Satellites & solid state electronics test concrete pressure water pipelines

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ABSTRACT

Like all structures, water pressure pipelines have a finite life. Pipelines will eventually begin to fail, leaving the pipeline owner to deal with the quandary: what caused this to happen, can we prevent future failures, must we replace this structure now? The causes for pipeline failure include defects and anomalies which may occur in any phase of a pipeline's life: during the engineering, the manufacture, the construction, or the operation. Failure may simply be the result of environmental conditions or old age. In the past five years, passive acoustic emission detection technology has been adapted to concrete pressure pipelines. This method of inspection is based on the acoustic emissions made by the prestressed reinforcing wire as it releases its energy. A recently patented method of using this technology relies on a series of remote, independent test stations to detect, record and time-stamp these acoustic emissions. A low-powered, high-performance embedded processor system makes use of global positioning system time signals to synchronize multiple stations. These methods are re-defining the standard of care of water pressure pipelines. This paper describes pipeline failure mechanisms and a state-of-the-art data sampling system which has been developed to evaluate pipeline structural integrity.

Keywords: pipelines, water, concrete, failure, rupture, diagnostic, testing, embedded processor, GPS, hydrophones

1. INTRODUCTION

Diagnostic testing is an interesting challenge, and the progress over the past few decades, especially in the field of medicine, is testimony to be ingenuity of scientists in the field. A thorough medical examination at a modern facility is an education in the application of science to medicine: electronics, data loggers, transducers, passive acoustics, active acoustics, digital signal processing, optics, X-ray, transducers, and a myriad of other electronic devices are able to quickly and accurately diagnose conditions of interest to the physician.

Figure 1. Internal pipe inspection

Diagnostic testing in the field of the civil infrastructure is also making considerable progress, but is estimated to lag behind the medical field by about two decades. The diagnostic testing of buried concrete water pressure pipelines is a case in point. Ten years ago, the state-of-the-art in the testing of these structures was to physically enter the pipeline with a team of experts to perform a visual inspection. This is a very valid procedure, somewhat analogous to the doctor's stethoscope examination, but with many limitations - starting with the sizes of the pipelines, many of which are simply too small for entry by people. The environment in the inside of a potable water line is tolerable, however many of these lines carry water of lesser quality - including raw sewage. Needless to say, it is difficult to coax many top-performance engineers and scientists into this line of work. Also, the fact of the matter is that many serious structurally distressed conditions are not visible from the

surface of the pipeline.

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Like most of the civil infrastructure, pipelines are not designed for a specific life expectancy. If you ask a pipeline designer or pipeline owner what the life expectancy of the pipeline is, you will frequently hear that "we really have not thought about it." My own observation is that people will generally agree that anything less than 50 years would be disappointing, and that anything over 100 years would be remarkable. Maybe that is as good an answer as there is. Although some pipelines have reached centenarian age, the vast majority of our major water conveyance infrastructure has been built in the last 70 years. The engineers in the next century will "face the music" in a manner of speaking, regarding life expectancy of pipelines. Like many of us present in this room, the pipeline infrastructure is past middle age - and getting older. The U.S. Environmental Protection Agency estimates that the single greatest need in the area of safe drinking water in the next two decades is the installation and rehabilitation of transmission and distribution systems. The cost is estimated at more than $77 billion during that 20-year period.

2. WATER PRESSURE PIPELINES - PERFORMANCE, FAILURES & TESTING

Of course water pipelines come in all sizes and many materials - ranging from the 2-inch plastic pipes which supply most individual homes up to 21-foot diameter concrete pipes which may appear in large regional water projects. This paper focuses on concrete pressure pipelines which will typically range from 16 inches up to the 21-footer shown here. During the last four decades more than 20,000 miles of PCCP have been manufactured in the United States in diameters from 18 inches to 21 feet, representing an infrastructure investment of more than $40 billion. When properly manufactured and installed, PCCP is a durable, cost effective water conveyance vehicle. In pipe diameters greater than 48 inches, it is the most widely used high-pressure water pipe product in this country. It has been estimated that half of this pipe will be replaced in the next two decades due to deterioration or the need for additional capacity - an upgrade market of up to $2 billion per year. Much of this upgrade market will be new PCCP, adding to the existing inventory of this product, and assuring a continued need for the condition assessment of PTI.

