Leak detection and monitoring should be accomplished with direct transducer placement or with waveguides. Preliminary results indicate that in the case of underground storage tanks, hydrophones placed in the fluid will detect very low noise levels.

F. DEVELOPMENT OF TRANSDUCERS AND INSTRUMENTATION

In addition to the results and conclusions presented above, this work has resulted in the design and fabrication of transducers and instrumentation for application to underground leak detection. The new equipment includes the following items:

1. Eclectech piezofilm soil transducer - This sensor was the only tested device which was capable of sensing leak noise through short distances in sand and humus.

2. Eclectech integrated waveguide/transducer - This device uses a flat aluminum waveguide and a piezofilm transducer. It can be used in easily penetrated soils such as sand. The sensor can be used to penetrate soil to obtain pipe or tank wall contact, or it can be used as a subsurface soil probe. It has directional sensitivity that should be of value in locating leaks.

3. Eclectech fuel-sensitive acoustic probe - Preliminary testing of materials for use in a fuel-sensitive acoustic soil probe has been conducted. The probe transmits ultrasound through a fuel-soluble solid element fitted into a waveguide, typically 1/4 inch or

larger. Fuel, or other petroleum products, can be distinguished from water or air by the softening of the fuel-sensitive portion of the waveguide and the resultant changes in the frequency response of the waveguide tip. The basic Eclectech electronics developed for this study are capable of driving this probe. Results from preliminary tests of this technology are encouraging.

4. Computer-based instrumentation - During this Phase I effort, the core software and hardware for passive acoustic leak detection have been developed. The system is based on software which drives a high-speed analog to digital converter (A/D) and an arbitrary waveform generator (AWG). The system uses an IBM PC-compatible microcomputer and it can be configured as a portable or desktop system. Current specifications include two channel data acquisition, with sampling rates from 2 KHz to 20 MHz; "bandshifting" of either very high or very low frequency sounds into the audible (20 Hz to 20 KHz) range; acoustic emissions monitoring for very low-level or infrequent acoustic events; signal analysis, including frequency response functions, FFTs, time domain correlation, and spectral integration; graphical representation of raw data and signal analysis results; and data storage and retrieval.

SECTION VI

RECOMMENDATIONS FOR DETECTING AND LOCATING LEAKS FROM UNDERGROUND PETROLEUM STORAGE FACILITIES

A. INTRODUCTORY REMARKS

Two distinct, and not necessarily similar, tasks are involved in preventing environmental and financial damage from underground petroleum leaks. The first of these tasks is the realization of a leak monitoring system which would, ideally, be functional during normal facility operations. The second task involves the determination of the nature and location of the detected leak with a minimum of facility downtime. Obviously, leakage from buried piping as well as the storage vessel must be considered for a viable leak monitoring system.

B. METHODS FOR PASSIVE LEAK MONITORING OR DETECTION

As the previous sections of this report indicate, acoustic leak detection methods are most applicable for detection of leaks in pressurized piping and storage vessels. Previous comments have addressed the negative implications of the extreme attenuation of sound in sand with reference to passive leak detection through the sand. There is, however, a positive implication. Just as the sand prevents transmission of sound from the leaking pipe to a distant transducer, it also prevents transmission of air-borne and ground-borne background noise to the pipe. Piping buried in more than 2 feet of sand in the soil test facility was virtually immune to air-borne sound levels of over 100 dB, for frequencies over 1,000 Hz (see Figure 32). Leak noise as modified by the natural resonances of the piping typically contains significant energy above 1,000 Hz, as discussed in Section III. This provides an ideal environment for detection of leaks with transducers mounted on pipe walls or transducers mounted on waveguides which contact the pipe walls.

Two main sources of environmental noise are capable of exciting the higher modes of pipe resonance and thereby masking leak noise. These are turbulent flow conditions in the piping and direct pipe wall contact with high frequency noise sources. High product flow velocities and pump noises will probably be the limiting conditions for real-time, in-service acoustic monitoring systems. Such systems may still be acoustically tested by taking the system (and pumps) out of service. There should be little difficulty in monitoring for leakage when these conditions are not present in a pipeline with leak differential pressures of 5 PSI or above. High ground water levels produce backpressure, and even higher absolute system

