

# Ultrasonic Pipe Wall Thickness Measurement of Coated Buried Pipe

Phase II Report





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Phase II Report

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# PRODUCT DESCRIPTION

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This report describes the fundamental methodology of acquiring ultrasonic thickness measurements on coated piping. It provides an overview of ultrasonic techniques and presents results of testing performed to obtain accuracy and compatibility information by assessing pipe wall thickness through tape wrap, coal tar epoxy, coal tar enamel, and structural coating—coatings typical of those found in the nuclear power plant fleet.

## Background

During the Electric Power Research Institute's (EPRI's) Buried Pipe Integrity Group (BPIG) meetings, there was significant discussion about whether the thickness of a pipe wall could be accurately measured using ultrasonic testing (UT) without the removal of what appeared to be firmly adhered coating on the pipe outside diameter (OD). The alternative approach would be to remove all coatings from the OD surface in order to accurately measure remaining pipe wall thickness. However, the unnecessary removal of well-adhered coatings in the case where a valid ultrasonic technique can be deployed is costly and is not optimum for long-term pipe protection.

## Objectives

The goal of the project documented in this report was to create a comprehensive document on the use of ultrasonic techniques for measuring remaining wall thickness on metallic coated piping from the OD surface, including fundamental background information on ultrasonic methodology as well as an evaluation of the accuracy of typical commercially available UT equipment.

## Approach

The report provides a tutorial on the various ultrasonic techniques used for coated pipe thickness measurements. It also documents testing that was performed, involving the accurate machining of carbon steel test plates that contained thickness variations and surface contours. The plates were coated with three different protective coating types typical of those used in buried applications and representing the expected range of wall thicknesses. Technique compatibility assessments including wall thickness measurement accuracy tests were performed using numerous ultrasonic hardware combinations and measurement techniques. Test results were compared to the known thickness values of the test blocks, providing the basis for a quantitative analysis of the similarities and differences between the described techniques. Additionally, tests were performed on a structural coating to assess through-coating inspection capability.

## Results

This report demonstrates that highly accurate wall thickness measurements are possible on all of the tested coatings using specific hardware and technique combinations. Limitations were discovered, especially for coal tar enamel and structural coatings related to reflector size, thickness resolution, and temperature-related effects.

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### **Applications, Value, and Use**

Readers who are not proficient in ultrasonic testing can use the report to gain an understanding of the methodology used for thickness measurement of coated piping. The testing results provide inspectors with benchmark hardware and testing parameters that may be used for specific coating applications.

### **Keywords**

Buried pipe

Coatings

Electromagnetic acoustic transducer

NDE

Ultrasonic testing

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# 1

## INTRODUCTION

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Underground piping is an integral component of a nuclear power plant's comprehensive piping system. Underground piping that is in direct contact with soil is defined as *buried piping* by the United States Nuclear Regulatory Commission (NRC). Both the inner and outer surfaces of this type of piping are exposed to a potentially corrosive environment that can lead to failure of the containment boundary. Numerous buried piping circuits in a power plant exist, with functions ranging from plant cooling to waste water management. These pipes carry a variety of substances, from potable water to diesel fuel. In general, approximately 10% of a nuclear facility's buried piping contains either a radioactive isotope (typically tritium) or environmentally hazardous material [1]. The excavation of buried piping over the last several years has resulted in the discovery of leaks in the piping [2]. Although these leaks have not resulted in plant safety issues, they have raised environmental concerns.

Buried piping used during the construction of existing nuclear power plants was typically fabricated from low-carbon steel materials and protected on the OD (outer diameter) surface using one of several different coating systems. These OD coating systems tended to be very effective in preventing corrosion when intact. However, small penetrations (holidays) in the coating barrier can lead to the introduction of moisture, causing corrosion on the outer surface of the pipe. In contrast, the pipe inner surface is commonly directly exposed to the fluids contained within, since ID (inner diameter) coating (lining) is often not used. ID surface corrosion varies significantly depending on the fluid contained, the flow rate of the fluid, and the condition of the ID coating if applicable. Although other failure modes such as cracking or connection leaks exist, wall thinning due to ID corrosion is the primary focus of this report.

Currently, the most practiced method for evaluating the integrity of buried pipe involves excavating a short section of the pipe, thus providing access to the OD surface. The pipe wall is then analyzed using a nondestructive testing technique, and the most commonly used method is ultrasonic testing. Typically, ultrasonic wall measurements are performed on piping without the presence of an OD coating material. In the case of buried piping, the coating is commonly removed to expose the outer surface of the pipe, assuring conditions that are conducive for accurate wall thickness measurements. However, the removal of the OD coating material may not be preferred, since it could necessitate the application of a new OD coating "patch" if the pipe is found to be in good condition. When possible, ultrasonic measurements to determine remaining pipe wall thickness should be performed without compromising the integrity of the original OD coating. However, the capability to ultrasonically measure remaining wall thickness of a coated pipe is not well documented. The compatibility, limitations, and related accuracies of applicable ultrasonic techniques for use on different OD coating types are not well understood. Utilities need to clearly understand their options when contemplating the use of ultrasonic techniques for assessing the condition of an aging coated component. The consequences of applying an inappropriate technique can include the need to recommission a defective component or replace a component that has significant remaining life.

This report addresses this topic by investigating and describing ultrasonic techniques that may be used to accurately measure pipe wall thickness through OD coatings when defined preconditions exist. Examples of ultrasonic signals obtained through coatings are provided through the use of fabricated specimens with known wall thickness values. Obstacles to obtaining good results are addressed for each technique, and examples are presented where possible. This report also provides fundamental information on performing thickness measurements using ultrasonic testing. It should be noted that the intended audience for this report includes the NDE novice as well as the established ultrasonic practitioner.

## Measurement Units

The following table lists customary measurement units used in this report and corresponding International System (SI) units.

**Table 1-1**  
**Measurement units**

| <b>Customary Unit</b> | <b>SI Unit</b> | <b>Abbreviations and Conversion Factor</b>    |
|-----------------------|----------------|---|
| Inch                  | Millimeter     | 1 in. = 25.4 mm                               |
| Mil                   | Millimeter     | 1 mil = 0.0254 mm                             |
| Degree Fahrenheit     | Degree Celsius | $^{\circ}\text{C} = 5/9(^{\circ}\text{F}-32)$ |

# 2

## OUTSIDE DIAMETER COATINGS FOR BURIED PIPE

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Buried Pipe Integrity Group (BPIG) surveys and other sources were used to identify the most commonly used coatings applied to the outside diameter (OD) of buried pipes typical of those found at nuclear power plants. After a review of the data, three coating types were selected for investigation, each applied in a thinner and thicker configuration according to application specifications. These coatings were expected to cover a full range of difficulty, from thin hard coating (minimal signal attenuation), representing a best-case scenario, to thick soft coatings (large signal attenuation), representing a worst-case scenario.

Fabrication of the EPRI test blocks for this project is covered in Section 3. They were all made from the same lot of steel for consistency in grain structure and manufactured within strict machining tolerances. Each test block was thoroughly measured for metal thickness at multiple locations prior to the application of any coatings.

This section covers the OD coatings that were actually used and provides a key to which test block received which coating. Additional test blocks were manufactured and not coated as a contingency for additional coatings as required.

