R-94-17

# ACOUSTIC MONITORING OF PRESTRESSED CONCRETE PIPE AT THE AGUA FRIA RIVER SIPHON

December 1994

U.S. DEPARTMENT OF THE INTERIOR
Bureau of Reclamation
Technical Service Center
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13. ABSTRACT *(Maximum 200 words)*

The Bureau of Reclamation conducted investigations to determine the viability of using hydrophones to detect the failure of the prestressing wire in prestressed concrete pipe. Field tests were conducted at the Agua Fria River Siphon near Phoenix, AZ, to record hydrophone signals as prestressing wires were broken and as other sounds were introduced into the siphon. The analysis of these test data revealed characteristics of the sound propagation in the siphon and showed that the sound of a breaking wire is distinctive and can be discerned from other noises present in the siphon. By processing the signals from an array of hydrophones installed over the length of a siphon, the location of a wire break can be determined. A complete system of hydrophones with a computerized signal processing system has been installed at the Agua Fria River Siphon for evaluation.

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# ACOUSTIC MONITORING OF PRESTRESSED CONCRETE PIPE AT THE AGUA FRIA RIVER SIPHON

by

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Materials Engineering and Research Laboratory
Technical Service Center
Denver, Colorado

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*Mission Statement*

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# INTRODUCTION

## Background

The Central Arizona Project of the Bureau of Reclamation (Reclamation) delivers water to various municipal, industrial, and agricultural users through a 336-mile aqueduct system and several hundred miles of smaller distribution canals. The aqueduct can transport water to the arid southwest at a rate of over 22,000-gal/s. In the main aqueduct system, large concrete pipelines (inverted siphons) are used to transport the water beneath existing watercourses. These siphons vary in length from one-fourth to two miles and are constructed using PCP (prestressed concrete pipe) sections. Each pipe section is 22 feet in length and has a 21-foot inside diameter. Each pipe section is constructed with a 19-5/8-inch-thick concrete core, which is helically wrapped with between 5 and 21 miles of high-strength steel wire. This wire, a key strengthening component in this type of pipe, is wrapped under a tension of 180,000 lbf/in$^2$. The wire must remain under tension for the life of the pipe to counteract the internal water pressure and other forces. This prestressing wire is protected with a cement mortar coating. Figure 1 shows a cross-section of the pipe structure.

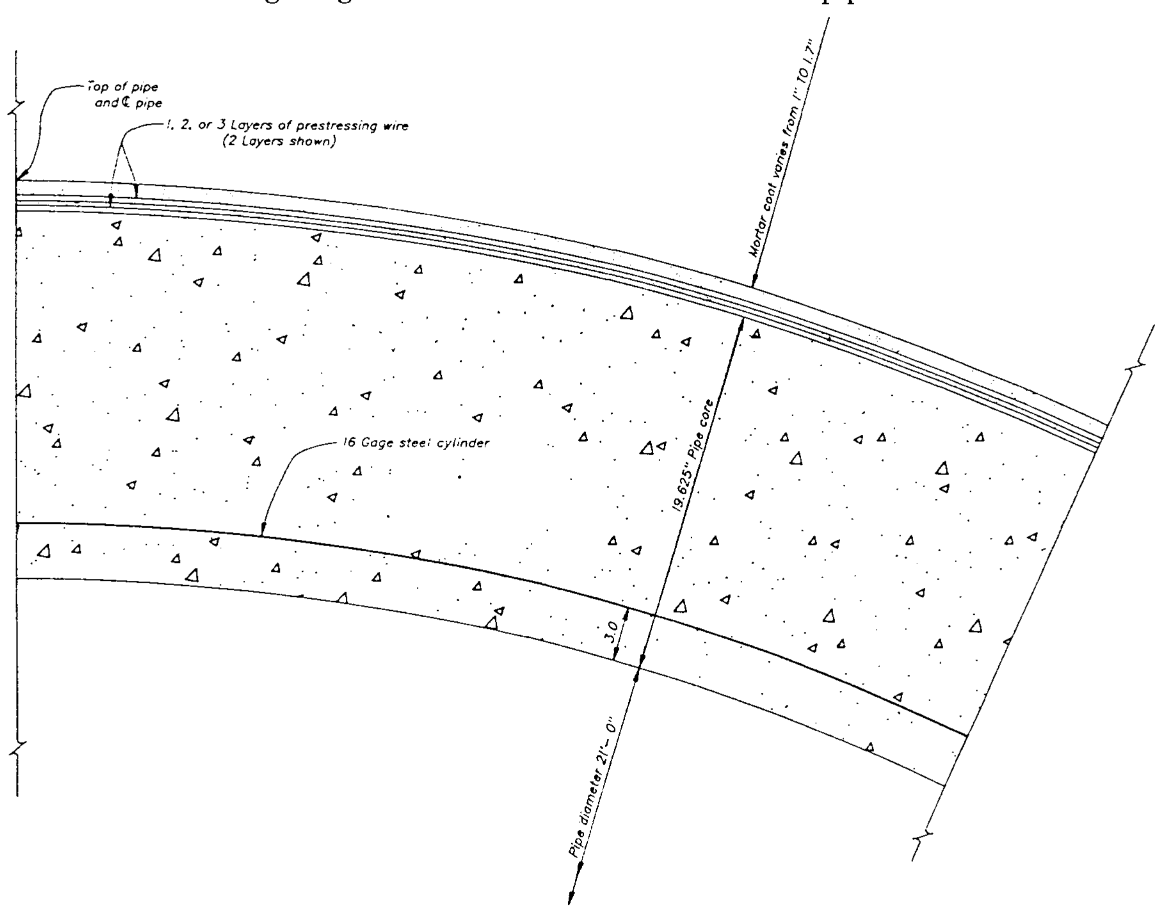



Figure 1. - Cross-section, prestressed concrete pipe structure.

## Prestressing Wire Failure Found

In 1990, Reclamation discovered corroded and broken wires on pipe sections located in the Agua Fria River Siphon during routine ground potential surveys. Subsequent investigations were initiated at the five other siphons in the CAP and similar distress was found on those as well. Breakage of a sufficient number of adjacent wires could result in catastrophic failure of the pipe. Measures were initiated to determine the extent of the damage and repair it.

### Repair Methods Developed

Reclamation developed repair methods for the PCP which range from splicing individual wires to removing all the existing wire and rewrapping an entire pipe section with steel tendons (Randolph and Worthington, 1992). These repair methods appear to be very effective and are now being used by entities outside Reclamation.

### Location Method Needed

After the initial discovery of the deterioration of the reinforcing wires, a major effort was mounted in early 1991 to determine the extent of the distress and to repair the damaged areas. As part of this effort, investigations were initiated to determine the most effective way to locate distressed areas. Although the corrosion was originally found from data taken using ground potential measurements, excavation of all of the indicated sites showed this method to be inaccurate in many cases. It was therefore considered likely that additional damaged areas were not found. It was also considered likely that the corrosion process was continuing. Consequently, a reliable method for detecting and locating distressed areas was needed in order to prolong the life of the existing siphons by making repairs where required. It was felt that a system that would locate these areas within 1 pipe section (22 feet) would provide the accuracy required to be a viable solution to maintaining a siphon.

Many methods were investigated to find one that could reliably locate corroded areas. These methods included potential measurements on the pipe interior, soil resistivity measurements, thermal stress analysis, interior and exterior visual inspection, electrical continuity of the prestressing wire, interior and exterior infrared imagery, electrical potential patterns, magnetic deflection, mortar surface alkalinity, interior and exterior manual sounding, acoustic pulse-echo, and line penetrating radar. These methods proved largely ineffective (Worthington, 1992).

The best results were obtained by excavating the pipe for a visual inspection to locate cracked or missing mortar, followed by "sounding" the pipe (tapping on the pipe and listening for hollow-sounding areas caused by a disbonding of the cement mortar coating). This method is impractical for the large scale periodic inspection required; additionally, the disbonded areas would often not show up for several months after a pipe had been uncovered. A further limitation is that a pipe can only be excavated to its horizontal centerline because it requires the structural support provided by the soil on which it rests. The method that showed the most promise for a practical implementation was the use of hydrophones to listen for the sound made by the failure and subsequent slippage of a prestressing wire. This report details the investigations conducted to develop an acoustic monitoring system for detecting and locating areas of prestressing wire failure.

## CONCLUSIONS

Investigations have shown that the concept of detecting the sound generated by a prestressing wire failure is practical:

1 A hydrophone system can detect reinforcing wire failure on a prestressed concrete pipe at a distance of 1000 feet minimum.

2. A signal processing system can be built that will distinguish wire-break sounds from other acoustic transients occurring in a siphon.

3. Using arrival time of the wire-break signal at two hydrophones and velocity of sound in water, the wire-break location can be calculated with sufficient accuracy to be useful.

4 The propagation of the acoustic energy down the pipe length is complicated by multiple reflections off of the inside walls of the pipe. These reflections make determination of the arrival time of signals at the hydrophones difficult and limit the certainty of the precise origin of the sound; however, the accuracy is acceptable for this application.

5 The experimental results have been validated by excavating sites indicated by field testing and locating distressed pipe based on the data.

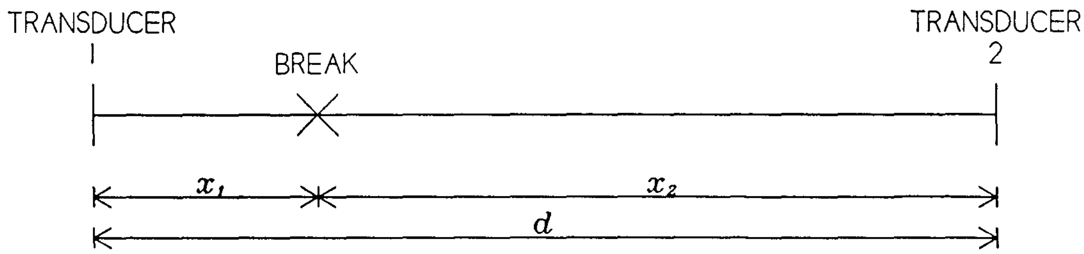
## CONCEPT DEVELOPMENT

The discovery of abnormal ground potential readings prompted pipeline excavation at several locations. Some of the excavated areas showed marked deterioration of the cement mortar coating and the reinforcing wire below it (fig. 2).

Figure 2. Deteriorated mortar coating with corroded and broken prestressing wire underneath.

field personnel were present when reinforcing wires failed. The sound of a failure reportedly resembled the sound of a small caliber rifle, which gave rise to the idea that an acoustic system could be used to listen for these events. Because the pipeline is buried, it was suggested that the sound would travel through the pipe structure and also through the water in the pipe. AE (acoustic emission) technology was suggested to detect sound traveling through the pipe structure, and hydrophones were suggested for "listening" to the sounds in the water column contained in the pipe.

It was speculated that if the sound of a breaking wire were of sufficient magnitude and sufficiently unique to be distinguished from other sounds in the siphon that an electronic system could be developed to detect these sounds. The idea was extended to include the use of multiple hydrophones or AE transducers to determine the location at which the sound originated. The formulas for determining the locations are:




$$x_1 = \frac{v*(t_1 - t_2) + d}{2}$$

and

$$x_2 = \frac{v*(t_2 - t_1) + d}{2}$$

where:

| | | |
|---|---|---|
| | $x_1$ | = distance from break to transducer 1 |
| | $x_2$ | = distance from break to transducer 2 |
| | $v$ | = velocity of sound in transmission medium |
| | $t_1$ | = time of sound arrival at transducer 1 |
| | $t_2$ | = time of sound arrival at transducer 2 |
| | $d$ | = distance between transducers 1 and 2 |

When using hydrophones, this formula does not account for the water flow velocity. This simplification is considered acceptable because, with a hydrophone spacing of 1000 feet, the maximum flow velocity of 8 ft/s results in a maximum break location error of only 0.8 feet.

With the ready availability of powerful real-time computer systems, it was postulated that a system could be developed that would continuously monitor the transducers on a pipeline. The system would analyze the sounds detected and classify them in real time as either wire breaks or other sounds. The events classified as wire breaks would then have the origin of the event calculated and stored in a data base. Analysis of the data base would indicate active areas. When the number of breaks in a specific location exceeded a threshold, the site would be excavated, the distress verified, and subsequently repaired.

A hydrophone system was hypothesized to be better suited to this application than an AE system. The sound generated by a wire break would propagate through two primary media: the pipe structure and the water in the pipe. Although the pipe structure would be the immediate recipient of the energy released by a breaking wire, this energy would also readily be propagated into the water. The pipe structure, primarily concrete, would provide a solid path for acoustic energy transmission; however, each pipe section is only 22 feet long. Each section is connected to the next using a bell and spigot joint, which uses a rubber gasket to seal the joint and a grout cap to fill the remaining gap. The acoustic attenuation of concrete is about 100 dB/m (Uomoto, 1988); however, the solid concrete path is assumed to provide a reasonably good transmission path over the pipe section length. Although each pipe would provide potentially good sound transmission characteristics within itself, the joints could be highly attenuative. By contrast, the water column would act as a continuous path for the sound once the sound energy is coupled into it. The attenuation of water is significantly less than concrete—around 1 dB per 1000 yards at the frequencies of interest (Urick, 1975).

