



# Acoustic Identification of Filler Materials in Unexploded Ordnance

FINAL REPORT

UXO PROJECT 1382

University of Denver Research Institute  
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## List of Acronyms

ATC	Aberdeen Test Center
cm/sec	centimeter per second
DOD	Department of Defense
HE	high explosive
ID	filler identification
m/sec	meter per second
MHz	megahertz
NSWC	Naval Surface Warfare Center
NAVEODTECHDIV	Navy Explosive Ordnance Technology Division (Indian Head, MD)
PELAN	Pulsed Elemental Analysis with Neutrons
POP	plaster of Paris
UXO	Unexploded ordnance

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## **Executive Summary**

Personnel who must remediate Department of Defense sites need better tools to discriminate between un-exploded ordnance (UXO) and non-hazardous items. Although great effort has gone into detecting and localizing UXO in the ground and underwater, there are currently few devices that can inspect and identify the filler materials. The ability to make a quick and safe filler identification (ID) would significantly lower the risks to personnel and the cost of remediation. This project utilizes acoustic waves to identify the materials inside sealed UXO. Small sensors clamped to the outside of the ordnance send low-energy acoustic waves through the container walls and filler. The received signals are processed to determine the characteristic acoustic properties of the filler material. To identify the filler, these measured properties are compared to a database of properties for known explosive and inert filler materials.

This final report describes a two-year project to develop and test an ordnance identification system. A portable system has been developed and tested on both live and inert ordnance items. Initial laboratory and field measurements have confirmed the ability of the acoustic ID technology to discriminate inert filler types, including cement, plaster and wax from “other” items including explosives. A series of field tests are described that focus on acoustic measurements on both inert and live ordnance. The report also describes new sensor configurations developed to improve performance for curved or corroded body shapes. In addition, an initial assessment of the reliability of the acoustic technique is provided.

### **1. Objective**

The objective of this project is to utilize acoustic waves to identify the materials inside sealed unexploded ordnance (UXO). Acoustic waves are high frequency pressure fluctuations (sound) that travel through materials. Small sensors clamped to the outside of the ordnance send low-energy acoustic waves through the container walls and filler. The received signals are analyzed to determine the characteristic acoustic properties of the filler material. To identify the filler, these measured properties are compared to a database of properties for known explosive and inert filler materials.

A device based on this acoustic technique would permit personnel to quickly identify common inert UXO items, and optimize subsequent verification. Significant cost savings can be achieved through more efficient and safer clean-up procedures and the reduction of “blow in place” remediation procedures. Currently, 75 % of the costs associated with cleanup of UXO contaminated sites are derived from remediating non-hazardous items.

## 2. Background

To remediate Department of Defense sites, better tools are needed to discriminate between UXO and non-hazardous items. Although great effort has been expended to detect and localize UXO in the ground and underwater, there are currently few devices that can inspect and identify the filler materials. The ability to make a quick and safe identification would significantly lower the risks to personnel and the cost of remediation. In addition, to improve speed and safety, the filler identification method must be non-intrusive and operate while the ordnance item is partially or completely uncovered.

Although there has been a great deal of work done to detect and localize UXO in the ground and underwater, there are currently few devices that can inspect and identify the filler materials. Chemical “sniffers” can indicate that leaking ordnance is somewhere within a search area, but cannot easily identify if the trace signal is coming from a particular item, or what material is inside it. Once a hazardous chemical is detected, all ordnance must initially be assumed to be hazardous, even though only one of many items may be leaking hazardous material. If UXO is indicated, other sensors can be employed to better locate items [1]. Once an item is located and partially exposed, visual inspection is used to confirm the condition of the ordnance and, if possible, identify the fuse type. At this point in the cleanup process there are few tools to help the operator, except their experience. The radiographic inspection systems that are available can provide valuable information on UXO internals [2], but these systems are large and difficult to transport (i.e. airlift). In addition, items must be judged “safe to handle” and fully removed from the ground. The operators must also be protected from the ionizing radiation.

The only known technology being developed for filler identification relies on detection of gamma rays emitted by stimulating the ordnance item with a neutron beam. One system that uses this technology is termed Pulsed ELemental Analysis with Neutrons (PELAN). PELAN is a man-portable system for explosives detection, based on the principle that explosives contain various chemical elements such as H, C, N, O, etc. in quantities and ratios that differentiate them from other innocuous substances. Although PELAN can provide accurate filler identification for larger UXO, it often gives false readings for smaller ordnance because the signal from the explosive is overwhelmed by signals from the surrounding environment [3].

For artillery shells that weapons inspectors know are filled with liquid chemical or biological weapons materials, an acoustic device has been demonstrated that identifies the type of liquid. The swept-frequency acoustic technique that is used relies on the measurement of characteristic resonances inside the shell to identify the liquid [4]. These resonances require that the acoustic wave travel back and forth between the shell walls many times before being received by an external sensor. Thus the liquid must have a low attenuation for this technique to provide good discrimination [5]. However, the resonant technique will not work for UXO filled with solid explosives or inert materials. The acoustic attenuation of these materials is very high and the waves are almost totally absorbed before they travel between the container walls. Thus, a new acoustic method is required to identify the type of filler materials in UXO.

For the proposed method, the acoustic waves only need to travel once through the container walls and filler material. Thus the technique is suitable even for materials with high attenuation such as solid fillers. This acoustic method has distinct advantages over other characterization methods. Not only is acoustics non-intrusive, but it is also quick, portable, low-cost, and uses low-energy (< 20 milliwatt), non-ionizing radiation. Unlike radiographic techniques, acoustics can provide information on the chemical constituents in materials, and can track composition changes over time. The only requirement is that the energetic materials are in direct contact with the case (e.g. case-bonded). This is true for a large number of ordnance, including artillery shells and many bombs.

Although acoustics has been used to measure the composition of explosives, it has not been used for identification of fillers. To identify the filler, both the velocity and the attenuation properties of the material are used. Differences in the properties can be used to discriminate between filler materials. Little is known about the acoustic attenuation properties of explosive materials. Fortunately, however, the acoustic velocity (sound speed) is known for many explosives and these values can be used to estimate the discrimination capabilities of the proposed technique. The acoustic velocity values are available because they are an essential part of the calculation of detonation shock velocity for the explosive [6]. Figure 1 shows a comparison of the acoustic velocities for several explosives commonly used in ordnance. Note that the acoustic velocity values are quite different for each explosive. The smallest velocity difference between the values is 120 meters-per-second (m/sec) for Octol (2710 m/sec) and Comp B (2830 m/sec). However, velocity measurements can be measured very accurately even when the material is encased inside a metal shell. We commonly measure fluid materials with an accuracy of 1 m/sec or better. Thus many filler materials can be identified just using the acoustic velocity. However, the acoustic wave also loses energy as it travels through any material, and this attenuation can also be used to discriminate between filler materials. Combining both measurements can provide an accurate, reliable identification.

**Filler materials can be discriminated well in the lab by their acoustic velocity**

*Can we ID fillers even with material property variations and the complications of a case?*

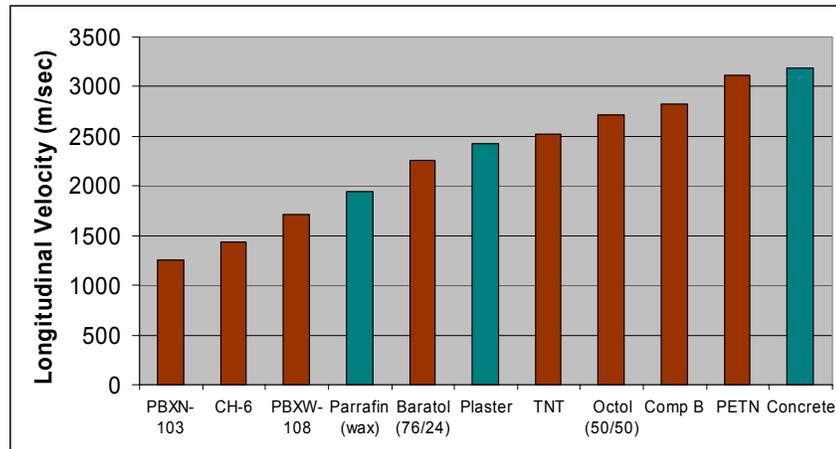


Figure 1 Comparison of the acoustic velocities for several common explosives (red) and inert (green) fillers.

The acoustic technique for UXO characterization has grown out of many years of experience with the characterization of materials flowing through pipes and other vessels. The technique was developed in part under a Department of Energy innovation grant [7] to measure trace contaminants in fluid streams. This work resulted in a commercial instrument that has been used for fluid characterization for a wide range of vessels and materials [8]. Prior to this study, the technique has not been used to identify ordnance fillers. Our concept to use the technique for UXO grew out of joint work with the Naval Surface Warfare Center (NSWC) in acoustic characterization of energetic materials.

### **3. Materials and Methods**

#### **3.1. Method of identification**

The proposed identification method works by matching field measurements of acoustic properties to those in a database of known filler materials. The best reliability is achieved when the filler properties are very specific, and do not vary significantly with manufacture or aging. The measurement of velocity and attenuation must also be accurate so that the acoustic properties of the material can be discriminated. This work developed a measurement error model for the acoustic method. For selected ordnance size and filler materials, the model output the expected acoustic property values, and the associated errors. These values were then compared to the range of acoustic property values for the filler, and the likelihood of a correct identification was estimated.

The first part of this study focused on the design and construction of a clamp-on sensor and a portable electronics system to make the acoustic measurements. Figure 2 is a sketch of the proposed filler-identification system that is shown attached to an artillery shell. The spring clamp holds the two acoustic sensors on either side of the casing while the waves are emitted and travel through the case and filler. The portable electronics receive the transmitted wave signal, make the acoustic measurements, and identify the filler material using a pre-recorded database. The known properties of the case are used in these calculations to remove the influence of the case. That way, the filler properties can be measured independently of the container, and only these properties are used for identification.

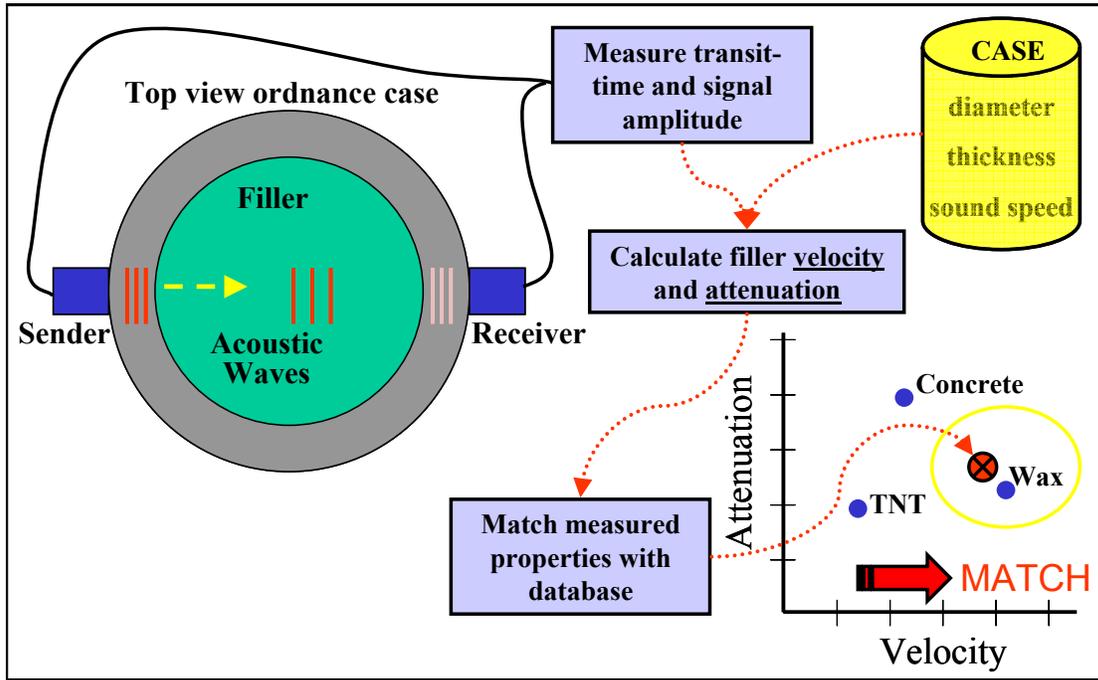


Figure 2. Sketch of the filler-identification system shown attached to an artillery shell.

### 3.2. Model for identification reliability

In order to test the ultimate reliability of the method, a measurement error model for the acoustic method has been developed. The model was developed using the "calculus of errors" mathematical method [9]. In the model, the error in the velocity of the filler material,  $\Delta V_{Filler}$ , is computed from the following variables (see Figure 3):

- $D_{Total}$  is the total distance between acoustic sensors (i.e. OD of container) as measured with a caliper.
- $T_{Total}$  is the travel time through the total container as measured by the acoustic clamp system.
- $T_{Wall}$  is the travel time through both container walls as measured by pulse-echo acoustic time-of-flight.
- $V_{Wall}$  is the velocity in the container walls and is known from the material type and tabulated values.
- $C$  is the temperature of filler material as measured by temperature sensors mounted on the case.
- $K$  is the slope of travel time change with temperature for the filler material and is estimated from tabulated or measured values for similar filler materials.

Using this model the relationships between the measured variables are expressed by the following equations:

$$T_{Total} = T_{Wall} + \frac{D_{Filler}}{V_{Filler}}$$

$$D_{Filler} = D_{Total} - T_{Wall} * V_{Wall}$$

$$f \equiv V_{Filler} = \frac{D_{Total} - T_{Wall} V_{Wall}}{T_{Total} - T_{Wall}}$$

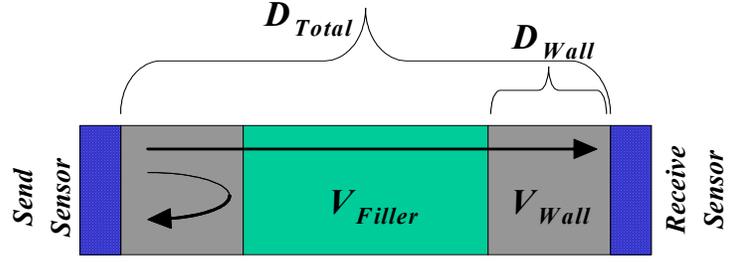


Figure 3. Schematic of sensors attached to projectile body and ultrasonic waves passing through the case and filler.

Since the measured filler velocity depends on the temperature, we also need to estimate velocity errors caused by errors in the measurement of the true filler temperature. These errors may be present for several reasons. For example, there may be a difference between the measured case temperature and that of the filler due to solar heating. To model these errors, the total travel time of the acoustic signal is assumed to have a linear dependence on temperature  $C$ .

$$T_{Total} = T_{C_0} + K * (C - C_0)$$

Substituting this relation into the equation for  $\Delta V_{Filler}$  above, the effect of an error in measured filler temperature,  $\Delta C = C - C_0$ , can be estimated. The calculus of errors provided the following form for the error in the filler velocity based on errors ( $\Delta s$ ) in the other variables. Note that the partial derivatives of the function  $f$  are easy to express symbolically. The entire form can then be evaluated once the errors for each variable are estimated.

$$\begin{aligned} \Delta V_{Filler} = & \Delta T_{Total} \left( \frac{\partial f}{\partial T_{Total}} \right) + \\ & \Delta T_{Wall} \left( \frac{\partial f}{\partial T_{Wall}} \right) + \\ & \Delta D_{Total} \left( \frac{\partial f}{\partial D_{Total}} \right) + \\ & \Delta V_{Wall} \left( \frac{\partial f}{\partial V_{Wall}} \right) + \\ & \Delta C \left( \frac{\partial f}{\partial C} \right) \end{aligned}$$

The accuracy of this model is tested in the “Results” section below . For these tests, each of the errors ( $\Delta s$ ) was estimated from the measurements of these variables. For example,  $\Delta D_{Total}$  is estimated as the standard deviation of the multiple caliper readings of the case diameter. Other errors like  $\Delta V_{Wall}$  can be estimated from the differences between the literature values for the acoustic wave velocity in steel. Once these estimates are known, we can determine the ultimate reliability of the method for various case sizes and measurement conditions.

### 3.3. Portable acoustic test system

A key objective of this study was the development of a clamp-on sensor and a portable electronic system to make the acoustic measurements. The clamp is an important part of the filler identification system. It must hold the acoustic sensors rigidly to the sides of deformed, corroded ordnance bodies while maintaining good alignment. Figure 4 shows the clamp attached to a 5 inch-38 projectile body.



Figure 4. Photo of the clamp that was developed to align the two sensors on opposite sides of a 5” – 38 test projectile body

The portable electronics system was developed to calculate and store acoustic velocity readings taken using the clamp-on sensors. Figure 5 shows a photograph of the portable system. The clamp-on test system has been used to collect laboratory measurements of acoustic velocity and attenuation on several inert fillers contained in many different shell types and sizes. The primary goal of these tests was to confirm that accurate measurements of the filler velocity could be made, even with the complications of a case around the material. A second goal was to initially test how well the fillers could be identified using the acoustic measurements.

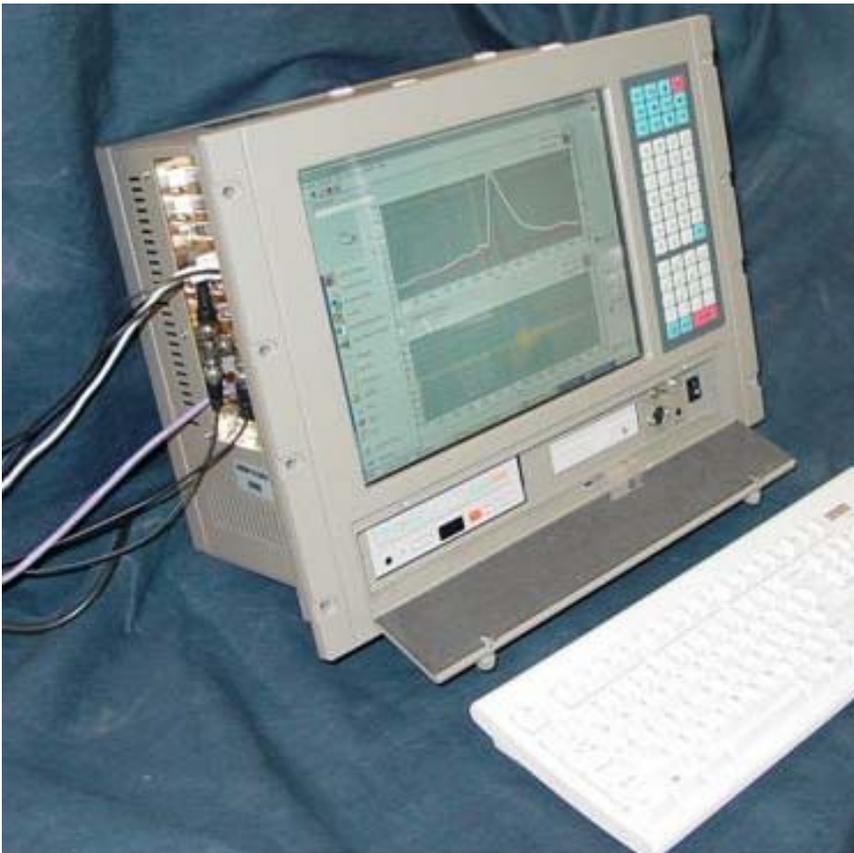


Figure 5. Portable acoustic test system.