- Coal Tar Enamel (TGF-3) in accordance with American Water Works Association (AWWA) C203 [3]; toward the thin side of the specification (130 mil) - **Test Block #1**
- Coal Tar Enamel (TGF-3) in accordance with AWWA C203; toward the thick side of the specification (189 mil) - **Test Block #2**
- Coal Tar Epoxy in accordance with AWWA C210 [4]; toward the thin side of the specification (16 mil) - **Test Block #3**
- Coal Tar Epoxy in accordance with AWWA C210; toward the thick side of the specification (20 mil) - **Test Block #7**
- Tape Wrap in accordance with AWWA C214 [5]; toward the thin side of the specification (50 mil) or 2 layers - **Test Block #5**
- Tape Wrap in accordance with AWWA C214; toward the thick side of the specification (80 mil) or 3 layers (coating on pipes 54 inches in diameter and larger must be 80 mil) - **Test Block #4**

### Coal Tar Enamel (TGF-3)

The application of the coal tar enamel was in accordance with AWWA C203, “Coal-Tar Protective Coatings and Linings for Steel Water Pipelines - Enamel and Tape - Hot-Applied.” The process started with the application of the appropriate Society for Protective Coatings (SSPC) blasting profile as was recommended by the coating supplier. This was followed by an initial coating of the test block with the coal tar enamel, followed by a first layer (20 mil) of

fiberglass applied side by side without overlap. After another layer of liquid coal tar enamel, a second layer (40 mil) of fiberglass was applied side by side without overlap. The seams of the second layer were staggered with the seams of the first layer. Another layer of enamel was then applied, which was covered by craft paper to prevent ultraviolet deterioration when exposed to the sun. The craft paper was removed prior to all ultrasonic testing. The thickness of properly applied TGF-3 varied from 0.120 inch to 0.200 inch, with thickness controlled by the amount of coal tar enamel used. Test Block #1 (130 mils actual) and Test Block #2 (189 mils actual) represented the thin and thick coating samples of TGF-3. Figure 2-1 is a photograph of one of the coal tar enamel (TGF-3) coated test blocks. Actual average coating thicknesses are provided in Table 2-1.

Coal tar enamel, also known as TGF-3, was likely the most commonly used coating type used during the construction of the nuclear power plant fleet. Earlier versions of TGF-3, expected to be found in the older plants of the U.S. fleet, are most likely slightly different from the above description. They had the same inner layer of fiberglass, but the second layer was an asbestos felt, hence the name TGF, which stood for tar-glass-felt. The TGF-3 coating used on the EPRI test blocks did not contain any asbestos; in fact, strictly speaking it could be said that they were coated by TGG-3 as opposed to TGF-3.



**Figure 2-1**  
**Picture of coal tar enamel (TGF-3) test block**

## **Coal Tar Epoxy**

The application of coal tar epoxy was in accordance with AWWA C210, “Liquid-Epoxy Coating Systems for the Interior and Exterior of Steel Water Pipelines.” The process started with the application of the appropriate SSPC blasting profile as recommended by the coating supplier. This was followed by the application of a two-part coal tar epoxy that was first mixed and then sprayed directly onto the plate surface. The thickness of a properly applied coating should be between 0.016 inch to 0.025 inch. Two test blocks were coated with the coal tar epoxy, with the

thinnest being Test Block #3 (15 mils actual) with a targeted thickness of 0.016 inch, and Test Block #7 (20 mils actual) with targeted thickness of 0.020 inch. Figure 2-2 is a photograph of one of the coal tar epoxy coated test blocks. Actual average coating thicknesses are provided in Table 2-1.

Coal tar epoxy started to replace coal tar enamel late in the construction of the U.S. fleet, primarily due to increasing concerns about injuries incurred during application of the coal tar enamel.



**Figure 2-2**  
**Picture of coal tar epoxy test block**

## **Tape Wrap**

The application of the tape wrap coating was in accordance with American Water Works Association (AWWA) C214, "Tape Coatings for Steel Water Pipe." The process started with the application of the appropriate SSPC blasting profile as recommended by the coating supplier. This was followed by the application of a primer to the surface of the test blocks. A 0.020-inch layer of tape was then applied, followed by a second 0.030-inch layer. This process produced the thinnest tape wrap configuration, with a total target thickness of approximately 0.050 inch, identified as Test Block #5 (49 mils actual). Tape wrap coating was also fabricated in a thicker configuration where an additional 0.030-inch layer was added. This test block was identified as Test Block #4 (79 mils actual). Figure 2-3 is a photograph of one of the tape-coated test blocks. The as-built coating thicknesses were measured at 15 locations on each specimen, with an average calculated. Table 2-1 summarizes the average thickness values for all test blocks.

Although 50% tape overlapped is typical of buried piping, no overlap was used on the test blocks so that a consistent tape layer thickness would exist over all reflectors.



**Figure 2-3**  
Picture of tape-coated test block

**Table 2-1**  
Average coating thickness for the six test blocks (based on 15 measurements)

| Plate ID | Description of Coating | Average Coating Thickness (0.001 inch) |
|----------|------------------------|--|
| 1        | TGF-3 Low Mils         | 130.0                                  |
| 2        | TGF-3 High Mils        | 189.3                                  |
| 3        | Coal Tar Epoxy 16 Mils | 14.9                                   |
| 4        | Tape 80 Mils           | 78.9                                   |
| 5        | Tape 50 Mils           | 48.9                                   |
| 7        | Coal Tar Epoxy 20 Mils | 20.0                                   |

### Other Buried Pipe OD Coatings

Other buried pipe OD coatings (in addition to TGF-3) that contained coal tar enamel were historically used. Although not tested within this project, they are expected to affect the ultrasonic signal similarly as seen on the test blocks with TGF-3 (depending on thickness). The coal tar enamel component is expected to remain somewhat soft (and thus have significant attenuation) for its entire lifespan.

# 3

## LABORATORY TESTING

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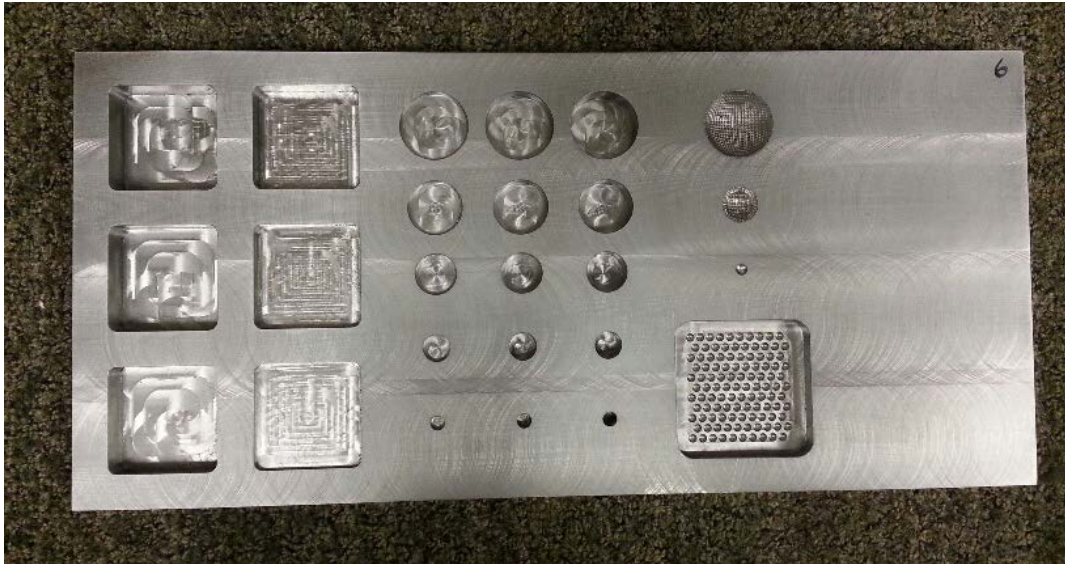
### Objective

The objective of this section is to provide the reader with information related to the capabilities of ultrasonic thickness measurements based on results obtained from laboratory testing. The information presented in this section is meant to complement the information presented in Appendix A through the inclusion of test data obtained using commercially available ultrasonic instrumentation and realistic test blocks. All testing was performed using flat coated specimens containing various wall thicknesses and machined reflectors of various shapes and sizes. The test blocks were fabricated within close tolerances so that measured dimensions could be compared to actual wall thicknesses using various coatings and reflector shapes. The intent was to obtain typical accuracies and compatibility when measuring wall thickness using conventional piezoelectric ultrasonic techniques through different coating systems. Numerous off-the-shelf piezoelectric transducer types and frequencies were selected using both the single-echo method (SEM) and multiple-echo method (MEM) techniques, with testing performed at nominal coating temperatures of 52°F, 72°F, and 92°F to simulate field conditions.