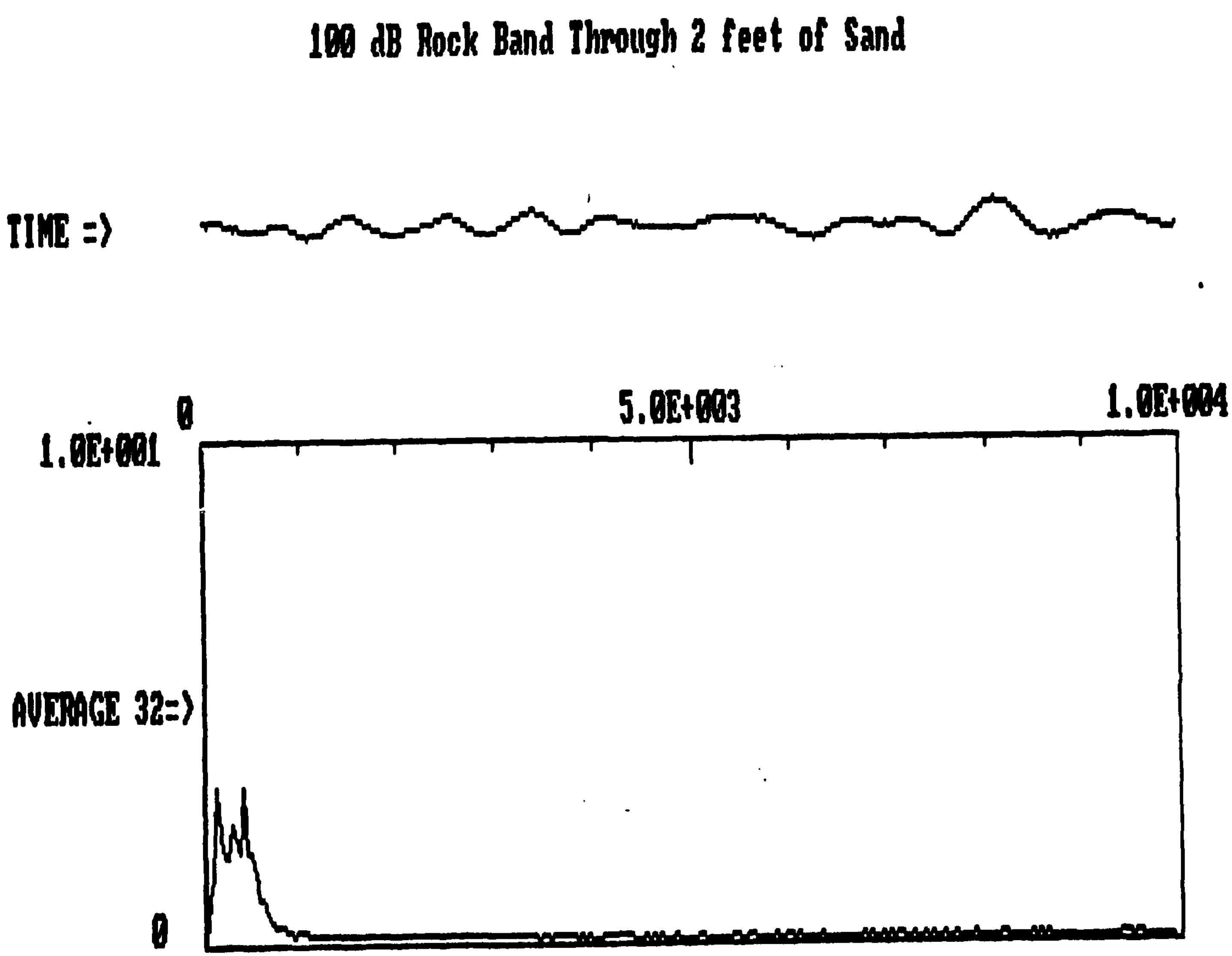


Figure 32. Attenuation of High Ambient Noise.

pressures would be required. In standard piping with 25 pound fittings, it should always be possible to pressurize sufficently for test purposes if the piping can be pressurized without damage to other system components.

Passive acoustic methods are not feasible for in-service monitoring of underground storage systems operated at ambient pressures or where significant flow or pump noise exists. Leakage occurring at elevations within about ten feet of the highest fuel elevation could have silent laminar flow, which would not be detected with passive acoustic techniques. If the UST system cannot be pressurized for test purposes, alternative leak detection techniques must be considered.

C. METHODS FOR ACTIVE ACOUSTIC LEAK DETECTION

The present study did not conclusively identify a reliable method of active acoustic leak detection. Introducing a sound into a fluid contained in a pipe and then attempting to detect the sound in the soil surrounding a leak site was unsuccessful because the sand attenuated this signal, just as it attenuated the leak noise. At high levels of intensity, the sound radiated from the pipe walls, with no discernable difference at the leak site.

The acoustic properties of sand were examined with dry sand, water-saturated sand, and fuel-saturated sand (see Section IV). Although relative differences were readily apparent in a carefully controlled environment, further study will be necessary to apply this knowledge to leak detection under field conditions.

A preliminary analytical exploration of an intrusive, active leak detection system for piping systems was also conducted. Every piping system has characteristic natural frequencies for oscillations of pressure within the contained fluid. These resonant frequencies, which depend on the system geometry, the compressibility of the fluid, and the elasticity of the pipe walls, will be affected by leaks in the piping. Thus, it may be possible to detect leaks by exciting and monitoring the natural frequencies of the contained fluid. Eclectech can develop this approach through both computer modeling and actual testing. This technique merits additional research to define its sensitivity and to demonstrate its practicality.

D. METHODS FOR DETERMINING LEAK LOCATION

Two methods were developed and tested for determining leak location when the leak discharge is from a pressurized system. Both methods are passive and can be used as components of a portable leak locating system. These methods, when used together, are capable of reliably locating leaks from pressurized underground storage facilities if the leaks are within one foot of the surface or if the soil (such as sand) can be penetrated by waveguides. The first method, leak detection from the surface, employs the Eclectech soil transducer. The survey is conducted by simply placing the transducer on the soil surface above the suspect pipe. If an acoustically active leak exists within about one foot of the transducer, there is a high probability of detection. Large fuel leaks on the order of 65 GPH at 30 PSI can be detected to distances approaching 2 feet. Because of the extreme attenuation of the leak noise in sand and organic soils, leak detection with this method is equivalent to determining leak location. Alternatively, the leak can be pinpointed by moving the transducer on the surface until the the spectral content of the sound has the highest observed frequency components. Because sound is more strongly attenuated at higher frequencies in sand, the surface location at which the highest frequency was observed will be the closest surface point to the leak.