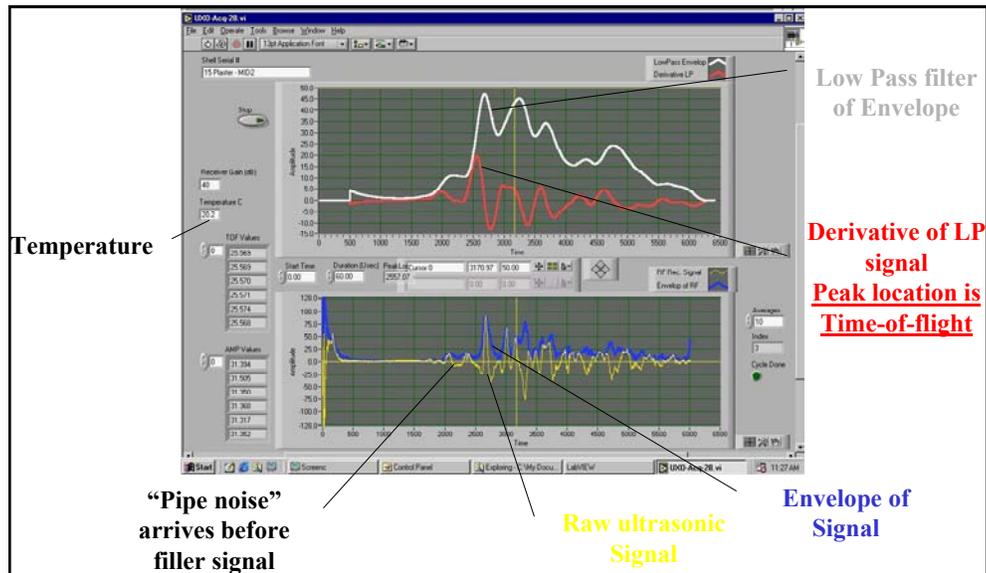


Figure 6. Digital processing for enhanced signal detection (signal for plaster in 76 mm shell).

The data acquisition system processes the received acoustic signals and measures the acoustic velocity through the filled test body. This processing helps to identify the signal for the thru-transmission waves that pass through the filler. Figure 6 is an example computer screen showing the acoustic signals for a plaster-filled 76mm shell. The digitized signal received through the case is envelope-detected to provide a positive-only signal for further processing (blue). The envelope is then processed to help separate the thru-transmission signal (first large blue peak) from the “case noise” signals that sometimes arrive at about the same time (low level yellow before first blue peak). The case noise is caused by acoustic waves that travel through the case walls rather than through the filler. The envelope is first low-pass filtered to remove high frequency signals (white signal). Taking the derivative of the filtered signal then provides a signal with a sharp peak located at the rise of the thru-filler signal (peak of red signal). The time location of this peak is the total transit time measurement used for the filler velocity calculation.

Note that the time of this signal peak is at the middle of the rise of the leading signal, not at the time where the signal rises from zero amplitude which is the time normally used for velocity measurement. Thus there is a slight bias in the velocity calculation from this arrival time and the velocity will not equal the literature values. For most items measured, however, this difference was very small and less than the velocity errors caused by other factors. In general, the filler velocities measured in this manner agreed well with independent laboratory measurements and textbook values for the materials tested.

Good signal quality is essential for accurate filler identification. Signal quality is described for each of the ordnance items in Table 1 and the appendix. “Good” signal quality means that the signal received through the filler has characteristics that clearly differentiate it from the case noise that will always be present. First, the time signal must

rapidly increase in amplitude from the baseline noise level to some high amplitude oscillation of at least a few cycles at the center frequency of the sensor. The Figure 7 bottom trace shows a very good received signal for a 5”-38 shell filled with glycerin. There is a small amount of case noise just before the clear, abrupt rise in the signal when the filler waves arrive at the receiver. Second, the received signal often has the form of multiple echoes occurring at equal time delays after the first cycles of the filler wave. These multiple echoes are caused by waves that reflect within the walls of the case near the transmitting sensor. As the waves reflect, some wave energy is transmitted into the filler and follows after the direct wave. These multiple echoes are also evident in Figure 7 and clearly differentiate the filler signal from case noise. Case noise signals never have the unique “equal time spacing” characteristic of the “good” filler signal.

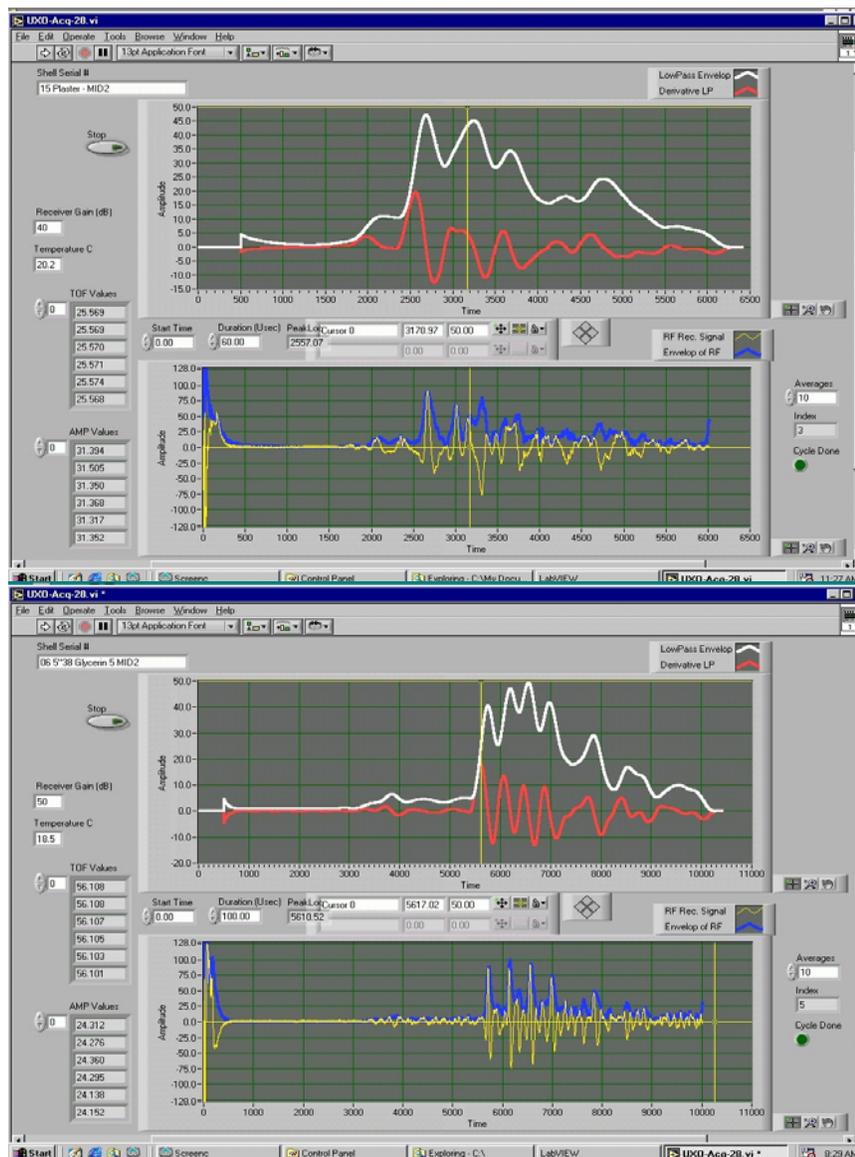


Figure 7. Example waveforms: Top - 76 mm projectile filled with plaster; Bottom - 5” projectile filled with glycerin

Multiple echoes are often present in the filler signals for many ordnance items tested, but not all. Corrosion and distortion of the case walls can reduce the amplitude and spread out the multiple reflections over time, making them less distinct. Often, especially for damaged cases, only a single wave through the filler is clearly received. The multiple echoes are best resolved by high frequency sensors which emit only a few short cycles of acoustic energy (see Figure 7 bottom for 5 MHz sensors). Unfortunately, these high frequency waves are highly attenuated by the solid fillers and may not be received at all, especially through large ordnance cases. To overcome the high attenuation, we have used lower frequency sensors at 1 and 2.2 MHz for many of the ordnance items. Although not as pronounced, the multiple echoes are often observed at these lower frequencies as well (see appendix item 4).

### **3.4. Ordnance test items**

One of the challenges of this study has been to find inert filled ordnance items that could be used to test the acoustic method. Since they are not identified as inert, most inert filled UXO are simply “blown in place” during remediation. Due to the lack of actual UXO items for testing, we contacted several DOD ordnance test facilities and inquired about test items that might be available. Fortunately, these organizations were able to provide several inert items that had never been fired, or the cases of ordnance items that were never filled or had the fillers removed. Overall more than 50 items filled with different fillers were tested as part of this study.

The solid inert fillers used for this study included wax, cement and plaster, since these are considered some of the most likely inert fillers to be found in UXO. For the initial testing, many of the measurements were made in 2-inch steel pipe sections, because these provided oval bodies similar to dented UXO. The initial tests also included unfilled projectile bodies obtained from Naval Surface Warfare Center - Crane. A number of unfilled 76 mm mortars, 5inch-38 and 155 mm projectile bodies were tested. These same types of ordnance bodies were later tested during high explosive tests at Crane. A photograph of these test bodies is shown in Figure 8.

Several other ordnance items were obtained from the Navy Explosive Ordnance Technology Division (NAVEODTECHDIV, Indian Head, MD) which included some items with the original wax and plaster fills. In addition, a few fired ordnance items were provided which had been recovered and had the filler removed. These items were highly corroded after being underground for many years. To simulate real, un-buried UXO, we filled these items with fresh inert fillers and performed the standard acoustic tests in the laboratory.

Finally, other items with different sizes and body types were tested by taking the data collection system to several DOD test sites. Each of these organizations had additional ordnance items available that could not be shipped to the University of Denver Research Institute. Inert items were bench tested at both NAVEODTECHDIV and the Army Aberdeen Test Center (ATC). The items tested at ATC were part of the “Aberdeen Proving Ground Standardized UXO Technology Demonstration Site” inert ordnance collection. All live high explosive items were tested at a bunker facility at the NSWC Crane Ordnance Test Center, Crane IN.



Figure 8. Empty shells that were later filled with inert fillers for the initial laboratory testing

## Results and Accomplishments

### 3.5. Laboratory and DOD Test Site Results

#### 3.5.1 Initial test on pipe sections to test the error model

To test the accuracy of the error model described above, multiple measurements of the filler velocity were made for several test bodies. The accuracy of the error model was tested by comparing the calculated error bound with the scatter in the measurements of filler velocity. Figure 9 below shows a plot of the measured filler velocity as computed from  $V_{Filler}$  above (solid symbols) versus the true filler velocity. The scatter in the

measured filler velocity is caused by errors in both the dimensional and timing measurements. The true filler velocity was measured in the laboratory using machined samples of the same material used to fill the test bodies. The laboratory sample measurement system was a unique instrument developed by NASA [10]. The velocity error for this instrument was estimated to be  $\pm 0.0015$  cm/microseconds.

Six time-of-flight and signal peak amplitudes are recorded for each clamp location on the shells. To estimate the variance of the filler velocity measurement for real bodies, the measurements were made at 6 to 12 different locations on each body.  $T_{Total}$  readings were converted to filler velocity using an Excel spreadsheet and the equation for  $V_{Filler}$  above. In addition to several common inert fillers, one 2-inch pipe section was filled with an epoxy simulant formulated to match the expected velocity (but not attenuation) of a typical high explosive like TNT.

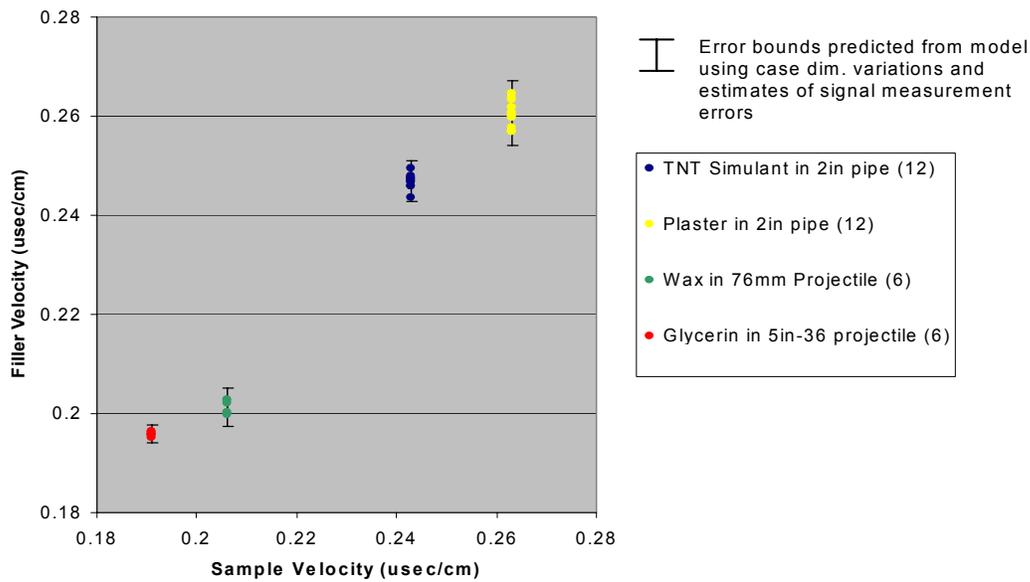


Figure 9. Filler velocity measurement vs. error predicted from model

As indicated in the figure, the agreement between the error model and the measurements is good for each test body and filler material. In all cases, the measurement scatter is bounded by the predicted model error. Thus, we now have a verified model for the filler velocity error. Knowing projectile dimensions and measurement errors, we can estimate ID reliability for any sized ordnance and filler material.

### 3.5.2 Initial laboratory tests on inert filled shells

Initial tests of the acoustic system were made using the inert-filled ordnance items described above (see Figure 8). These tests included wax, cement and plaster and several liquids. To test the variances caused by filler formulations, two different types of plaster filler were prepared with different velocities. These were prepared by mixing different amounts of water with the plaster powder. Liquids were used to test the velocity measurements for fillers with low velocity readings. Almost all solid fillers have velocities above these liquids. In addition, testing with water filler was done to establish

a “baseline” signal for the different shell bodies. Since the acoustic attenuation in water is almost zero, this filler provides a consistent signal that is affected only by the size, shape and condition of the case.

The velocity measurements for the test bodies and fillers are summarized in Figure 9. To estimate the variance of the filler velocity measurement for real bodies, the measurements were made at three to six different locations on each body. The filler velocity values were plotted against the measured acoustic velocity for a machined sample of the filler material when such a sample was available. Since no case was present, the “true” velocity and attenuation of these machined filler samples could be measured very accurately in the laboratory.

In spite of the data scatter and the variety of case sizes and types, the velocity readings reveal the unique signature of the fillers. As indicated in the figure, the clamp-on filler velocity agreed well with the analytical (true) value for each of the seven filler materials and three case types/sizes. Thus, even with the complications of a case, the acoustic measurement system provided accurate filler velocity readings that can be used to identify the filler material.

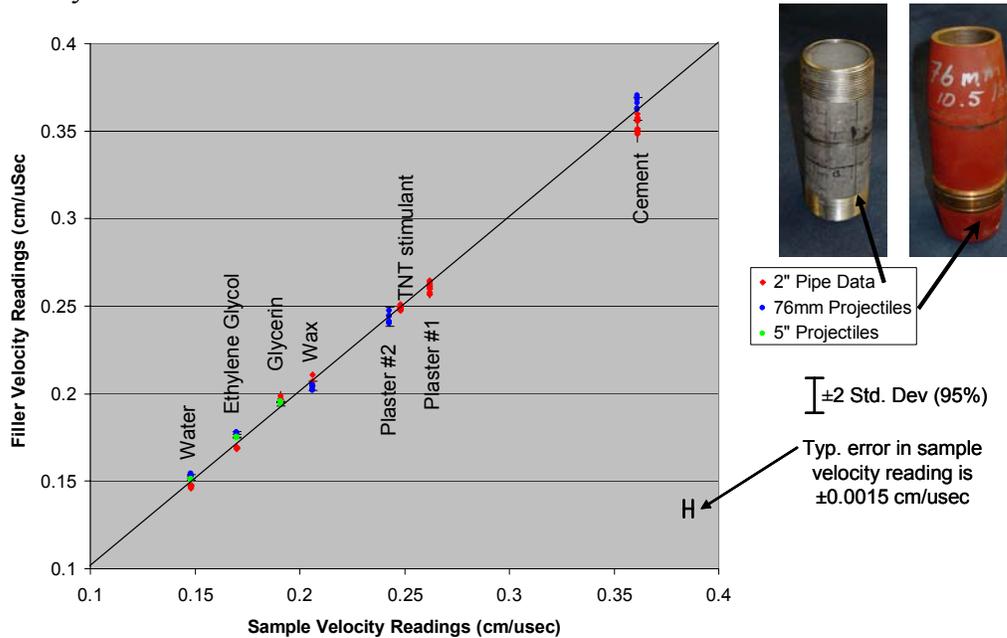


Figure 10. Measured acoustic velocities for several case types and fillers plotted versus the “true” velocity for the filler material.

In a similar way, the attenuation (loss) of the acoustic signal as it travels through the case can also be used to discriminate between filler materials. Figure 11 shows a plot of filler attenuation readings versus the analytical attenuation value for the machined samples. The filler attenuation was calculated in dB/cm as:

$$\alpha_{filler} = \frac{20 * \log(A_{filler} / A_{water})}{D_{filler}}$$

Water was used as the reference filler since it has almost no attenuation at the acoustic frequencies used. Thus all loss is characteristic of attenuation in the case and the geometry of the acoustic path. In practice, values for  $A_{water}$  would not be available, and a pre-measured, reference value would be used for different case types.

In Figure 11, note that most of the filler attenuation readings are in excellent agreement with the machined sample value. The readings for the highly-attenuating wax are lower than expected. This is probably because the signal amplitudes for the filled bodies are low enough to be affected by electronic noise. Nevertheless, as shown below, the high attenuation can be measured and used to discriminate the wax filler from the other types.

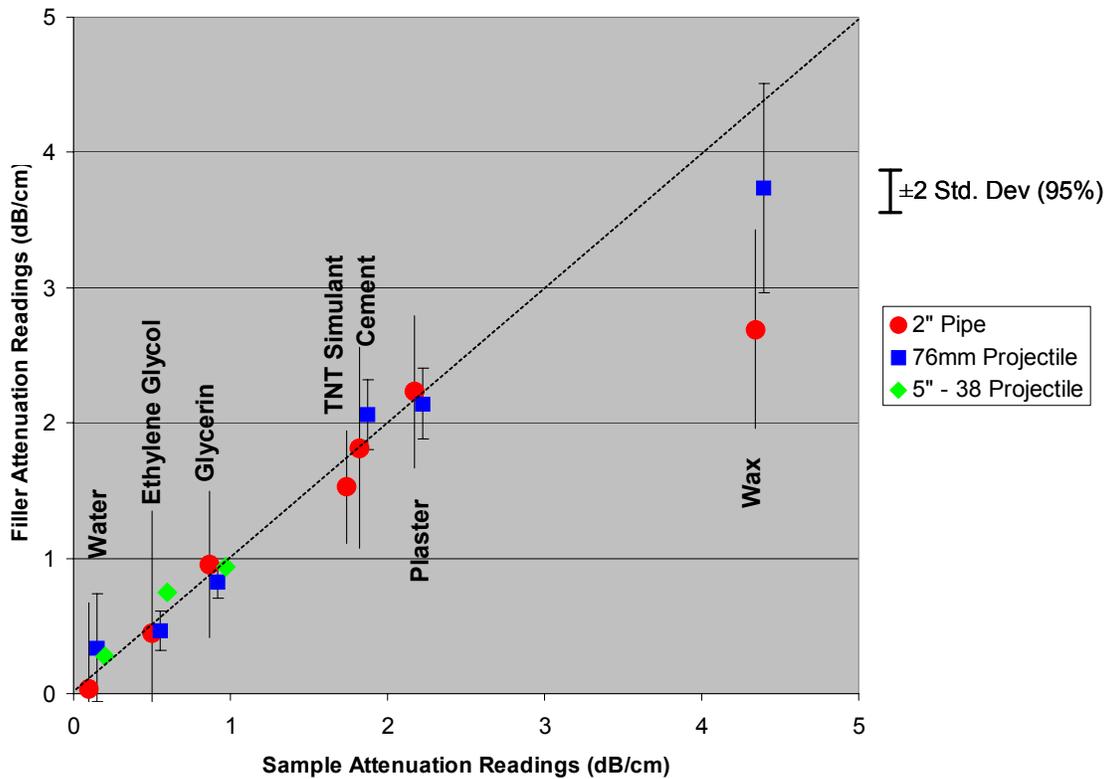


Figure 11. Attenuation readings discriminate between filler types.