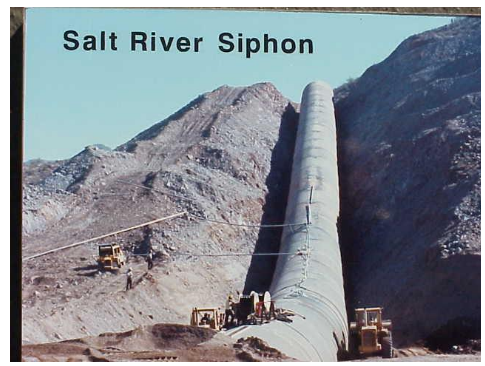

Figure 2. 21-foot diameter PCCP pipeline

PCCP is manufactured from steel and concrete. It makes very efficient use of the basic materials due in part to the method by which the reinforcing steel is applied. A very highly alloyed, heat treated, steel wire is spirally wrapped under high tension around a concrete core to provide the basic structure of the pipe. This "prestressing wire" is then covered by a ¾-inch layer of mortar to provide protection from the elements. Compared to alternative pipe materials, PCCP competes very well.

2.1 The need for diagnostic testing

One of the problems associated with pipelines in general, and PCCP pipelines in particular, is that deterioration is difficult to pinpoint and identify. Many inspection methods now available require access to the pipe interior and/or to the exterior. This is usually costly at best, and in some situations it is impracticable or impossible to excavate the exterior or de-water the interior for inspection. The only commonly used traditional method which does not require access to the interior pipe surface depends on the detection of the electrical potentials (measured in millivolts) generated by the corrosion of steel. These electrical potentials are commonly measured either on the ground surface or at electrical leads connected to the prestressing wire, referred to as cell-to-cell or pipe-to-soil potentials respectively. Due to varying conditions and background "noises" which influence to both electrical potentials and electrical conductivity, this method has not proven reliable.

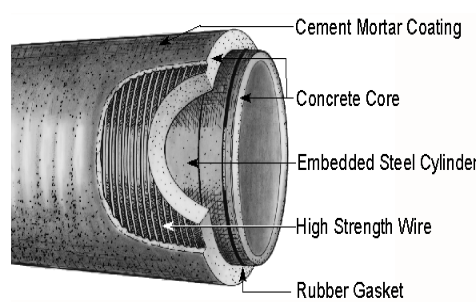

Figure 3. Cutaway view of PCCP

2.2 Pipeline Failures

The adage "out of sight, out of mind" describes a prevailing attitude towards buried pipelines. We wish it were so easy. Unfortunately, pipelines do deteriorate and fail.

A rupture of PCCP is usually sudden, with no warning, and entails a relatively dramatic release of water, pieces of pipe, and surrounding soil. Due to the water pressures frequently carried in PCCP lines, and to the structural characteristics, PCCP pipelines usually do not leak at all in advance of a rupture, or give any indication of pending rupture as lines constructed of other materials frequently do. An obvious question at this point is "Why do they fail? What can go wrong with a buried pipeline that it should suddenly rupture?"

Figure 4. Pipeline rupture in Lynn, MA

An analysis of the causes of failure of a line is helpful in understanding the role in pipeline maintenance that non-destructive testing will play. PCCP failures have been attributed to the following:

<u>Pipe design</u>

- Inadequate thrust resistance
- Inadequate surge protection
- Excessive transient pressures
- Cathodic protection, or lack thereof
- Spacing of reinforcing steel
- Soil conditions
- Stresses within the pipe structure

<u>Pipe Manufacturing</u>

- Defective prestressing wire
- Spacing of reinforcing steel
- Carbonation of the pipe core surface
- Porosity of mortar coating
- Poor wire encasement by mortar

<u>Pipeline Construction</u>

- Damage by construction equipment
- Improper bedding and backfill placement
- Damage by large rocks in backfill
- Damage during pipe handling and transportation

<u>During Pipeline operating life</u>

- Excessive water pressures
- Excessive vehicle loads on pipeline
- Damage by third parties – such as power pole augers and excavators
- Misapplication of cathodic protection
- Old age