The Eclectech integral waveguide/transducer provides a means for locating leaks which occur more than 1 foot below the surface in soils, such as sand, which can be easily penetrated by a thin waveguide. The instrument may be used in direct contact with the pipe or tank surface or to search in the subsurface soil for ground-borne leak noise. Again, detection of ground-borne leak noise is equivalent to determining leak location in sand because of the very high attentuation.

E. RECOMMENDATIONS FOR FURTHER DEVELOPMENT

A significant amount of work remains to be done before a complete acoustic leak detection package can be produced. The most obvious portion of the effort is the need for the field testing and "de-bugging" of existing equipment and the evaluation of the acoustic characteristics of large fuel storage tanks.

The fundamental concern with storage tanks, as opposed to piping, concerns not leak noise generation, which will involve identical sound generating mechanisms, but the effect of the tank on the generated sound and the identification of optimal methods for sensing the sound. A variety of actual tanks should be examined in the field for acoustic properties using simulated leak noises injected into the tank at locations where leaks are most likely to occur. The field examinations should be preceded by a brief large-scale model study to ensure that all pertinent factors are included in the field examinations. The work should include:

1. Fabrication and preliminary testing of a large model with dimensions of about 2 wavelengths of the mean anticipated emission sound;

2. Determination of the acoustic characteristics of tanks under field conditions, including the contributions of tank wall material, tank wall geometry, soil contact, product level, tank fittings, and sound source (leak) location;

3. Identification of optimal transducer placement locations including examinations of exterior tank wall placement, interior tank wall placement, placement on tank fittings (such as the drop tube), and placement in the contained fuel (hydrophone);

4. Investigation of background noise levels which will undoubtedly be much higher in tanks than in buried piping.

Software and instrumentation for automated UST system leak monitoring and/or testing should also be developed. Because some tank systems may not be able to support adequate test pressures for generating acoustic emissions, the development effort should include examination of alternative technologies for leak detection, such as level detection and the Eclectech acoustic probe. This effort should produce a working, field-tested, prototype leak detection system for EPA evaluation and approval.

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APPENDIX A

LEAK DETECTION BY ACOUSTIC EMISSIONS MONITORING: AN ANNOTATED BIBLIOGRAPHY

INTRODUCTION

This annotated bibliography provides summaries of articles related to the current project, "Leak Detection by Acoustic Emission Monitoring." The bibliography is organized into five sections. This introductory section provides information on the organization of the bibliography. The second section includes a number of examples from the wide range of literature available on the general topic of acoustic emissions. The third section includes articles on the generation and transmission of acoustic emissions in soil. The fourth section provides general information on leak detection, especially leak detection for underground storage tanks, and the fifth section focuses on acoustic methods for leak detection.

ACOUSTIC EMISSIONS (GENERAL)

Drnevich, V.P., and Gray, R.E., Eds., Acoustic Emissions in Geotechnical Engineering Practice, ASTM STP 750, American Society for Testing and Materials, Philadelphia, 1981.

> This volume contains the papers presented at an ASTM symposium in Detroit on 24 June 1981. The papers include a review of acoustic emission techniques as applied to rock structures and several papers describing the application of acoustic emissions to soil monitoring. (The soil monitoring papers are described in another section of this bibliography.)

Fowler, T.J., "Acoustic Emission Testing of Vessels and Piping," Chemical Engineering Progress, Vol. 83, No. 5, May 1987, pp. 25-32.

> The article provides a brief, but thorough, discussion of AE techniques for proof testing of vessels and piping, periodic inspection of in-service tanks, continuous monitoring, and requalification testing. Difficulties presented by background noise, attenuation, and acoustic geometry are also discussed.

Hardy, H.R., and Leighton, F.W., Eds., *Proceedings of the First Conference on Acoustic Emission/Microseismic Activity in Geologic Structures and Materials*, Trans Tech Publications, 1977.

Papers included in these proceedings describe laboratory, field, and analytical studies on acoustic emissions from rocks and soils. Several relevant papers are reviewed below.

Hardy, H.R., and Leighton, F.W., Eds., *Proceedings of the Second Conference on Acoustic Emission/Microseismic Activity in Geologic Structures and Materials*, Trans Tech Publications, 1980.

Papers included in these proceedings describe laboratory, field, and analytical studies on acoustic emissions from rocks and soils. Several relevant papers are reviewed below.

Hardy, H.R., and Leighton, F.W., Eds., *Proceedings of the Third Conference on Acoustic Emission/Microseismic Activity in Geologic Structures and Materials*, Trans Tech Publications, 1984.

Papers included in these proceedings describe laboratory, field, and analytical studies on acoustic emissions from rocks and soils. Several relevant papers are reviewed below. An extensive "Master Bibliography" is also provided.

Mowrey, G.L., "Computer Processing and Analysis of Microseismic Data," in Hardy and Leighton (1977), pp. 427-444.

This paper discusses aspects of signal processing for acoustic emission data, including analog to digital conversion and source location.

Nakamura, Y., "Detection and Analysis of Acoustic Emission Signals," in Hardy and Leighton (1977), pp. 445-458.