### 3.5.3 Sensor signal improvements

During the initial laboratory and DOD site testing we learned that the current acoustic sensor configuration works on shell bodies with uniform inner and outer diameter. (e.g. flat profile in the middle of 76 mm shells). However, this configuration did not provide

useable signals for curved sections. Signal strength was very low because the curved shell walls bent the acoustic beam away from the receiving sensor. The 81mm shells (M362) and 105 mm (M548) ordnance did not have a uniform section anywhere along the body, and no useful signals were received from the 5 MHz sensors. The bending of the acoustic waves was later confirmed through simulation of wave travel through curved bodies

In addition to problems with curved bodies, there was a concern that good signals may not be received for corroded items typically found at a cleanup site. For the acoustic ID technique to be useful on many ordnance types, we determined that the sensor configuration must be modified to work for curved and corroded bodies. Following guidance received during the spring 2005 SERDP IPR meeting, we redirected our efforts to the development of new sensor configurations that overcome problems with curved or corroded shell bodies.

Our first target was to develop new sensor configurations to permit signal reception for high-attenuation fillers and curved-shell bodies. The goal was to identify new approaches and determine how much of a signal improvement may be possible. The specific approaches that were tested include 1) lower frequency sensors for better filler penetration, 2) “sensor caps” to reduce the casing noise, and 3) tilting the acoustic beam for optimum signal reception. The results for each of these studies are described below.

#### *3.5.4 Lower frequency sensors*

Low frequency acoustic waves are less attenuated than higher frequency waves. At the start of this project, 5 MHz sensors were selected because of the good signal quality observed for liquid-filled test shells. However, we have found that improved signals can be obtained by using lower frequencies in the 1 to 2 MHz range. The lower frequencies are especially useful for highly attenuating fillers such as wax, and medium attenuation fillers like plaster.

Figure 12 below illustrates the improvement obtained for 76 mm plaster filled shells when the sensor frequency is changed from 5 MHz to 2.2 MHz. At 2.2 MHz, the signal through the filler is much more easily resolved from the casing noise (marked in the figure). Casing noise is caused by acoustic waves that travel through the shell wall only, not the filler. Improving the filler signal amplitude results in a much more accurate and reliable measurement of the acoustic velocity and therefore, better identification of the plaster filler.

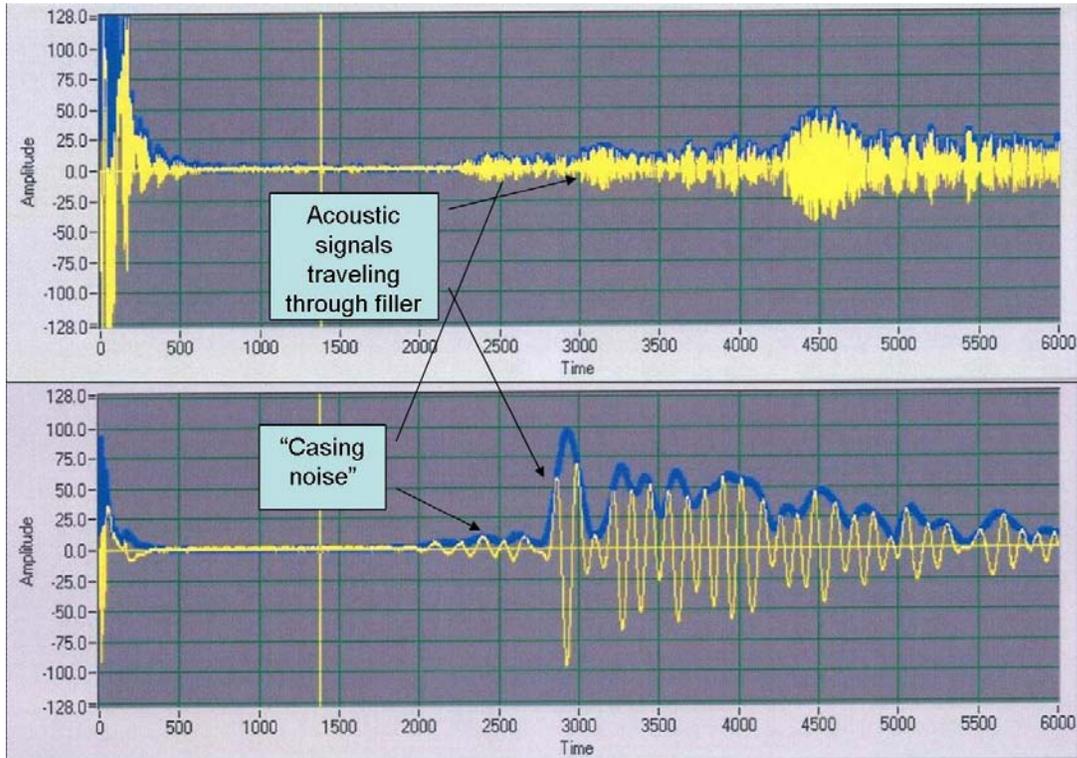


Figure 12. Measured acoustic signal received through a 76 mm casing filled with plaster. The sensor frequency is 5 MHz for the upper time signal trace, and 2.2 MHz for the lower trace.

### 3.5.5 Sensor Caps

As a second step in signal improvement, we developed a way to increase the signal quality by reducing casing noise. For all shell cases, the received signals going through the filler are masked by noise signals that enter and travel around the metal shell casing. Acoustic simulations have shown that these “casing noise” signals can be reduced by curving the sensor face to conform to the casing diameter. We developed novel, shaped “caps” for the flat acoustic sensors that reduce the casing noise and improve signal quality. These 1” diameter aluminum caps are flat on the sensor side and conform to the case diameter on the other side. The caps are easily replaced for different sized cases. To couple the acoustic waves through these caps, a small amount of gel or grease is applied to both surfaces before the sensor and cap are clamped to the case.

Initial tests on curved sections of 76mm shells filled with water show a significant improvement for 5 MHz sensors. This improvement is illustrated in Figure 13, which shows signal traces for a 76 mm shell filled with water. Note that both signals were recorded using the same signal gain. The top trace is the waveform for 5 MHz, flat acoustic sensors placed directly against the outer casing of the shell. The casing noise appears as the small signals that arrive before the water-filler signal. Although these signals are smaller than the water borne signal, this is not always the case for most fillers that are more attenuating than water. For attenuating fillers like plaster, the casing noise can often mask the signal traveling through the plaster.

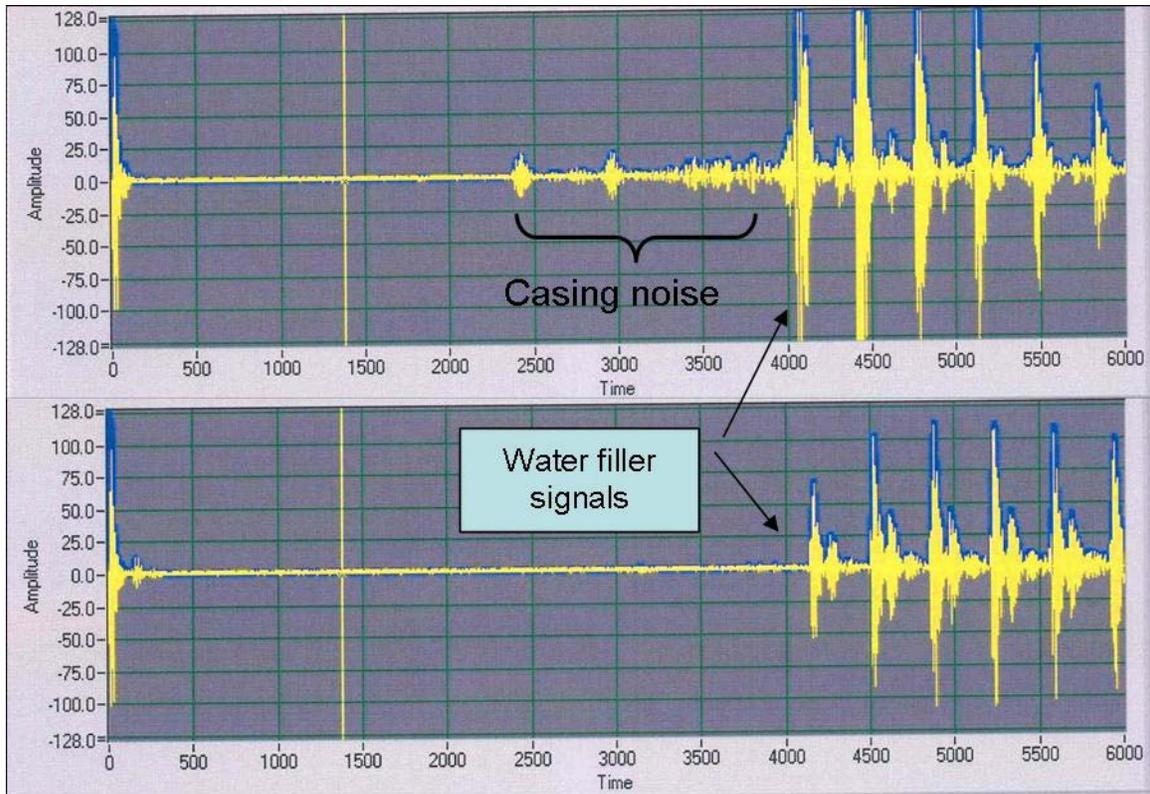


Figure 13. Acoustic signals for a water-filled 76 mm shell. Top trace: 5MHz, flat sensors placed directly against the casing. Lower trace: same sensors with aluminum caps to conform to the case.

The lower trace in Figure 13 shows the signal improvement that is achieved when the aluminum cap is placed over both flat sensors. The case noise is no longer present. In Figure 13, the signal-to-noise ratio changes from 5 without caps to 18 with the caps. This is a very significant improvement that has been repeated for several other case types and fillers. The use of the caps has resulted in good acoustic velocity measurements even for highly-attenuating, wax fillers.

### 3.5.6 Tilting the acoustic beam

As noted above, curved shell bodies lower the received signal strength because the curved walls bend the acoustic beam away from the receiving sensor on the opposite wall. Acoustic simulations have also shown that for curved shells the bent beam can be re-directed toward the receiving sensors by angling the emitting sensor. Figure 14 illustrates the re-directed beam for an 81 mm, type M374 shell. When the sensors are angled, the wave travels through the filler, perpendicular to the shell axis, and reaches the receiver.

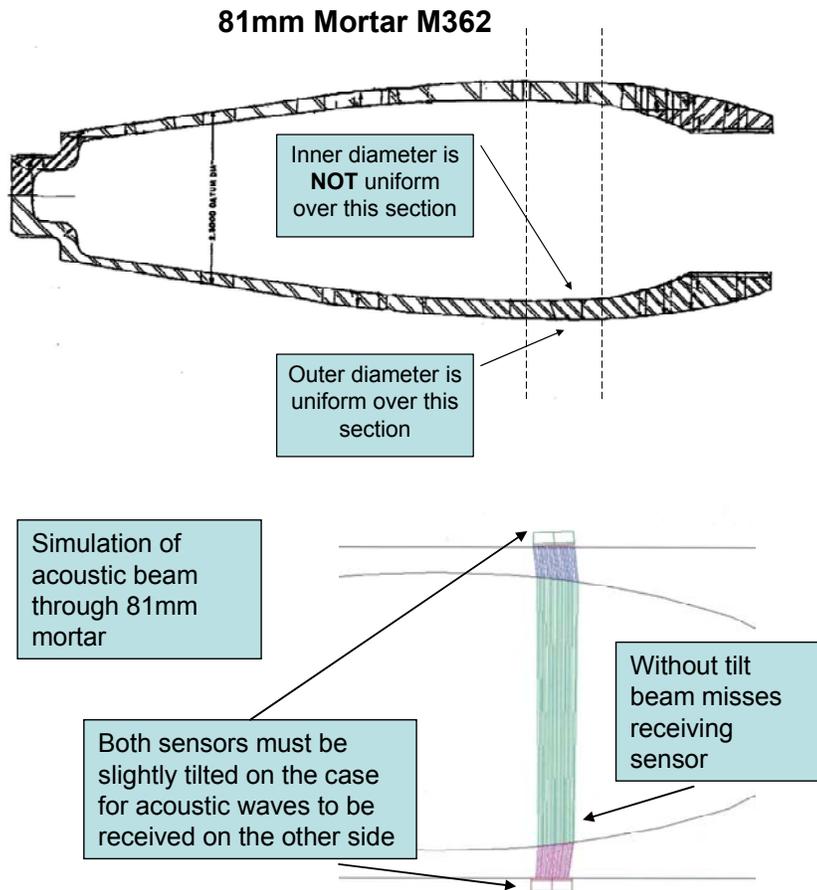


Figure 14. Illustration for a curved-case shell showing how a slight tilt of the transmitting and receiving sensors will result in a strong signal.

Figure 15 shows a comparison of the signals for a water filled 76 mm shell. For the data shown in this figure, the sensors were purposely located on a non-cylindrical section towards the bottom of the case. At this location, the waves were significantly bent, and the filler signal was not clearly received (upper trace). However, when the sensors are tilted by about  $5^\circ$  as suggested by simulations, the signal quality greatly improves, and the filler signal is clearly received.

These initial tests on the 76 mm shells indicate that a slight angle ( $< 5^\circ$ ) can improve the signal to noise ratio by a factor of 7. Thus, angling the sensors may significantly improve the signal strength for a given location on a curved shell body. In practice, this could be done by fitting the sensor with a cap that is designed for a given location on a particular shell size. Alternately, new sensors could be designed to electronically adjust the angle of the acoustic beam through the curved sections.

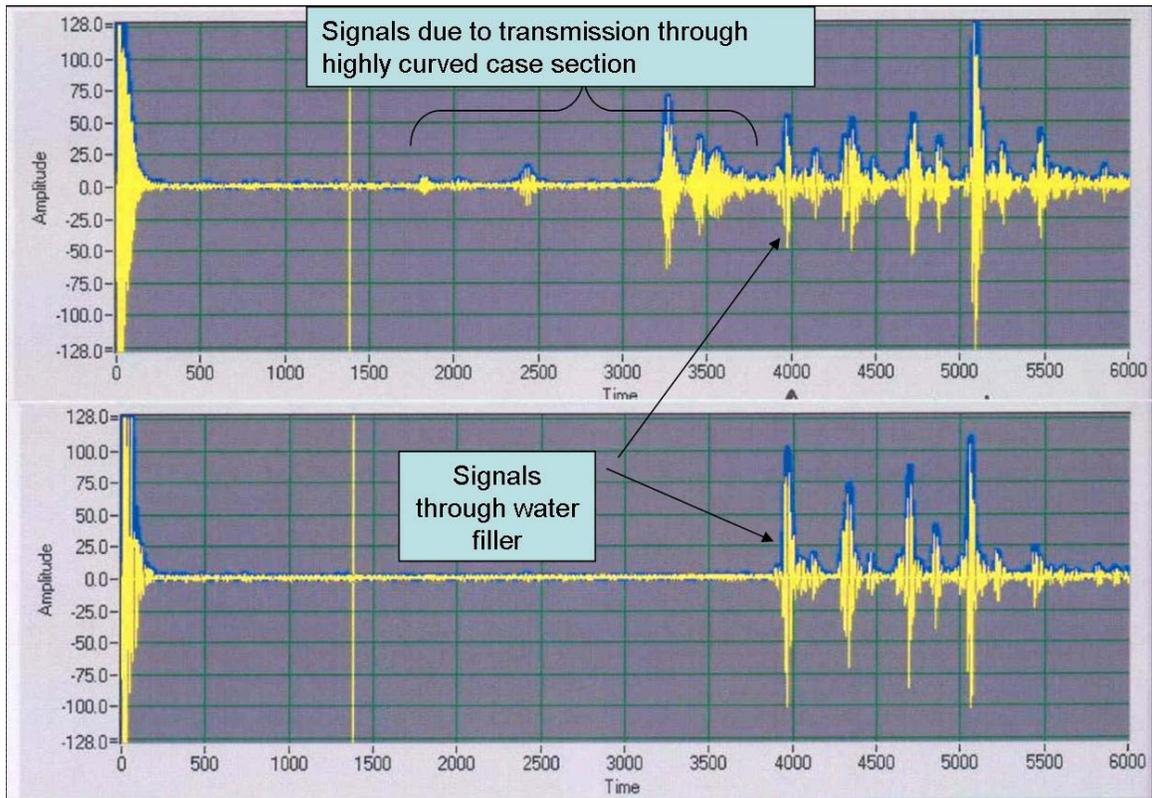


Figure 15. Acoustic signals for water filled 76 mm shell. Top trace: 5MHz sensors located flat against the case near a section where the ID was highly curved. Lower trace: same location but with the sensors tilted by 5°.

### 3.6. Field Tests

The clamp-on test system has been used to collect field measurements of acoustic velocity and attenuation at several DOD ordnance test facilities. The primary goal of these tests was to confirm that accurate measurements of the filler velocity could be made even with the complications of a case around the material. A second goal was to initially test how well the fillers could be identified using the acoustic measurements.

Testing on a wide range of bodies helps determine the utility of the technique for different shells types and its ultimate accuracy for remediation. The first test location was NAVFACORDTECHDIV in Indian Head, Maryland. There we tested several inert items that had been prepared for prior testing of a Pulsed ELEMENTAL Analysis with Neutrons (PELAN) system. These items included additional 60 mm and 81 mm POP and red-wax filled mortars. Other corroded, un-buried shells were available, but were empty or filled with unsuitable filler for acoustic identification (dirt, sand). Good identification signals were received for the POP filled shells as well as the 60 mm red-wax shells (items 16 and 18 in appendix). However, as expected, the larger 81 mm wax-filled shell did not show any clear filler signals, due to the high attenuation in wax for shells larger than 60 mm. Only case noise was observed in the received signals for the 81 mm wax shells (Item 17 in appendix)

In addition to the items mentioned above, other NAVEODTECHDIV shell types were tested in the lab, included highly corroded shells like the one pictured in Figure 16. Corrosion and dents cause wall thickness variations that make the acoustic readings less consistent. Nevertheless, accurate measurements can still be made. The results for the 60 mm shell of Figure 16 are plotted in the figures below as part of the plaster-filled data and shown as Item 22 in the appendix.



Figure 16. Highly corroded 60 mm mortar being tested using the clamp-on sensor system

Following these first field tests, the signal acquisition system and improved sensor systems were taken to the Army Aberdeen Test Center (ATC) for additional tests on inert ordnance in the “standard UXO repository” and empty shells. These tests included both original wax-filled 60 mm shells and cement-filled 2.75” (~70 mm) shells. The results for the wax filled shells are included in the data plots below. Unfortunately, the cement formulation was poor and the 2.75” filled-shells never hardened completely. Unlike all the previous tests on cement, no filler signals were received for these poorly filled items.



Figure 17. Portable test system and live ordnance items being tested in the field.

A third and final set of site tests were conducted at NSWC in Crane, Indiana on a number of live ordnance items. Although the ultrasound was not expected to initiate any of the high explosive fillers, there was concern about the sensitivity of the fuse materials. For this reason, all tests on fused items were done from inside a bunker as shown in Figure 17. After placing the sensor clamp on the items, the ultrasonic system was activated only while personnel were inside the bunker.

The velocity readings for all the ordnance items tested are shown in Figure 18. In spite of the data scatter caused by the variety of case sizes, types and conditions, the velocity readings clearly reveal the unique signature of the fillers. As indicated in the figure, the clamp-on filler velocity agreed well with the analytical (true) value for each of the six filler materials and five case sizes. Thus, even with the complications of a case, the acoustic measurement system provided accurate filler velocity readings that can be used to identify the filler material.