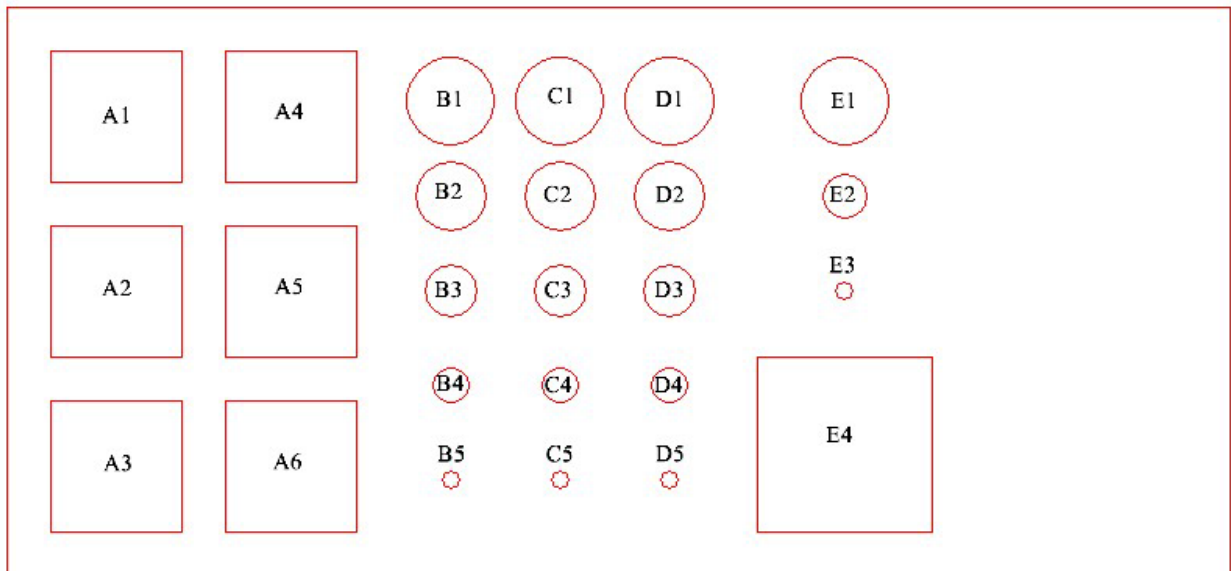
### Test Blocks

Test blocks were designed and fabricated specifically for use in evaluating the performance of ultrasonic methods when attempting to measure remaining wall thickness of outside diameter (OD) coated pipe. The test blocks were 5/8-inch (0.625-inch or 15.9-mm)-thick flat plates machined from a low-carbon steel similar to that used in pipe fabrication. Each test block had numerous reflectors categorized as being either flat-bottom or shaped-bottom reflectors. The flat-bottom reflectors were used to simulate “remaining wall” thicknesses ranging from 1/16 inch (0.063 inch or 1.6 mm) to 1/2 inch (0.500 inch or 12.7 mm) where both the entry surface (that is, the pipe outer surface) and back wall surface (that is, the pipe inner surface) were parallel. Machined flat-bottom holes of various areas (diameters) and depths were introduced so that reflector size effects could also be evaluated. The shaped-bottom reflectors were meant to simulate a corroded back wall surface using machined reflector designs that could be reproduced. Figure 3-1 is a photograph of the reflectors machined into each test block. Figure 3-2 is provided as the flaw map used for identifying all reflectors. Table 3-1 provides the design dimensions for each of the machined reflectors.

A total of six test blocks were used for this evaluation, each with a different coating type or thickness except for one uncoated specimen used for system calibration. The coating used included tape wrap, coal tar epoxy, and coal tar enamel. All test blocks were coated by a company that specializes in the industrial coating of buried piping as described in Section 2.



**Figure 3-1**  
Test block used for evaluating technique performance



**Figure 3-2**  
Sketch showing the layout of the machined reflectors in each block

**Table 3-1**  
**Test block reflector dimensional information**

| Flaw ID | Flaw Type                | Flaw Diameter in inches (mm) | Flaw Length in inches (mm) | Flaw Width in inches (mm) | As-Built Depth (inch) | As-Built Ligament (inch) | Ligament Percent Thru Wall |
|---------|--------------------------|------------------------------|----------------------------|---------------------------|-----------------------|--------------------------|----------------------------|
| A1      | Square Pocket            | NA                           | 1.5 (38.1)                 | 1.5 (38.1)                | 0.536                 | 0.064                    | 10%                        |
| A2      | Square Pocket            | NA                           | 1.5 (38.1)                 | 1.5 (38.1)                | 0.474                 | 0.126                    | 20%                        |
| A3      | Square Pocket            | NA                           | 1.5 (38.1)                 | 1.5 (38.1)                | 0.413                 | 0.187                    | 30%                        |
| A4      | Square Pocket            | NA                           | 1.5 (38.1)                 | 1.5 (38.1)                | 0.351                 | 0.249                    | 40%                        |
| A5      | Square Pocket            | NA                           | 1.5 (38.1)                 | 1.5 (38.1)                | 0.225                 | 0.375                    | 60%                        |
| A6      | Square Pocket            | NA                           | 1.5 (38.1)                 | 1.5 (38.1)                | 0.100                 | 0.5                      | 80%                        |
| B1      | Flat Bottom Hole         | 1(25.4)                      | N/A                        | N/A                       | 0.131                 | 0.469                    | 75%                        |
| B2      | Flat Bottom Hole         | 0.8(20.3)                    | N/A                        | N/A                       | 0.132                 | 0.468                    | 75%                        |
| B3      | Flat Bottom Hole         | 0.6(15.2)                    | N/A                        | N/A                       | 0.128                 | 0.472                    | 75%                        |
| B4      | Flat Bottom Hole         | 0.4(10.6)                    | N/A                        | N/A                       | 0.133                 | 0.467                    | 75%                        |
| B5      | Flat Bottom Hole         | 0.2(5.0)                     | N/A                        | N/A                       | 0.135                 | 0.465                    | 75%                        |
| C1      | Flat Bottom Hole         | 1(25.4)                      | N/A                        | N/A                       | 0.287                 | 0.313                    | 50%                        |
| C2      | Flat Bottom Hole         | 0.8(20.3)                    | N/A                        | N/A                       | 0.285                 | 0.315                    | 50%                        |
| C3      | Flat Bottom Hole         | 0.6(15.2)                    | N/A                        | N/A                       | 0.284                 | 0.316                    | 50%                        |
| C4      | Flat Bottom Hole         | 0.4(10.6)                    | N/A                        | N/A                       | 0.287                 | 0.313                    | 50%                        |
| C5      | Flat Bottom Hole         | 0.2(5.0)                     | N/A                        | N/A                       | 0.291                 | 0.309                    | 50%                        |
| D1      | Flat Bottom Hole         | 1(25.4)                      | N/A                        | N/A                       | 0.443                 | 0.157                    | 75%                        |
| D2      | Flat Bottom Hole         | 0.8(20.3)                    | N/A                        | N/A                       | 0.443                 | 0.157                    | 75%                        |
| D3      | Flat Bottom Hole         | 0.6(15.2)                    | N/A                        | N/A                       | 0.44                  | 0.16                     | 75%                        |
| D4      | Flat Bottom Hole         | 0.4(10.6)                    | N/A                        | N/A                       | 0.443                 | 0.157                    | 75%                        |
| D5      | Flat Bottom Hole         | 0.2(5.0)                     | N/A                        | N/A                       | 0.446                 | 0.154                    | 75%                        |
| E1      | Shaped Bottom Hole       | 1(25.4)                      | N/A                        | N/A                       | 0.302                 | 0.298                    | 50%                        |
| E2      | Shaped Bottom Hole       | 0.5(12.7)                    | N/A                        | N/A                       | 0.151                 | 0.449                    | 75%                        |
| E3      | Shaped Bottom Hole       | 0.2(5.0)                     | N/A                        | N/A                       | 0.039                 | 0.561                    | 90%                        |
| E4      | Simulated Corrosion Area | N/A                          | 2(50.8)                    | 2(50.8)                   | 0.336                 | 0.264                    | 50%                        |