A further problem is that of locating areas where distress occurred before monitoring began. Laboratory testing has verified that although the bond between the wire and the mortar coating is broken immediately adjacent to the break, within 18 to 24 inches on either side of the break the bond remains intact and retains the full original stress in the wire. Reinforcing wire failure severely compromises the mortar coating integrity, which can cause further wire corrosion in that location. This corrosion causes deterioration of the mortar coating in the area that still is bonded to the wire. It is postulated that this bond will be compromised when this deterioration becomes severe enough, and another energy release will occur as the bond is broken. This break will cause another acoustic event that will be detectable. Although it has not been experimentally verified, it is believed that as this process continues, the number of acoustic events from a distressed area will increase as the area expands.

## FIELD INVESTIGATIONS

To verify the practicality of the concept of listening for wire breaks with hydrophones, field testing was considered necessary. Over a period of eighteen months, four field tests were conducted. During these tests, reinforcing wires were intentionally broken while the signals from hydrophones were recorded. To prepare the wires for breaking, the protective mortar coating was removed. Because of the severe distress found on the siphons, breaking a few wires on an individual pipe section obviously would not compromise the integrity of the pipe. Adjacent wires were not broken, but several were left intact between each wire that was intentionally broken.

### Field Tests, April 1991

During the initial investigations of early 1991, three of the CAP siphons were dewatered for inspection. The AFRS (Agua Fria River Siphon), one of the three, was chosen as a test bed for continuing investigations in studying methods for locating distress because of its close proximity to the Project Office. While the AFRS was dewatered in January 1991, two hydrophones were installed. One hydrophone was located 40 feet from the inlet and the second was installed 43 feet from the outlet. These hydrophones were mounted on steel brackets about 3 feet from the pipe wall at about the 7 o'clock position.

In April 1991, Reclamation conducted a field test of the hydrophones installed in the AFRS. The purposes of the test were (1) to verify that the sound of a breaking wire could be detected using hydrophones, and (2) to obtain information about how far away the sound could be detected. These tests consisted of recording the sounds from the breaking of prestressing wires on the siphon and the sounds generated by a 12-kHz pinger, which periodically emits a pulsed sound at 12 kHz. Two sites were selected at which to break wires, one about 500 feet upstream from the outlet hydrophone and the other 5000 feet from the outlet hydrophone near the siphon midpoint. These sites were selected to take advantage of pipeline sections already exposed from previous excavations. The protective mortar coating was removed and two prestressing wires were ground using a rotating abrasive wheel until the wire's cross section was reduced to the point where the stress in the wire caused it to break (fig. 3). Both wire-break signals were detected by the outlet end hydrophone.

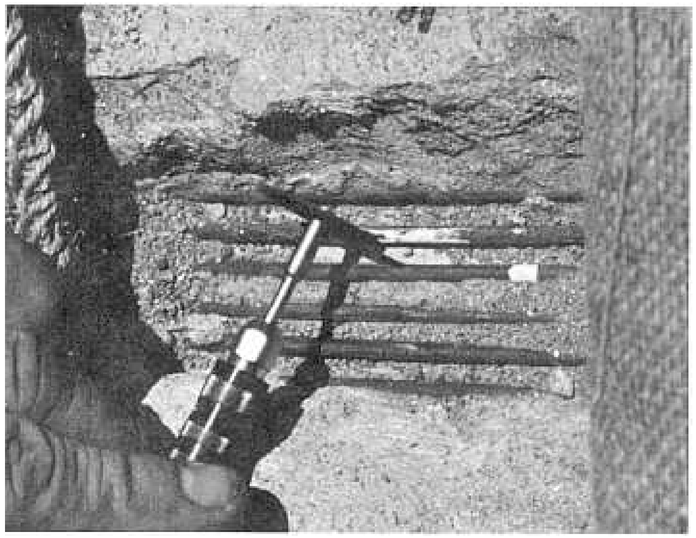


Figure 3. - Prestressing wire being ground with rotating abrasive wheel to induce breakage.

**Results of the April 1991 Tests:**

1 The time-domain waveforms of the signals recorded at the outlet had no distinguishing characteristics, and frequency spectrums of the waveforms resembled those of broad-band noise. Audio playback of the signals was dramatic; the snap caused by the breaking wire was unmistakable. This initial test gave credence to the idea that an acoustic system could detect wire breaks.

2. The pinger signal could be detected over nearly the entire length of the siphon.

3. The hydrophone located at the inlet of the siphon was ineffective because of air entrained in the water. Air bubbles in the water dramatically raised the transmission loss. The air entrainment resulted from turbulence caused as the water passed under the radial gates used to control siphon flow. By lowering the pinger into the siphon at the inlet and listening to the output of the outlet hydrophone, it was determined that the entrained air was being forced into the siphon about 200 feet. The inlet hydrophone was useless in this entrained air because it was located only 40 feet from the inlet. To eliminate the turbulence and entrained air during subsequent tests, operational procedures for the siphon were changed to raise the gates above the water at the inlet.

4. The hydrophone signals contained excessive electrical noise, suggesting that preamplification located as close as possible to the hydrophone elements would be necessary.

It was concluded that this initial test showed sufficient promise to warrant further testing.

**Field Tests, July and October 1991**

In July and October 1991, additional tests were conducted at AFRS. The goals of these test programs were to (1) gather the data required to perform a quantitative analysis of the wire-break signal characteristics, (2) determine if the amount of mortar removed affects the signal characteristics, (3) determine the attenuation of the signal as a function of distance along the siphon, and (4) record the signal resulting from other artificially induced noises, such as hammer blows, to the outside surface of the pipe. From the analysis of these test data, it was hoped that a determination could be made regarding optimum hydrophone spacing and processing of the hydrophone signal.

For these tests, Reclamation divers installed two additional hydrophones near the outlet of the siphon. These hydrophones contained internal preamplifiers. Nine accelerometers and seven AE transducers were attached to the pipe to test the hypothesis about the acoustic transmission characteristics of the pipe structure. In these tests, data from a number of forced wire breaks effected at various locations along the length of the siphon were recorded using an analog instrumentation recorder.

**Results of the July and October 1991 Tests:**

1. The data were plagued with excessive electrical noise, in spite of efforts to eliminate it with preamplifiers located at the hydrophones, proper grounding, and use of coaxial cable.

2. An attempt was made to characterize the wire-break signals using spectral analysis. The data were filtered to reduce the steady-state, power-frequency related electrical noise. Spectral analysis of the July data revealed that the wire-break signal had a wide-band noise-like power spectrum with a slight rise around 3.5 kHz. Further investigation showed that the sound made by the rotating abrasive wheel, used to break the wire, also had a similar spectral peak. Consequently, modified bolt cutters were used in subsequent tests to eliminate the noise from the abrasive wheel (fig. 4). The spectral analysis of the wire-break waveforms from the October data did not show the rise in the power spectrum in the 3.5-kHz range that was typical of the July spectrums. No correlation between the length of mortar removed and the wire-break spectrums was found.

3. Time domain analysis of the data was done manually from strip charts produced by playing the signals into a multi-channel strip-chart recorder. This analysis revealed that the farther the break was located from the hydrophone, the less distinct was the start of the waveform (fig. 5). This result was attributed to the fact that less of the energy would reach the hydrophone directly and more would arrive after having been reflected off of the inside walls of the pipe. This occurrence is referred to as multipath distortion.

   Because of the constraints imposed by using existing excavation sites, wire breaks could not be positioned between two hydrophones. Consequently, break locations could not be calculated from the test data for comparison with the actual locations. An alternative

Figure 4. - Modified bolt cutters being used to induce wire breakage.

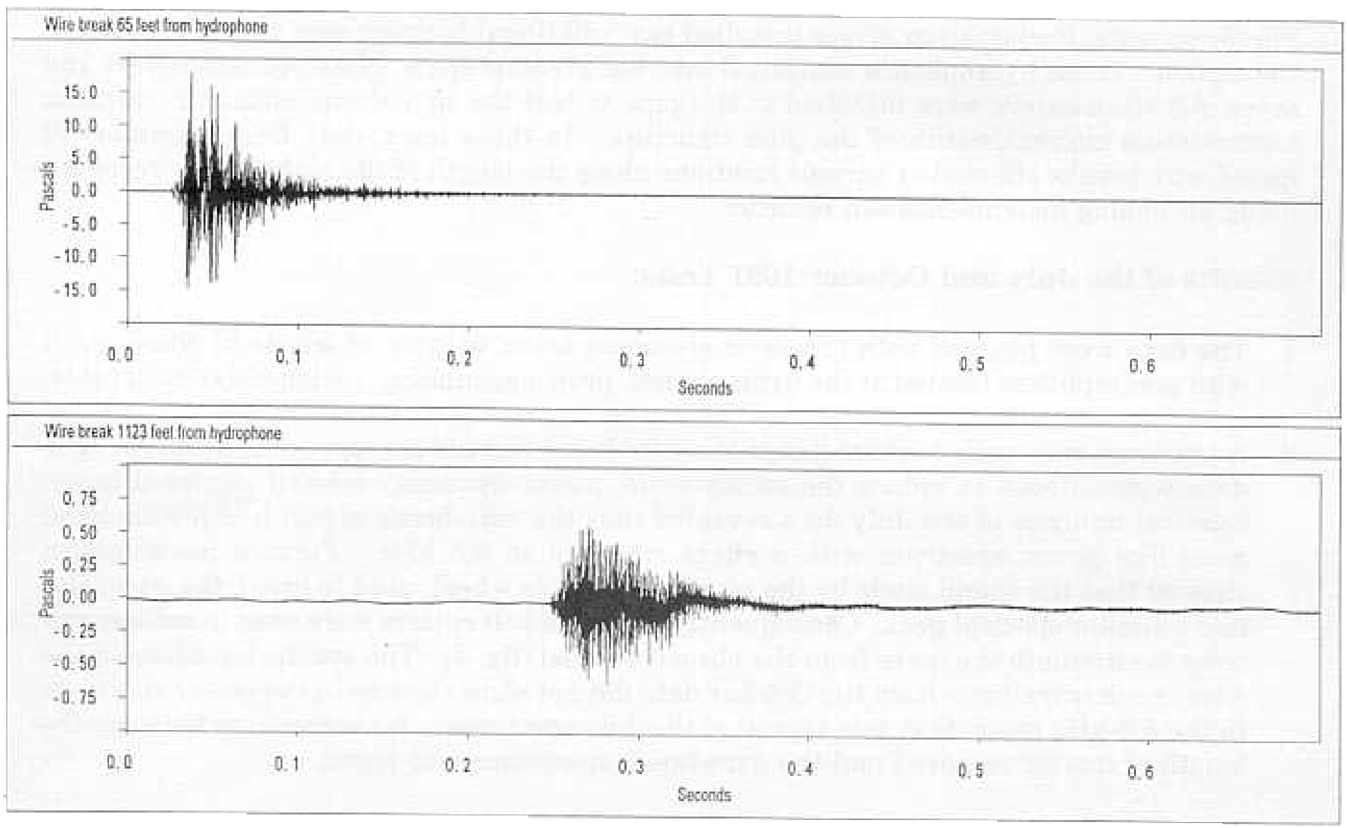



Figure 5. - Comparison of waveforms at hydrophones located different distances from a wire break.

calculation was made that involved the same parameters. The velocity of sound in water was calculated using the known hydrophone spacing and the difference in arrival times of the waveform at two hydrophones. This velocity was then compared to the known velocity of sound in water at the temperature present.

The calculated velocities ranged nearly ±15 percent from the expected values. The wide range arose from the difficulty in determining the time at which the waveform first arrived at the hydrophone. Note the ambiguity in selecting the arrival time on figure 6. Each millisecond would represent an error of 2.5 feet in the location calculation. The arrival time could be selected to be as early as 0.244+ seconds or as late as 0.248+ seconds, which represents a difference of around 10 feet in the calculated location. This ambiguity in the velocity would translate into unacceptable uncertainties when calculating the location of wire breaks. Numerous criteria were applied to the waveforms in efforts to determine the precise signal arrival times at the hydrophones, but none gave satisfactory results. Because of the distortion of the waveforms, attempts to use cross-correlation were also unsuccessful.