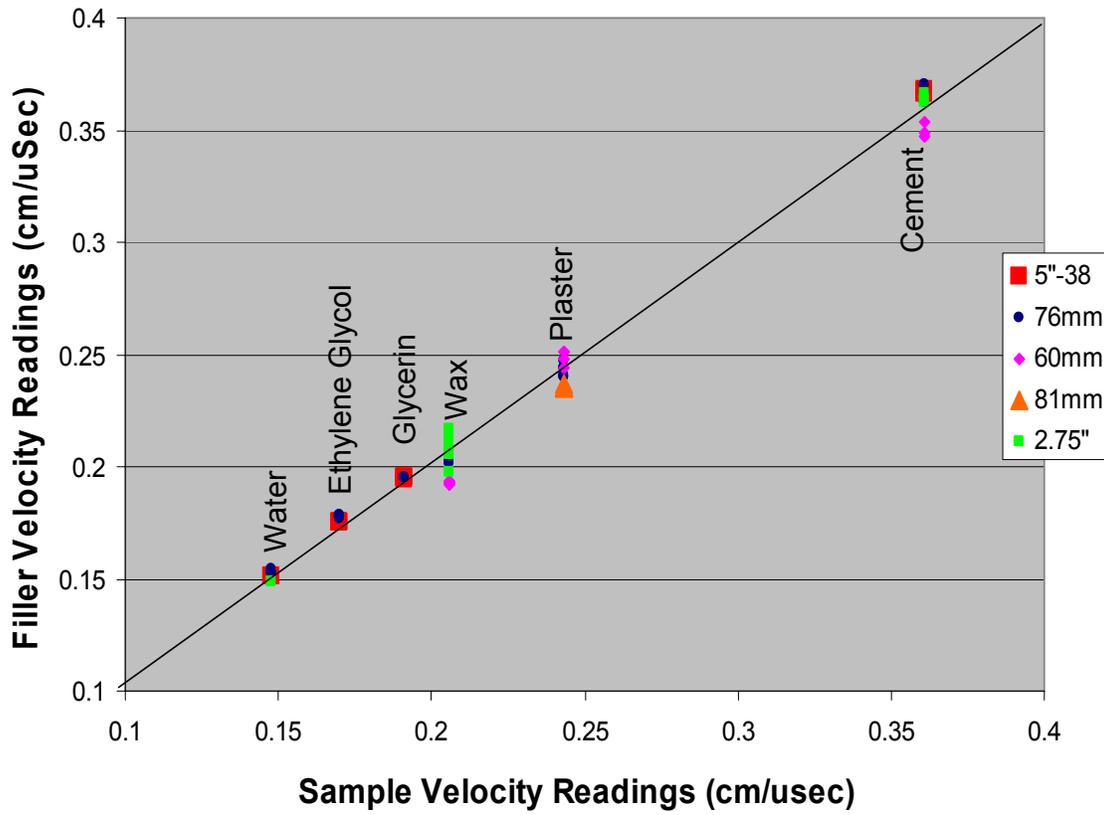


Figure 18. Measured acoustic velocities for several case types and fillers plotted versus the “true” velocity for the filler material.

A comparison of both the acoustic velocity and attenuation measurements made it clear that the fillers could be uniquely identified using the two characteristic acoustic values. Figure 19 shows the clusters of these data points for both attenuation and velocity. The shaded ovals indicate the extents ( $\pm 2$  standard deviations) of the measurement scatter for each filler and test body. Note that, because of the unique acoustic properties, each filler material occupies its own area of the cluster plot. **For all of the filler materials tested, the fillers could be differentiated inside these bodies.**

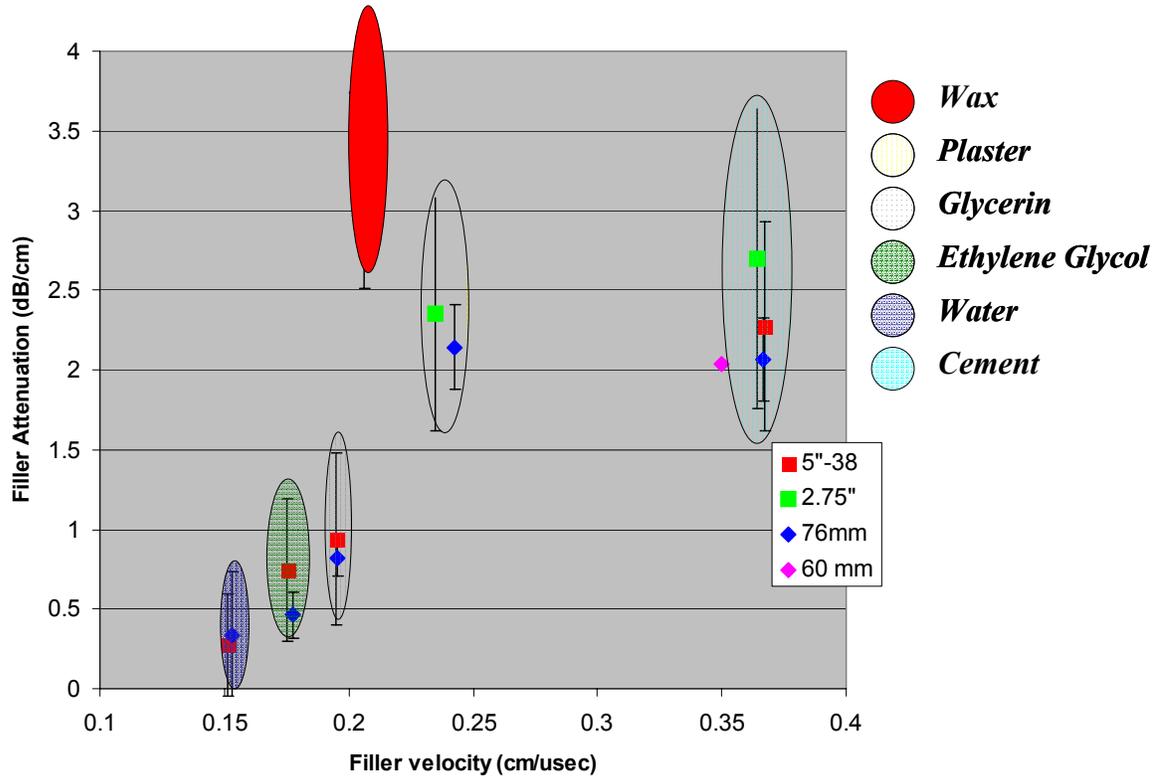


Figure 19. Data clusters for the acoustic velocity and attenuation measurements on several shell types and fillers

### 3.7. Performance of the Technique

Appendix A contains a list of measured data and photographs for many of the ordnance items tested in this study. For some ordnance sizes and types, additional items of the same size and filler type were tested, but not shown in the appendix. However, Table 1 does contain a complete list of all sizes and body types tested. In this table, the sensor frequency is marked by a number and a letter. The number refers to the center frequency of the acoustic sensors used (e.g. “2” is a 2 MHz frequency sensor) and the letter refers to the frequency bandwidth code. The “S” refers to a standard bandwidth sensor and the “G” refers to extended bandwidth. The last two columns are standardized shell identification numbers used by the Army (DODIC) and Navy (NSN). The following is a brief summary of our conclusions for each filler material.

TABLE 1  
List of Body Sizes and Types

Item #	Size	# Shells Tested	Body	Filler	Filler Signal?	Condition	Sensor Freq.	DODIC	NSN
1	2.75"	1	XM230	Plaster	Yes	Dented	2S		
2	2.75"	1	XM230	Cement	Yes	Corroded	2S	-	
3	2.75"	3	XM230	Red Wax	Yes	Good	1S	-	
4	5"-38	1	MK51	Cement	Yes	Good	2S		1315010783740
5	5"-38	1	MK51	Plaster	No	Good	2S		1315010783740
6	5"-38	1	MK51	Glycerin	Yes	Good	5G		1315010783740
7	5"-38	1	MK51	Ethylene Glycol	Yes	Good	5G		1315010783740
8	5"-38	1	MK51	Water	Yes	Good	5G		1315010783740
9	76mm	1	MK165	Plaster	Yes	Good	1S		
10	76mm	1	MK165	Cement	Yes	Good	5G		
11	76mm	1	MK165	Glycerin	Yes	Good	5G		
12	76mm	1	MK165	Ethylene Glycol	Yes	Good	5G		
13	76mm	1	MK165	Water	Yes	Good	5G		
14	76mm	1	MK165	Wax	No	Good	2S		
15	81mm	1	M374	Plaster -Orig.Fill	Yes	Good	2S		8013T02003
16	81mm	1	M374	Wax Orig.Fill	No	Corroded	2S		EOD-05150
17	60mm	1	M49A5	Red Wax - Orig. Fill	Yes	Corroded	5S		EOD-07038
18	60mm	1	MK47	Water	Yes	Good	5S		EOD-07865
19	60mm	1	M49A4	Plaster-Not Orig. Fill	No	Plaster loose	5S		EOD-1172
20	60mm	1	Mk47	Cement-Not Orig. Fill	Yes	Corroded	2S		EOD-07645
21	60mm	1	Mk47	Water	Yes	Corroded	2S		EOD-07646
22	60mm	3	XM720	Red Wax - Orig. Fill	Yes	Good	1S	RVP-1 (1976)	
23	60mm	1	XM720	Water (for Noise Base)	Yes	Good	1S	RVP-1 (1976)	
24	76mm	3	MK165	COMP A-3	No	Good	1S	C112	1315-01-058-7984
25	76mm	1	MK165	Water (for Noise Base)	Yes	Good	1S	C112	
26	90mm	1	M71	Wax Not Orig. Fill	No	Good	2S		EOD-3149
27	5"-38	3	MK51	Comp A-3	No	Good	1S	D238	1320-01-108-2811
28	5"-38	1	MK51	Water (for Noise Base)	Yes	Good	1S		1315-01783740
29	81mm	3	M879	Comp B	No	Good	1S	C223	1315-00-542-0177
30	105mm	3	XM5480	Comp B	No	Good	1S	C463	1315-00-926-4065
31	2"	1	Pipe	Plaster	Yes	Oval	5G		
32	2"	1	Pipe	Cement	Yes	Oval	5G		
33	2"	1	Pipe	Wax	Yes	Oval	5G		
34	2"	1	Pipe	Water	Yes	Oval	5G		
35	2"	1	Pipe	Ethylene Glycol	Yes	Oval	5G		
36	2"	1	Pipe	Glycerin	Yes	Oval	5G		

Total Shells Tested 48

### *3.7.1 Identification of Cement fillers*

Cement is a widely used cast filler that is easy to identify using the acoustic technique. For all the shell sizes and body types available, strong acoustic signals were received that were characteristic of a cement filler material. One reason for this is the relatively high acoustic velocity for cement of 0.36 cm/sec, higher than any other filler tested. This results in a signal that travels quickly through the filler, and arrives before the confounding case noise. Thus, with strong signals due to the relatively low attenuation, the cement filler signals are easily separated from the case noise and the time of arrival can be accurately measured. As shown for even the large 5"-38 shell (Item 4 in the appendix), the signal through the cement filler is strong and has the characteristic multi-echo shape described earlier that clearly distinguishes it from case noise. The very high velocity of cement also helps to differentiate cement from other filler materials. Thus, cement filled items should be the most accurately identified by the acoustic technique.

### *3.7.2 Identification of Plaster fillers*

Plaster of Paris or POP is also a very common type of inert filler used in ordnance. Unlike the high velocity of cement, the lower acoustic velocity of POP (0.24 cm/microsecond) is closer to the velocity of many other materials (e.g. plastics). This velocity is closer to that for wax (0.21 cm/microsecond), the other common filler material tested. However, the velocities are different enough to easily identify these fillers in all the items for which sufficient filler signals were received.

For all but the largest 5"-38 shell tested, strong acoustic signals were received that were characteristic of a plaster filler material. In many cases, multiple echoes were present indicating a strong signal through the plaster. For example, see the signal for plaster filler in a 2.75" shell (ordnance Item #1) in the Appendix. Although many of the plaster filler items tested were empty and later filled on-site, a few items with original POP filler were tested (item 16 in the Appendix). These original items showed strong multiple echo signals.

### *3.7.3 Identification of Wax fillers*

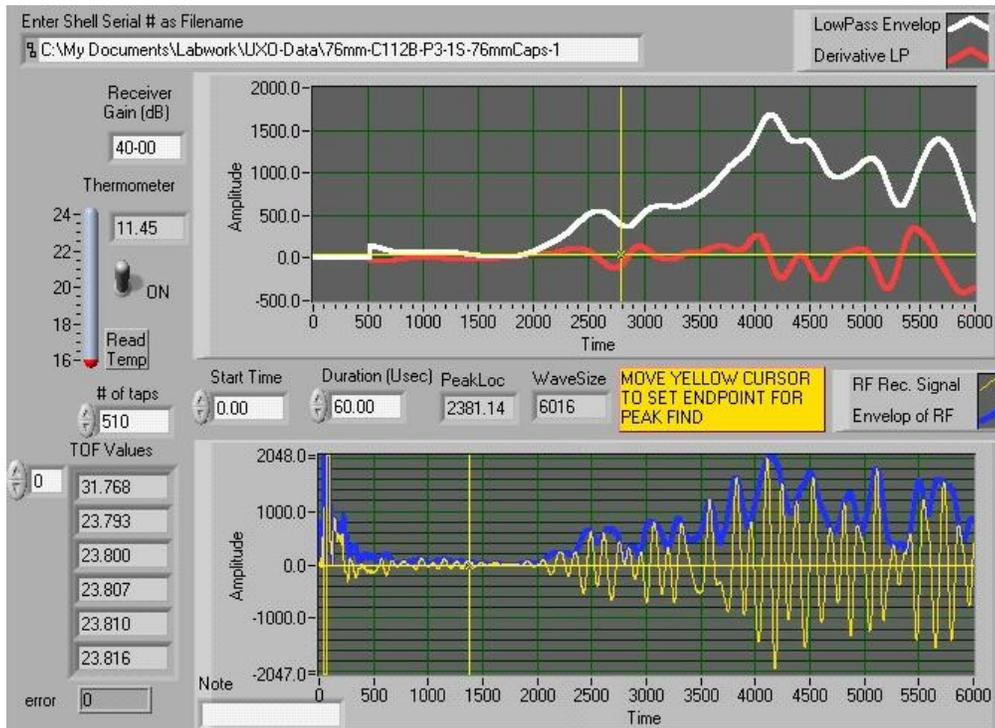
Wax has an acoustic velocity of 0.21 cm/microsecond, the lowest of the three solid, inert fillers tested in this study. This velocity is low enough to clearly differentiate the wax filler from plaster when sufficient signals are received. However, of the three inert filler materials tested in this study, wax is the most difficult material to on which to obtain sufficient filler signals. As shown in the ordnance data in the appendix, wax filler signals were observed for smaller items up to 60 mm, but no filler signals were received for larger ordnance items. For example, the signals for the 60 mm ordnance Item 23 with original wax fill shows clear filler signals with multiple echoes. However, such strong signals were not present in all locations around the item, possibly indicating localized separation of the wax from the case. Based on limited testing on molten wax in the laboratory, we observed that, under certain cooling conditions, poured wax can pull away from the case during cooling.

At the current state of the acoustic identification technology the method is not considered reliable for wax filled items larger than 60 mm. Note that the measured signals would not provide a false reading of another filler type, rather the lack of signal would just result in a “no read.” Although the method is restricted to only the smaller wax-filled items, it is important to note that 60 mm ordnance is the most commonly uncovered UXO [11].

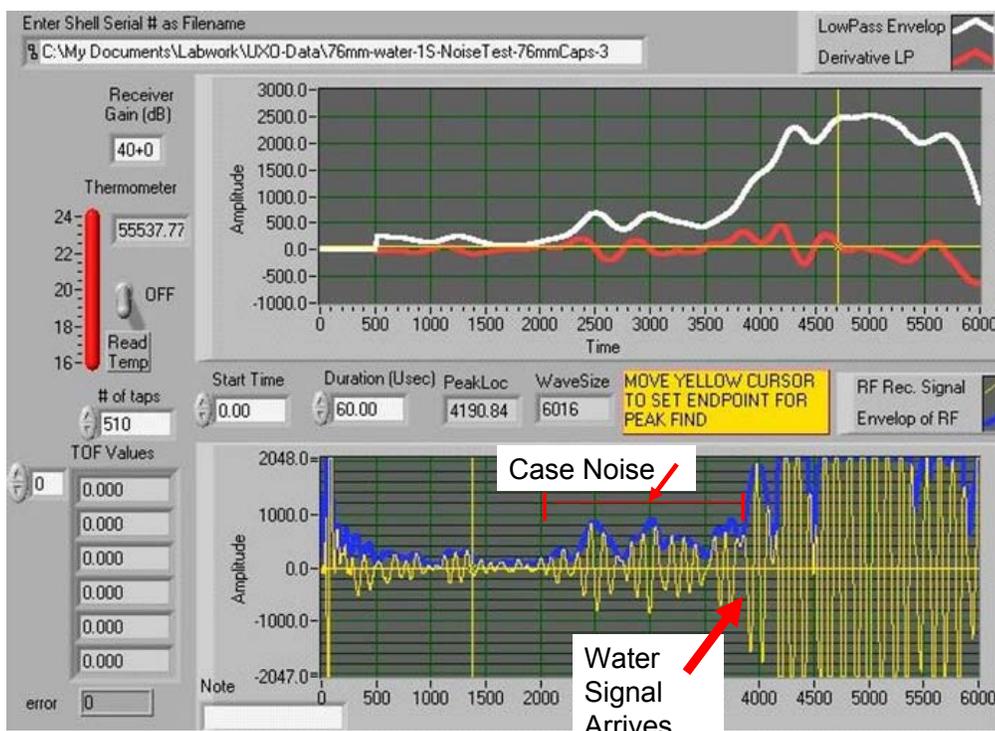
#### *3.7.4 Identification of High Explosive (HE) fillers*

No clear filler signals were received for any ordnance item filled with high explosive (HE). Since HE is poured in a molten state and is known to contract upon cooling, the lack of signal may be due to shrinkage away from walls (as suspected for wax). The lack of filler signal may also be due to excessive attenuation of the acoustic waves in the HE materials. Little is known about the acoustic attenuation properties of common HE such as Comp A and TNT. Although some measurements of acoustic velocity have been reported in the literature [5 and Figure 1.] almost no attenuation values are available. The author has measured the attenuation of CH-6 explosive samples (97% RDX) in the laboratory. The attenuation at 0.5 MHz acoustic frequency is approximately 9.5 dB/cm, which is comparable to the attenuation in wax (paraffin) of 10.5 dB/cm at 1.0 MHz [12]. Since the attenuation in these materials increases rapidly with frequency, the CH-6 explosive is expected to have a higher attenuation than wax at 1 MHz. Note that 1 MHz is the lowest frequency used to measure ordnance items in this study. Thus, like the wax-filled items, we would not expect to receive any filler signals through items bigger than 60 mm that were filled with such a highly attenuating material. Although CH-6 may not be representative of the HE materials tested, this analysis supports our supposition that the lack of filler signals for the HE items is caused by high attenuation in these materials.

The absence of filler signals for the HE items means that only the case noise is received. It is important to note that this noise, even at high receiving gain, appears quite different from a “good” filler signal. For example, compare the case noise signals with HE filler (Comp-A3) in the 76 mm shell in Figure 20a to the same type of shell filled with water (Figure 20b). Even at relatively high 40 dB gain, only the gradually increasing case noise is seen in the signal trace for the HE filled item. The signals for the water filled shell are quite similar up to the time, at about 4000 samples (40usec), when the water signals arrive. Since the same high gain is used, the amplitude of water signals quickly goes off-scale. However the noise before the water filler signal is almost identical to that noise in the HE filled shell. Since the HE signal should arrive before the water signals for the same size shell, this confirms that no HE-filler signal is being received. Again, we believe this is due to high attenuation in the HE, or possible hairline separation of the HE from the shells as described above. Note that the measured signals would not provide a false reading of another filler type, rather the lack of signal would result in a “no read.”



(A)



(B)

Figure 20. Comparison of case noise and water filled signals for 76 mm shells. (A) HE filled shell, (B) Water filled shell

To provide an initial test of the potential accuracy of the technique, a linear discriminant analysis was developed. Discriminant analysis predicts classification variables (filler-type) based on a known continuous response (measured velocity). Discriminant analysis can be regarded as inverse prediction from a multivariate analysis of variance. The analysis looks at the velocity variance for groups of each filler type, and then classifies each item by filler type based on each reading. For this analysis, we used only the measured velocity values from ordnance test items that provided a good filler signal. For the other test items, only noise was measured, and there was no velocity reading to use. The data set consists of a total of 56 readings around the cases of those ordnance items in Table 1 with a good signal. These included wax, cement and plaster fillers.

Table 2

Results of the linear discriminant analysis

Counts: Actual Filler Rows by Predicted Filler Columns	Cement	Plaster	Wax
Cement	18	0	0
Plaster	0	19	0
Wax	0	0	19

Note that all of the identifications for these 56 readings were completely correct (no off-diagonal counts). The analysis shows the accuracy of the technique for discriminating among these three inert filler types. Note that, an ordnance item in Table 1 that did not have a good signal would automatically be identified as an “OTHER” category. This other category would include all “no-read” items and include fillers of HE, sand, pellets, etc.