Much of the damage resulting from these causes will be confined to a very small localized area. For instance, defective wire used in the pipe manufacture may be the result of excessive wire surface temperature that occurred for very short intervals during the wire manufacturing process. A failure resulting from this would likewise be confined to a few pipe sections, yet it might be mistakenly assumed to exist on the entire line. Aggressive soil conditions would include the presence of sodium chloride (NaCl, or common table salt) which may be very localized along the pipeline. Other examples could be cited, but the point is that one or more ruptures do not necessarily signal the end of the useful life of an entire pipeline. Yet in the absence of some means of identifying these conditions, the entire line may be replaced following rupture occurrence.

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2.3 Passive acoustic emission technology

Acoustic Emission Technology, or AET, is an adaptation of SONAR devices which use the sounds emitted by submarines to reveal their presence and location. This same SONAR uses the sounds which are emitted by pipelines experiencing structural distress to identify and locate these problems and it has shown great promise.

Figure 5. Ruptured pipeline from the late 1800's

AET is particularly adapted for use on Prestressed Concrete Cylinder Pipe or PCCP. As the name implies, PCCP is manufactured with prestressing wire that is helically wrapped around a concrete core. When PCCP deterioration occurs, it usually originates on the exterior of the pipe and causes the prestressing wire to break. Each broken wire will subsequently slip and move many times within the protective mortar, creating a noisy environment that continues as long as the deterioration is in progress. The corrosion spreads from wire to wire, increasing the quantity of sounds. These sounds are propagated though the pipe walls and into the water in the pipe. By using a sophisticated signal processing computer and software, it is possible to detect and distinguish wire-related sounds from other noise such as water turbulence, vehicular traffic and debris movement.

2.4 The concept of the autonomous test point

Early configurations of the acoustic test systems used wire or optic fiber for real-time signal transmission to a signal processor. The system worked well, however it's limitations became readily apparent. First, the communications links were of necessity permanently installed underground. This is expensive. As experience was gained, we realized that a relatively short period was required for diagnosis, and it became desirable to have mobile systems. We needed a means of avoiding the high cost of the real-time communication link.

The autonomous test system does this by eliminating the real-time communication link altogether. The description of the four main components in an autonomous system helps understand how it works.

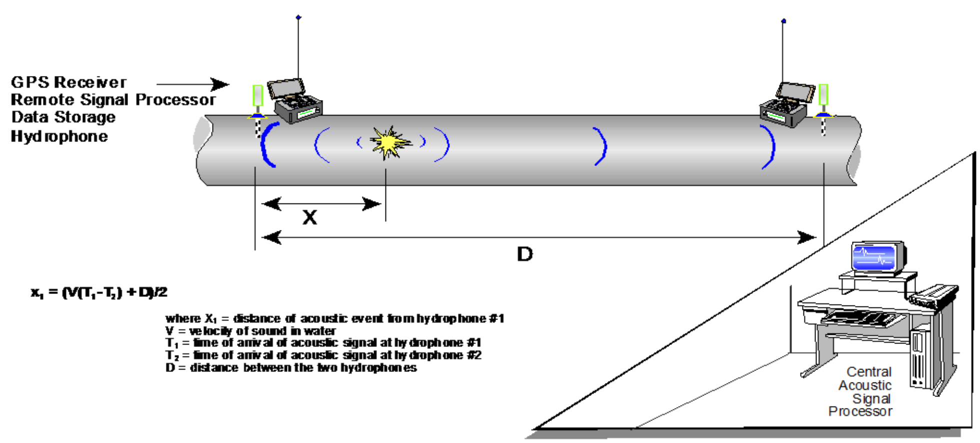

Figure 6. Schematic of automous test point

Hydrophones - A series of two or more sensitive hydrophones is used to detect noise in the pipeline. The sensor is specifically designed for the acoustic signal frequencies which accompany PCCP deterioration, and is mounted on the end of a stainless steel shaft which is inserted into the pipeline through a series of seals and valves while the pipeline is in service at operating pressure. The hydrophones are normally installed a thousand feet or more apart and are placed in the pipeline so that the hydrophone sensors project into the main water column in the pipeline. The acoustic signal is continuously transmitted by wire the few feet to the signal processor.