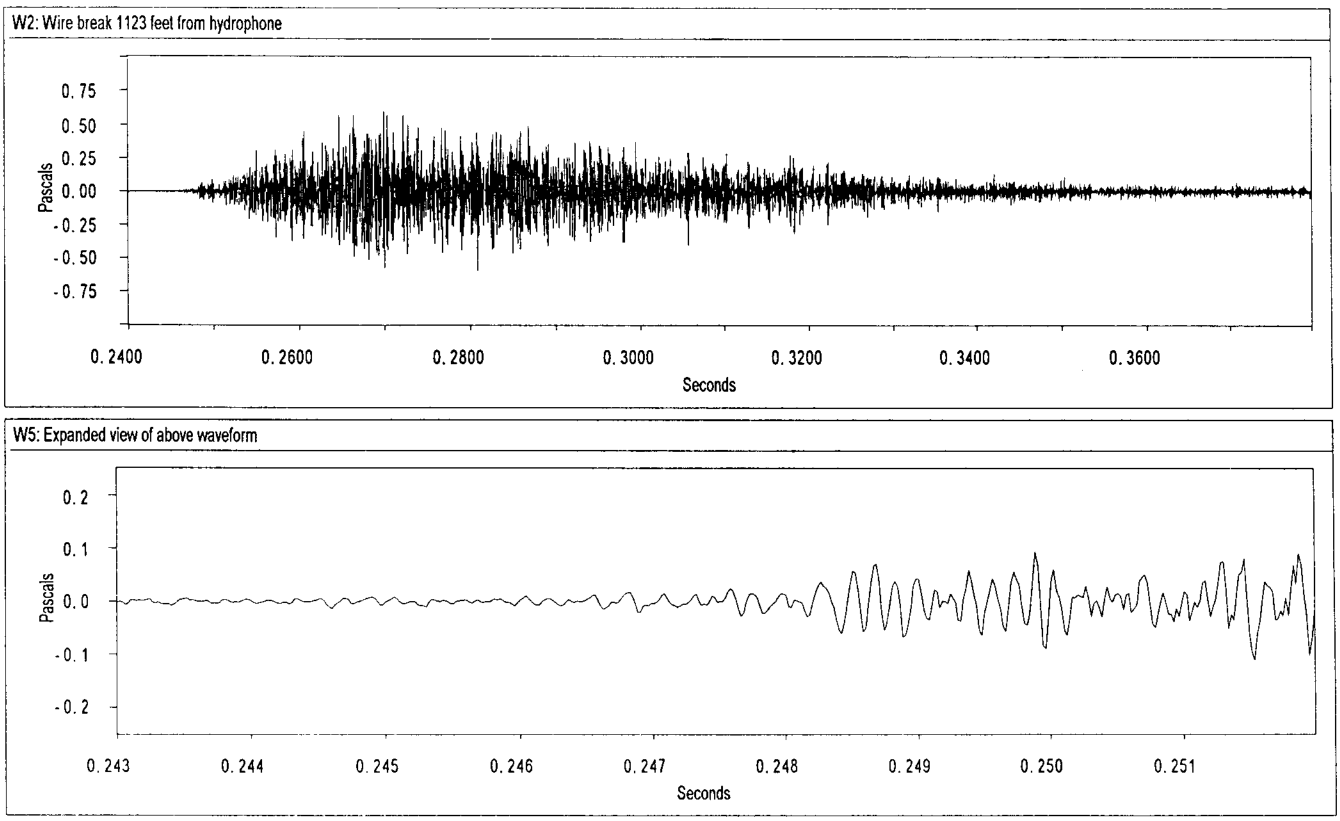



Figure 6. - Illustration of the difficulty in selecting the arrival time of the signal at a hydrophone. The upper figure represents the full waveform and the lower figure represents the first 9 ms.

The magnitude of the spread of calculated sound velocities may be primarily attributed to the fact that the uncertainty in determining the arrival time of the signal at each hydrophone was a significant percentage of the total transit time of an acoustic signal between hydrophones. The hydrophones were located only 100 feet apart, and the transit time was only about 20 ms. The difficulty in determining the arrival time of the waveform was caused by the severe multipath distortion and a poor signal-to-noise ratio. This last factor included high-frequency noise components and non-power-related random noise bursts that could not be removed by filtering without also severely reducing or eliminating the desired signal. The severe power frequency noise was successfully reduced by filtering.

4. Analysis of the accelerometer and acoustic emission data showed that although transmission of the wire-break signal was acceptable through an individual pipe section, the acoustic coupling between adjacent pipe sections was often unreliable as hypothesized. Additionally, the damping of the signals by the earth cover caused additional severe attenuation over relatively short distances. It appeared that for systems of this type to be effective, a sensor would be required on every pipe section.

These tests highlighted two problems that would require solutions to make a system usable. The first was the persistent problem of the electrical noise. The failure to solve the noise problems using normal methods indicated that extraordinary measures would be required for subsequent tests. This problem, although proving more difficult to solve than expected, was not considered insurmountable. The second problem, that of the multipath distortion of the wire-break signals making the precise time of waveform arrival difficult to determine, looked more significant. It was hoped that a better signal to noise ratio would improve the signal to the point that the wavefront arrival could be more accurately determined.

**Conclusions - July and October 1991 tests:**

1. A simple level detection scheme for triggering on wire-break signals would not be effective because of randomly occurring transients that cause false triggering of the recording equipment.

2. The determination of a precise signal arrival time is difficult because of multipath distortion of the waveform.

3. The electrical noise problems were not eliminated by conventional techniques. It was postulated that the electrical contact of the hydrophone with the water, combined with the conductivity of the 346-ft$^2$ cross-section of the water column in conjunction with the signal ground in the instrumentation cables, resulted in very large ground loops and magnetic induction loops that could not be dealt with using conventional noise reduction techniques.

4. The length of disbonded mortar showed no significant influence on the wire-break waveform.

5. Detecting wire breaks using acoustic emission transducers or accelerometers attached to the pipe structure is not viable.

6. The bolt cutter appears to introduce less extraneous noise into the wire-break waveform than the rotating abrasive wheel, and is therefore the preferred tool to use when breaking wires for test purposes.

7. The sound of a wire break was easy to distinguish audibly from that of other transient noises occurring in the pipe. The spectrum of the wire-break waveform resembled that of wide band noise with few distinguishing characteristics.

8. The spectrum of a hammer blow signal was quite repeatable, having a distinguishable peak in the 3- to 3.5-kHz region. Audibly, it was easily discerned from that of a wire break, though it was more similar to that of a wire break than any of the other transients occurring in the pipe.

Although the wire-break spectrums showed no prominent distinguishing characteristics, it was considered significant that the sound was readily recognizable audibly and markedly unique. It was hoped that elimination of the extraneous electrical noise would improve the quality of the signals to the point where distinguishing characteristics would come to light. It was considered likely that because the sound of a breaking wire could be audibly distinguished from other sounds so easily, a sophisticated signal processing system could be developed that could also reliably distinguish wire breaks from other sounds.

Prior to the next test program, a consultant was retained to evaluate the practicality of the hydrophone concept. The NRL (Naval Research Laboratory) was also given a contract to investigate the acoustical properties of the siphon. The consultant's and NRL's findings are discussed later in this report. Based on the potential seen from the field test results and positive indications from the consultant and NRL, the decision was made to begin development of specifications for a hydrophone-based AMS (Acoustic Monitoring System) for installation on the Agua Fria River Siphon. This decision was prompted by the urgency to obtain as much information about the continuing deterioration of the siphon as possible.

### September 1992 Field Tests

The purposes of this testing program were to gather data which would be made available to the contractor for the AMS and for further study of the sound propagation in the siphon. The instrumentation was to have a wide dynamic range, and was to be free of electrical noise. The data to be collected during this test were as follows:

1. Recordings of the acoustic background noise in the siphon at several different flow velocities.

2. Impulse response of the siphon and the response to a burst input at various frequencies.

3. Hydrophone signals for wire breaks at several distances from a hydrophone and at more than one flow rate.

4. Wire breaks located between two or more hydrophones.

5. Recordings of hammer blows to the pipe exterior at several distances from a hydrophone.

6. Multiple wire breaks at each location.

These data should be adequate to determine the characteristics of wire-break signals, determine the effect of flow on background noise, determine maximum hydrophone spacing, evaluate the accuracy of calculating wire-break locations, and collect data that would be used to further study the propagation of sound through the siphon. A contractor would use these data to develop the signal analysis algorithms and hardware required to recognize wire breaks and determine their origin. Several hydrophone spacings were required to determine the maximum practical hydrophone spacing. It was also considered important to be able to break wires located between two hydrophones to allow the calculation of break location so that the accuracy of this calculation could be evaluated.

The constraint imposed in previous tests of using existing excavation sites would not provide the required data. Reclamation divers could not install hydrophones spanning the location of the planned wire breaks because of the depth of the water. Consequently, a new type of hydrophone, referred to as a wet-tap hydrophone, was developed. This type of hydrophone is installed through the wall of the pipe as shown on figure 7.

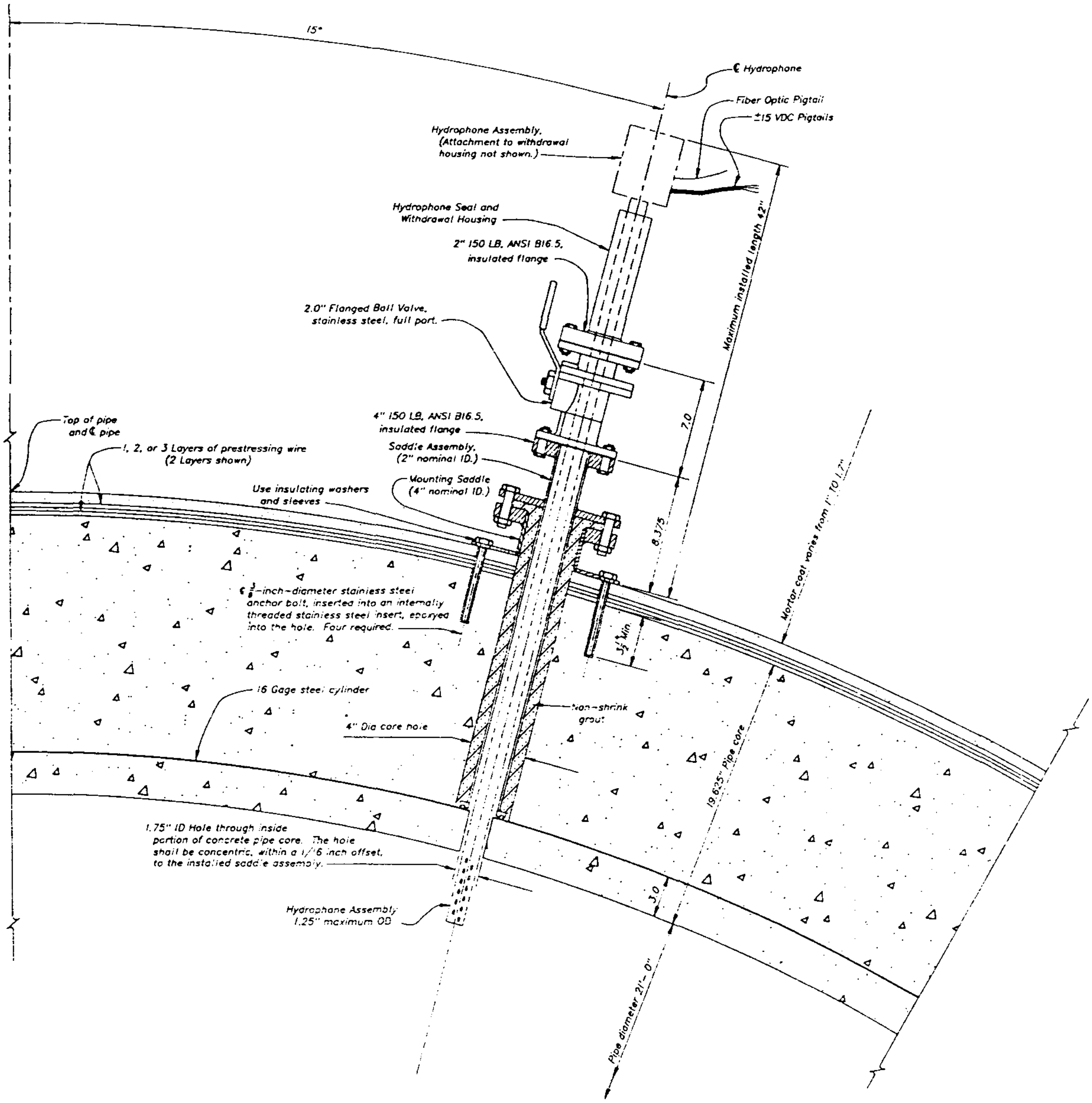



Figure 7. - Wet-tap hydrophone installation details.

The pipe is "wet-tapped" by mounting a valve assembly on the outside of the pipe and then boring a hole through the open valve into the pipe wall from the outside while the pipe is under full pressure. The hydrophone is inserted into the pipe through an adaptor with O-ring seals and a ball valve assembly as pictured on figure 8. This system allows for the installation and maintenance of a hydrophone from the outside during normal operation without the use of divers.

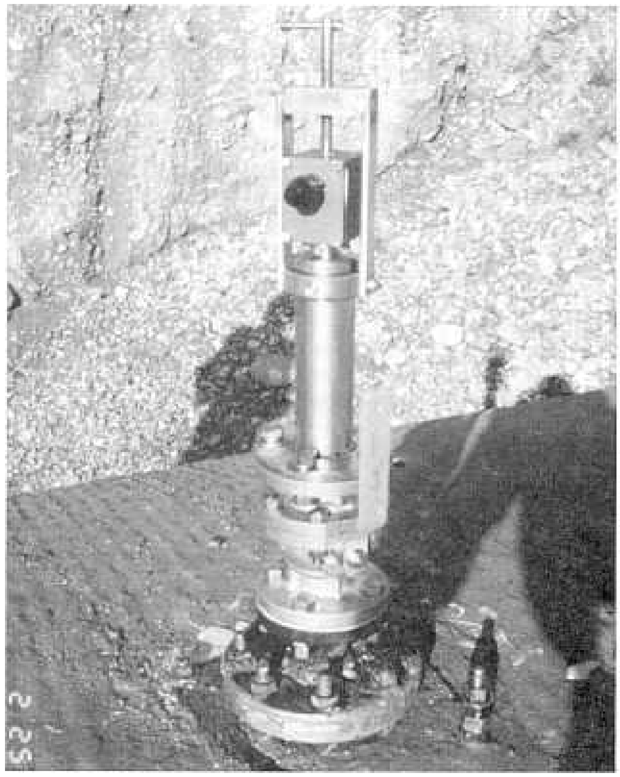


Figure 8. - Wet-tap hydrophone installation.