## Ultrasonic Technique Description

Each flaw was subjected to a total of ten unique conventional ultrasonic techniques for determining remaining wall thickness. These techniques utilized three different instruments and nine different transducer configurations.

### **Test 1: Single-Echo Method—Thickness Gage Instrument/Dual-Element Transducer**

This test utilized an advanced ultrasonic thickness gage and a 5-MHz dual-element transducer as shown in Figure 3-3, designed specifically for obtaining thickness measurements on coated components. This test was based on a single back wall measurement technique like that shown in Figure A-12. Ultrasonic thickness gages utilize signal detection algorithms designed to provide highly accurate thickness measurements. The 38DL Plus has a “Thru-Coat” feature that permits the simultaneous measurement of both the remaining wall thickness and the thickness of the coating. Calibration of this instrument required an uncoated sample of machined steel containing

two known thicknesses spanning the range of expected measurements. Also required was a plastic shim of known thickness used to calibrate the instrument for coating sound velocity. It is important to note that thickness gages utilize software that attempts to correctly identify interface reflections, with the primary output being thickness values. The thickness gage did have a small A-scan display that identified the signal used by the algorithm when calculating thickness to assure the operator that proper signals had been selected. In special cases where the algorithm was unable to identify a signal that met its criteria, no thickness value was displayed for the coating layer, which was an indication to the operator that the displayed wall thickness was invalid. This instrument was only used in a mode where a valid thickness was displayed with no signal manipulation.

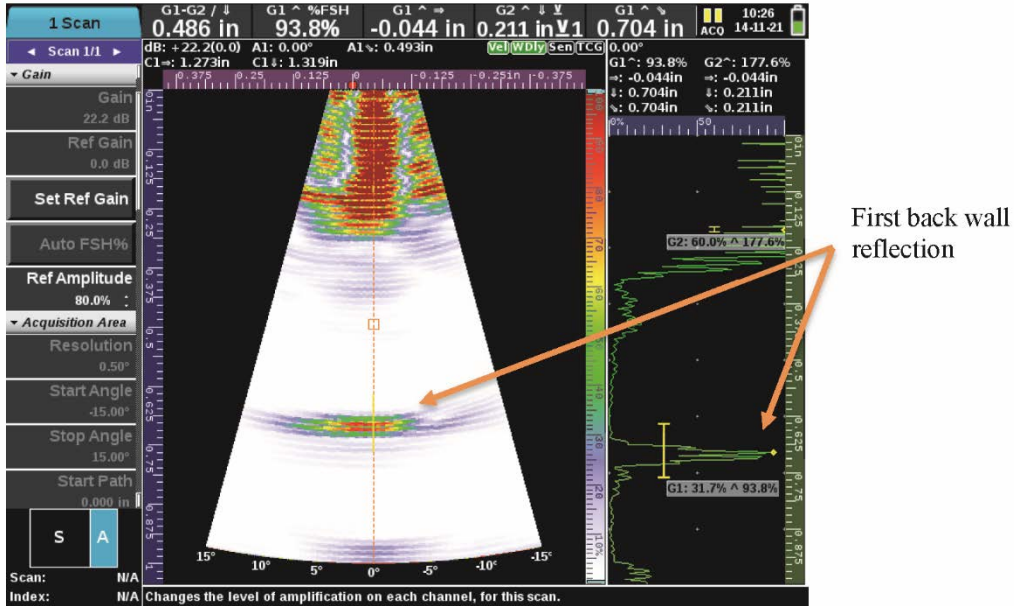


**Figure 3-3**  
**Advanced thickness gage and dual-element probe**

### ***Test 2: Single-Echo Method—Phased Array Instrument/Phased Array Probe with Delay Line***

This test utilized a standard portable ultrasonic phased array instrument and a 5-MHz phased array transducer attached to a 1-inch delay line as shown in Figure 3-4. The phased array probe was composed of one linear array with 10 elements with a 0.6-mm pitch. A sectorial scan was used whereby the sound wave was electronically steered from  $-15^{\circ}$  to  $+15^{\circ}$ . Calibration was performed using the  $0^{\circ}$  beam angle. This test was based on a measurement technique using a pulse-echo technique with delay line as illustrated in Figure A-11. Calibration was performed on an uncoated calibration block of known thickness to determine the material velocity of the carbon steel. Thickness measurements were performed using the two A-scan gates provided on the instrument A-scan display for the  $0^{\circ}$  beam angle. The first gate was adjusted once the probe was coupled to the coating so that its position corresponded to the signal peak of the coating/steel interface reflection that arrived in time immediately following the first delay line reflection (Signal R1 in Figure A-11). This gate was adjusted at low gain since this interface signal





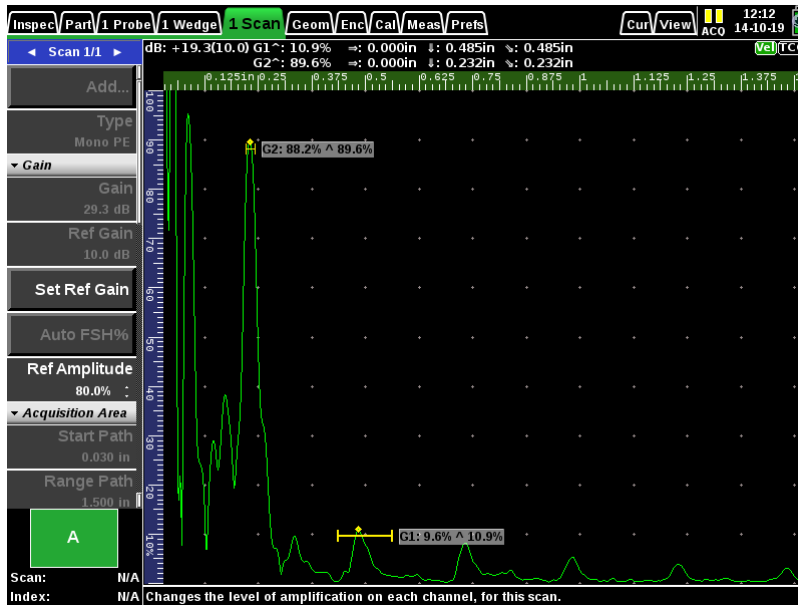
**Figure 3-6**  
 Gate set on back wall signal at higher gain values. Note that the coating-to-metal interface signal is saturated. Image was collected on 80-mil tape wrap at 1/2-inch metal thickness.