## 4. Conclusions

An acoustic filler ID technology has been developed and proven during a two-year SERDP program of device development and lab/test-site evaluation [13] [14]. We have demonstrated the feasibility of using low-energy acoustic waves for UXO filler identification. The technique has the potential to quickly identify partially-uncovered UXO during site clean-up activities. The need for this type of filler ID technology was identified as a reclamation priority in FY 2003.

After the first prototype ID devices were developed, they were tested at three DOD test sites including the Naval Surface Warfare Center (NSWC Crane), Army Aberdeen Test Center (ATC), and the Navy Explosive Ordnance Technology Division (NAVEODTECHDIV). Ordnance items used in these tests included a wide variety of mortar and shells ranging in size from 60 mm to 5"-38. Fillers included both inert and high explosive (HE) materials.

These field tests showed that, although the technology will not identify all ordnance types and filler materials, it provides a simple, low-cost way to identify some of the most common filler materials. The technology works best on fillers that are cast into the shell body and are intimately bonded to the metal walls. In this case, the sound waves easily travel from one side of the shell, through the walls and center of the filler, and can be received on the opposite side. Thus, Plaster of Paris (POP) and cement fillers provide good signals for identification, whereas loose sand and gravel do not. Although signals for other cast filler materials have been measured, wax and HE fillers do not provide consistent signals for identification. A "good" signal has characteristic features that distinguish it from noise signals. A filler ID is only provided when signals with these characteristics are received. Although corrosion reduces the amplitude of the received signals, good signals were received for a number of highly corroded items filled with cement and POP.

Although this technology is new, this study provided a great deal of information on the ultimate capabilities and reliability of the technology. First, the current acoustic technique shows good identification accuracy for inert fillers based on data clusters for velocity and attenuation. Second, acoustic technology operates best for smaller shells that do not significantly attenuate the signal traveling through the filler (40 mm to 81 mm). Third, if a good quality signal is received through the item, the identification is highly accurate. In all cases, a good quality signal is easily distinguished from a poor quality signal. Filler identification should not be attempted on the basis of a poor quality signal. Fourth, several new techniques to improve signal quality have been developed and tested. Each of these techniques shows promise for improving the signal quality for curved shells, corroded items and highly attenuating fillers. Finally, throughout this study, no safety issues have developed, even with fused items.

## **5. Technical Papers and Presentations**

W.N. Cobb, "Acoustic Identification of Filler Materials in Unexploded Ordnance,"  
SERDP Conference: 2005 Partners in Environmental Technology Technical Symposium  
& Workshop, November 29-December 1, Washington, DC

## 6. Appendix A - Data and descriptions for selected ordnance test items

### Measurements codes for following tables:

MV – Measured Velocity (cm/usec)

MA – Measured Attenuation (dB/cm)

VV – Validated Velocity (Lab - cm/usec)

VA – Validated Attenuation (Lab - dB/cm)

SF - Sensor Frequency (MHz)

OF – Location Offset (sensor from top – cm)

CO – Configuration (sensor caps, etc.)

SG – Sensor Gain (dB rel.)

WallThk. Case Wall Thickness (cm)

DA – Date

TE – Temperature (°C)

LO – Test Location (ATC – Aberdeen Test Center; CRN – NSWC Crane,  
NAV – NAVEODTECHDIV, DRI –Denver Research Inst.)

### Notes:

1. For any column, the dashes in lower rows indicate the same value as row above.
2. If no “Good” acoustic signals are received, then there are no values to report for velocity or attenuation
3. Sensor frequency codes
  - “1S”–1 MHz, standard bandwidth, 3/8” dia., Staveley CM0106
  - “2S”–2.2 MHz, standard bandwidth, 3/8” dia., Staveley CM0206
  - “5S”–5 MHz, standard bandwidth, 3/8” dia., Staveley CM0506
  - “5G”–5 MHz, wide bandwidth, 3/8” dia., Staveley G0506
4. If the CO field is blank, no cylindrical sensor caps were used
5. If no empty body of the same type was available, no reference signal for water could be measured and no signal attenuation is reported.





## Ordnance Data for Item # 3

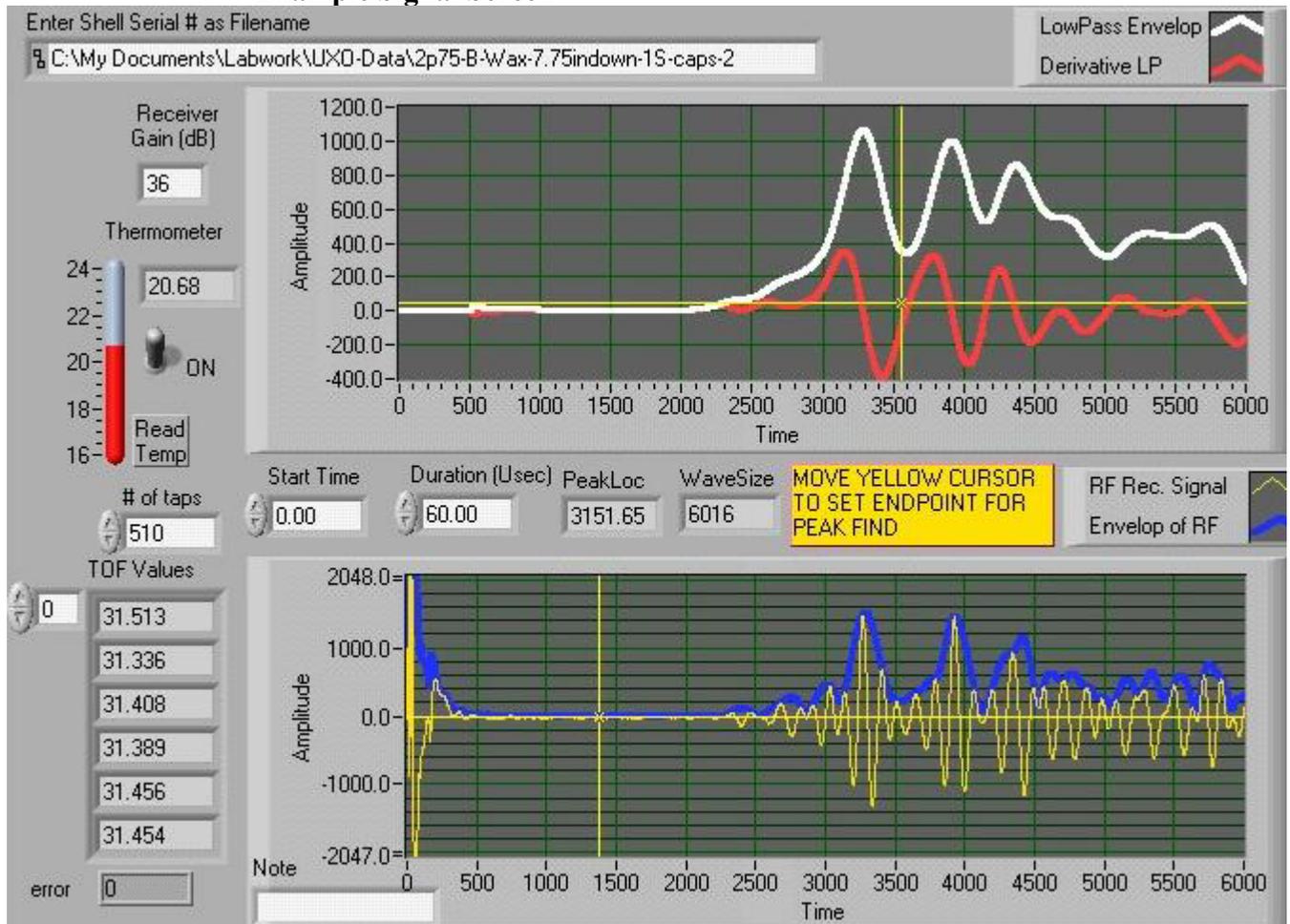
Size	Body	Filler	Condition	WallThk.	DODIC	NSN
2.75"	M495-	Red Wax	Good	1.11	-	-

### Measurements

MV	MA	VV	VA	SF	OF	CO	SG	DA	LO	TE
.210	3.08	.21	4.39	1S	18.7	caps	30	11/03/05	DRI	20.1
.215	3.69	.21	4.39	-	-	-	-	-	-	-
.212	3.73	.21	4.39							
.205	3.48	.21	4.39							



### Example Signal Screen



#### MEASUREMENTS CODES:

MV – Measured Velocity (cm/usec)  
 VA – Validated Attenuation (Lab - dB/cm)  
 CO – Configuration (sensor caps, etc.)  
 DA – Date

MA – Measured Attenuation (dB/cm)  
 SF - Sensor Frequency (MHz)  
 SG – Sensor Gain (dB rel.)  
 TE – Temperature (°C)

VV – Validated Velocity (Lab - cm/usec)  
 OF – Location Offset (sensor from top – cm)  
 WallThk. – Case Wall Thickness (cm)  
 LO – Test Location

## Ordnance Data for Item # 4

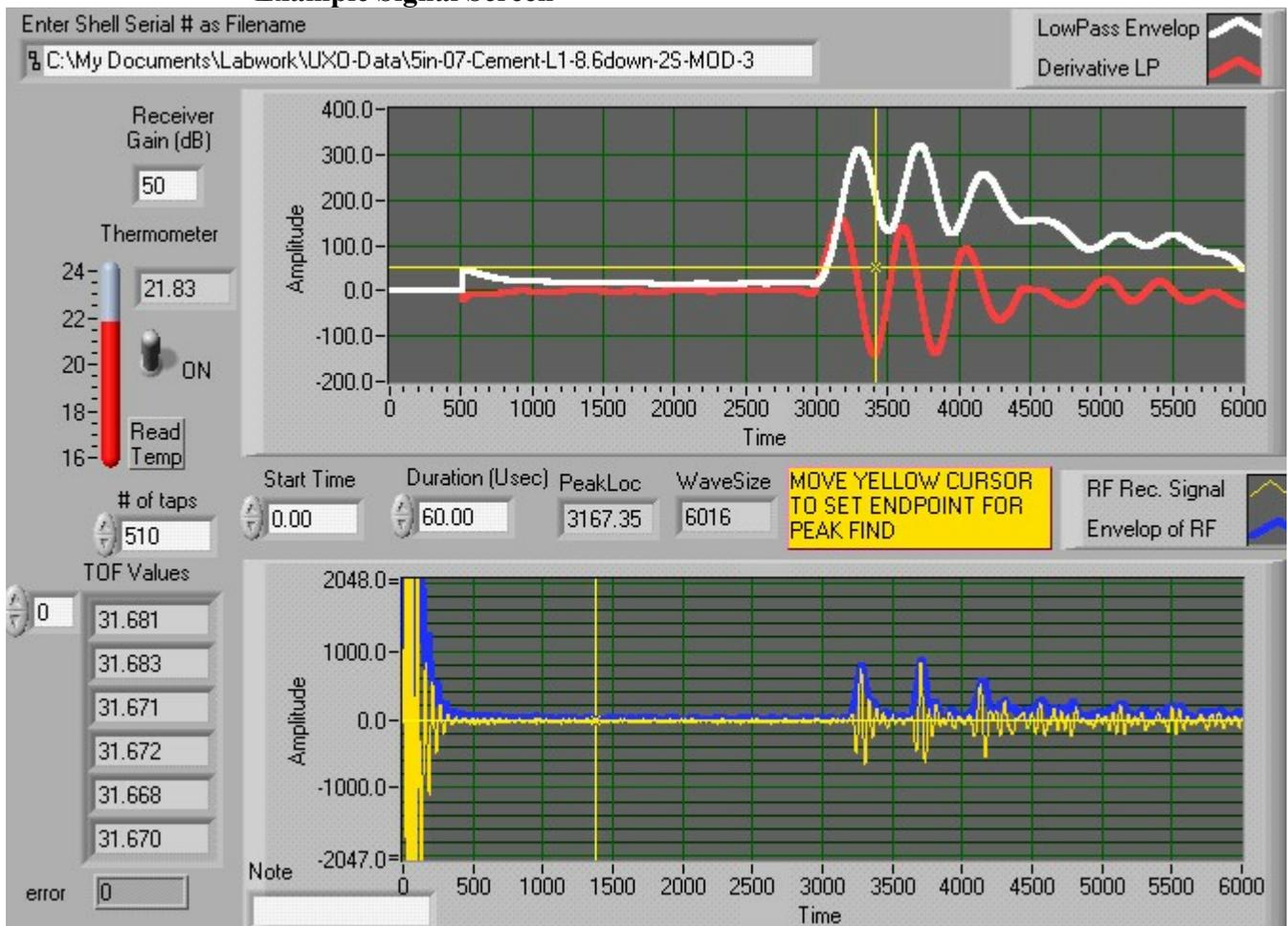
Size	Body	Filler	Condition	WallThk.	DODIC	NSN
5"-38		Cement	Good	1.23		131501 0783740

### Measurements

MV	MA	VV	VA	SF	OF	CO	SG	DA	LO	TE
.366	1.98	.361	1.87	2S	22.2		46	11/17/05	DRI	22
.367	2.24	.361	1.87	2S	-	-	-	-	-	-
.367	1.88	.361	1.87	2S						
.367	2.26	.361	1.87	2S						
.368	2.54	.361	1.87	2S						
.367	2.75	.361	1.87	2S						



### Example Signal Screen



#### MEASUREMENTS CODES:

MV – Measured Velocity (cm/usec)  
 VA – Validated Attenuation (Lab - dB/cm)  
 CO – Configuration (sensor caps, etc.)  
 DA – Date

MA – Measured Attenuation (dB/cm)  
 SF - Sensor Frequency (MHz)  
 SG – Sensor Gain (dB rel.)  
 TE – Temperature (°C)

VV – Validated Velocity (Lab - cm/usec)  
 OF – Location Offset (sensor from top – cm)  
 WallThk. – Case Wall Thickness (cm)  
 LO – Test Location



# Ordnance Data for Item # 6

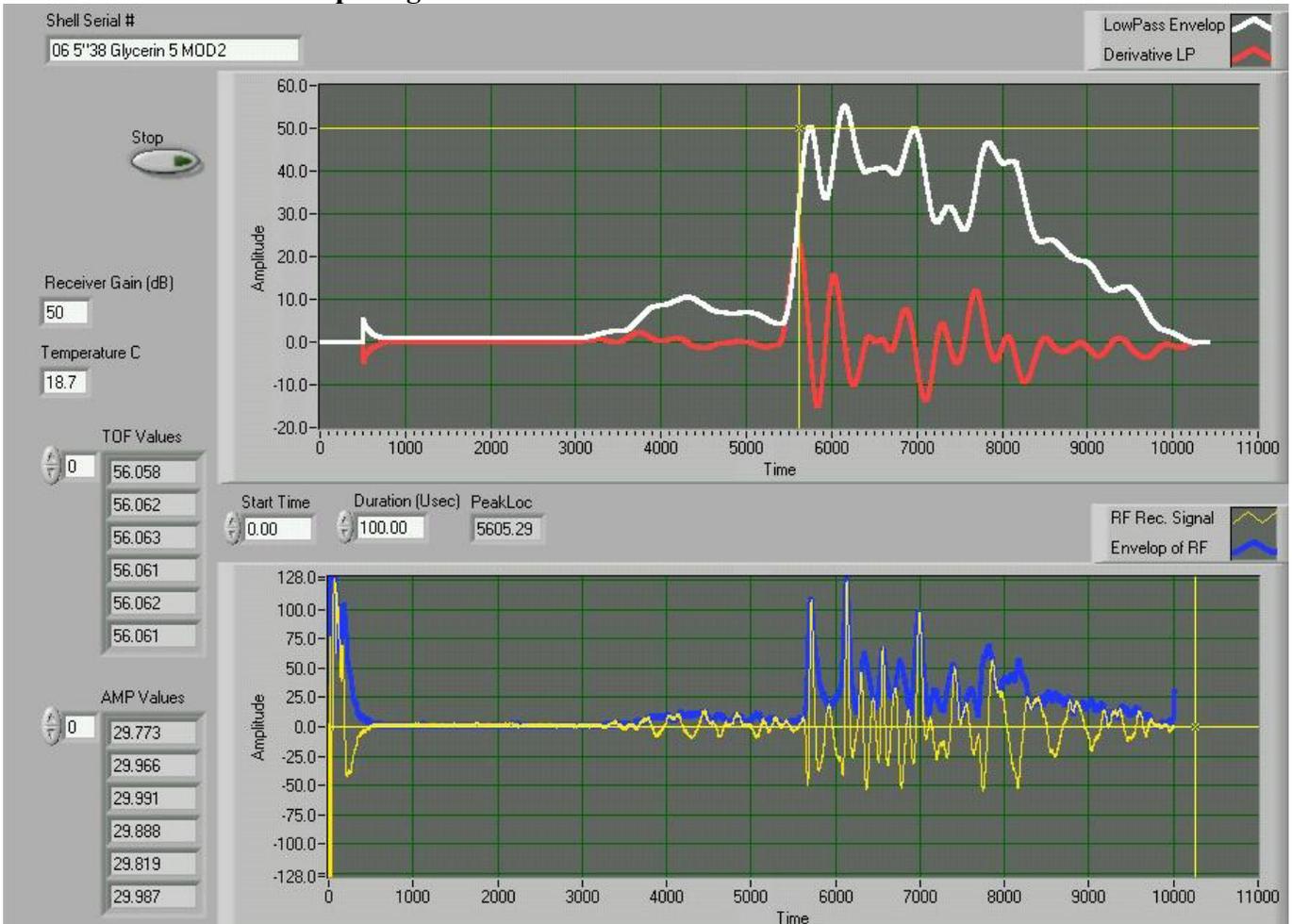
Size	Body	Filler	Condition	WallThk.	DODIC	NSN
5"-38		Glycerin	Good	1.22		131501 0783740



## Measurements

MV	MA	VV	VA	SF	OF	CO	SG	DA	LO	TE
.194	0.51	.191	0.97	5G	22.2		40	9/23/04	DRI	19
.195	1.30	.191	0.97	-	-		-	-	-	-
.195	0.93	.191	0.97							
.195	0.80	.191	0.97							
.195	1.12	.191	0.97							
.196	0.97	.191	0.97							

## Example Signal Screen



### MEASUREMENTS CODES:

MV – Measured Velocity (cm/usec)  
 VA – Validated Attenuation (Lab - dB/cm)  
 CO – Configuration (sensor caps, etc.)  
 DA – Date

MA – Measured Attenuation (dB/cm)  
 SF - Sensor Frequency (MHz)  
 SG – Sensor Gain (dB rel.)  
 TE – Temperature (°C)

VV – Validated Velocity (Lab - cm/usec)  
 OF – Location Offset (sensor from top – cm)  
 WallThk. – Case Wall Thickness (cm)  
 LO – Test Location