Signal Processor - Signals from these hydrophones are continuously monitored by a small, battery-powered computer located close to the hydrophone. The signal processor installed in this portable computer receives the electronic signals and screens them against a series of criteria - some of which are established by the operator at the time of the testing. It samples the incoming signals from each hydrophone thousands of times per second. The computer records all signals matching the operator's criteria on special data storage disks for later classification.

Precision Timing Device - A third component of the system is the Global Positioning System (GPS) antenna and processor, which is incorporated into the signal processor. The GPS provides the location where the data was gathered in latitude and longitude. Secondly, and most importantly, it serves as a very accurate clock. It provides a time signal which allows the signal processor to determine the precise time of passage of the signal to an accuracy greater than a millionth of second (or micro-second). This precise time of passage is compared to the same information at adjacent hydrophones to determine the point of origin of the sound.


Figure 7. 1-inch diameter hydrophone

These three components comprise a self-contained autonomous hydrophone test unit. When the unit is installed on a pipeline and energized, the acoustic wave spectrum in the pipeline is continuously converted to an analog signal by the hydrophone. That analog signal is transmitted to the signal processor where it is digitized, and then processed by a series of algorithms which comprise a signal detector.

When a detection is made, the signal processor immediately records the entire signal along with time of detection and other characteristics of that signal. These tasks are performed in a fraction of a second, at which time the Signal processor returns to the business of monitoring the continuous signal coming from the hydrophone.

Once a day, an operator retrieves the data from the Signal processor, checks for proper operation, recharges the battery, and places the Signal processor back in operation.

Data Analysis System - The fourth component of the AH System is the Central Acoustic Signal Processor (or CASP) which is located away from the test site. The CASP is a computer with the software necessary to processes and analyze the data recorded during the test. The CASP determines the location of the origin of the signal, or in signal processing terms, to “localizes” the signals. This is where the calculation is accomplished based on the exact distance in the pipeline between the hydrophones, the speed of sound in water, and the precise timing of the transient signals by the AET system's signal processor. Recorded signals from the pipeline are compared to the signatures of actual acoustic signals of pipeline distress. A final determination is made as to whether the acoustic event is related to distress in the pipe, and if so, where it came from.

In some respects, this patented AET technology is definitely high-tech. It relies on the most advanced high-performance, low power embedded software signal processing equipment and on the constellation of GPS satellites used for a multitude of purposes. On the other hand, it is easy to understand how it works. The real beauty of the technology lies in its simplicity, however, and in the ease of its use.

The first two generations of the autonomous hydrophone test system were based on PC 104 layouts and Pentium processors. These systems served to prove the capability of the system, however several shortcomings existed. The current draw was about 3 ½ amps from the 12-volt lead acid batteries which were used. At best, the battery had to be re-charged once a day. Secondly, this power demand generated considerable heat - enough so that in warm temperatures the system was difficult to maintain in reliable operation. Thirdly, the systems generated internal noise which was undesirable. The third generation overcame these limitations.

3. THE THIRD GENERATION AUTONOMOUS HYDROPHONE

3.1 System Overview

The AH-3 hardware is based on low-powered high performance embedded processors. Due to the number of hardware interfaces the AH-3 hardware is partitioned into two controllers. The Master controller, handles communications with the laptop computer used for configuring the instrument for autonomous data collection and updating the real-time clock with the current GPS time. The Slave controller, handles the data sampling, noise floor estimations, and threshold event detection. The slave is also responsible for managing the non-volatile memory (i.e. IDE mass storage device). The AH-3 instrument is configured for data collection using a custom MS Windows PC application. This application also the user to setup desired threshold, event duration minimums, data sample rates, data sample lengths, and other parameters used while collecting data autonomously. Once configured the AH-3 samples the acoustic channels continuously. Once the input channel has exceeded the preset threshold detector, the processor continues the event discrimination by analyzing the duration of the event. If the duration is sufficiently long, the processor time tags the data samples and stores them in the non-volatile memory. The electronics hardware provides a separate gain stage for each channel, settable in 1 dB increments, from 0 to 40 dB. Event recording is accomplished using a programmable dual 16 bit ADCs with a microcontroller and SRAM interface. The sampling engine continuously samples, averages, and compares the results to the preset threshold. The autonomous sampling system additionally provides the users with the ability to listen to the individual signals through a set of headphones