A brief review of AE detection and analysis techniques is presented. Topics addressed include frequency range, transducers, multiple-transducer applications, noise rejection, and source location. AE signals are interpreted on the basis of event counting (which may be weighted by signal amplitude or signal energy), RMS level, frequency spectrum, and amplitude distribution.

Spanner, J.C., Acoustic Emission Techniques and Applications, Intex, Evanston, Illinois, 1974.

This text gives a comprehensive (but dated) overview of acoustic emission monitoring. The term "acoustic emissions" is used by the author to describe monitoring of materials for ultrasound produced by localized, microscopic failures of material bonds which typically occur during plastic deformation in metals. The text discusses a broad range of experimental and applied work in the field. Topics covered include emission sources, propagation, sensor-medium coupling, signal conditioning, readout methods, material research applications, weld monitoring applications, structural integrity applications, geological applications, and AE instrumentation.

ACOUSTIC EMISSIONS IN SOIL

Environmental Protection Agency (EPA), "Acoustic Monitoring to Determine the Integrity of Hazardous Waste Dams," Report No. EPA 625/2-79-024, Industrial Environmental Research Laboratory, Cincinnati, Ohio, August 1979.

This report presents results from tests to demonstrate the utility of acoustic emission monitoring for assessing dam soil stability. Emissions are produced by individual soil particles moving with respect to one another and producing noise. Most emissions occurred in the 2,000 Hz to 3,000 Hz range. Attenuation in soils increased sharply with frequency. In laboratory tests, the average signal amplitude in sand at failure was one hundred times greater near failure than at twenty percent of the failure stress. Signal levels in clay were 1/2 to 1/400 the level of signals in sand. Eighteen field sites, including a flood control dam, an ore stockpile, a tailings dam, a chemical waste containment, a petroleum waste containment, and a sludge lagoon, were also monitored. Rods, pilings, rebars, casings, and pipes were used as waveguides. Piezoelectric accelerometers were typically used as AE transducers. Results were generally acceptable, indicating

that AE monitoring in soil can provide important information for dam stability, seepage detection and location, repair monitoring, and location of instability. Information on system cost is also provided.

Huck, P.J., and Koerner, R.M., "Acoustic Emission Monitoring of Soil and Rock Grouting," ASTM STP 750, American Society for Testing and Materials, Philadelphia, 1981, pp. 155-163.

Laboratory and field studies indicated that the monitoring of acoustic emissions could be used to help control the injection pressure during a grouting operation and to monitor for seepage flow through the grouted region. Monitoring for seepage flow required a quiet site. The authors reported, "Acoustic emission detection of groundwater seepage is, however, still in its infancy, and much remains to be learned."

Koerner, R.M., Lord, A.E., McCabe, W.M., and Curran, J.W., "Acoustic Emission Behavior of Granular Soils," Journal of the Geotechnical Engineering Division, Vol. 102, No. GT7, American Society of Civil Engineers, July 1976, pp. 761-773.

A brief overview of the use of acoustic emissions for geotechnical monitoring is provided. Results are reported from laboratory tests measuring acoustic emissions from stressed soil specimens tested in unconfined compression. Wave speeds from 400 ft/s to 800 ft/s, depending on density and water content, were measured in granular soil. The waves were characterized as "accumulations of all types of waves (P, S, and R) generated at the individual sites within the soil mass." Silty sand soil exhibited emissions which were predominantly in the 500 Hz to 2 kHz region for unconfined compression. Triaxial shear creep tests performed on the same soil at a higher water content exhibited emissions which were predominantly in the 4 kHz to 8 kHz region. Attenuation of acoustic emissions in soil was shown to be frequency dependent, with more rapid attenuation occurring at higher frequencies. Below 1 kHz, attenuation values ranged from 0.2 dB/ft to 40 dB/ft, and, above 1 kHz, attenuation values ranged from 100 dB/ft to 300 dB/ft. Granular soil samples with more angular particles produced more pronounced acoustic emissions.

Koerner, R.M., Lord, A.E., and McCabe, W.M., "Acoustic Emission Behavior of Cohesive Soils," Journal of the Geotechnical Engineering Division, Vol. 103, No. GT8, American Society of Civil Engineers, August 1977, pp. 837-850.

Results from laboratory tests with cohesive soils are reported. Soils included clayey silt, kaolinite clay, silty clay, and Bentonite clay. Attenuation of acoustic emission signals decreases with increased water content in cohesive soils. For one type of cohesive soil, attenuations of 57 dB/ft were measured in dry soil, and attenuations of 30 dB/ft were observed for a water content of 15%. The average amplitude of the observed emissions was 2 to 400 times lower than from granular soils (sand). A high pass filter set at 1,000 Hz is recommended for field testing if the level of background noise is high. The predominant frequencies for the acoustic emissions in clayey silt were in the range from 2 kHz to 3 kHz for both unconfined and confined compression tests.

Koerner, R.M., Lord, A.E., and McCabe, W.M., "Acoustic Emission Studies of Soil Masses in the Laboratory and Field," in Hardy and Leighton (1977), pp. 243-256.

Laboratory studies with large soil masses and field experiences with AE soil monitoring are summarized. The effects of metal waveguides on the measured acoustic signals were examined experimentally. Koerner et al. (1981) provides a more comprehensive summary of this information.

Koerner, R.M., Lord, A.E., and McCabe, W.M., "The Challenge of Field Monitoring of Soil Structures Using AE Techniques," in Hardy and Leighton (1980), pp. 275-290.