## Ordnance Data for Item # 7

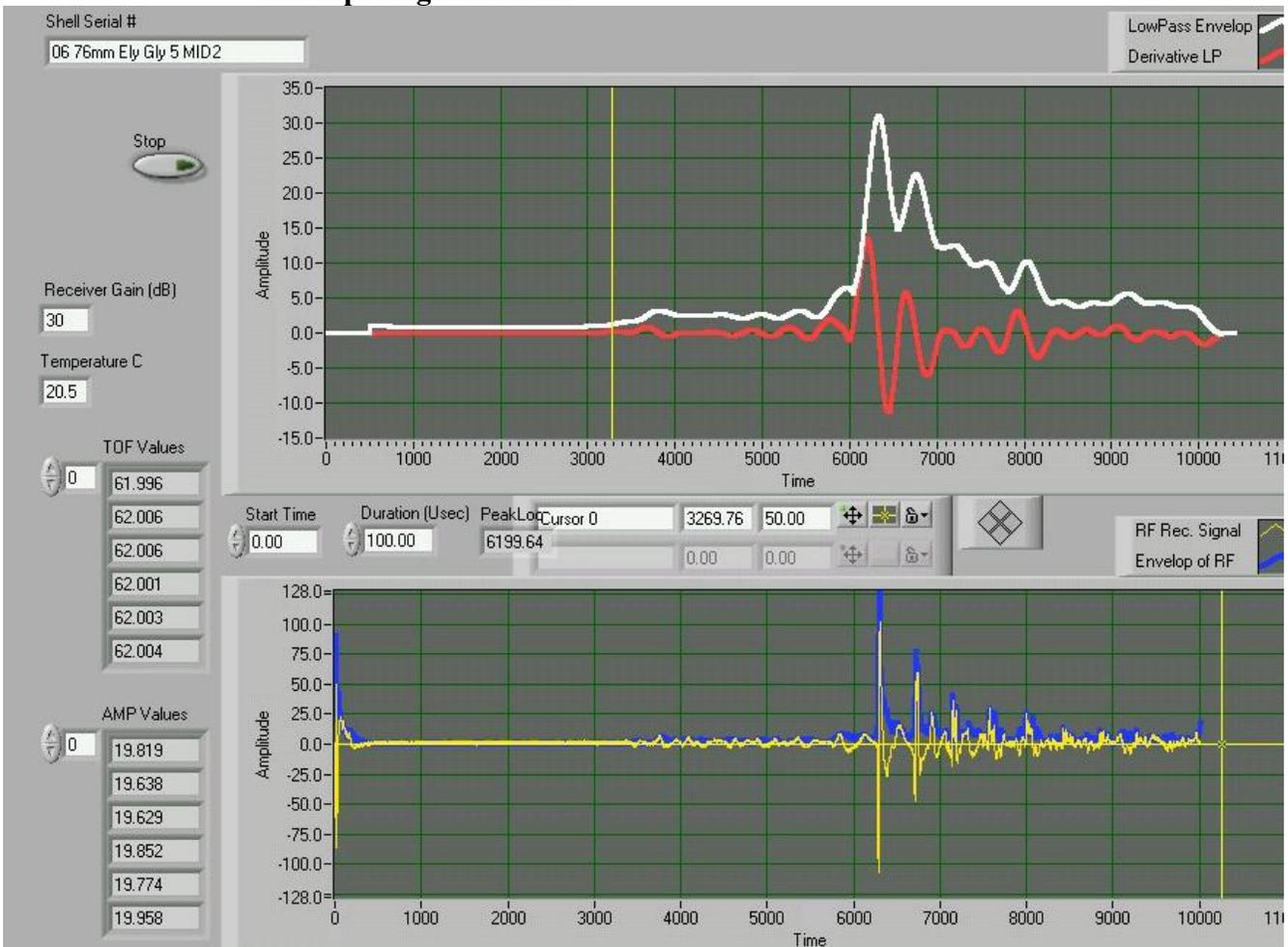
Size	Body	Filler	Condition	WallThk.	DODIC	NSN
5"-38		Ethylene Glycol	Good	1.21		131501 0783740



### Measurements

MV	MA	VV	VA	SF	OF	CO	SG	DA	LO	TE
.175	0.62	.17	0.6	5G	22.2		30	9/22/04	DRI	21
.175	0.49	.17	0.6	-	-		-		-	-
.175	0.63	.17	0.6							
.175	1.10	.17	0.6							
.175	0.91	.17	0.6							
.175	0.73	.17	0.6							

### Example Signal Screen



#### MEASUREMENTS CODES:

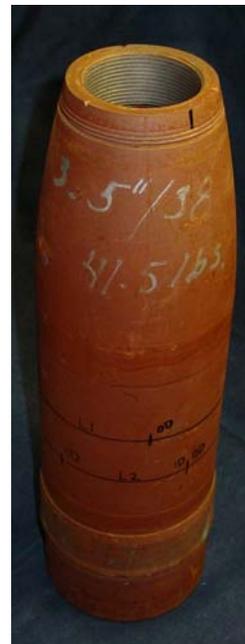
MV – Measured Velocity (cm/usec)  
 VA – Validated Attenuation (Lab - dB/cm)  
 CO – Configuration (sensor caps, etc.)  
 DA – Date

MA – Measured Attenuation (dB/cm)  
 SF - Sensor Frequency (MHz)  
 SG – Sensor Gain (dB rel.)  
 TE – Temperature (°C)

VV – Validated Velocity (Lab - cm/usec)  
 OF – Location Offset (sensor from top – cm)  
 WallThk. – Case Wall Thickness (cm)  
 LO – Test Location

# Ordnance Data for Item # 8

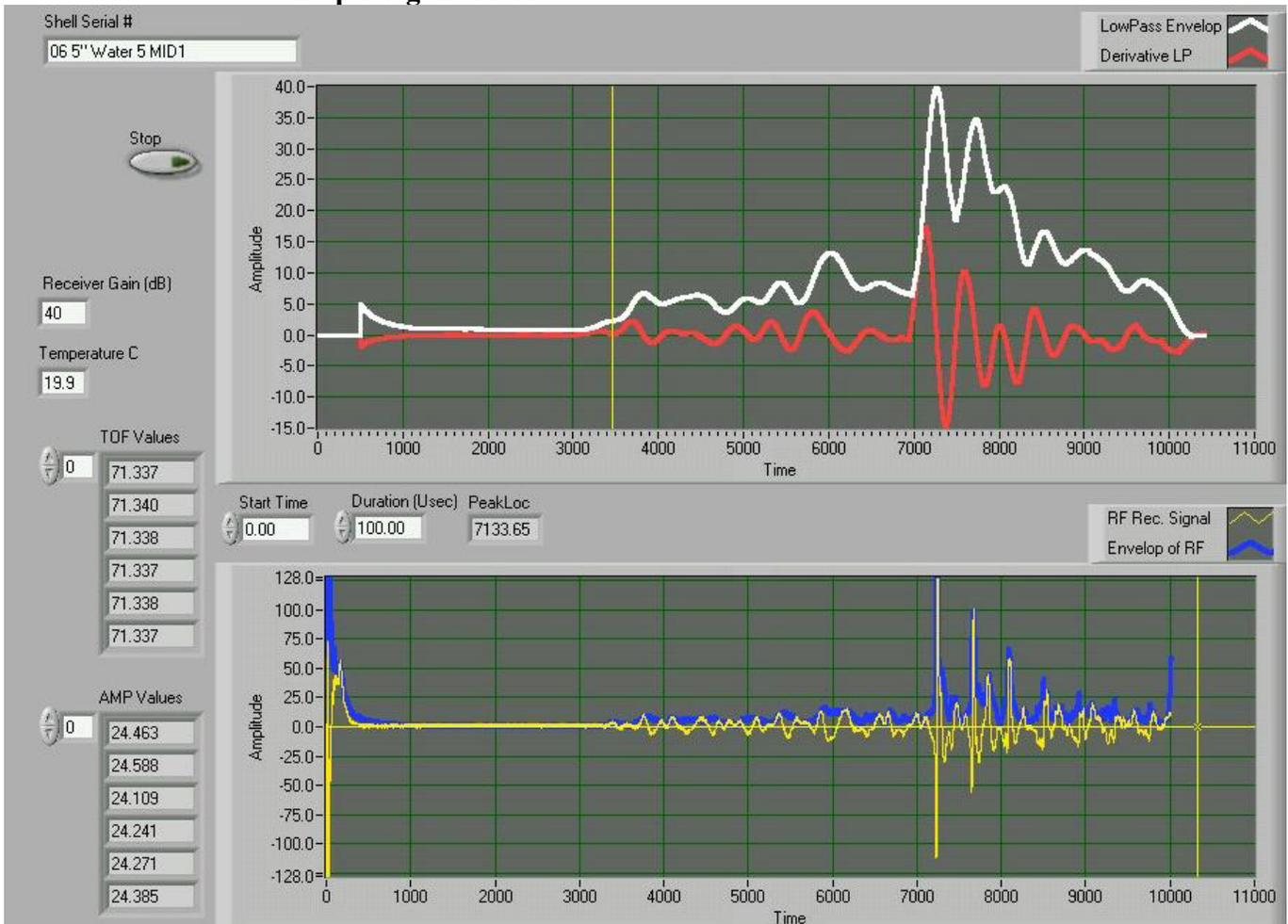
Size	Body	Filler	Condition	WallThk.	DODIC	NSN
5"-38		Water	Good	1.21		131501 0783740



## Measurements

MV	MA	VV	VA	SF	OF	CO	SG	DA	LO	TE
.151	0.30	.148	0.2	5G	22.2		40	9/22/04	DRI	20
.151	0.44	.148	0.2	5G	-	-	-	-	-	-
.151	0.44	.148	0.2	5G						
.151	0.31	.148	0.2	5G						
.151	0.82	.148	0.2	5G						
.151	0.87	.148	0.2	5G						

## Example Signal Screen



### MEASUREMENTS CODES:

MV – Measured Velocity (cm/usec)  
 VA – Validated Attenuation (Lab - dB/cm)  
 CO – Configuration (sensor caps, etc.)  
 DA – Date

MA – Measured Attenuation (dB/cm)  
 SF - Sensor Frequency (MHz)  
 SG – Sensor Gain (dB rel.)  
 TE – Temperature (°C)

VV – Validated Velocity (Lab - cm/usec)  
 OF – Location Offset (sensor from top – cm)  
 WallThk. – Case Wall Thickness (cm)  
 LO – Test Location

# Ordnance Item Data # 9

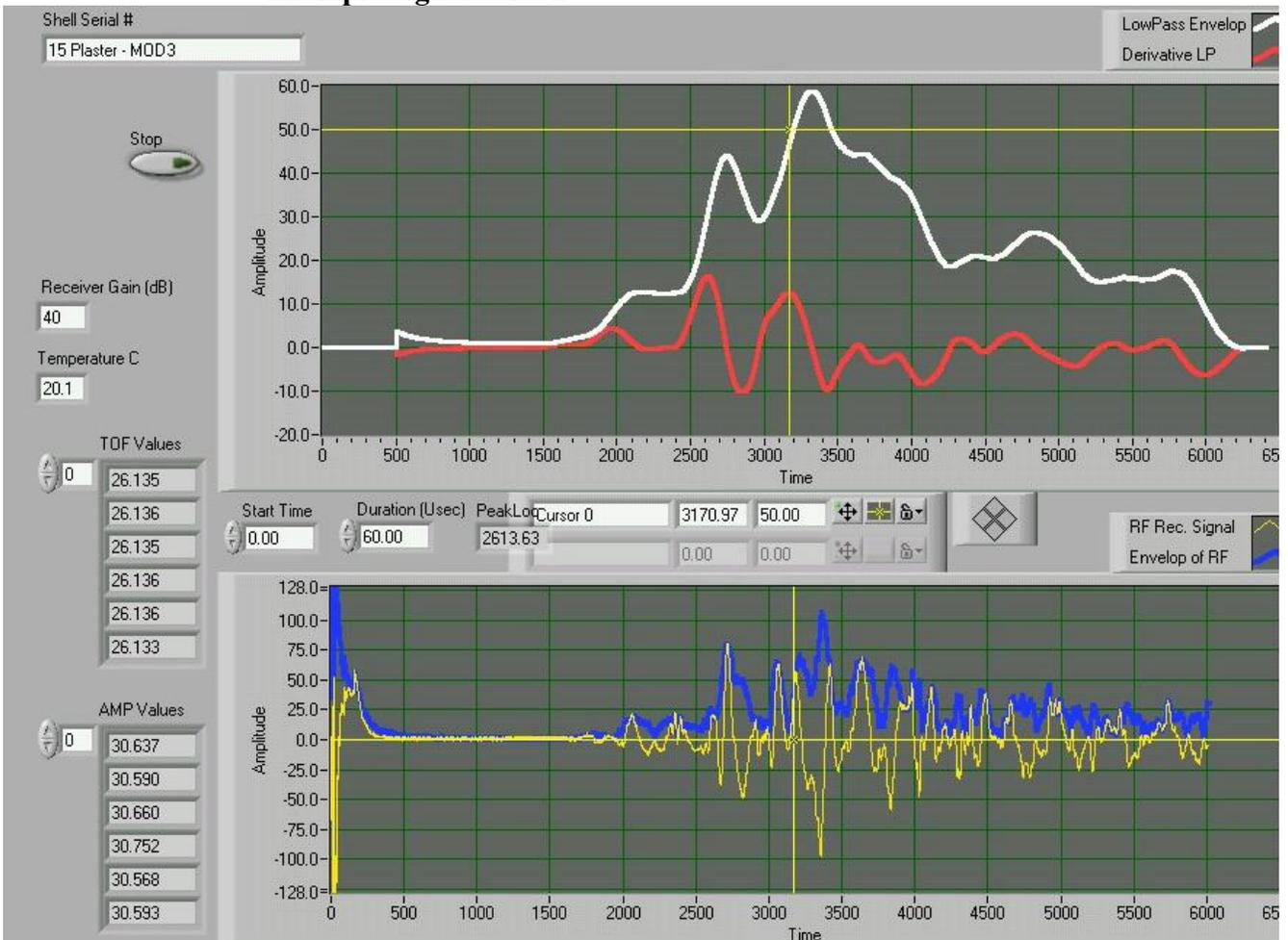
Size	Body	Filler	Condition	WallThk.	DODIC	NSN
76mm	-	Plaster	Good	1.02		131501 0783740

## Measurements

MV	MA	VV	VA	SF	OF	CO	SG	DA	LO	TE
.244	2.12	.243	2.22	5G	4.25		40	9/20/04	DRI	20
.247	1.98	.243	2.22	5G	-		-		-	-
.244	2.28	.243	2.22	5G						
.240	2.17	.243	2.22	5G						
.240	2.30	.243	2.22	5G						
.241	2.02	.243	2.22	5G						



## Example Signal Screen



### MEASUREMENTS CODES:

MV – Measured Velocity (cm/usec)  
 VA – Validated Attenuation (Lab - dB/cm)  
 CO – Configuration (sensor caps, etc.)  
 DA – Date

MA – Measured Attenuation (dB/cm)  
 SF - Sensor Frequency (MHz)  
 SG – Sensor Gain (dB rel.)  
 TE – Temperature (°C)

VV – Validated Velocity (Lab - cm/usec)  
 OF – Location Offset (sensor from top – cm)  
 WallThk. – Case Wall Thickness (cm)  
 LO – Test Location

# Ordnance Item Data # 10

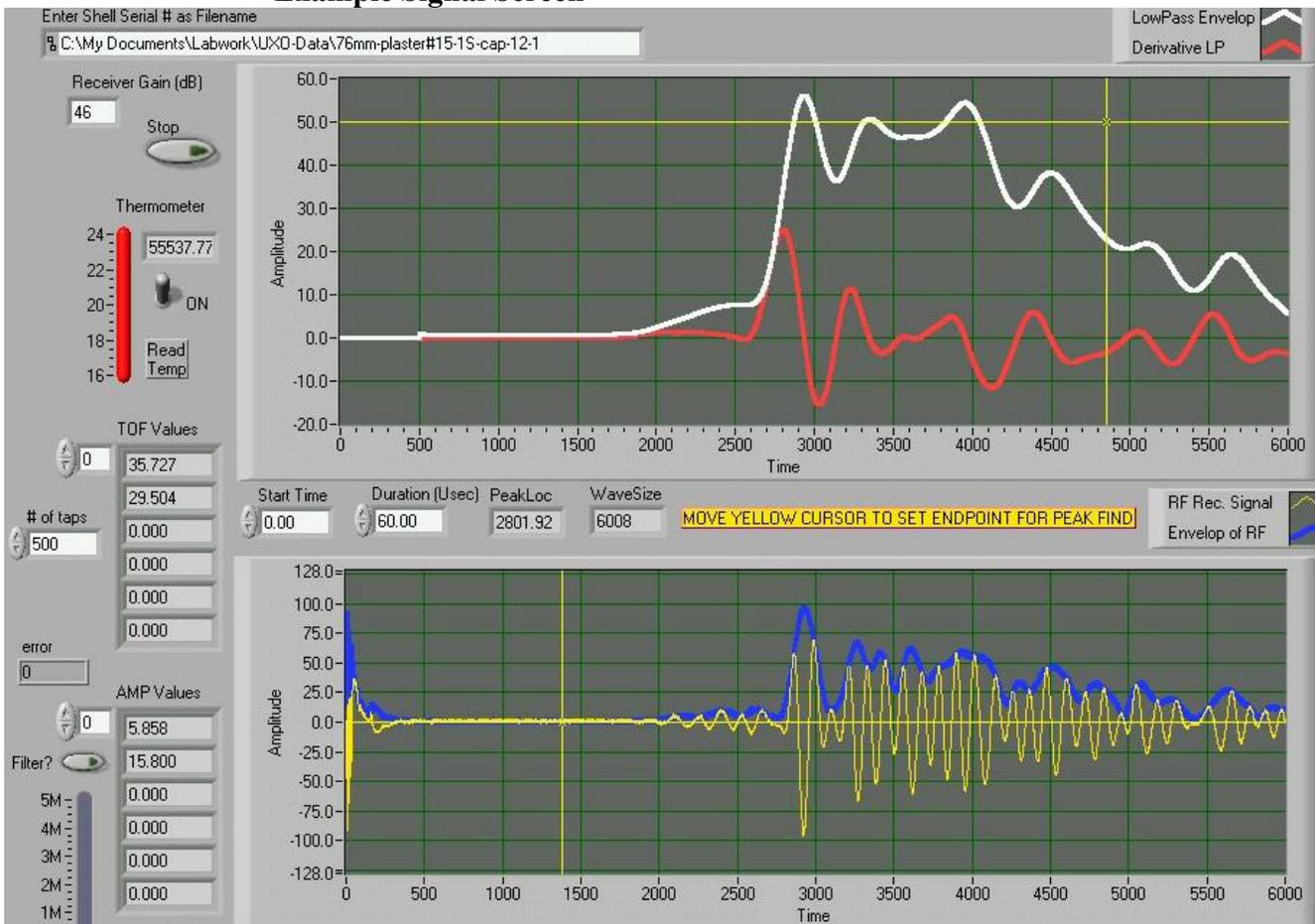
Size	Body	Filler	Condition	WallThk.	DODIC	NSN
76mm	-	Plaster	Good	1.02		131501 0783740



## Measurements

MV	MA	VV	VA	SF	OF	CO	SG	DA	LO	TE
.244	2.12	.243	2.22	1S	4.25	caps	46	6/21/05	DRI	20
.247	1.97	.243	2.22	-	-	-	-	-	-	-
.244	2.27	.243	2.22							
.240	2.16	.243	2.22							
.240	2.29	.243	2.22							
.241	2.01	.243	2.22							

## Example Signal Screen



### MEASUREMENTS CODES:

MV – Measured Velocity (cm/usec)  
 VA – Validated Attenuation (Lab - dB/cm)  
 CO – Configuration (sensor caps, etc.)  
 DA – Date

MA – Measured Attenuation (dB/cm)  
 SF - Sensor Frequency (MHz)  
 SG – Sensor Gain (dB rel.)  
 TE – Temperature (°C)

VV – Validated Velocity (Lab - cm/usec)  
 OF – Location Offset (sensor from top – cm)  
 WallThk. – Case Wall Thickness (cm)  
 LO – Test Location