**Test 3: Single-Echo Method—Flaw Detector Instrument/Single-Element Transducer with Delay Line**

This test utilized a digital ultrasonic flaw detector and a 5-MHz, 1/4-inch-diameter, single-element transducer attached to a 1/2-inch delay line as shown in Figure 3-7. This test was based on a single back wall measurement technique like that shown in Figure A-11. Calibration was performed on an uncoated calibration block of known thickness to determine material velocity. During wall measurements, thickness was measured using the two A-scan gates. The first gate was minimized in width and set at lower gain to detect the peak of the coating-to-metal interface signal (Signal R1 in Figure A-11), with the second gate adjusted to detect the peak of the back wall signal as shown in Figure 3-8. The instrument was adjusted to display the difference in thickness measured between the first and second gate peaks.



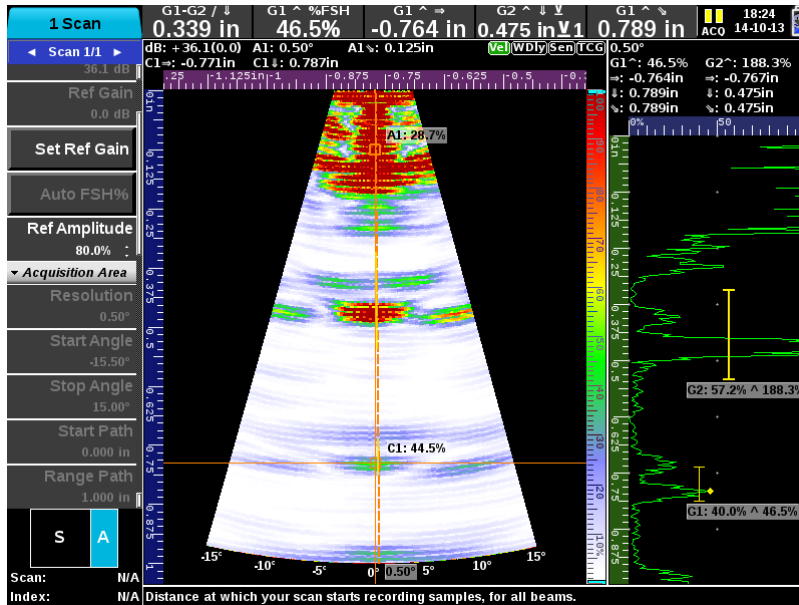
**Figure 3-7**  
 5-Mhz, 1/4-inch-diameter contact transducer shown with delay line attached



**Figure 3-8**  
**A-scan display showing gates positioned at coating-to-metal interface signal (G2) and first back wall reflection (G1)**

#### ***Test 4: Multiple-Echo Method—Phased Array Instrument/Phased Array Probe with Delay Line***

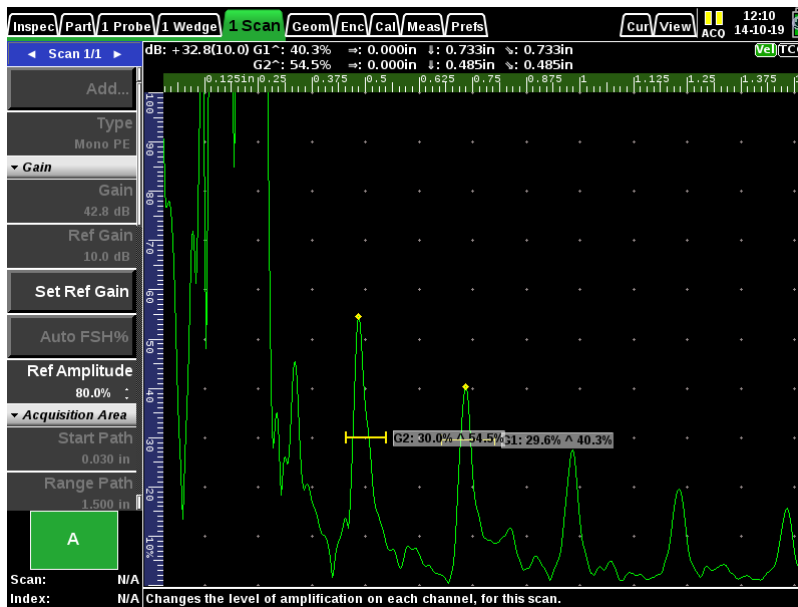
This test utilized a portable ultrasonic phased array instrument and a 5-MHz phased array transducer attached to a 1-inch delay line as shown in Figure 3-4. The phased array probe was composed of one linear array with 10 elements with a 0.6-mm pitch. A sectorial scan was used whereby the sound wave was electronically steered from  $-15^{\circ}$  to  $+15^{\circ}$  as shown in Figure 3-9. Calibration was performed using the  $0^{\circ}$  beam angle on a block of known thickness. This test was based on a measurement technique requiring the reception of two back wall multiple reflections as shown in Figure A-14. Calibration was performed on an uncoated calibration block of known thickness to determine material velocity. Material thickness measurements were taken on coated specimens only where two or more back wall reflections were present. In those regions, one A-scan gate was placed to detect the first back wall reflection, and a second gate was placed to detect the second back wall signal as shown in Figure 3-9. The instrument was adjusted to display the difference in thickness measured between the first and second gate peaks, which provided the actual wall thickness.



**Figure 3-9**  
**Phased sectorial scan showing first and second back wall multiple reflections with measurement gates over each reflection**

***Test 5: Multiple-Echo Method—Flaw Detector Instrument/Contact Transducer***

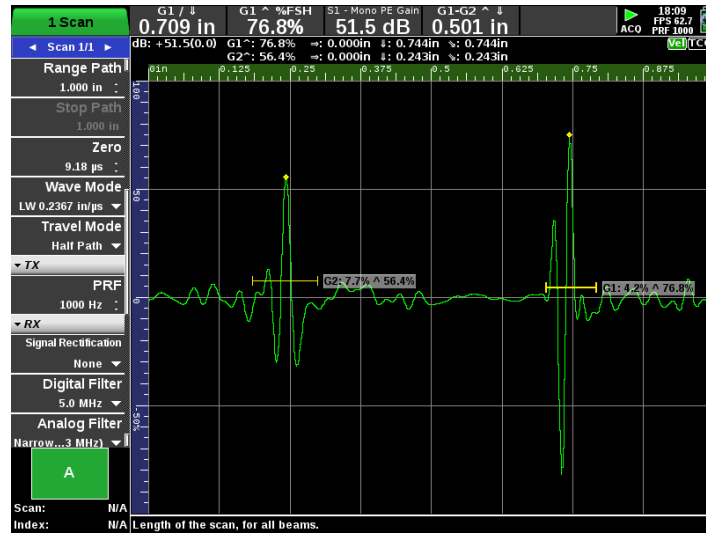
This test utilized a digital ultrasonic flaw detector and a 5-MHz, 1/4-inch-diameter, single-element transducer used without a delay line. Calibration was performed using a steel block of known thickness. This test was based on a measurement technique requiring the reception of two back wall multiple reflections as illustrated in Figure A-13. Calibration was performed on an uncoated calibration block of known thickness to determine material velocity. Material thickness measurements were taken on coated specimens only where two or more back wall reflections were present. In those regions one A-scan gate was placed over the first back wall reflection and a second gate over the second back wall signal as shown in Figure 3-10. The instrument was adjusted to display the difference in thickness measured between the first and second gate peaks, which provided the actual wall thickness.