Laboratory and limited field experiences with AE soil monitoring are summarized. Instrumentation for a typical field test is described. Koerner et al. (1981) provides a more comprehensive summary of this information.

Koerner, R.M., McCabe, W.M., and Lord, A.E., "Acoustic Emission Behavior and Monitoring of Soils," _Acoustic Emission in Geotechnical Engineering Practice_, ASTM STP 750, American Society for Testing and Materials, Philadelphia, 1981, pp. 93-141.

This is a "state-of-the-art" paper on AE activity in soils. Results are presented from a variety of small-scale and large-scale laboratory tests, as well as case histories of field studies. Typical instrumentation included wave guides (1/2-inch diameter steel rods), ceramic-style AE sensors, a preamplifier, a band-pass filter, an amplifier, a counter, an oscilloscope, and a recorder. Sand was found to emit the largest number of AE events and the highest amplitude AE events, followed by silt and clay. Three important factors in soil AE monitoring include the signal strength of the acoustic emissions produced in soils, the frequency content of the emissions, and the attenuation of the acoustic emissions in soil. The predominant frequencies for acoustic emissions in soil were from 250 Hz to 8,000 Hz, with some frequency content around 100 kHz. Soil strain correlated positively with AE events. In a laboratory test of a model footing placed on dry sand, the bearing capacity failure of the footing was accompanied by a dramatic increase in the number of AE events. Acoustic emissions were also shown to correlate with seepage flow rate in an exponentially increasing manner.

The field tests described in the paper included AE monitoring to determine dam and embankment stability at sixteen sites; settlement and deformation monitoring at four sites; seepage monitoring at five sites; and grout and hydrofracture monitoring at three sites. For some field tests, existing structures such as borehole casings, reinforcing rods, and pipes were used as waveguides. Heavy rainfall was observed to increase the AE count rate. The authors identified background noise as the most troublesome feature of AE monitoring in soils. Three suggestions for minimizing the influences of background noise include filtering on the basis of selected frequencies; providing a "floating threshold" which depends on the rise time of the signal; and physical shielding of the sensor, for example by using a downhole AE sensor.

Koerner, R.M., Lord, A.E., and McCabe, W.M., "Acoustic Emission Monitoring of Soil Stability," Journal of the Geotechnical Engineering Division, Vol. 104, No. GT5, American Society of Civil Engineers, May 1978, pp. 571-582.

Results from this research are presented in Koerner et al. (1978).

Nyborg, W.L., Rudnick, I., and Schilling, H.K., "Experiments on Acoustic Absorption in Sand and Soil," Journal of the Acoustical Society of America, Vol. 22, No. 4, July 1950, pp. 422-425.

Experiments were conducted to determine the acoustic absorption of sand and soil in the 10 kHz to 100 kHz range. In water-saturated soils, the attenuation coefficients depended markedly on the amount of gas present in the mixture.

Tanimoto, K., and Nakamura, J., "Studies of Acoustic Emission in Soils," ASTM STP 750, American Society for Testing and Materials, Philadelphia, 1981, pp. 164-173.

Acoustic emissions from soil undergoing triaxial compression tests were correlated with the rate of axial strain and with the work done by the external stresses. The tests used a dry, sandy soil (decomposed granite). A high pass filter, set at 1 kHz, was used to eliminate mechanical noise.

Tanimoto, K., and Nakamura, J., "Use of AE Technique in Field Investigation of Soil," in Hardy and Leighton (1984).

This paper summarizes Tanimoto and Nakamura (1981) and provides additional information on results from field investigations of soil, in which an instrumented (internal AE transducer and preamplifier) cone penetrometer was passed through alternating layers of sand and clay. Using AE count rate, the researchers easily distinguished between layers of pure sand and pure clay, but experienced difficulty in distinguishing layers of fine sand from layers of sandy clay.

Villet, W.C.B., Mitchell, J.K., and Tringale, P.T., "Acoustic Emissions Generated During the Quasi-Static Cone Penetration of Soils," ASTM STP 750, American Society for Testing and Materials, Philadelphia, 1981, pp. 174-193.

An active technique was developed for characterizing soils. A rigid metallic cone was pushed into soil samples (sand), and the acoustic emissions produced by the soil grains were monitored and analyzed. The analysis included determining peak-to-peak voltages, root-mean-square voltages, and frequency distributions. Frequency distribution curves depended on the level of confining stress and the penetration rate. Higher signal amplitudes were observed for the dry sand samples compared to the saturated sand samples.

LEAK DETECTION (GENERAL)

Chen, M.L., and Martin, H.R., "Pipeline Leak Detection Using System Identification," Proceedings of the 4th International Modal Analysis Conference, Los Angeles, CA, Volume I, Union College, Schenectady, New York, 1986, pp. 624-628.

A technique is described for detecting leaks in a pipeline by exciting the pipeline with a pressure signal and measuring its frequency response. The paper presents a theoretical analysis and an experimental study of a simple piping system with an arbitrarily positioned leak. The theoretical results demonstrate that the amplitude of the imaginary portion of the frequency response function varies with leak magnitude. The experimental results are suggestive, but not conclusive.

Cole, E.S., "Methods of Leak Detection: An Overview," Journal of the American Water Works Association, Vol. 52, pp. 73-75, February 1979.