To eliminate electrical noise, a preamplifier was mounted as close to the hydrophone elements as possible on the dry end of the wet-tap hydrophone. The preamplifier signal fed directly into a system that converted the electrical signal to an optical signal for transmission to an instrumentation van on fiber optic cable. The signal was then converted back to an electrical signal and was recorded using a digital instrumentation recorder. All preamplifiers and fiber-optic transmitters were battery powered. The digital instrumentation recorder had a 16-bit dynamic range; however, the fiber-optic link limited the system's dynamic range to 12 bits. The hydrophone preamplifier gain was manually adjustable and was set prior to each test to compensate for flow conditions and the proximity to the wire being broken. The measures taken to eliminate the electrical noise that plagued previous tests were successful.

The test plan called for nine hydrophones—the four original hydrophones, three wet-tap hydrophones, one hydrophone to be used as a projector, and one hydrophone to monitor the projector output. The four original hydrophones were not expected to provide much quantitative data because they were not calibrated and could not be removed for calibration. During test setup, it was discovered that none of the four original hydrophones were functional because of cable failure. The location of the five remaining hydrophones used for testing is shown on figure 9. Hydrophones Hf, Hg, and Hh were of the wet-tap design. Divers installed Hr and Hp near the siphon outlet; they were suspended in the center of the pipe from elastic bands. Hp was used as a projector to inject known signals into the siphon. Hr, located 5 feet from Hp, was used as a reference to measure the signal injected by Hp.

| | Inlet Headwall | Break A | Break B | Hyd Hf | Break F | Break F1 | Hyd Hg | Break 24" G | Break 12" G | Break 48" G | Break H | Hyd Hh | Break I | Hyd Hr | Projector Hp | Outlet Headwall |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Inlet Headwall | 0 | 173 | 357 | 5568 | 5653 | 7455 | 7962 | 8022 | 8028 | 8033 | 9084 | 9150 | 9459 | 9789 | 9794 | 9842 |
| Break Site A | 173 | 0 | 185 | 5395 | 5480 | 7283 | 7789 | 7849 | 7855 | 7861 | 8912 | 8977 | 9286 | 9616 | 9621 | 9669 |
| Break Site B | 357 | 185 | 0 | 5211 | 5295 | 7098 | 7605 | 7664 | 7670 | 7676 | 8727 | 8793 | 9101 | 9432 | 9437 | 9485 |
| Hydrophone Hf | 5568 | 5395 | 5211 | 0 | 85 | 1888 | 2394 | 2454 | 2460 | 2466 | 3517 | 3582 | 3891 | 4221 | 4226 | 4274 |
| Break Site F | 5653 | 5480 | 5295 | 85 | 0 | 1803 | 2309 | 2369 | 2375 | 2381 | 3432 | 3497 | 3806 | 4136 | 4141 | 4189 |
| Break Site F1 | 7455 | 7283 | 7098 | 1888 | 1803 | 0 | 507 | 566 | 572 | 578 | 1629 | 1695 | 2003 | 2334 | 2338 | 2386 |
| Hydrohpone Hg | 7962 | 7789 | 7605 | 2394 | 2309 | 507 | 0 | 59 | 65 | 71 | 1122 | 1188 | 1496 | 1827 | 1832 | 1880 |
| Break G - 24" | 8022 | 7849 | 7664 | 2454 | 2369 | 566 | 59 | 0 | 6 | 12 | 1063 | 1129 | 1437 | 1768 | 1772 | 1820 |
| Break G - 12" | 8028 | 7855 | 7670 | 2460 | 2375 | 572 | 65 | 6 | 0 | 6 | 1057 | 1123 | 1431 | 1762 | 1766 | 1814 |
| Break G - 48" | 8033 | 7861 | 7676 | 2466 | 2381 | 578 | 71 | 12 | 6 | 0 | 1051 | 1117 | 1425 | 1756 | 1760 | 1808 |
| Break Site H | 9084 | 8912 | 8727 | 3517 | 3432 | 1629 | 1122 | 1063 | 1057 | 1051 | 0 | 66 | 374 | 705 | 710 | 758 |
| Hydrohpone Hh | 9150 | 8977 | 8793 | 3582 | 3497 | 1695 | 1188 | 1129 | 1123 | 1117 | 66 | 0 | 309 | 639 | 644 | 692 |
| Break I | 9459 | 9286 | 9101 | 3891 | 3806 | 2003 | 1496 | 1437 | 1431 | 1425 | 374 | 309 | 0 | 331 | 335 | 383 |
| Hydrophone Hr | 9789 | 9616 | 9432 | 4221 | 4136 | 2334 | 1827 | 1768 | 1762 | 1756 | 705 | 639 | 331 | 0 | 5 | 53 |
| Projector Hp | 9794 | 9621 | 9437 | 4226 | 4141 | 2338 | 1832 | 1772 | 1766 | 1760 | 710 | 644 | 335 | 5 | 0 | 48 |
| Outlet Headwall | 9842 | 9669 | 9485 | 4274 | 4189 | 2386 | 1880 | 1820 | 1814 | 1808 | 758 | 692 | 383 | 53 | 48 | 0 |

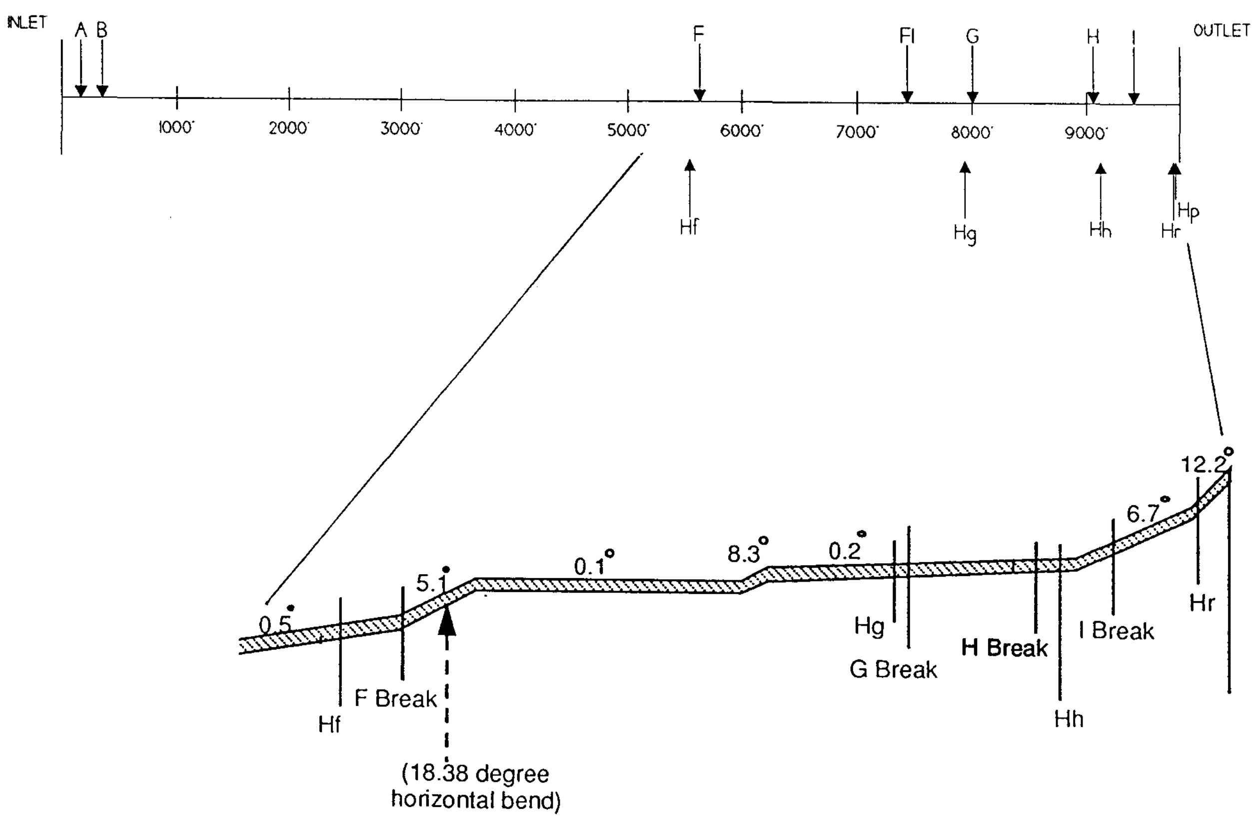



Figure 9. - Agua Fria River Siphon field test, September 1992. Hydrophone and break locations with details of siphon layout.

Ten wires were cut at each of sites A, B, F, F1, and H. At site G, 30 wires were broken; 10 each with 3 different lengths of mortar removed. The three lengths of mortar removed were 12, 24, and 48 inches. At site I, 4 wires were broken. Ten wires were broken at most sites to provide a statistically significant sample size. A total of 84 wires were broken.

The following data were recorded within about eight hours of recording over six days:

1. Acoustic background noise at several flow rates.

2. Acoustic transients caused by hammer blows to the siphon exterior at several locations.

3. Acoustic response of the siphon to a burst input. The projector was excited to produce a burst of sine waves at various frequencies and durations.

4. The acoustic transient caused by inducing breakage of reinforcing wires.

5. Inadvertently, naturally occurring transients that sounded similar to induced wire breaks.

6. Water temperature at the inlet and outlet of the siphon.

### Results of the September 1992 Tests

***Acoustic Background Noise.***-The acoustic background noise was recorded at a total of 6 different flow rates. During no flow conditions, the background noise level was extremely low, as low as 26 dB re 1μPa. The maximum flow available during the testing was only 2/3 of the capacity of the siphon but the background noise level increased dramatically from no-flow conditions. It was necessary to raise the lower 3-dB point of the hydrophone preamplifiers from 17-Hz to 170-Hz because the low frequency flow-induced noise was saturating the input to the preamps. Even with this change, the noise measured at the instrumentation recorder still increased by 50-dB from the no-flow level.

***Impulse and Burst Response.***-The injection of a signal into the siphon proved to be more difficult than expected. The energy delivered in an impulse was insufficient to be detected any further than Hr which was only 5 feet from the projector. Sine wave bursts at several frequencies were successfully detected at hydrophone Hh, however, past that the signal was masked by the acoustic background noise. Figure 10 demonstrates the complex waveform that results from the multiple reflections with the receiving hydrophone only 5 feet from the projector. As would be expected, each waveform shows a series of distinct bursts separated by the transit times of the reflections. The waveforms appear to be independent of frequency in their temporal characteristics. It should be noted that the amplitudes vary between frequencies as a result of the nonlinear frequency response of the projector.

Figure 11 shows waveforms for Hr and Hh at different frequencies. The 6-kHz waveform at Hh appears clipped, but closer examination shows that it was not. The amplitude ratio between Hh and Hr varies with frequency—0.65, 1.0, and 0.66 at 3, 6, and 12 kHz, respectively. The wavefront shapes, with envelopes of increasing amplitude, are of particular interest, indicating that constructive interference results as more reflections arrive at the hydrophone. This interference, and the fact that the amplitude ratios at different frequencies vary, mean that the spectrum of a wire-break would change depending on where it is measured.

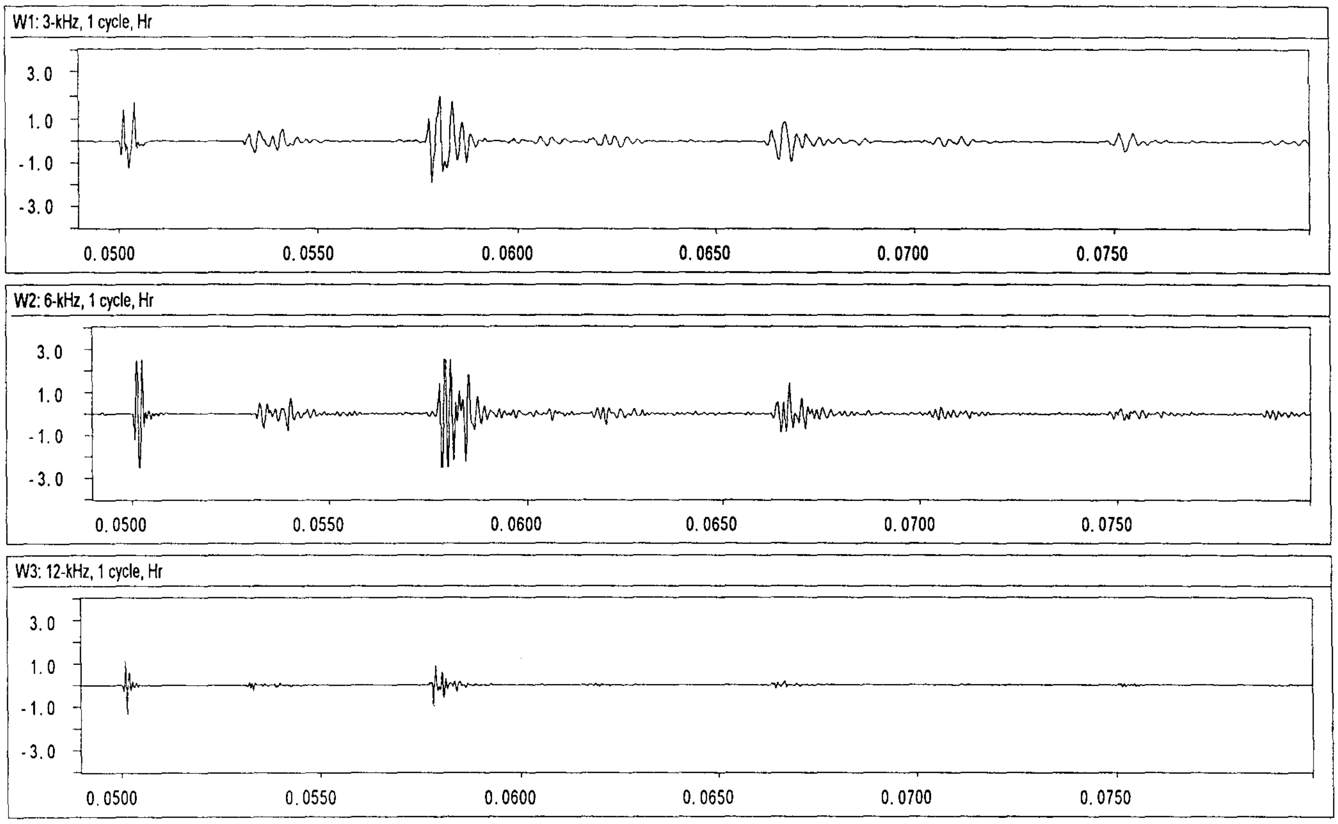



Figure 10. - Example of the signals received at Hr from the projector located 5 feet away.