**Figure 3-10**  
A-scan display showing two back wall reflections used for measuring wall thickness

### ***Test 6: Single-Echo Method—Flaw Detector Instrument/Dual-Element Transducer***

This test utilized an ultrasonic flaw detector and a 5-MHz dual-element transducer as shown in Figure 3-3, designed specifically for obtaining thickness measurements on coated components. This test was based on a single back wall measurement technique, but unlike the measurements collected in Test 1, all data was collected using an A-scan display provided by a flaw detector. Calibration of this instrument required an uncoated sample or step calibration block spanning the range of expected thickness measurements. This technique required the operator to correctly identify the coating/block interface signal and the first back wall reflection as shown in Figures 3-11 and A-12. Once identified, electronic gates were positioned over the two signals and a wall thickness displayed. This test was meant to evaluate the capability of using a dual-element thickness probe independently of using a thickness gage that relied on signal detection algorithms like Test 1. Test 6 demonstrated what can be achieved when a trained operator is used in place of an automated algorithm, which can be significant in cases of low-amplitude signals.



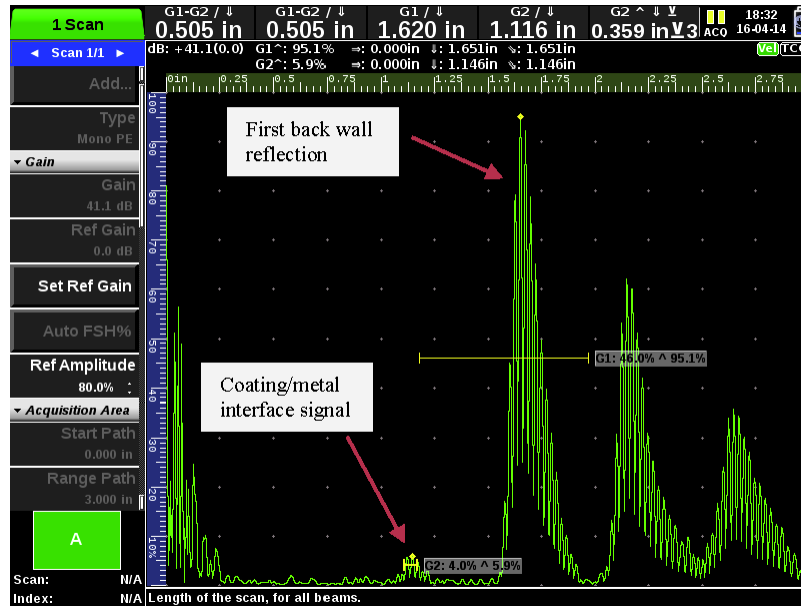
**Figure 3-11**  
Coating/steel interface signal and first back wall reflection observed using dual-element transducer operated with flaw detector

**Test 7: Single-Echo Method—Flaw Detector Instrument/Dual-Element Transducer**

This test utilized a digital ultrasonic flaw detector and a 2.25-MHz, ½-inch-diameter, single-element transducer as shown in Figure 3-12. This test was based on a single back wall measurement technique like that shown in Figure A-12. Calibration was performed on an uncoated calibration block of known thickness to determine material velocity. During wall measurements, thickness was performed using the two A-scan gates. The first gate was minimized in width and set at lower gain to detect the peak of the coating-to-metal interface signal, with the second gate adjusted to detect the peak of the first back wall signal as shown in Figure 3-13. The instrument was adjusted to display the difference in thickness measured between the first and second gate peaks. This transducer was similar in construction to that described for Test 1 and Test 6 except for operating at a lower frequency and having larger elements. The dual-element construction eliminated “dead zones” produced by ringing of the piezoelectric crystal observed on single-crystal transducers. The lower frequency and larger elements increase the penetration capability of the transducer while restricting resolution capability. In general, larger-element transducers have more difficulty in detecting smaller reflectors, and lower-frequency probes lose the ability to resolve two reflectors that are closely spaced (that is, thin layers).



**Figure 3-12**  
2.25-MHz, ½-inch-diameter dual-element contact transducer



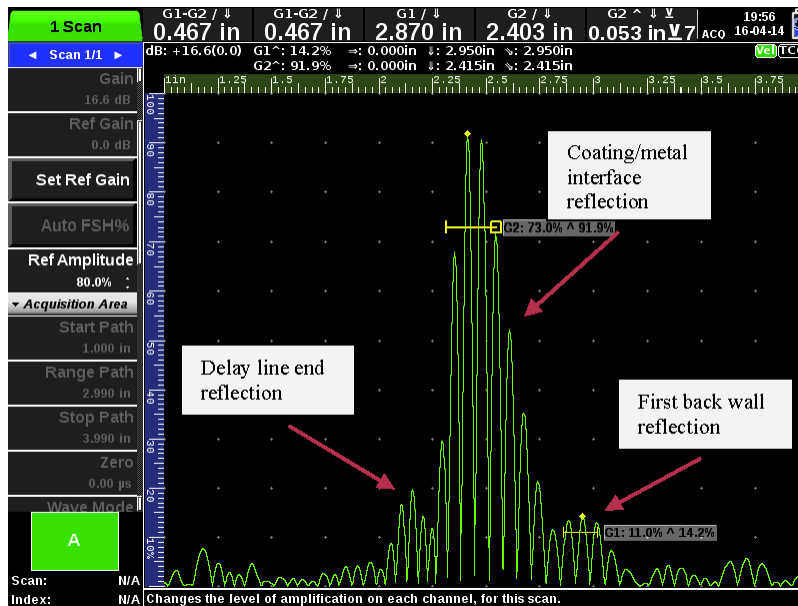
**Figure 3-13**  
 Typical A-scan presentation on a coated specimen using the 2.25-MHz, ½-inch-diameter dual-element transducer

### ***Test 8: Single-Echo Method—Flaw Detector Instrument/Single-Element Transducer with Delay Line***

This test utilized a digital ultrasonic flaw detector and a 1.0-MHz, ½-inch-diameter, single-element transducer attached to a 1-inch delay line as shown in Figure 3-14. This test was based on a single back wall measurement technique like that shown in Figure A-11. Calibration was performed on an uncoated calibration block of known thickness to determine material velocity. During wall measurements, thickness was performed using the two A-scan gates. The first gate was minimized in width and set at lower gain (when required) to detect the peak of the coating-to-metal interface signal (Signal R1 in Figure A-11), which appeared following the delay line end reflections. A second gate was adjusted to detect the peak of the first back wall signal, as shown in Figure 3-15. The instrument was adjusted to display the difference in thickness measured between the first and second gate peaks. This transducer was similar to that used in Test 3 but had a much lower frequency as well as a larger-diameter element. The lower frequency and larger elements increase the penetration capability of the transducer while restricting resolution capability. In general, larger-element transducers have more difficulty in detecting smaller reflectors, and lower-frequency probes lose the ability to resolve two reflectors that are closely spaced (that is, thin layers).