The author provides a brief review of leak detection methods, including a table of U.S. patents granted from 1935 to 1976 for leak detection methods or devices.

Environmental Protection Agency (EPA), "Underground Storage Tanks; Proposed Rules," Federal Register, Vol. 52, No. 74, 17 April 1987, pp. 12662-12864.

Subtitle I, Section 9003, of the Resource Conservation and Recovery Act, as amended, requires the EPA to establish requirements for leak detection, leak prevention, financial responsibility, and corrective action for all underground storage tanks containing regulated substances. This document presents EPA's proposed regulations for underground storage tanks containing petroleum or substances defined as hazardous under the Comprehensive Environmental Response, Compensation, and Liability Act of 1980, as amended (except hazardous wastes regulated under Subtitle C of the Resource Conservation and Recovery Act). This comprehensive and lengthy document presents a wide range of information concerning leaks from underground storage tanks.

Heim, P.M., "Conducting a Leak Detection Search," Journal of the American Water Works Association, Vol. 71, February 1979, pp. 66-69.

Leak detection methods for municipal water supply and techniques for conducting a leak survey are described. Detection methods include acoustic monitoring and tracer gas surveys.

Henry, M.F., "Update on the Underground Leakage Problem," Fire Journal, January 1986, pp. 26-27.

EPA regulations relating to underground storage tanks are described. National Fire Protection Association (NFPA) standards for underground tank testing are discussed, including NFPA 329 which establishes a minimum sensitivity of 0.05 gph leakage flow as a requirement for tank tightness testing. The difficulties in applying this minimum requirement to testing of large modern tanks is addressed. The article concludes, "There are many who see in-tank monitoring, coupled with out-of-tank leak detection, as the long-term solution to the leakage problem."

Laverty, G.L., "Leak Detection: Modern Methods, Cost, and Benefits," Journal of the American Water Works Association, February 1979, Vol. 72, pp. 61-63.

The author traces the history of leak detection in municipal water supply systems. The successful experiences of the East Bay Municipal Utility District in leak location using a portable acoustic monitoring system are described.

McMaster, R.C., Ed., Nondestructive Testing Handbook: Volume 1, Leak Testing, 2nd ed., American Society for Metals, 1982.

This comprehensive handbook contains information on a wide variety of leak detection techniques, covering their theory, equipment, and procedures. Chapters include "Applications of Leak Testing in the Nuclear Power Industry" and "Techniques of Leak Testing Using Ultrasonic Vibration Detectors," which is reviewed below.

Russell, D.L., and Hart, S.W., "Underground Storage Tanks: Potential for Economic Disaster," Chemical Engineering, March 1987, pp. 61-69.

This article provides an excellent overview of the scope and nature of the underground storage tank problem, the construction methods for new installations, leak detection methods, and tank testing procedures.

Schwendeman, T.G., and Wilcox, H.K., Underground Storage Systems: Leak Detection and Monitoring, Lewis Publishers, Inc., Chelsea, Michigan, 1987.

In this book, the authors provide information on regulations for underground storage systems; the types of underground storage tanks, pipes, and fittings; the types of pumping systems; and the types of release detection and monitoring systems. Leaks occur most frequently in the piping systems. Leaks most commonly result from corrosion, improper installation, or lack of maintenance. Extensive information is provided on tank integrity testing, temperature compensation techniques, product level measurements, and containment alternatives. Appendices provide a hazardous substance list; storage system gauging procedures; and a description of underground storage regulatory programs for California, Delaware, and Florida.

Schwendeman, T., "Detecting Underground Piping Leaks," Civil Engineering, August 1987, pp. 56-58.

This article presents a brief summary of Schwendeman and Wilcox (1987).

ACOUSTIC LEAK DETECTION

Anderson, G.L., "The Ultrasonic Leak Detector: What Every Engineer Should Know," Materials Evaluation, Vol. 42, October 1984, pp. 1298-1302.

The author presents a non-technical summary of Brown et al. (1982), which is reviewed below.

Brown, A.E., et al., "Techniques of Leak Testing Using Ultrasonic Vibration Detectors," in McMaster (1982), pp. 625-685.

The first section of this chapter discusses the principles of sonic and ultrasonic leak testing. The acoustic detectability of leaks is shown to depend on detector sensitivity, detector selectivity, acoustic shadowing, viscosity of the fluid, velocity of the fluid, pressure differential, and leak geometry. The second section provides a brief description of available instrumentation for acoustic leak detection. The instrumentation is almost

exclusively for detecting airborne noise from high pressure leaks. The remainder of the chapter provides examples of the application of acoustic leak detection to pressurized industrial systems, evacuated systems, engine and valve maintenance, and pressurized telephone cables. The application of multiple acoustic emission sensors to leak monitoring in pipelines is also discussed. Operating characteristics of a successful AE-based leak detection system should include evaluation of broadband frequency content; recognition of an increase in amplitude of continuous leak signals over the intermittent environmental noise signal; and capability for location of the leak source.

Brown, T.G., "Basic Leak Detection is Necessary for Any System," Opflow, American Water Works Association, Volume 11, October 1985, pp. 5-6.

This article discusses the usefulness of acoustic leak monitoring techniques in operating and maintaining a municipal water supply system. The costs and benefits of leak detection are qualitatively discussed. Modern leak monitoring equipment, which can include a microphone, filters, and amplifier, is described. A van-mounted, computerized leak noise correlator is also described and illustrated.