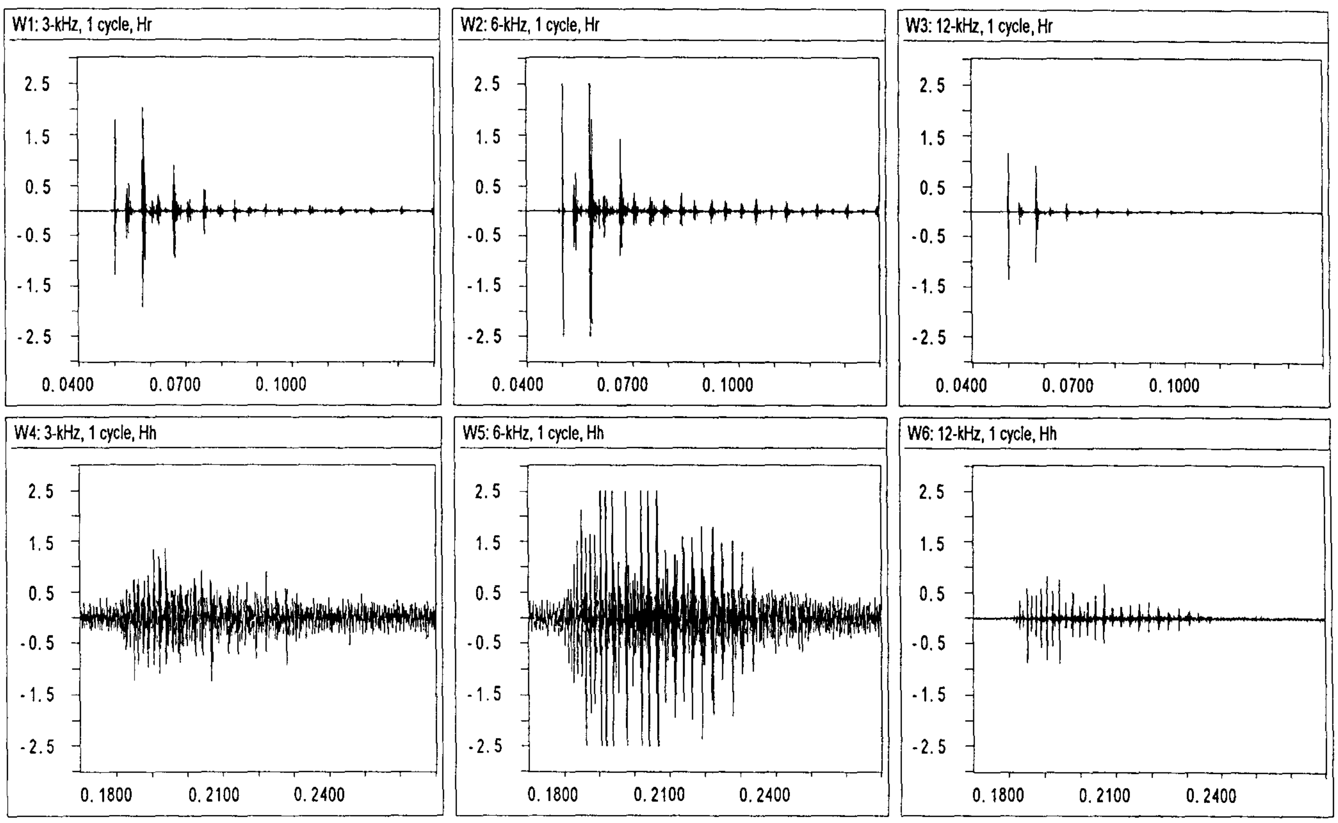



Figure 11. - Siphon response to a single cycle burst input at three frequencies for hydrophones Hr and Hh.

***Hammer Blows.***-Hammer blows were done at each break location and most other available sites. Audibly, these blows sounded distinct from wire breaks, having a lower, more full bodied metallic sound. The hammer blows were too numerous to do a full scale analysis; however, averaged spectrums are shown on figure 12. The examples from hydrophones Hg and Hh are similar, but that from Hr shows a broader band of frequency content. The difference in the mounting position of Hr, which was mounted in the center of the pipe, as opposed to the mounting position of a wet-tap hydrophone, may account for this difference.

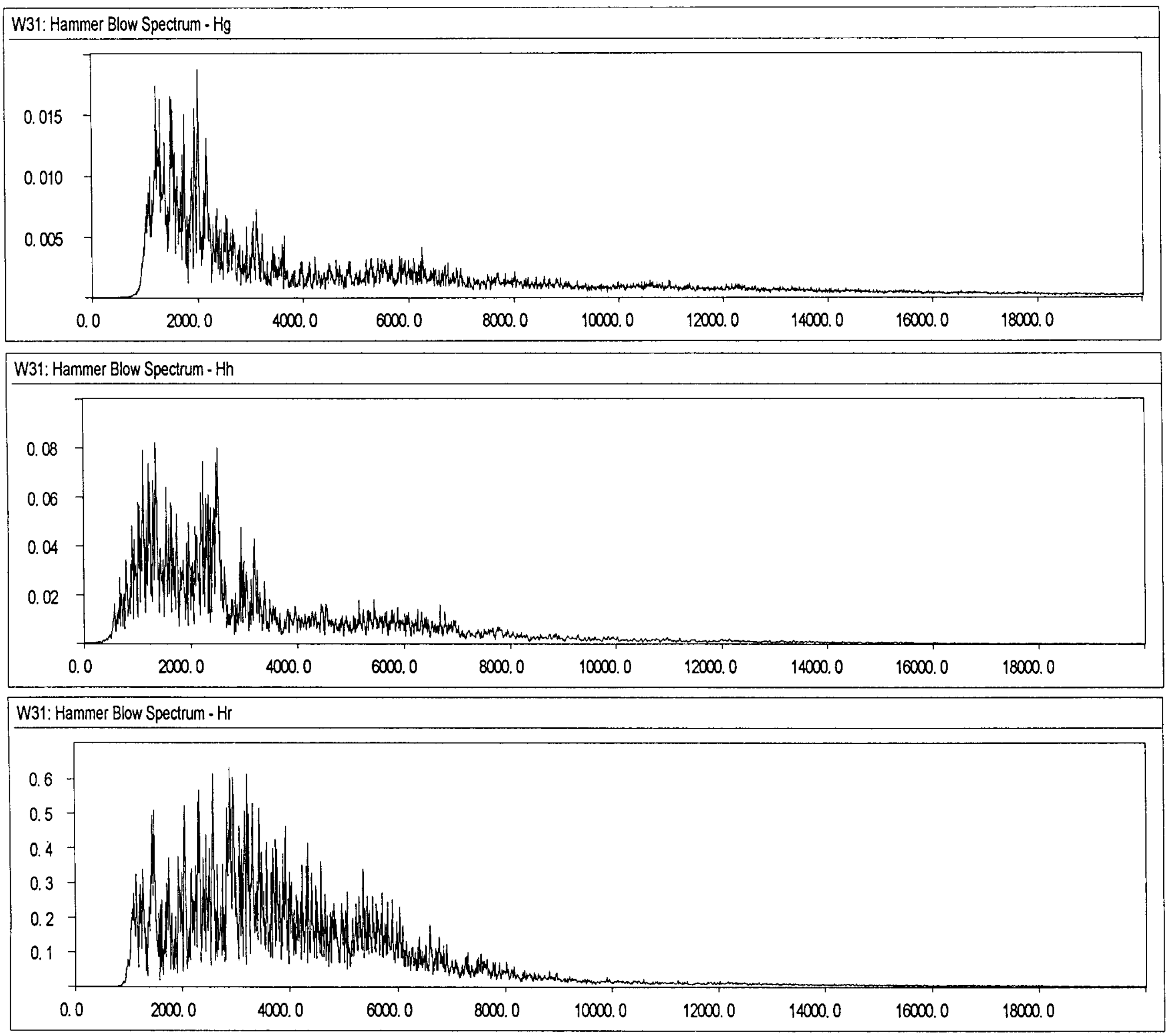



Figure 12. - Spectrums for hammer blows at Site H.

***Wire-Break Analysis.***-Recorded wire-break waveforms from the breaks at sites F, F1, G, H, I, and from all 4 hydrophones, a total of 256 waveforms, were digitized. A 140-ms window of each waveform, which included 5 to 10 ms of pretrigger data, was high-pass filtered at 1 kHz and plotted. It was then characterized by measuring and tabulating the maximum, minimum, peak to peak, RMS, area, and time of arrival of the time domain waveform. The waveform area was derived by computing the area under the absolute value of the waveform. Time of arrival was picked visually. A power spectrum of each waveform was also plotted and the prominent spectral peaks were tabulated. The average spectrum for all ten breaks from a group was plotted as was the density for each group. These group plots aided in spotting general trends in a data set and also in reducing the number of plots for comparison. A typical set of plots at a single hydrophone, for a single break is shown on figure 13. The wire-break signals for breaks at Sites A and B, although audible on the recordings, proved to be so low in amplitude that any meaningful analysis could not be performed.

***Time Domain Break Characteristics.-***

## 1. Signal Strength

Time-domain characteristics of each wire-break waveform were compared to determine consistency in signal propagation from one break to another at the same location. Previous work on similar pipe indicated that the magnitude of the energy released from similar breaks varied little from one break to the next (Peabody, 1990). This work had used strain gages to measure stress-relief on a wire that was cut. This testing showed a COV (coefficient of variation) of around 5% for stress relief among a group of wires. Based on this work, the variation in strength of waveform signals between breaks at the same location was expected to be small. Table 1 shows the characteristics measured for all of the wire-break waveforms for the 12 inch breaks at site G for all hydrophones.

Table 1. - Waveform characteristics measured for 12-inch breaks at site G.

Hydrophone H Waveform Characteristics

| Break # | Max | Min | P-P | RMS | Area | Time |
|---|---|---|---|---|---|---|
| 1 | 5.9840 | -5.9300 | 11.9140 | 1.1110 | 0.1010 | 0.2472 |
| 2 | 6.5220 | -6.7330 | 13.2550 | 1.2500 | 0.1120 | 0.2461 |
| 3 | 5.5220 | -5.6980 | 11.2200 | 0.9520 | 0.0850 | 0.2428 |
| 4 | 6.1340 | -5.9470 | 12.0810 | 1.1020 | 0.1000 | 0.2461 |
| 5 | 3.9030 | -4.1910 | 8.0940 | 0.7770 | 0.0720 | 0.2461 |
| 6 | 4.9760 | -4.7200 | 9.6960 | 0.9150 | 0.0850 | 0.2461 |
| 7 | 4.2660 | -4.7690 | 9.0350 | 0.8700 | 0.0810 | 0.2450 |
| 8 | 4.8730 | -5.1250 | 9.9980 | 0.9440 | 0.0880 | 0.2461 |
| 9 | 4.6760 | -4.7820 | 9.4580 | 0.8830 | 0.0810 | 0.2472 |
| 10 | 4.7190 | -5.4180 | 10.1370 | 0.8730 | 0.0790 | 0.2461 |
| mean | 5.1575 | -5.3313 | 10.4888 | 0.9677 | 0.0884 | 0.2459 |
| std. dev. | 0.8523 | 0.7586 | 1.5867 | 0.1429 | 0.0122 | 0.0012 |
| max | 6.5220 | -4.1910 | 13.2550 | 1.2500 | 0.1120 | 0.2472 |
| min | 3.9030 | -6.7330 | 8.0940 | 0.7770 | 0.0720 | 0.2428 |
| coef. var. | 17% | -14% | 15% | 15% | 14% | 1% |