**Figure 3-14**  
1.0-MHz, 1/2-inch-diameter single-element contact transducer with 1-inch delay line



**Figure 3-15**  
Typical A-scan presentation on a coated specimen using the 1.0-MHz, 1/2-inch-diameter dual-element transducer with delay line

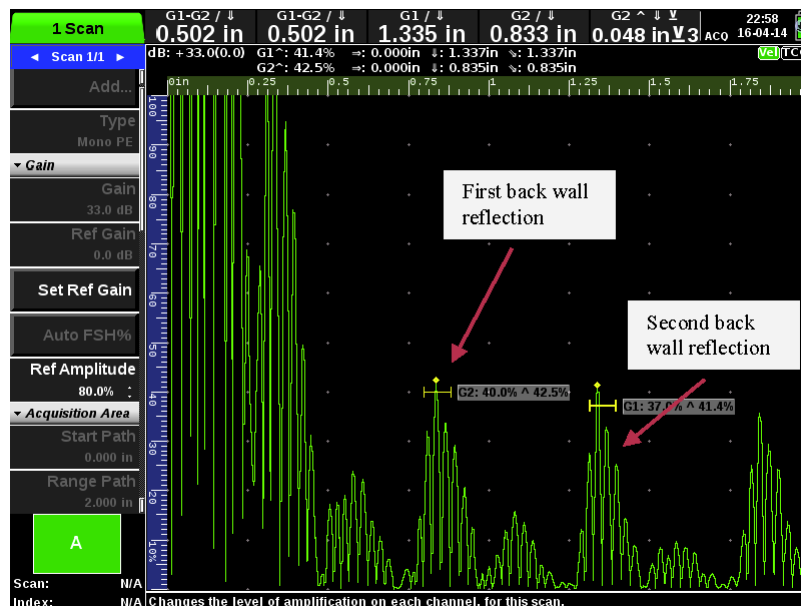
**Test 9: Multiple-Echo Method—Flaw Detector Instrument/Contact Transducer**

This test utilized a digital ultrasonic flaw detector and a 2.25-MHz, 3/4-inch-diameter, single-element contact transducer used without a delay line, as shown in Figure 3-16. Calibration was performed using a steel block of known thickness in order to establish a proper material velocity value. This test was based on a measurement technique requiring the reception of two back wall multiple reflections as illustrated in Figure A-13. Calibration was performed on an uncoated calibration block of known thickness to determine material velocity. Material thickness measurements were taken on coated specimens only where two or more back wall reflections

were present. In those regions, one A-scan gate was placed over a back wall reflection, and a second gate was placed over the following reflection signal as shown in Figure 3-17. The instrument was adjusted to display the difference in thickness measured between the first and second gate peaks, which provided the actual wall thickness.



**Figure 3-16**  
2.25-MHz,  $\frac{3}{4}$ -inch-diameter element contact transducer



**Figure 3-17**  
Typical A-scan presentation on a coated specimen using the 2.25-MHz,  $\frac{3}{4}$ -inch-diameter single-element transducer

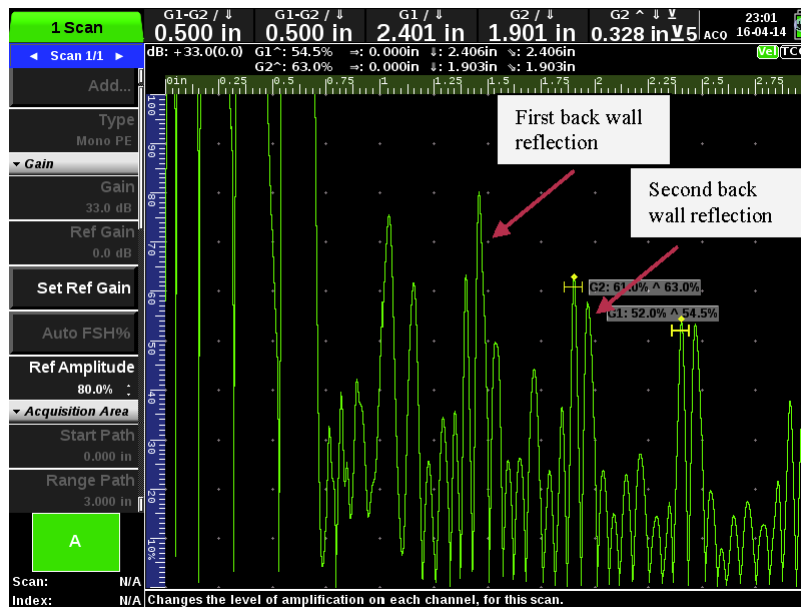
### ***Test 10: Multiple-Echo Method—Flaw Detector Instrument/Contact Transducer***

This test utilized a digital ultrasonic flaw detector and a 1.0-MHz, 1-inch-diameter, single-element contact transducer used without a delay line, as shown in Figure 3-18. Calibration was performed using an uncoated steel block of known thickness in order to establish a proper material velocity value. This test was based on a measurement technique requiring the reception

of two back wall multiple reflections as illustrated in Figure A-13. Material thickness measurements were taken on coated specimens only where two or more back wall reflections were present. In those regions, one A-scan gate was placed over a back wall reflection, and a second gate was placed over the following reflection signal as shown in Figure 3-19. The instrument was adjusted to display the difference in thickness measured between the first and second gate peaks, which provided the actual wall thickness. The transducer used in this test was similar to that used in Test 9 except for being lower in frequency and larger in diameter. The larger-diameter crystal, lower-frequency transducer should provide increased penetration capability while sacrificing resolution.



**Figure 3-18**  
1.0-MHz, 1-inch-diameter element contact transducer



**Figure 3-19**  
Typical A-scan presentation on a coated specimen using the 1.0-MHz, 1-inch-diameter single-element transducer

## **Thickness Measurement Comparisons**

This section provides a comparison of the results of thickness measurements performed on the test specimens using the ten different ultrasonic tests described above. Thickness measurements were attempted on every machined reflector on the six different coating type/thickness combinations for three different coating temperatures. The temperatures selected for the collection of data were 52°F, 72°F, and 92°F (+/- 5°F tolerance for all tests). These temperatures were selected to represent possible field environmental conditions that could be experienced by technicians when performing similar tests. Each plate was heated or cooled to the targeted temperature over a significant time period to assure that the entire plate and coating material were at the targeted temperature. An infrared thermometer was used to measure specimen temperature at the location where measurements were taken.

### **16-Mil Coal Tar Epoxy Specimen**

Tables 3-2 through 3-4 summarize the ultrasonic thickness data collected on the 16-mil coal tar epoxy specimen using ultrasonic Tests 1–10 for the three temperatures tested. Shaded areas on these tables indicate that a valid measurement was not possible. Technique performance was excellent for Tests 1–6, with RMS values ranging from 0.002 to 0.022 inch when the measured values were compared to the as-built dimensions. Test 7 also performed well, with the exception of not being able to measure the thinnest wall (0.062 inch) reflector as a result of operating at a lower frequency. In this case, the 2.25-MHz probe was not able to resolve the individual back wall multiple signals due to the larger wavelength of this transducer. In comparison, Tests 1–6 all utilized 5-MHz transducers.

Tests 8, 9, and 10 did not perform as well on the 16-mil coating when compared to Tests 1–7. The observed deficiencies were related to the use of lower-frequency probes with larger element sizes. Signals related to small reflectors were not easily detected using the larger probes, and the lower-frequency probes were incapable of resolving the back wall signals associated with the thinner materials due to the larger wavelengths. The data obtained on the 16-mil specimen indicated that the use of lower-frequency probes with large elements was not warranted, since attenuation associated with this coating did not prevent the use of smaller, higher-frequency probes with better resolution characteristics.