Davis, J.L., Singh, R., Stegman, B.G., and Waller, M.J., "Innovative Concepts for Detecting and Locating Leaks in Waste Impoundment Liner Systems: Acoustic Emission Monitoring and Time Domain Reflectometry," Report No. EPA-600/2-84-058, EPA Municipal Environmental Research Laboratory, Cincinnati, Ohio, February 1984.

Acoustic emission monitoring was examined to evaluate its applicability for detecting significant leaks in lined waste impoundments before the leaking material can seriously damage groundwater. Experiments were conducted using a four meter long section of PVC pipe, 30 centimeter in diameter, containing soil, a buried microphone, water, and acoustic insulation. Acoustic signals at frequencies up to 500 Hz were observed for water flowing through sand and pea gravel at velocities between 0.3 and 1 cm/sec, with amplitude increasing greatly with velocity. Amplitude also increased with increased variation in soil grain size and decreased with increased soil density. No significant sounds were detected for water flowing through rips in PVC liner material. Results indicated that the most

significant source of the acoustic signals was the shifting of soil grains with respect to each other. Another potentially useful technique for leak detection, time-domain reflectometry (TDR), was also tested, and results from laboratory tests are described in the report.

Dawes, M.I., "*Ultrasound* Detectors *for* Leaks, Machine Noise, and Electrical Discharge," Ultrasonics, January 1967, pp. 1-7.

A wide variety of acoustic leak detection devices is described. Applications include detecting leaks in vessels, boiler tube inspections, pipeline leak detection, telephone cables, vacuum leaks, machinery noise, and electrical discharge. A list of manufacturers of acoustic leak detection devices is also included.

Dimmick, J.G., and Cobb, J.M., "Ultrasonic Leak Detection Cuts Valve Maintenance Costs," Power Engineering, August 1986, pp. 35-38.

The authors discuss principles of acoustic leak monitoring for valves in power plants and describe experiences in applying the principles in operating plants. Background noise can mask the noise from small leaks, but placing the transducer directly on the valve stem maximizes the signal.

Harding, W.M., "Acoustic Emission Leak Detection in Above-Ground Storage Tanks," Materials Evaluation, Vol. 45, March 1987, pp. 265-266.

The Hartford Steam Boiler Inspection and Insurance Company's "TankScan" system is briefly described. The tank is overfilled and allowed to stabilize. Operational noises and other background noises ("from machinery, weather, nearby roads, pumps, railroads, birds, etc.") are minimized. Multiple AE sensors with a 30 kHz resonance are placed around the bottom of the tank, on the outside. A system calibration is achieved by generating emission pulses at individual sensors and analyzing the resulting signals at the other sensors. During a thirty to sixty minute test, the results at each sensor for individual AE events are analyzed and compared. A leak source is identified if it appears in more than four data points during a test period. The technique has been applied to tanks containing a variety of petrochemical and chemical products, and results from the AE testing have been verified by comprehensive inspections. The signal processing and computational equipment for this testing is housed in a large van.

Huebler, J.E., Saha, N.C., and Craig, J.M., "Identification of Leaks: Internal Acoustic Technique," Report No. GRI-80/0143, Gas Research Institute, Chicago, Illinois, August 1982 (Abstract reviewed only).

A microphone placed inside a simulated gas main was evaluated in the laboratory as a potential means for detecting, locating, and characterizing small leaks in gas distribution systems. Leaks were detected at pressures less than 0.1 psi.

Huebler, J.E., "Identification of Leaks - Internal Acoustic Method Phase II," Report No. GRI-84/0141, Gas Research Institute, Chicago, Illinois, August 1984.

Results are presented from investigations of acoustic methods for detecting leaks in low pressure (less than 0.2 psig) natural gas lines. Because the sound produced by the low pressure leaks was found to be so low, it was necessary to investigate methods for placing an acoustic sensor inside the gas line, as indicated in Heubler et al. (1982). Four microphone carriers were designed, and the best design was evaluated in field tests. The insertion and manipulation of the microphone carrier within a gas main was demonstrated. However, the acoustic detection of a low pressure leak in the field was not successfully demonstrated.

Huebler, J.E., Ziolkowski, C.J., Eynon, S.B., and Altpeter, L.L., "Sonic Leak Pinpointer," Pipeline and Gas Journal, November 1985, pp. 26-33.

The authors describe a portable acoustic leak detector which has been developed to locate leaks in underground natural gas distribution lines. The approximate location of the leak is determined using other methods, such as a combustible gas indicator. Nine or ten waveguides are driven into the ground along the pipeline in the vicinity of the leak, and an additional waveguide is installed at one side to provide background noise. An AE sensor is attached magnetically to the top of each probe, and readings are taken from each and analyzed. Data is only

taken during the brief "quiet times" when the background noise is minimal. Field test results demonstrate the utility of the technique, and commercialization of the technique is planned.

Huebler, J.E., Ziolkowski, C.J., Saha, N.C., "Fabrication and Field Testing of a Prototype Sonic Leak Pinpointer for Medium- and High-Pressure Gas Pipelines," Report No. GRI-86/0044, Gas Research Institute, Chicago, Illinois, March 1986 (Abstract reviewed only).

This report provides detailed information on the prototype leak detector for gas pipelines, which is described above in Heubler et al. (1982) and Heubler et al. (1985).