Hydrophone F Waveform Characteristics

| Break # | Max | Min | P-P | RMS | Area | Time | Atten G-F |
|---|---|---|---|---|---|---|---|
| 1 | 1.5030 | -1.6650 | 3.1680 | 0.3360 | 0.0350 | 0.5196 | -36.7 |
| 2 | 1.5990 | -1.5560 | 3.1550 | 0.3530 | 0.0360 | 0.5196 | -36.3 |
| 3 | 1.3940 | -1.4980 | 2.8920 | 0.2860 | 0.0300 | 0.5185 | -36.9 |
| 4 | 1.4790 | -1.3750 | 2.8540 | 0.3370 | 0.0350 | 0.5185 | -36.6 |
| 5 | 1.2960 | -1.3420 | 2.6380 | 0.2890 | 0.0300 | 0.5207 | -35.9 |
| 6 | 1.5650 | -1.7610 | 3.3260 | 0.3350 | 0.0340 | 0.5218 | -35.8 |
| 7 | 1.4570 | -1.3920 | 2.8490 | 0.3100 | 0.0310 | 0.5201 | -35.8 |
| 8 | 1.6050 | -1.4860 | 3.0910 | 0.3350 | 0.0340 | 0.5201 | -35.6 |
| 9 | 1.3810 | -1.6310 | 3.0120 | 0.3100 | 0.0320 | 0.5201 | -36.0 |
| 10 | 1.4380 | -1.4300 | 2.8680 | 0.2930 | 0.0300 | 0.5185 | -36.3 |
| mean | 1.4717 | -1.5136 | 2.9853 | 0.3184 | 0.0327 | 0.5198 | -36.2 |
| std. dev. | 0.1001 | 0.1379 | 0.2025 | 0.0238 | 0.0024 | 0.0011 | 0.4 |
| max | 1.6050 | -1.3420 | 3.3260 | 0.3530 | 0.0360 | 0.5218 | -35.6 |
| min | 1.2960 | -1.7610 | 2.64 | 0.2860 | 0.0300 | 0.5185 | -36.9 |
| coef. var. | 7% | -9% | 7% | 7% | 7% | 0% | -1% |

Hydrophone R Waveform Characteristics

| Break # | Max | Min | P-P | RMS | Area | Time | Atten H-R |
|---|---|---|---|---|---|---|---|
| 1 | 4.311 | -4.357 | 8.668 | 0.8669 | 0.0813 | 0.3730 | -2.2 |
| 2 | 4.418 | -5.259 | 9.677 | 0.9461 | 0.0886 | 0.3719 | -2.4 |
| 3 | 3.933 | -3.773 | 7.706 | 0.7650 | 0.0717 | 0.3708 | -1.9 |
| 4 | 4.705 | -5.069 | 9.774 | 0.8673 | 0.0807 | 0.3730 | -2.1 |
| 5 | 4.200 | -3.618 | 7.818 | 0.6896 | 0.0637 | 0.3730 | -1.0 |
| 6 | 4.508 | -4.259 | 8.767 | 0.8177 | 0.0755 | 0.3730 | -1.0 |
| 7 | 3.285 | -3.534 | 6.819 | 0.6902 | 0.0656 | 0.3730 | -2.0 |
| 8 | 3.594 | -4.064 | 7.658 | 0.7560 | 0.0710 | 0.3730 | -1.9 |
| 9 | 4.051 | -3.945 | 7.996 | 0.7465 | 0.0702 | 0.3730 | -1.5 |
| 10 | 3.910 | -3.484 | 7.394 | 0.7420 | 0.0699 | 0.3719 | -1.4 |
| mean | 4.092 | -4.136 | 8.228 | 0.7887 | 0.0738 | 0.3726 | -1.7 |
| std. dev. | 0.431 | 0.617 | 0.970 | 0.0837 | 0.0077 | 0.0008 | 0.5 |
| max | 4.705 | -3.484 | 9.774 | 0.9461 | 0.0886 | 0.3730 | -1.0 |
| min | 3.285 | -5.259 | 6.819 | 0.6896 | 0.0637 | 0.3708 | -2.4 |
| coef. var. | 11% | -15% | 12% | 11% | 10% | 0% | -28% |

Hydrophone G Waveform Characteristics

| Break # | Max | Min | P-P | RMS | Area | Time |
|---|---|---|---|---|---|---|
| 1 | 181.50 | -147.80 | 329.30 | 23.040 | 1.8180 | 0.0253 |
| 2 | 200.80 | -156.60 | 357.40 | 23.160 | 1.8260 | 0.0253 |
| 3 | 178.80 | -162.80 | 341.60 | 20.090 | 1.5800 | 0.0242 |
| 4 | 155.00 | -170.70 | 325.70 | 22.670 | 1.7660 | 0.0264 |
| 5 | 123.30 | -132.50 | 255.80 | 18.020 | 1.4860 | 0.0253 |
| 6 | 152.10 | -157.60 | 309.70 | 20.640 | 1.6630 | 0.0264 |
| 7 | 138.20 | -176.10 | 314.30 | 19.170 | 1.5740 | 0.0276 |
| 8 | 147.90 | -159.30 | 307.20 | 20.290 | 1.6680 | 0.0276 |
| 9 | 134.60 | -180.30 | 314.90 | 19.450 | 1.6100 | 0.0276 |
| 10 | 139.20 | -163.80 | 303.00 | 19.140 | 1.5950 | 0.0264 |
| mean | 155.14 | -160.75 | 315.89 | 20.567 | 1.6586 | 0.0262 |
| std. dev. | 24.44 | 13.85 | 26.99 | 1.804 | 0.1128 | 0.0012 |
| max | 200.80 | -132.50 | 357.40 | 23.160 | 1.8260 | 0.0276 |
| min | 123.30 | -180.30 | 255.80 | 18.020 | 1.4860 | 0.0242 |
| coef. var. | 16% | -9% | 9% | 9% | 7% | 4% |

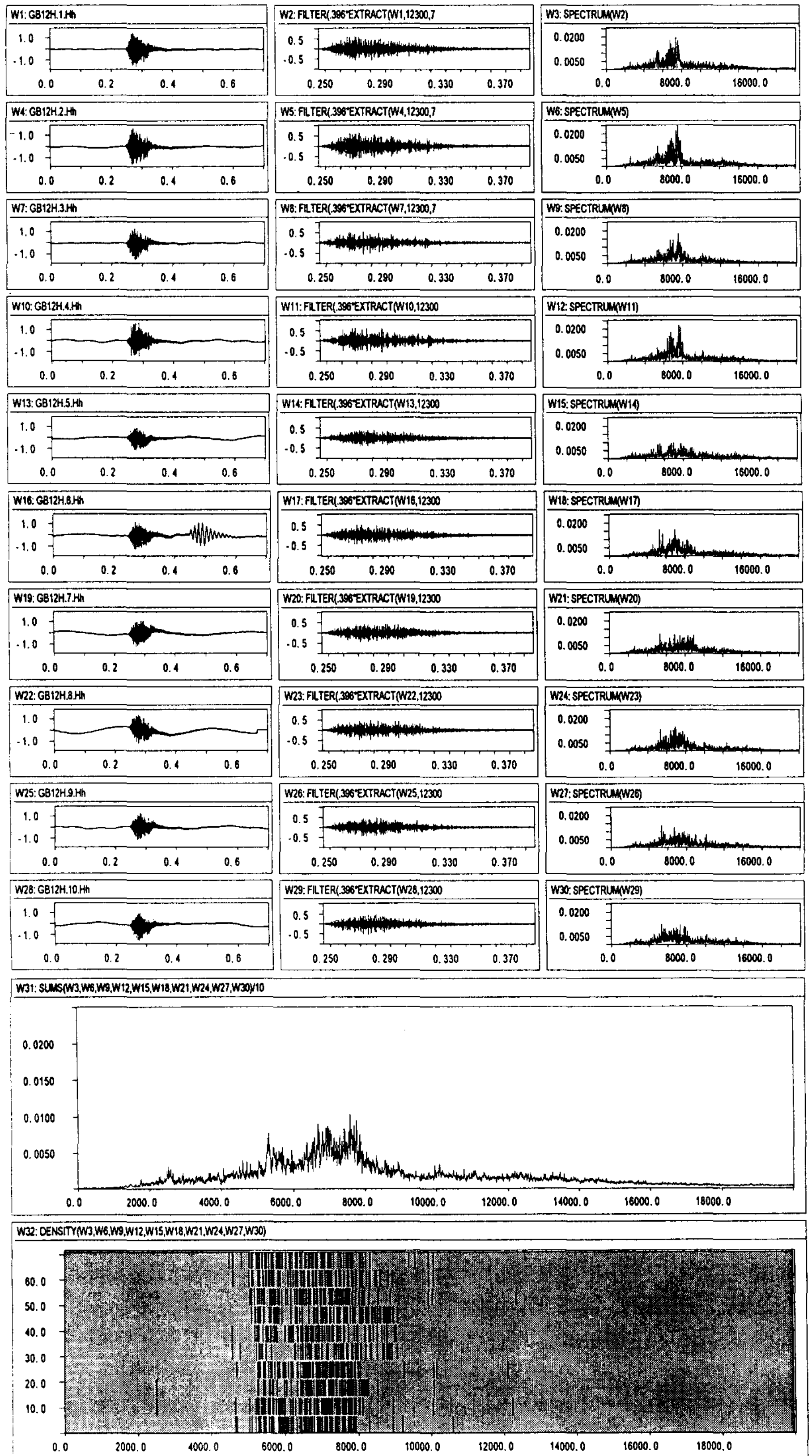



Figure 13. - Typical plots generated for each wire break at each hydrophone. Each group of three is the time series, the high-pass filtered waveform extracted from the time series, and the power spectrum.

When comparing break waveform characteristics, the best characteristic to use should give the most consistent values for breaks at the same location. Generally the maximum, minimum, and peak to peak values had a higher COV than did the RMS and area characteristics. In 85% of the cases, the RMS or area characteristic gave the lowest COV between breaks in a group. This result is attributed to the sensitivity of the maximum, minimum, and peak to peak parameters to momentary spikes in the signal. The RMS characteristic was slightly better than the area characteristic and from this result, it was decided that intragroup comparisons would be made using the RMS characteristic.

As noted above, previous work on similar pipe showed a COV for multiple wire breaks on a single pipe section as measured by strain gages of about 5%. More than half of the COVs for the RMS values are 10% or less, which is considered to be in good agreement with the strain gage data. However, the remaining RMS values ranged as high as 60% COV, indicating that the signal received at the hydrophone may not be a direct function of how much energy is released when a wire fails. This lack of correlation could be the result of several factors, including the energy coupling from the wire to the pipe, coupling from the pipe to the water, and energy propagation through the water to the hydrophone.

For the breaks at site G, the mean RMS of the waveforms for each hydrophone is plotted versus the length of mortar removed in figure 14. This plot indicates that no relation appears to exist between the length of mortar removed and the magnitude of the signal.

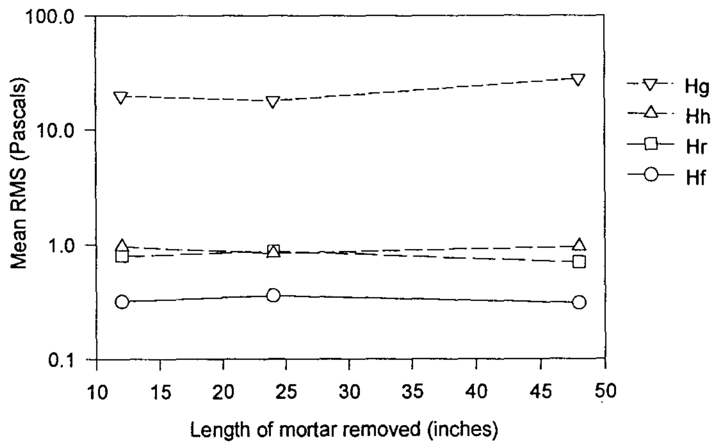



Figure 14. - Mean waveform RMS versus length of mortar removed. Notice apparent lack of correlation.

## 2. Attenuation

Acoustic wave attenuation through the siphon is believed to be fairly low. Transmission loss of the signal is affected by two factors, spreading loss and loss caused by attenuation (Urick, 1975). Urick states that for the "academic" case of a lossless tube of constant cross section, the spreading loss would be zero. The AFRS pipe is of constant cross section, but because the signal is not launched in one direction, only half of the energy will travel toward the hydrophone of interest. This loss would be analogous to the spreading loss. Other losses, classified as absorption, scattering, and leakage, could be considered attenuation losses. Absorption loss will be less than 1 dB/kyd at the frequencies of interest. Scattering loss is expected to be low because of the smooth finish on the inside surface of the pipe; however, losses caused by bends in the pipe could also be classified as scattering losses. The remaining attenuation loss, from leakage, is expected to be the predominant type. The numerous reflections from the walls of the pipe as the acoustic wave travels to the hydrophone, particularly because the waveform is not launched along the axis of the pipe, will have a slight loss at every reflection. This loss, though pervasive, is expected to be low because the pipe structure is smooth, stiff, and massive, and little energy should be lost into the pipe.