# Ordnance Item Data # 11

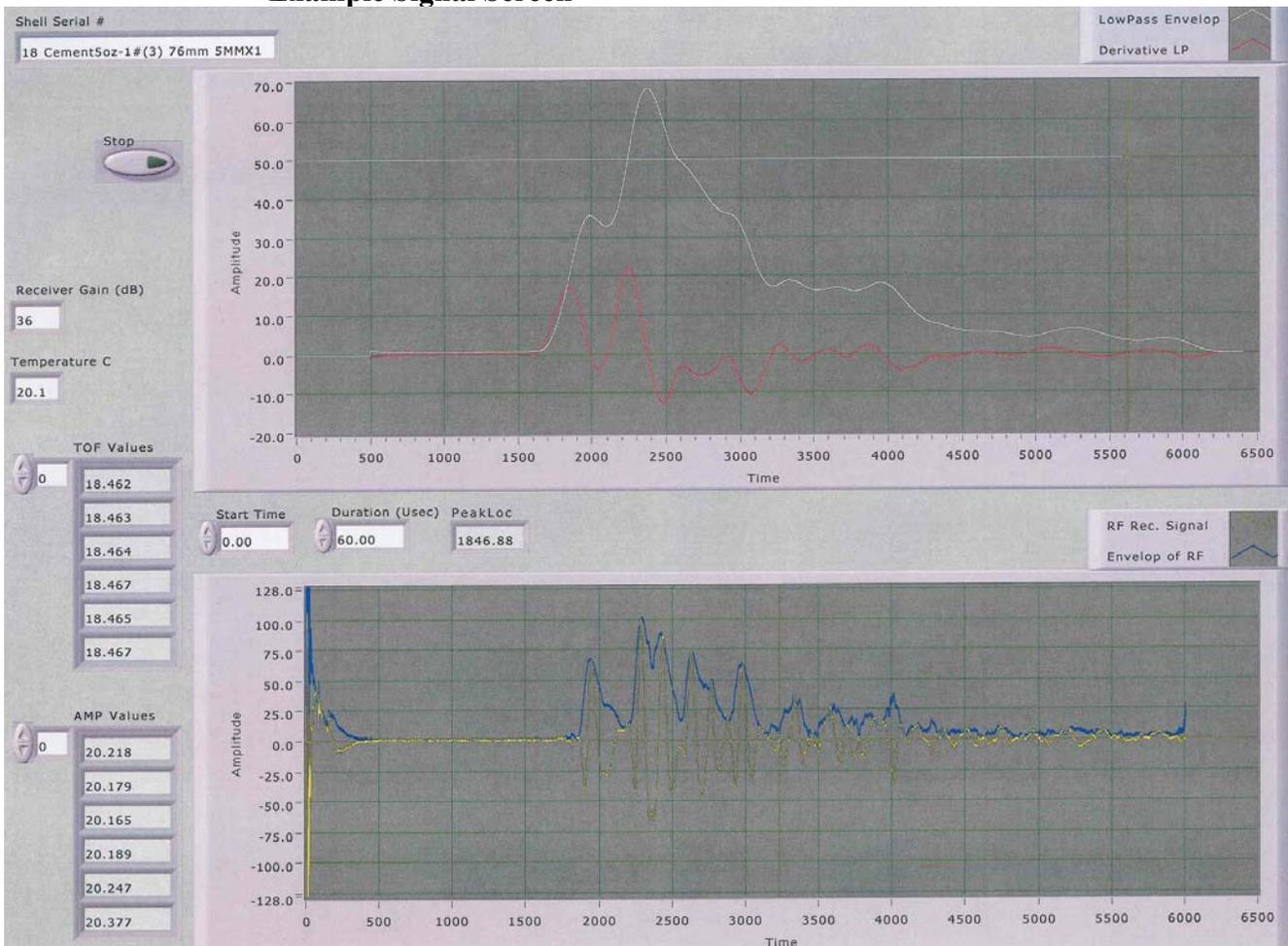
Size	Body	Filler	Condition	WallThk.	DODIC	NSN
76mm	-	Cement	Good	1.02		131501 0783740



## Measurements

MV	MA	VV	VA	SF	OF	CO	SG	DA	LO	TE
.363	1.95	.361	1.87	5S	4.25		36	11/24/04	DRI	20
.366	1.99	.361	1.87	-	-	-	-	-	-	-
.363	2.17	.361	1.87							
.369	2.07	.361	1.87							
.370	1.93	.361	1.87							
.368	2.26	.361	1.87							

## Example Signal Screen



### MEASUREMENTS CODES:

MV – Measured Velocity (cm/usec)  
 VA – Validated Attenuation (Lab - dB/cm)  
 CO – Configuration (sensor caps, etc.)  
 DA – Date

MA – Measured Attenuation (dB/cm)  
 SF - Sensor Frequency (MHz)  
 SG – Sensor Gain (dB rel.)  
 TE – Temperature (°C)

VV – Validated Velocity (Lab - cm/usec)  
 OF – Location Offset (sensor from top – cm)  
 WallThk. – Case Wall Thickness (cm)  
 LO – Test Location

# Ordnance Item Data # 12

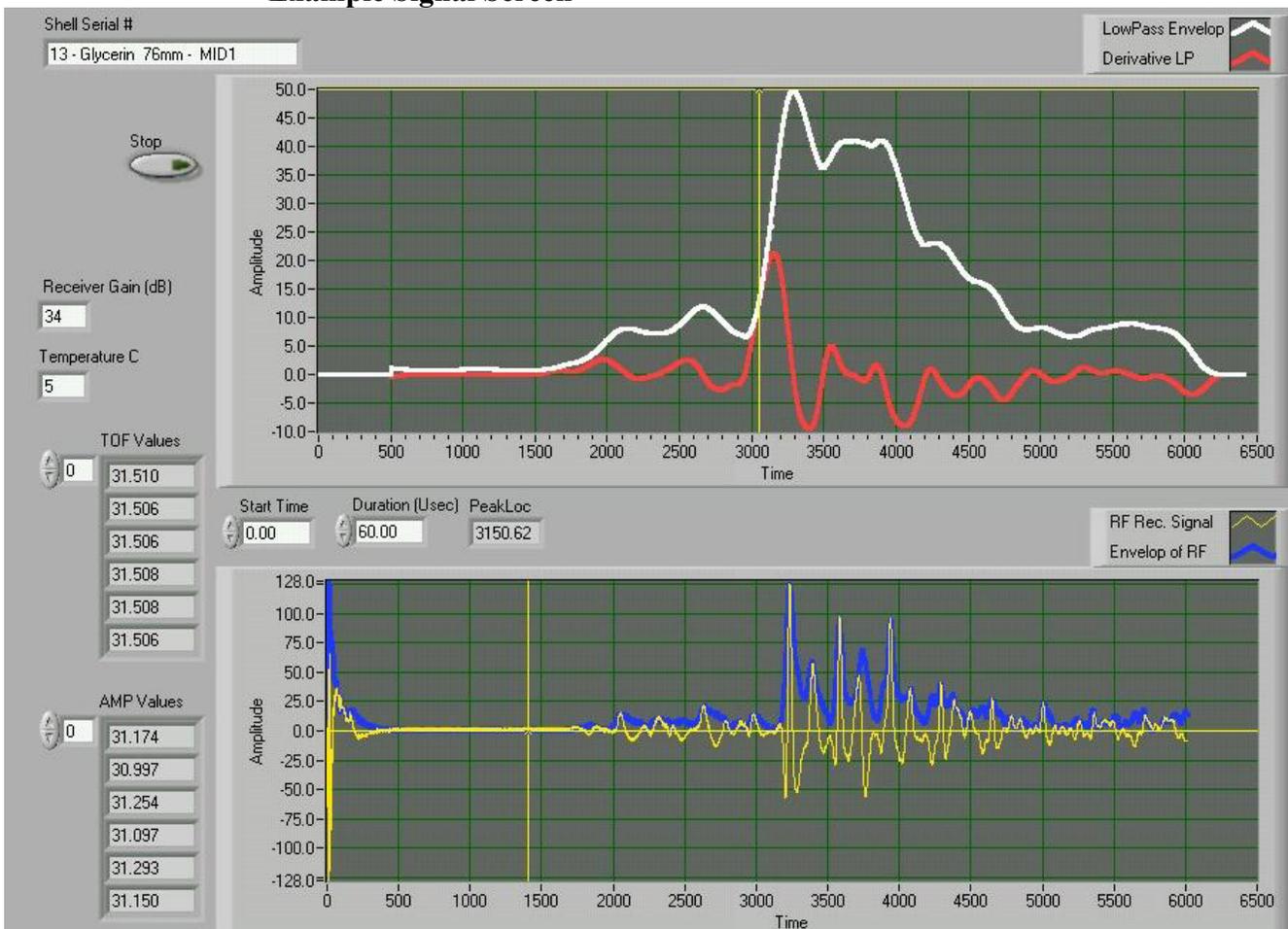
Size	Body	Filler	Condition	WallThk.	DODIC	NSN
76mm	-	Glycerin	Good	1.02		131501 0783740

## Measurements

MV	MA	VV	VA	SF	OF	CO	SG	DA	LO	TE
.195	0.90	.191	0.92	5G	4.25		34	9/14/04	DRI	21
.195	0.77	.191	0.92	-	-		-	-	-	-
.195	0.75	.191	0.92							
.195	0.87	.191	0.92							
.195	0.84	.191	0.92							
.195	0.81	.191	0.92							



## Example Signal Screen



### MEASUREMENTS CODES:

MV – Measured Velocity (cm/usec)  
 VA – Validated Attenuation (Lab - dB/cm)  
 CO – Configuration (sensor caps, etc.)  
 DA – Date

MA – Measured Attenuation (dB/cm)  
 SF - Sensor Frequency (MHz)  
 SG – Sensor Gain (dB rel.)  
 TE – Temperature (°C)

VV – Validated Velocity (Lab - cm/usec)  
 OF – Location Offset (sensor from top – cm)  
 WallThk. – Case Wall Thickness (cm)  
 LO – Test Location

# Ordnance Item Data # 13

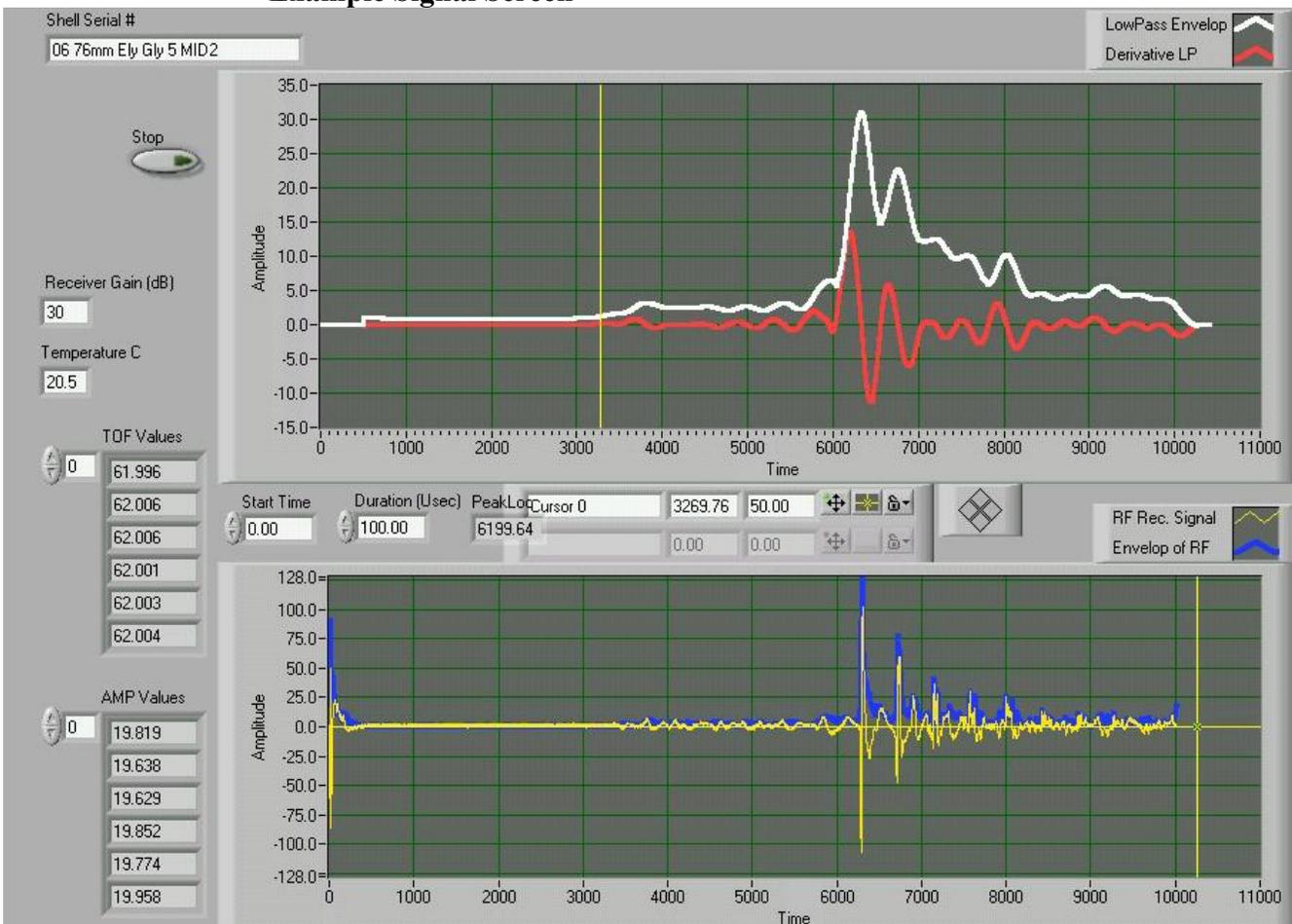
Size	Body	Filler	Condition	WallThk.	DODIC	NSN
76mm	-	Ethylene Glycol	Good	1.01		131501 0783740



## Measurements

MV	MA	VV	VA	SF	OF	CO	SG	DA	LO	TE
.178	0.43	.17	0.55	5G	4.25		26	9/21/04	CRN	20
.178	0.50	.17	0.55	-	-		-	-	-	-
.177	0.52	.17	0.55							
.178	0.45	.17	0.55							
.178	0.54	.17	0.55							
.177	0.34	.17	0.55							

## Example Signal Screen



### MEASUREMENTS CODES:

MV – Measured Velocity (cm/usec)  
 VA – Validated Attenuation (Lab - dB/cm)  
 CO – Configuration (sensor caps, etc.)  
 DA – Date

MA – Measured Attenuation (dB/cm)  
 SF - Sensor Frequency (MHz)  
 SG – Sensor Gain (dB rel.)  
 TE – Temperature (°C)

VV – Validated Velocity (Lab - cm/usec)  
 OF – Location Offset (sensor from top – cm)  
 WallThk. – Case Wall Thickness (cm)  
 LO – Test Location

# Ordnance Item Data # 14

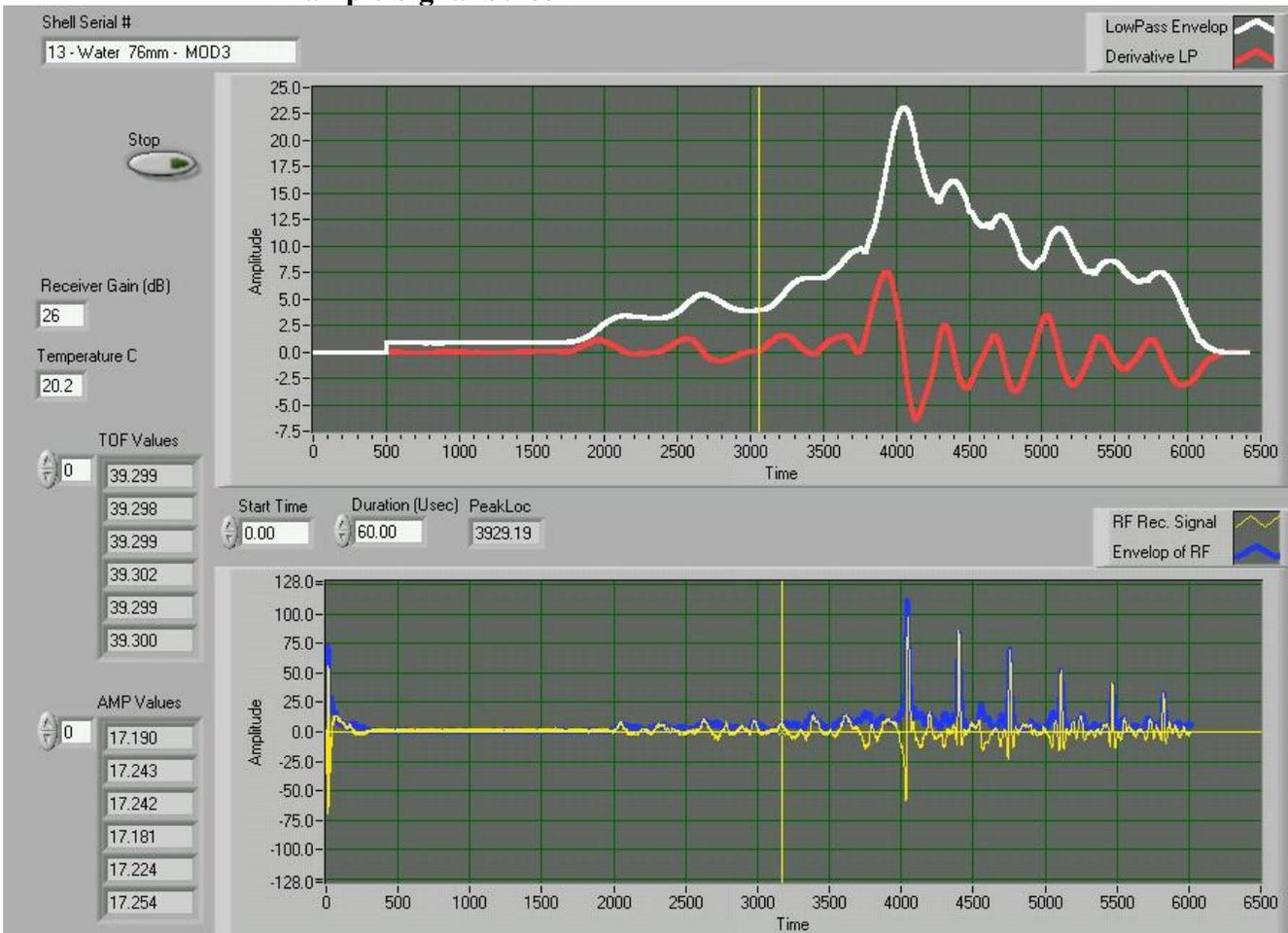
Size	Body	Filler	Condition	WallThk.	DODIC	NSN
76mm	-	Water	Good	1.02		131501 0783740

### Measurements

MV	MA	VV	VA	SF	OF	CO	SG	DA	LO	TE
.153	0.09	.148	0.15	5G	4.25		26	9/14/04	CRN	20
.153	0.41	.148	0.15	-	-		-	-	-	-
.154	0.67	.148	0.15							
.153	0.29	.148	0.15							
.153	0.20	.148	0.15							
.153	0.38	.148	0.15							



### Example Signal Screen



#### MEASUREMENTS CODES:

MV – Measured Velocity (cm/usec)  
 VA – Validated Attenuation (Lab - dB/cm)  
 CO – Configuration (sensor caps, etc.)  
 DA – Date

MA – Measured Attenuation (dB/cm)  
 SF - Sensor Frequency (MHz)  
 SG – Sensor Gain (dB rel.)  
 TE – Temperature (°C)

VV – Validated Velocity (Lab - cm/usec)  
 OF – Location Offset (sensor from top – cm)  
 WallThk. – Case Wall Thickness (cm)  
 LO – Test Location

# Ordnance Item Data # 15

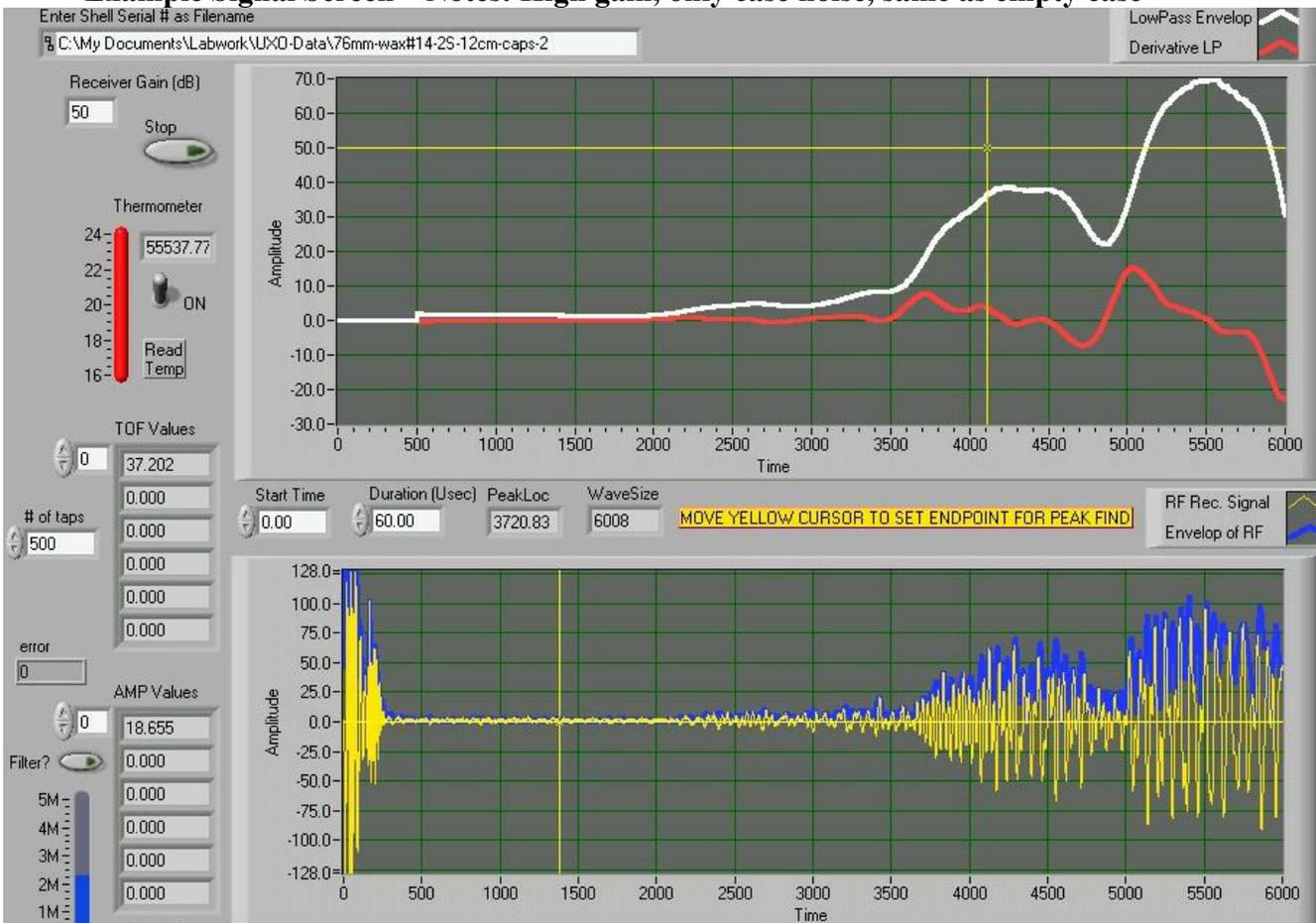
Size	Body	Filler	Condition	WallThk.	DODIC	NSN
76mm	-	Wax	Good	1.02		131501 0783740