Figure 8. External view of AH-3

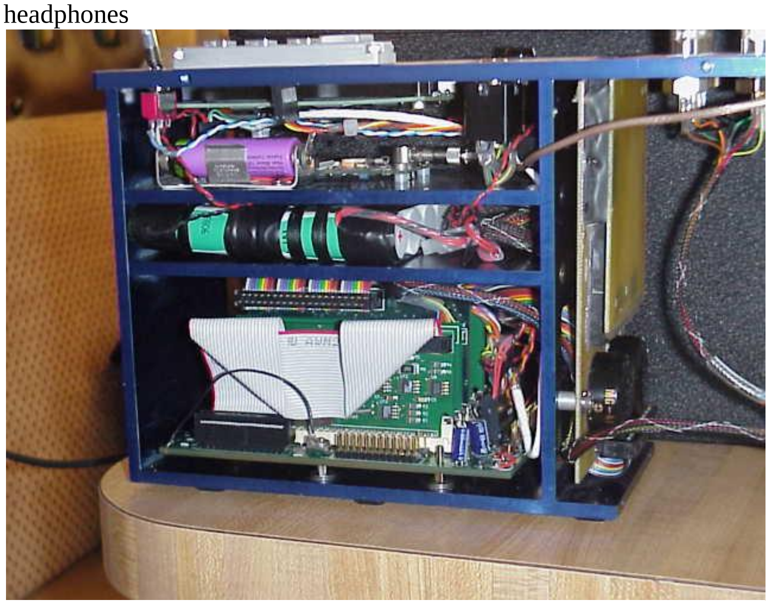

Figure 9. Internal view of AH-3

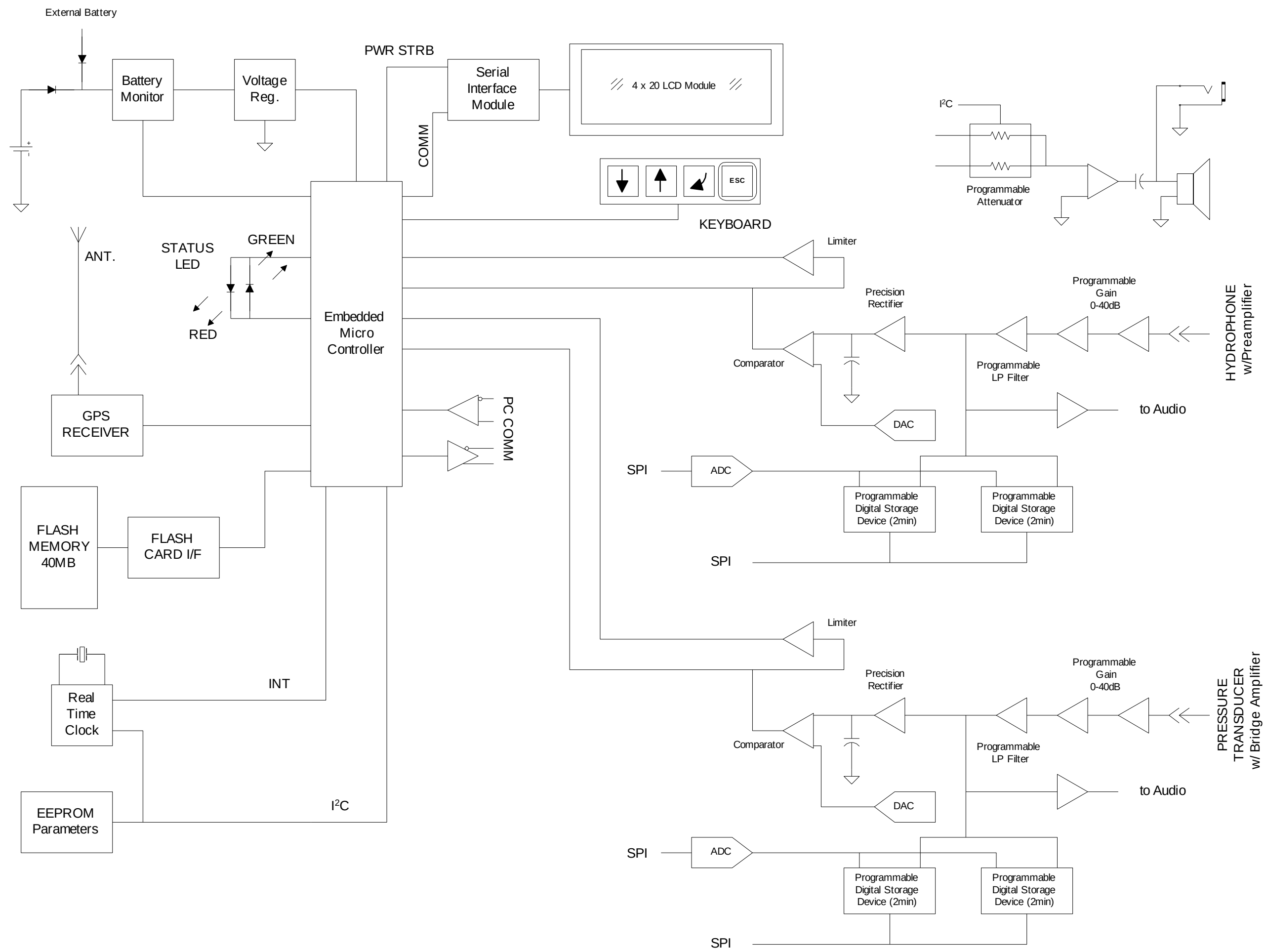

Figure 10. AH-3 Sampling system, block diagram

3.2 Receiver

The AH-3 Instrument has two independent input channels. Each channel has a digitally controlled gain setting from 0db to 40db, settable in 1db increments. The input to each channel from the external hydrophones is AC coupled providing a high-pass filtering. The receiver channels are sent to the stereo graphic equalizer.

3.3 Equalizer

This unit consists of a dual channel (stereo) 7 band graphic equalizer (EQ). Each channel can be set individually in gain or attenuation from –12 to +12db, in 1db increments. This allows the operator the ability to shape frequency response of the input channel. The EQ bands are set at 250Hz, 500Hz, 1000Hz, 2000Hz, 4000Hz, 8000Hz, and 16000Hz. The graphic equalizer is based on the National Semiconductor (LMC835) stereo 7 band graphic equalizer. The center frequency of each band is set with discrete valued resistors and capacitors.

3.4 Detector

The AH-3 utilizes a digital absolute value comparator to determine when an event has occurred. A 16bit A/D converter samples each channel. The input is then compared with an estimate of the channel noise floor. A trigger condition declared if the input is greater than the noise floor estimate and the preset threshold. Once a trigger condition exists the sampling continues to fill up the record buffer. In order to be classified as an event for recording the input signal must be of a sufficient duration. The duration parameter is checked during the collection of the remaining data. Once the duration interval meets the preset duration parameter, the input channel is compared again with the original channel noise estimate. If the input is still above the noise estimate and the threshold the signal is classified as an event. The input continues to collect data until the recording buffer is full. Once a detection has been classified, the entire contents of the SRAM buffer are written to the EEPROM disk drive memory. This allows the user to capture to acoustic signal before the event occurred. The amount of data to be recorded before and after the trigger point is a programmable parameter in the AH-3 instrument

3.5 Mass Storage Device

To facilitate offline data analysis, the AH-3 instrument stores the sampled data in MS Windows compatible file format. This is done by managing the data storage media in the same fashion as the disk operation system of the MS Windows environment. The AH-3 handles updating the File Allocation Table Cluster Map, Creating the Directory Entry Filenames, and Formatting the Data Segment. This allows the user to simply move the recording media (i.e. PCMIA Flash Disk Drive) from the AH-3 instrument and place it in a PCMIA slot of a MS Windows compatible computer or laptop. The MS Windows computer automatically assigns a drive letter to the device allowing the user to operate on the data directly.