Attenuation was calculated between hydrophone pairs for each break. The attenuation values are plotted against distance between hydrophones on figure 15. As the plot shows, the data are so disparate that no correlation appears to exist between attenuation and distance. The most curious aspect of this finding is that several of the points involving Hr actually showed a gain in signal strength rather than attenuation. This gain is attributed to the fact that Hydrophone Hr, not being a wet-tap hydrophone, was mounted in the center of the pipe, and the wet-tap hydrophones protrude into the pipe less than one foot. The gain suggests that the location of the hydrophone in the pipe affects the amount of the signal received more than its distance from the break. The inconsistent results from the other hydrophones also suggest that their individual location in relation to the origin of the break also bears on the signal they receive. This suggestion follows from the idea that the sound propagation follows many paths from the source. The sound would reach the hydrophone directly as well as through many paths reflecting off the inner walls of the pipe, which puts the hydrophones in a field of reinforcing and canceling waves. The conclusion is that regardless of the inability of the results to establish a single value for attenuation through the pipe, the wire breaks can be detected and located if an adequate signal to noise ratio exists and if the timing of the signal arrival can be established.

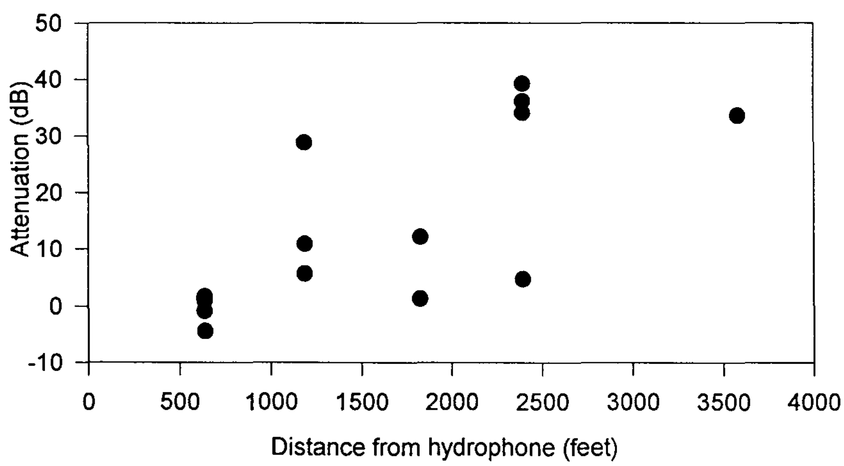



Figure 15. - Signal attenuation versus distance between hydrophones.

## 3. Sound Velocity

For each break, calculation of sound velocity was done using time of arrival of the waveform at each hydrophone and the known distance between hydrophones. This calculation yielded excellent results. Within a group of wire breaks, the COV was close to 1% in nearly all cases. Overall, the COV for all velocities for the combination of all groups was 2.4%. Velocity values appear in table 2. The cause of the variations in calculated velocity that exist between tests are attributed to ambiguities in selecting the time of signal arrival.

Table 2. - Sound velocities computed using various hydrophone pairs.

| | Hydrophone Pair | | | |
|---|---|---|---|---|
| Break Site | f-g | g-h | g-r | h-r |
| Site F velocity | | 4893 | 4935 | 5018 |
| coefficient of variation | | 1.4% | 0.8% | 1.2% |
| Site F1 velocity | | 4926 | 4889 | 4786 |
| coefficient of variation | | 0.8% | 0.9% | 1.4% |
| Site G12 velocity | 4851 | | | 5044 |
| coefficient of variation | 0.3% | | | 0.7% |
| Site G24 velocity | 4844 | | | 5109 |
| coefficient of variation | 0.6% | | | 1.0% |
| Site G48 velocity | 4834 | | | 5102 |
| coefficient of variation | 0.4% | | | 3.0% |
| Site H velocity | 4677 | | | |
| coefficient of variation | 2.1% | | | |
| Site I velocity | 4917 | 4812 | | |
| coefficient of variation | 0.4% | 1.8% | | |

## 4. Break Location

The break locations were calculated using the arrival time of the wire-break waveforms at each hydrophone. This calculation was done for each pair of hydrophones spanning a break. Because several velocity values were available for each break, several were tried in order to determine which gave the best calculated location. The velocity that typically yielded the best location calculation was the mean of the velocities from the breaks in that group, calculated using the closest hydrophone pair.

Location calculations were more accurate at no flow conditions and were worse at higher flows. This result is attributed to a better signal to noise ratio at the low flow condition. A good signal to noise ratio yielded a good location calculation in nearly every case. The best location values are obtained when the signal to noise ratio is high (which implies low flow), using an average of velocities taken from the closest neighboring hydrophone pair.

The location accuracy varied for a group from an average of 4 feet of error with a standard deviation of 3 feet, to a high of 23 feet of error with a standard deviation of 13 feet. The latter occurred at high flow for a long hydrophone spacing. The overall average location error for hydrophone spacings of 1188 feet or less, was 7.5 feet. For spacings over 1188 feet, the average error increased to 15.7 feet.

***Frequency Domain Analysis.***-The power spectrum of the waveform received at each hydrophone for each wire break was plotted. A general trend noted in nearly all cases was that little information of any significance appeared to exist above about 8 kHz.

Analysis of the break waveforms in the frequency domain was considered to be the most likely to provide a means of distinguishing wire break sounds from those sounds generated by other sources. This assumption was based on the distinct audible differences between the sound of a wire-break and that of the acoustic background present in the siphon.

## 1. Break to Break Comparison

The first analysis was done to determine the variation between all of the breaks at a given location. Each of the breaks in a group showed the same general spectral characteristics. A typical example is shown on figure 16. This result was expected because all of the breaks at one location were in relative close proximity to each other, making the path between each break and each hydrophone nearly identical.

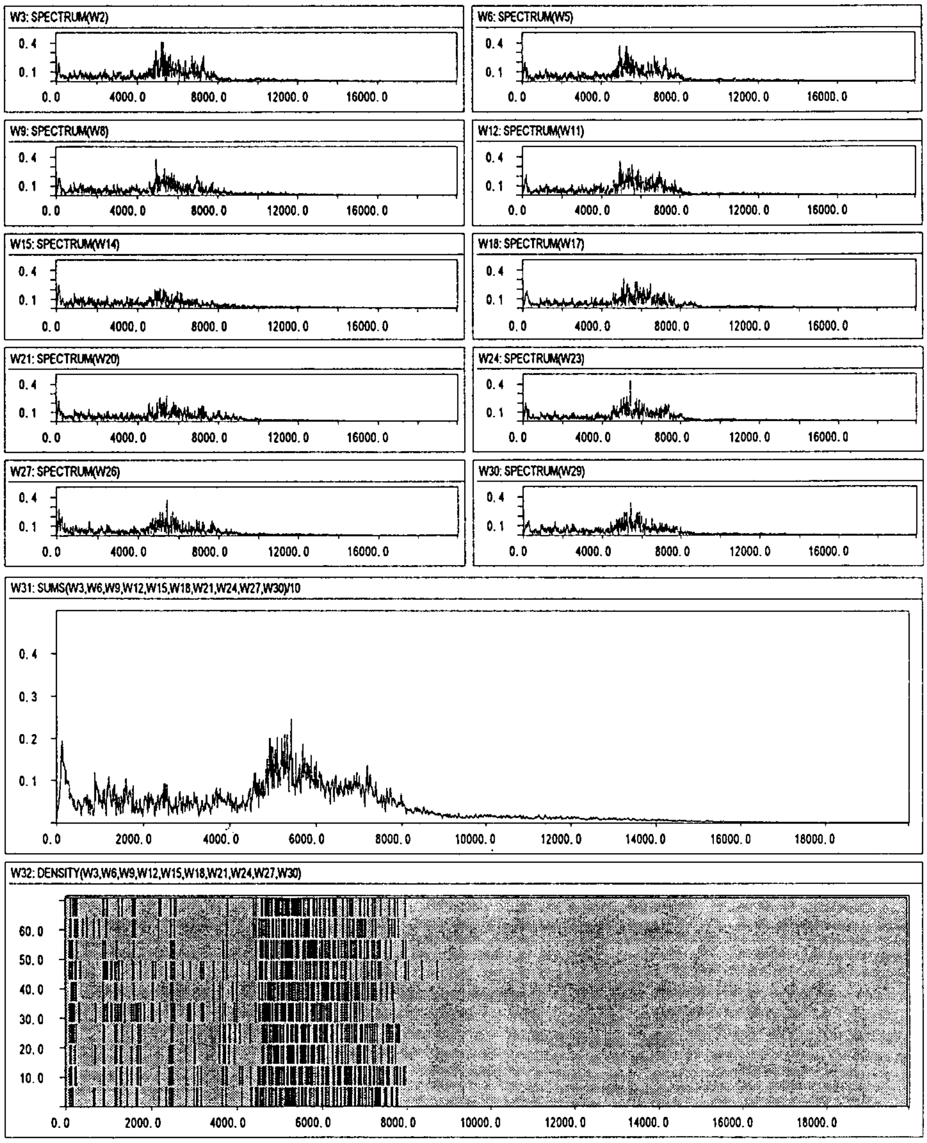



Figure 16. - Typical plot of spectrums for all ten wire breaks in a group with the average spectrum and density shown on the bottom.

## 2. Hydrophone to Hydrophone Comparison

Next, the average spectrums of the breaks at each location were compared for each hydrophone location as the acoustic wave traveled down the siphon. In nearly all cases, little resemblance existed between spectrums for the same group of breaks from one hydrophone to another. This result is again suspected to relate to the positioning of the hydrophone in the field of acoustic pressure waves. The waveform's different frequency components are assumed to have different propagation characteristics, resulting in a changing frequency spectrum as the waveform travels through the pipe, which is mainly attributed to constructive and destructive interference caused by multiple reflections in the pipe. This changing frequency spectrum suggests that finding a common set of wire-break characteristics may be difficult. Although this may be true, the unique sound heard audibly gives credence to the idea that even though the spectrums look different, commonalities exist that are not visually apparent.

## 3. Mortar Length Comparison

Thirty breaks were performed at Site G, 10 each with 12, 24, and 48 inches of mortar removed. The different lengths of mortar removal did appear to have a relationship to the spectrum of the wire-break waveform. Typically, the longer the length of disbonded mortar, the lower the frequency of the predominant peaks in the spectrum at each hydrophone. Comparing the spectrums on figure 17 illustrates this trend. This result directly contradicts the findings from the July and October 1991 tests. It is believed that any trend in the 1991 data was not apparent because of the limited data set and masking by the excessive electrical noise.

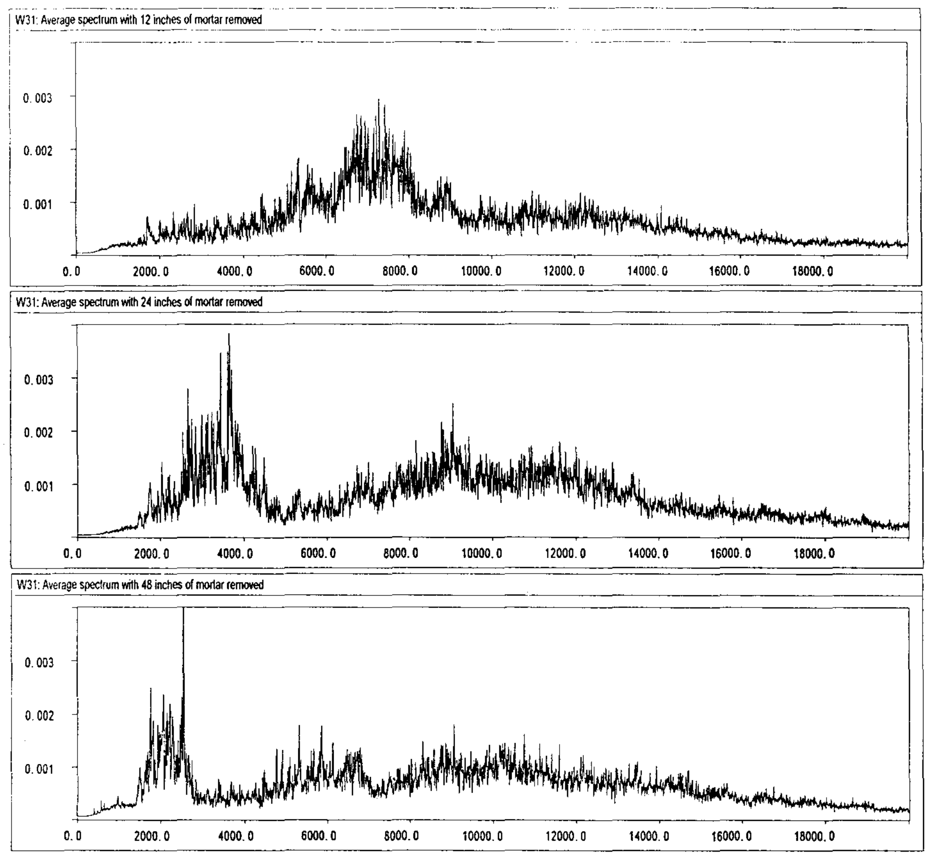



Figure 17. - Average spectrums of wire breaks for three lengths of mortar removal, 12-inch top, 24-inch middle, and 48-inch bottom.

***Natural Transients.***-A critical review of all recordings made during the testing revealed 38 transients of unknown origin that audibly resembled the sound of the staged wire breaks. Of these, the signals from 30 of the events were adequate to allow the location to be calculated. The calculated locations of 19 of the 30 events were clustered in two separate but distinct places along a short section of the siphon (fig. 18). The other 9 events were distributed within the remaining span of the test hydrophones. The section showing the concentration of events consisted of 10 pipe sections. This section was subsequently excavated. After completing the excavation and "sounding" the pipe, several disbonded areas were discovered. The disbonded areas correlated well with the locations where the greatest number of the 19 transient events were calculated to have originated.