## Measurements

MV	MA	VV	VA	SF	OF	CO	SG	DA	LO	TE
-	-	.206	4.39	2S	4.25	caps	50	7/06/05	DRI	20
				-	-	-	-	-	-	-



## Example Signal Screen – Notes: High gain, only case noise, same as empty case



### MEASUREMENTS CODES:

MV – Measured Velocity (cm/usec)  
 VA – Validated Attenuation (Lab - dB/cm)  
 CO – Configuration (sensor caps, etc.)  
 DA – Date

MA – Measured Attenuation (dB/cm)  
 SF - Sensor Frequency (MHz)  
 SG – Sensor Gain (dB rel.)  
 TE – Temperature (°C)

VV – Validated Velocity (Lab - cm/usec)  
 OF – Location Offset (sensor from top – cm)  
 WallThk. – Case Wall Thickness (cm)  
 LO – Test Location

## Ordnance Data for Item # 16

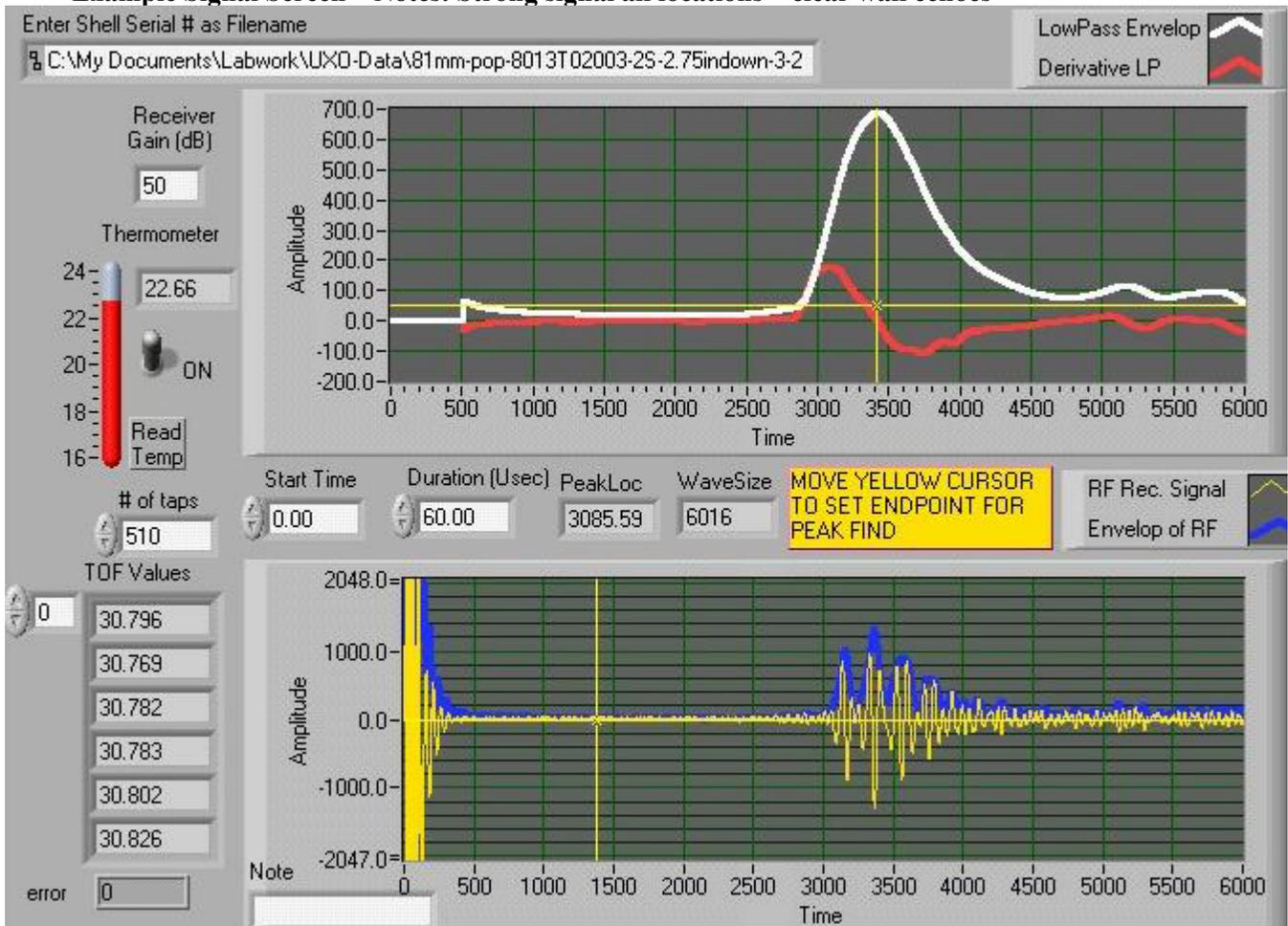
Size	Body	Filler	Condition	WallThk.	DODIC	NSN
81mm	374	Plaster Orig.Fill	Good	0.65		8013T02003

### Measurements

MV	MA	VV	VA	SF	OF	CO	SG	DA	LO	TE
.237	-	.243	2.22	2S	7.0	2.75	50	9/8/05	NAV	23
.225		.243	2.22	-	-	-	-	-	-	-
.235		.243	2.22							
.235		.243	2.22							
.235		.243	2.22							
.250		.243	2.22							



### Example Signal Screen – Notes: Strong signal all locations – clear wall echoes



#### MEASUREMENTS CODES:

MV – Measured Velocity (cm/usec)  
 VA – Validated Attenuation (Lab - dB/cm)  
 CO – Configuration (sensor caps, etc.)  
 DA – Date

MA – Measured Attenuation (dB/cm)  
 SF - Sensor Frequency (MHz)  
 SG – Sensor Gain (dB rel.)  
 TE – Temperature (°C)

VV – Validated Velocity (Lab - cm/usec)  
 OF – Location Offset (sensor from top – cm)  
 WallThk. – Case Wall Thickness (cm)  
 LO – Test Location



## Ordnance Data for Item # 18

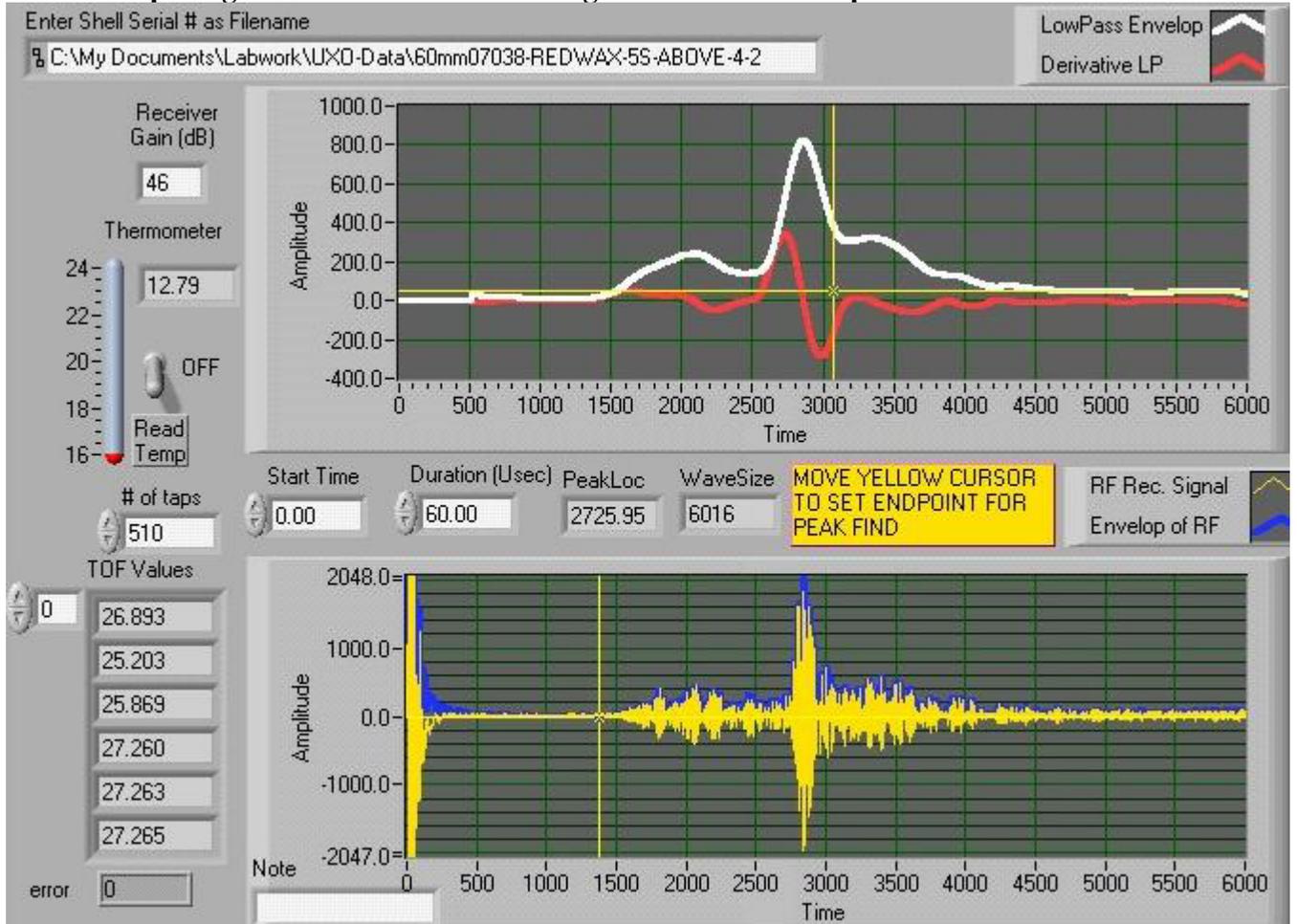
Size	Body	Filler	Condition	WallThk.	DODIC	NSN
60mm	M49A5	Red Wax	Orig. Fill Corroded	0.55		EOD-07038

### Measurements

MV	MA	VV	VA	SF	OF	CO	SG	DA	LO	TE
.192	-	.206	4.39	5S	4		46	9/08/05	NAV	20
.192		.206								
.192		.206								
.193		.206								
.192		.206								



### Example Signal Screen – Notes: Wax signal at 28usec – compare water noise item 19



**MEASUREMENTS CODES:**

MV – Measured Velocity (cm/usec)	MA – Measured Attenuation (dB/cm)	VV – Validated Velocity (Lab - cm/usec)
VA – Validated Attenuation (Lab - dB/cm)	SF - Sensor Frequency (MHz)	OF – Location Offset (sensor from top – cm)
CO – Configuration (sensor caps, etc.)	SG – Sensor Gain (dB rel.)	WallThk. – Case Wall Thickness (cm)
DA – Date	TE – Temperature (°C)	LO – Test Location



## Ordnance Data for Item # 20

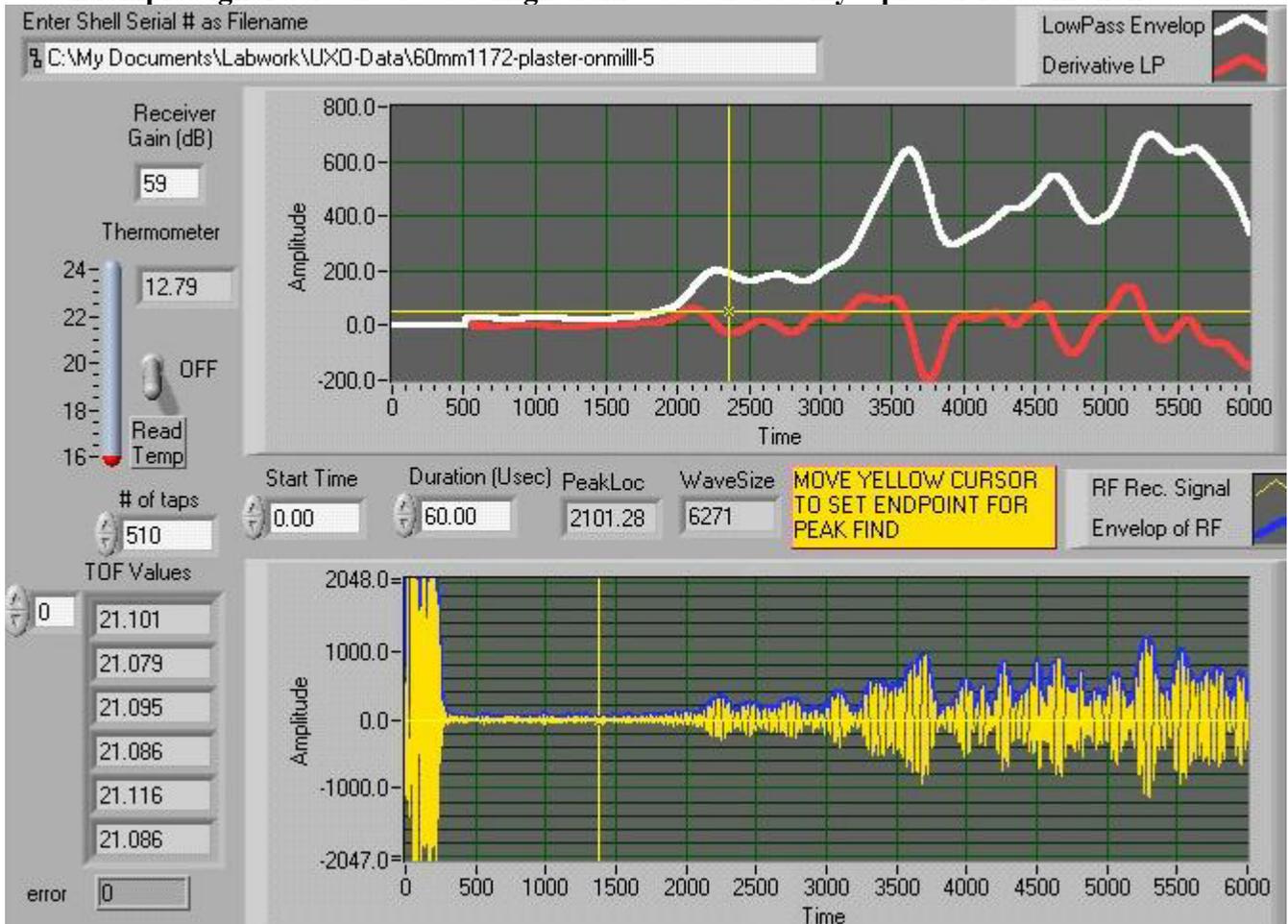
Size	Body	Filler	Condition	WallThk.	DODIC	NSN
60mm	M49A4	Plaster-Not Orig. Fill	Plaster loose	0.62		EOD- 1172

### Measurements

MV	MA	VV	VA	SF	OF	CO	SG	DA	LO	TE
		.243	2.22	2S	3.5		59	8/9/05	DRI	20
				-	-		-	-	-	-



### Example Signal Screen – Notes: High Gain – case noise only – plaster loose in shell !



#### MEASUREMENTS CODES:

MV – Measured Velocity (cm/usec)  
 VA – Validated Attenuation (Lab - dB/cm)  
 CO – Configuration (sensor caps, etc.)  
 DA – Date

MA – Measured Attenuation (dB/cm)  
 SF - Sensor Frequency (MHz)  
 SG – Sensor Gain (dB rel.)  
 TE – Temperature (°C)

VV – Validated Velocity (Lab - cm/usec)  
 OF – Location Offset (sensor from top – cm)  
 WallThk. – Case Wall Thickness (cm)  
 LO – Test Location























## 7. References

- 1 Hetet, A., Et. Al., "Buried Mines Detection And Classification With Low Frequency Sonar," Society For Counter-Ordnance Technology, 5th International Symposium, U.S. Naval Postgrad. School, Monterey, CA, April 22-25, 2002
- 2 "HYTEC assists Los Alamos' Applied Weapons Engineering Group," Los Alamos National Lab, News and Public affairs, (<http://www.lanl.gov/orgs/pa/newsbulletin/2002/11/25/text07.shtml>), 2002
- 3 Womble, Phillip C. , "PELAN-A Transportable Neutron-Based UXO Identification Probe- Phase 1 Demonstration Report Summary," Environmental Security Technology certification program (ESTCP) 200106, Western Kentucky University, February 13, 2004
- 4 LoPresti, V., "Sound Solutions for Safety, Health, and Security," Los Alamos Research Quarterly, Fall 2002 ([http://www.lanl.gov/quarterly/pdfs/sound\\_fall\\_02.pdf](http://www.lanl.gov/quarterly/pdfs/sound_fall_02.pdf))
- 5 Shina, D. et. al., "Swept frequency acoustic interferometry technique for chemical weapons verification and monitoring," Third International Conference On-Site Analysis, Houston, TX, January 22-25, 1995
- 6 Hall, T. N. and Holden, J. R., "Navy Explosives Handbook," NSWC report MP 88-116, White Oak Lab., 1988.
- 7 Cobb, W.N., "Acoustic Contamination Monitor", D.O.E., Office of Industrial Technologies, Innovative Concepts Conference, Denver, CO, April 20, 1995
- 8 Cobb, W.N., "Ultrasonic Measurement of Fluid Composition," 25th Annual Review of Progress in Qualitative Nondestructive Evaluation, July 19-24, Snowbird, Utah, 1998 (<http://www.du.edu/~dri/ultrasonics/files/QNDE-compostion.pdf>)
- 9 VNR Encyclopedia of Mathematics, Gellert et. al., Van Nostrand Reinhold, pp 607-614, 1975
- 10 Roth D.J. et. al.. Quantitative Mapping of Pore Fraction Variations in Silicon Nitride using an Ultrasonic Contact Scan Method. NASA TM-3377 1995 and Research in Nondestructive Evaluation 1995
- 11 Applied Physics Institute, Western Kentucky University, "Unexploded Ordnance (UXO) Environmental Cleanup Systems," at <http://www.wku.edu/API/research/en/uxo.html>
- 12 Onda Corporation, Acoustic Property Tables ([http://www.ondacorp.com/tecref\\_acoustictable.html](http://www.ondacorp.com/tecref_acoustictable.html))
- 13 Cobb, W. N., "Acoustic Identification of Filler Materials in Unexploded Ordnance," Annual report on SERDP Project UXO-1382 , December 15, 2005
- 14 Cobb, W. N., "Acoustic Identification of Filler Materials in Unexploded Ordnance," SERDP Conference: 2005 Partners in Environmental Technology Technical Symposium & Workshop, November 29-December 1, Washington, DC