Figure 11. SanDisk flash memory

3.6 Data Visualization

The AH-3 instrument formats the data space as a Microsoft Resource Interchange File Format (RIFF) file and moreover, as a MS Windows Waveform data file type (.WAV or WAVE file). Choosing this format preserves several key parameters required to 'playback' the recordings (i.e., number of channels, sample rate, sample size, sample length, etc.). CoolEdit by Syntrillium Software, Inc. for data analysis can import the AH-3 data directly during post-processing. (See example below)

3.7 AH-3 Data Header

To further facilitate data analysis the AH-3 stores the entire instrument parameters along with the sampled data in a section named 'UserData', part of the WAVE file header. This provides the user with a homogenous data set thereby reducing the error during data analysis resulting in the inability to catalog the sampled data with the hydrophone site. Each data sample contains the entire instrument setup as well as the GPS time/date of the event, GPS Latitude and Longitude, Event Duration.

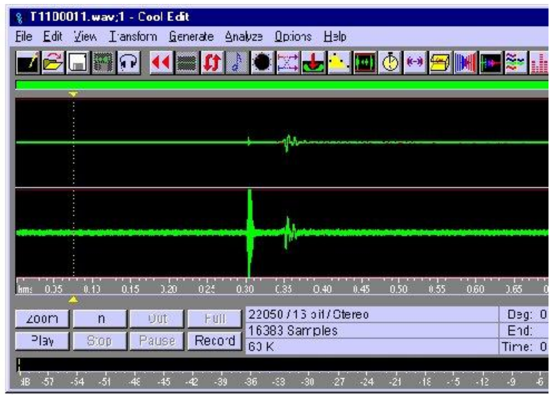

Figure 12. Time-domain graph of wire noise

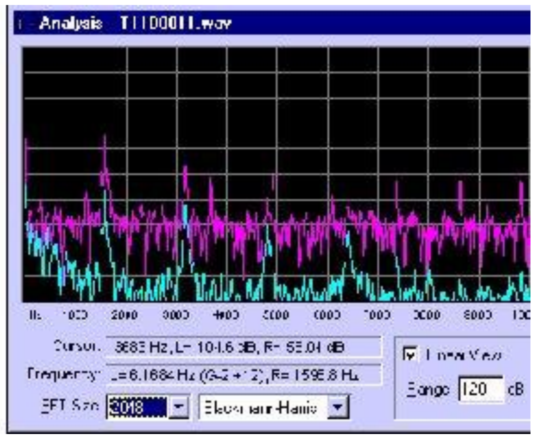

Figure 13. Frequency domain graph of wire break

4. CONCLUSION

The modern civil infrastructure is aging. The need for accurate cost-effective diagnostic test methods will become increasingly apparent, as will the application of scientific ingenuity to meet this need. Passive acoustic emission technology has surfaced as one of the leading methods of diagnostic testing of concrete water pressure pipelines. This non-destructive, non-invasive technique promises to identify active distress in the buried pipelines, permitting the spot repair of these areas and adding decades to the life of many pipelines. The economic advantage of intensive maintenance vs. replacement of these structures is compelling.

The third generation of the autonomous test point has capitalized on the latest in modern electronics to enable diagnostic testing more effectively and efficiently than ever before. Using low-powered high performance processors, the GPS satellite constellation, embedded software, flash disk drives, the AH3 represents a state of technology which would not have been possible a decade ago.

Figure 14. Deterioration detected by monitoring

We have only looked at the tip of the iceberg for diagnostic testing. Slight variations of the technology will allow many other uses. For instance, identification and localization of the source of the ever-illusive transient pressures is possible. This phenomenon is similar to the water-hammer you hear in buildings, but of course there is no one to hear it in buried pipelines. It can be very damaging. Another example: Water velocity is easy to measure using acoustic devices.

Taking this a step further – a system which can instantly measure pressure, velocity and elevation at a series of points along a pipeline can capitalize on Bernoulli's principles and evaluate hydraulic efficiency. This is within the capability of the AH-3 system, and will permit identification of debris, air pockets, closed valves, and other obstructions to water flow.

The civil infrastructure business is doing our best to overcome the two-decade lead enjoyed by the health care people. In ten years, we expect this acoustic emission technology, facilitated by the latest is solid-state electronics, to be as commonplace in the pipeline industry as the EKG is in health care today.

ACKNOWLEDGMENTS

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