Kitajima, A., Naohara, N., Aihara, A., "Acoustic Leak Detection in Piping Systems," CRIEPI Energy and Environment Laboratory, Report No. E283006, 1984.

The application of acoustic techniques to leak detection in nuclear plant piping was investigated. Characteristics of the leakage noise were identified, methods for detecting the noise were investigated, and background noise was measured. Leakage flowrate was linearly related to noise level on a log-log plot. The noise level from saturated steam was considerably higher than the noise level from pressurized water at the same leakage flowrate. In the field, wave guides were successfully attached to piping by using a silica-alumina cement. Background noise in an operating PWR was reasonable constant during steady operation and determined the minimum detectable flowrate. The researchers suggest, based on experience with a prototype system operating in a nuclear power plant, that the acoustic detection threshold should be set to 1.5 to 2.0 times the background noise level. Software features for the prototype monitoring system include the ability to set variable threshold levels depending on operating conditions; analysis of signal levels and duration times; and analysis of the frequency characteristics of the signals.

Koerner, R.M., Reif, J.S., and Burlingame, M.J., "Detection Methods for Location of Subsurface Water and Seepage," Journal of the Geotechnical Engineering Division, Vol. 105, No. GT11, American Society of Civil Engineers, November 1979, pp. 1301-1316.

This paper reviews nondestructive test methods for detecting subsurface seepage. The techniques which are discussed include water balance, velocity methods, radioactive and nonradioactive tracers, temperature methods, pulsed and continuous microwave techniques, geophysical (seismic) methods, and acoustic emissions. Uses, advantages, and disadvantages of each technique are discussed. Acoustic emission systems typically operate in the 100 Hertz to 10,000 Hertz range and require wave guides. Background noise is the greatest source of difficulty, and additional research is required. Field experiences with acoustic emission monitoring of seepage flow beneath an earth dam are described.

Lord, A.E., Deisher, J.N., and Koerner, R.M., "Attenuation of Elastic Waves in Pipelines as Applied to Acoustic Emission Leak Detection," Materials Evaluation, Vol. 35, No. 11, 1977, pp. 49-54.

The authors provide a literature review of wave mode types and attenuation of elastic waves in pipelines. Results from a variety of tests and researchers show a linear correlation between the logarithm of the attenuation and the logarithm of the frequency, with values of attenuation ranging from 0.00001 dB/ft at one Hz to 100 dB/ft at ten MHz. An approximation to the expected attenuation coefficient can be obtained from the expression:

$$a = (0.00001)f$$

where a = attenuation coeff. (dB/ft)

f = frequency (Hz).

The application of attenuation results for leak location is demonstrated in laboratory tests and in field tests.

Moyer, E.E., Male, J.W., Moore, C., and Hock, J.G., "The Economics of Leak Detection and Repair - A Case Study," Journal of the American Water Works Association, Vol. 75, No. 1, January 1983, pp. 29-34.

The costs and benefits of a leak detection and repair program for a water utility are analyzed. A sonic leak detector was found to be effective in locating leaks in water lines and providing a qualitative indication of the leak rates. Soil type, traffic noise, presence of other utility lines, and type of pipe influenced the leak noise to be interpreted by the surveyor.

New York Power Authority (NYPA), "Boiler Tube Leak Detection Project at Poletti," Research Today, No. 4, NYPA, New York City, January 1987, pp. 2-3.

An ongoing research study to test and evaluate an acoustic system for boiler tube leak monitoring is described. A wave guide is used to bring the acoustic signal from the boiler wall, and data is analyzed on a microcomputer. The boiler operates at pressures ranging from 600 psi at 150 MW to 2,500 psi at 825 MW, which is expected to create a difficult noise background. Discrimination of the leak noise from combustion roar, steam atomization, and soot blowing is under investigation.

Reason, J., "Microphones in the Boiler Give Early Warning of Tube Leaks," Power, July 1985, pp. 62-64.

For ten years, the Central Electricity Generating Board's Ratcliffe-on-Sour powerplant in Great Britain has used an acoustic system to detect boiler leaks. The CEGB has installed similar systems in 75 boilers in 21 powerplants. This system has recently been licensed to Babcock & Wilcox Company and to Combustion Engineering Inc. Acoustic waveguides and microphones are used to listen for noise. The signal is bandpass filtered in a 2 kHz to 15 kHz range to achieve the optimal signal to noise ratio. Acoustic monitoring systems have also been installed in Italy at 34 powerplants for detecting leaks in high-pressure feedwater heaters. These systems use piezoelectric pressure transducers in direct contact with the feedwater, where the leak noise is detected. These systems are bandpass filtered in the range of 5 kHz to 15 kHz.

Smith, J.R., Rao, G.V., and Gopal, R., "Acoustic Monitoring for Leak Detection in Pressurized Water Reactors," Acoustic Emission Monitoring of Pressurized Systems, ASTM STP 697, W.F. Hartman and J.W. McElroy, Eds., American Society for Testing and Materials, 1979, pp. 177-204.

This paper describes Westinghouse experiences with using AE monitoring for the detection of leaks in pressurized water reactors. In laboratory studies, acoustic emissions from notched pipe sections were monitored as through-wall fatigue cracks were generated. Acoustic emissions changed from a burst-type signal, characteristic of crack growth, to a continuous signal, characteristic of a leak, at the onset of the through-wall leak. Signal level-leak correlations for steam leaks through circular orifices were