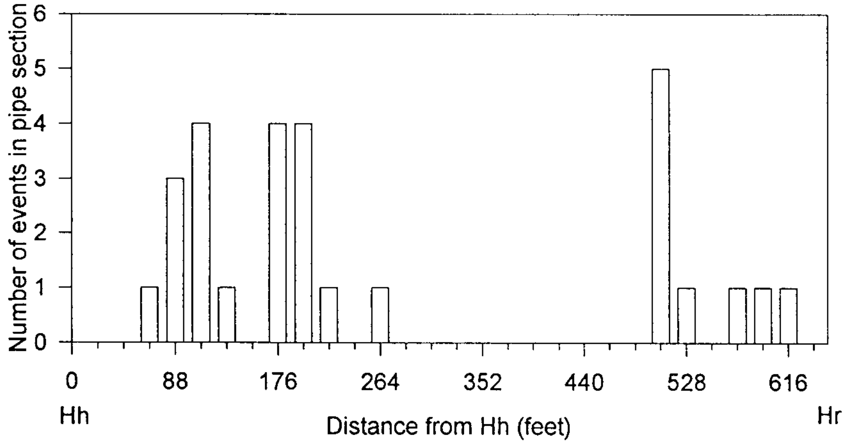



Figure 18. - Histogram of natural transient locations. These natural transients were suspected to be naturally occurring wire breaks.

The 38 transient events that were noted as possible wire breaks were not evenly distributed over the eight hours of recorded data. Twenty-eight of the 38 transients occurred during one day of testing (9 hours), and 18 of these occurred within 15 minutes of each other. This information suggests that if these transients were wire breaks, then wire breaks occur in bursts.

**Conclusions—September 1992 tests:**

1. A hydrophone spacing of 1000 feet should provide signals from which wire breaks can be located to within one pipe section.

2. The attenuation of the signal over the length of the siphon appears to be a function of factors other than distance. The location of the hydrophone in the field of reinforcing and canceling wavefronts, as well as the geometry of the siphon, is suspected to have a significant effect.

3. Correlation between the calculated locations of the naturally occurring transient activity and the newly discovered areas of pipe distress provided increased confidence that the permanent AMS will allow the user to locate distressed pipe sections within the siphon.

4. The use of preamplifiers mounted at the hydrophone and fiber-optic signal transmission eliminated electrical noise problems.

5. The 38 transient events suspected to be wire breaks occurred during the 8 hours of recorded data at a rate about 100 times greater than previous estimates.

## OTHER INVESTIGATIONS

### Signal Processing Consultant

A consultant retained prior to the September 1992 field tests evaluated the acoustic monitoring concept. The consultant's background was in underwater acoustic transient signal processing. The consultant was directed to review the available data (July 1991 test data) and to evaluate the practicality of implementing a system to detect acoustic events, identify those that were wire failure related, and locate the source of the events. The quality of these data suffered from severe electrical noise as noted earlier, which proved troublesome to his analysis. The consultant reached the following conclusions (DiMarco, 1992):

1. A simple level-detection system is not practical for this application.

2. Non-separable multipath distortion of the wire-break waveform is occurring within the siphon, making the determination of signal arrival time inexact when using the correlation function. Several other methods are available for estimating time of arrival and will require further investigation with more extensive test data.

3. Detection and classification of wire breaks versus other transient events, such as hammer blows, was possible.

The consultant was optimistic that a system meeting Reclamation's needs could be developed if additional test data were available. A system of this type would likely employ an algorithm that would form a continuous, long-term, statistical characterization of the background noise. Deviations from the background noise would be further analyzed to determine if the event fit the characteristics of a wire break.

### Naval Research Laboratory

The Naval Research Laboratory was contracted to perform additional work in two areas. NRL's Physical Acoustics Branch did preliminary work in the development of a model of the acoustical properties of the AFRS. The second portion of the contract was with NRL's Optical Sensors Section to develop a fiber optic hydrophone system for this application.

***Acoustic Modeling.***-The Acoustics Branch studied the effect the siphon geometry on signal propagation. Their findings showed that bends in the siphon can significantly impact the accuracy of locating the source of wire breaks. Bends also affect frequency content of the waveforms, attenuating higher frequencies and possibly introducing low frequency content.

NRL's method to determine signal arrival time employed a plot of the logarithmic envelope of the time series. This plot was obtained by computing the signal's complex Fourier Transform, zeroing the components above the Nyquist frequency, and taking the absolute value of the inverse transform. This process resulted in the waveforms shown on figure 19. By moving the time series envelopes from two hydrophone signals along the time axis until they over-lay, the time difference gives the value from which the location can be calculated. Alignment was tried visually and using cross correlation. Although the cross-correlation technique provides an objective computation of the time difference, visual alignment often provided more accurate locations; however, this method depends on subjective judgement of the envelope alignment.

NRL's report concluded that siphon bends play a critical role and for this reason, a hydrophone should be located at each bend. They recommended a hydrophone spacing of 500 feet; however, they indicated that this estimate was conservative and that the spacing could be increased. They recommended band-pass filtering the incoming signal to 0.4- to 4-kHz. They felt that a comprehensive acoustic model of the sound propagation could substantially improve the accuracy of localization and extend the distance between hydrophones.

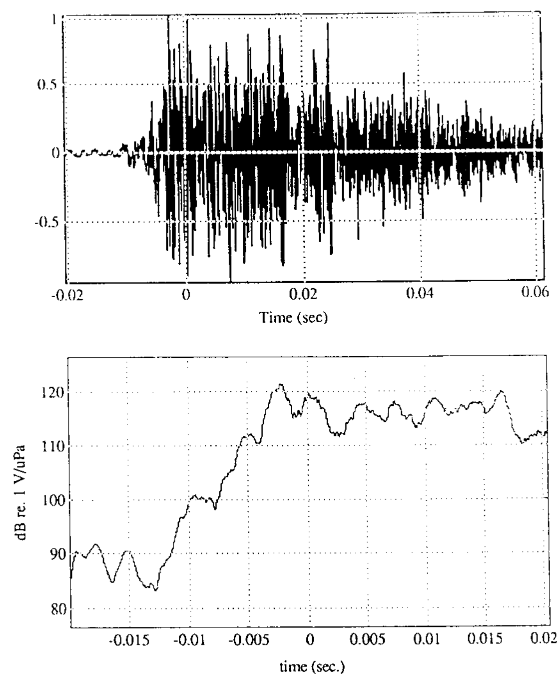



Figure 19. - Time domain plot of wire-break waveform (top) and logarithmic envelope of the time series (bottom).

***Fiber Optic Hydrophones.***-Early discussions with NRL suggested that their fiber optic hydrophone technology might have advantages in this application. This type of hydrophone employs a length of fiber optic cable as the sensing element. Coherent light is supplied through a fiber optic cable to the hydrophone. At the hydrophone, the incoming beam is split between two fibers which are configured to form a Mach-Zehnder Interferometer. The sensing element consists of a length of optical fiber that is wrapped around a plastic mandrel. This coil is exposed to the acoustic pressure waves impinging on the hydrophone. The pressure waves strain the optical fiber, resulting in a minute change in the length of the fiber. A second optical path through another coil of optical fiber that is not exposed to the pressure waves acts as the reference path for the interferometer. The output from the two paths are combined and the interference between the two provides a signal that is proportional to the acoustic pressure. The output is returned through a second optical fiber to the demodulating electronics for translation into an electrical signal.

NRL designed and built three fiber optic hydrophones for Reclamation that conform to the dimensional requirements of the wet-tap system. The signal conditioning equipment was packaged for use in the field and the system has been tested on the Agua Fria River Siphon. The hydrophones have given results comparable to those obtained with conventional hydrophones. The use of fiber optic hydrophones has several advantages over conventional hydrophones in Reclamation's application. The fiber optic hydrophones are totally waterproof, require no local power source, are unaffected by the high temperatures at the AFRS, and are immune to electrical interference. Conventional hydrophones require preamplification close to the hydrophone elements, which necessitates supplying power to each hydrophone. The preamplifiers must be designed to accommodate the extreme environmental conditions at the AFRS, including high ambient temperatures, complete submersion under water for extended periods, and excessive electrical noise. Additionally, transmission of the signal must also be immune to electrical interference, necessitating the use of an optical fiber transmission system. The main drawback to the fiber optic system is that it is not yet a commercial system and as such it requires periodic "tweaking," and the laser does not operate well under high ambient temperature conditions.

**Acoustic Emissions**

Reclamation has conducted limited investigations with the use of AE (acoustic emission) equipment to pinpoint areas of distress on a single pipe section. Laboratory work on an isolated pipe section and field testing at the AFRS have not shown this technology to be very effective. However, a concerted effort has not been made to fully evaluate the potential of AE in this application.

## INSTALLED ACOUSTIC MONITORING SYSTEM

In 1993, a contract was awarded to build an AMS (Acoustic Monitoring System) to monitor the Agua Fria River Siphon. This system was installed in July 1994. The system employs 12 hydrophones spaced about 1000 feet apart along the length of the siphon, and a real-time signal processing system is installed at the inlet end. The system employs two pingers built into hydrophones to establish the sound propagation velocity for location calculations. These pingers are pulsed periodically and the velocity is calculated from the arrival times at several of the hydrophones. A workstation, located at the project office, is used for in-depth manual signal evaluation and research. The hydrophones are the conventional piezoelectric type in a wet-tap type housing. Located on the dry end of each hydrophone, in a waterproof housing, is a preamplifier, a digitizer, and a fiber optic transmitter. Fiber optic cables carry the digitized waveforms and timing information to the processing equipment at the inlet structure.

The real-time signal processing system continuously monitors all twelve hydrophones and forms a continuous estimate of the characteristics of the acoustic background. Detection of a transient on any channel is initially screened by measuring its duration and signal to noise ratio, and searching for transients on other sensors within an appropriate time window. If the event passes this initial screening, it, and the associated events, are passed to the automatic classifier for a more detailed evaluation. This classifier is a multi layer neural network employing a multimodal Gauss-Bayesian algorithm, which is a pattern recognition algorithm that computes a vector from 77 features of the data and assigns a classification based on a minimum square distance to the nearest class. If the event is classified as a wire-break or other classification of interest, the location is calculated and all real-time data are archived. Two different options are available for location calculation. The first uses an edge detector to establish arrival times for the waveforms and calculates location from the edge times. The second uses cross correlation to establish the difference in time of arrival directly. The use of cross correlation generally does not yield good results because the coherence between hydrophones is usually poor.

The processor at the siphon downloads the archived data on a daily basis to the workstation at the project office. The workstation at the project office is used to manually review the wire break data and examine the waveform arrival edges used for event location. The workstation has the capability for audio playback of events, which continues to be the best method to confirm event classifications. As additional events are gathered and manually verified, the classification algorithm is "trained" to improve its accuracy. At present, all events are being reviewed manually to verify proper classification.

The AMS system was installed during the summer of 1994 and was fully functional starting in September 1994. The system has been functioning well and numerous events, classified as wire breaks and manually verified, have been located. The system has been detecting more events than anticipated and consequently, the storage capacity has proven to be inadequate. This inadequacy has prevented the system from being on-line continuously. In the 150+ hours of operation to this point, over 317 events have been classified as wire breaks. Figure 20 shows a histogram of one of the more active areas detected to date. If the system proves valuable at the AFRS, additional systems will be installed at other CAP siphons. At this time, the system shows much promise.

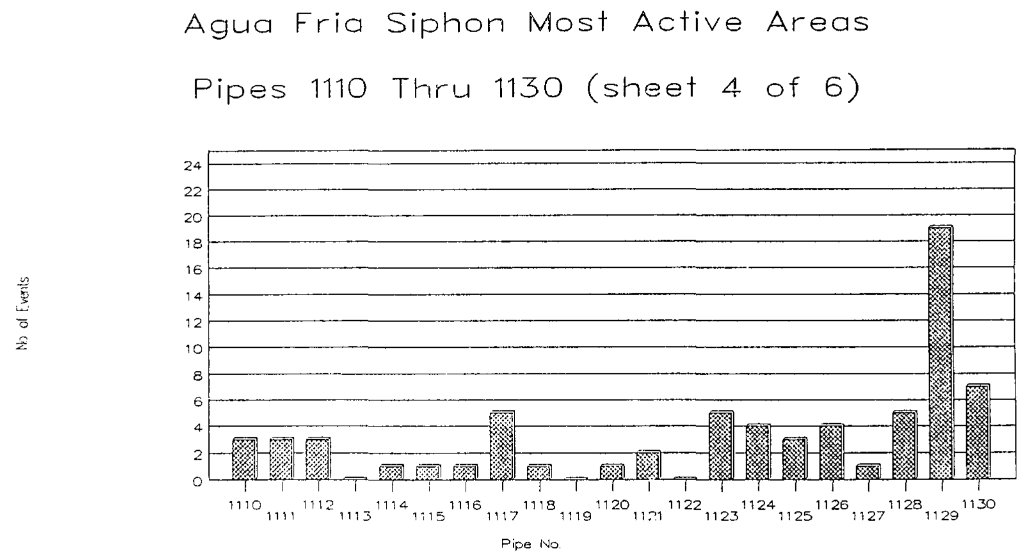



Figure 20. - Histogram of currently active wire break areas, Agua Fria River Siphon.

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## Mission

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American Public.