Temperature had no measureable effect on signal amplitude or measurement accuracy. All tests provided similar results regardless of the temperature of the coated specimen. The technique producing the most accurate measurements was the ultrasonic thickness gage (Test 1). The coal tar epoxy coating represented the exact configuration for which this specific instrument was designed. The coating provided minimal attenuation, resulting in strong interface reflections. The measurement algorithms used in the thickness gage have been optimized for time-of-flight accuracy using proprietary methodology, likely based on zero crossing reference points with high digital resolution.

In conclusion, it can be stated that the thickness of a pipe wall coated with 16-mil tape coal tar epoxy should be easily measured using ultrasonic techniques with excellent accuracies, assuming the integrity of the bond between the epoxy and the pipe outer surface is sufficient to permit the detection of a back wall signal. The results indicated that transducers operating at as high as 5 MHz with or without a delay line should be used with crystal sizes ranging from 0.25 to 0.5 inch in diameter. Both single- and dual-element conventional transducers, as well phased

array techniques, performed well on this coating when using 5-MHz transducers. Test results of this study indicated that lower-frequency transducers with large crystals are not needed to inspect this coating. These probes have limitations related to the detection of localized pitting and the capability to measure thin remaining wall thickness. However, it should be noted that the plates used for this investigation had coating that had not been exposed to environmental conditions and were not heavily corroded, a condition that may require the use of lower-frequency transducers.

**Table 3-2**  
**Ultrasonic thickness data collected on 16-mil coal tar epoxy specimen at 52°F**

| BLOCK 3 - Coal Tar Epoxy 16 mils @ 52° F |               |                          |   |              |  |              |   |              |   |              |  |              |   |              |   |              |  |              |  |              |   |              |
|--|---------------|--------------------------|---|--------------|--|--------------|---|--------------|---|--------------|--|--------------|---|--------------|---|--------------|--|--------------|--|--------------|---|--------------|
| Flaw ID                                  | Flaw Type     | AS-BUILT Ligament (inch) | Wall Thickness Measurements   |              |  |              |   |              |   |              |  |              |   |              |   |              |  |              |  |              |   |              |
|  |               |                          | TEST 1<br>38DL Plus Thru-Coat SEM Technique<br>7906 Probe 5MHz Dual |              | TEST 2<br>PAUT SEM Technique<br>5MHz w/ Delay Line |              | TEST 3<br>Flaw Detector SEM Technique<br>5MHz w/ Delay Line |              | TEST 4<br>PAUT MEM Technique<br>5MHz w/Delay Line |              | TEST 5<br>Flaw Detector MEM Technique<br>5MHz w/o Delay Line |              | TEST 6<br>Flaw Detector SEM Technique<br>7906 Probe 5MHz Dual |              | TEST 7<br>Flaw Detector SEM Technique<br>1/2", 2.25MHz Dual |              | TEST 8<br>Flaw Detector SEM Technique<br>1MHz 1/2" w/ Delay Line |              | TEST 9<br>Flaw Detector MEM Technique<br>3/4" 2.25MHz Single |              | TEST 10<br>Flaw Detector MEM Technique<br>1" 1.05MHz Single |              |
|  |               |                          | Measurement (inch)  | ERROR (inch) | Measurement (inch)                                 | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)                                | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)  | ERROR (inch) |
| A1                                       | Square Pocket | 0.062                    | 0.066   | 0.004        | 0.058  | 0.004        | 0.049   | 0.013        | 0.061   | 0.001        | 0.068  | 0.006        | 0.064   | 0.002        | Note 1  |              | Note 1   |              | 0.062  | 0.000        | Note 3  |              |
| A2                                       | Square Pocket | 0.125                    | 0.127   | 0.002        | 0.119  | 0.006        | 0.128   | 0.003        | 0.126   | 0.001        | 0.119  | 0.006        | 0.127   | 0.002        | 0.126   | 0.001        | Note 1   |              | 0.128  | 0.003        | 0.122   | 0.003        |
| A3                                       | Square Pocket | 0.187                    | 0.189   | 0.002        | 0.180  | 0.007        | 0.197   | 0.010        | 0.191   | 0.004        | 0.193  | 0.006        | 0.182   | 0.005        | 0.186   | 0.001        | Note 1   |              | 0.19   | 0.003        | 0.183   | 0.004        |
| A4                                       | Square Pocket | 0.248                    | 0.251   | 0.003        | 0.263  | 0.015        | 0.262   | 0.014        | 0.252   | 0.004        | 0.245  | 0.003        | 0.25  | 0.002        | 0.255   | 0.007        | 0.312  | 0.064        | 0.256  | 0.008        | 0.239   | 0.009        |
| A5                                       | Square Pocket | 0.373                    | 0.375   | 0.002        | 0.381  | 0.008        | 0.382   | 0.009        | 0.374   | 0.001        | 0.379  | 0.006        | 0.38  | 0.007        | 0.381   | 0.008        | 0.386  | 0.013        | 0.379  | 0.006        | 0.363   | 0.010        |
| A6                                       | Square Pocket | 0.498                    | 0.501   | 0.003        | 0.500  | 0.002        | 0.500   | 0.002        | 0.511   | 0.013        | 0.510  | 0.012        | 0.498   | 0.000        | 0.502   | 0.004        | 0.502  | 0.004        | 0.509  | 0.011        | 0.479   | 0.019        |
| B1                                       | Flat Hole     | 0.469                    | 0.470   | 0.001        | 0.478  | 0.009        | 0.474   | 0.005        | 0.471   | 0.002        | 0.479  | 0.010        | 0.469   | 0.000        | 0.472   | 0.003        | 0.481  | 0.012        | 0.512  | 0.043        | 0.454   | 0.015        |
| B2                                       | Flat Hole     | 0.469                    | 0.469   | 0.000        | 0.478  | 0.009        | 0.476   | 0.007        | 0.468   | 0.001        | 0.479  | 0.010        | 0.469   | 0.000        | 0.476   | 0.007        | 0.48   | 0.011        | 0.474  | 0.005        | 0.455   | 0.014        |
| B3                                       | Flat Hole     | 0.472                    | 0.468   | 0.004        | 0.478  | 0.006        | 0.473   | 0.001        | 0.471   | 0.001        | 0.490  | 0.018        | 0.469   | 0.003        | 0.476   | 0.004        | 0.479  | 0.007        | 0.479  | 0.007        | 0.462   | 0.010        |
| B4                                       | Flat Hole     | 0.467                    | 0.468   | 0.001        | 0.475  | 0.008        | 0.472   | 0.005        | 0.471   | 0.004        | 0.476  | 0.009        | 0.465   | 0.002        | 0.467   | 0.000        | 0.473  | 0.006        | Note 2   |              | Note 2  |              |
| B5                                       | Flat Hole     | 0.465                    | 0.469   | 0.004        | 0.475  | 0.010        | 0.473   | 0.008        | 0.475   | 0.010        | 0.486  | 0.021        | 0.465   | 0.000        | 0.465   | 0.000        | 0.47   | 0.005        | Note 2   |              | Note 2  |              |
| C1                                       | Flat Hole     | 0.312                    | 0.315   | 0.003        | 0.320  | 0.008        | 0.322   | 0.010        | 0.313   | 0.001        | 0.319  | 0.007        | 0.316   | 0.004        | 0.321   | 0.009        | 0.338  | 0.026        | 0.294  | 0.018        | 0.300   | 0.012        |
| C2                                       | Flat Hole     | 0.314                    | 0.314   | 0.000        | 0.324  | 0.010        | 0.322   | 0.008        | 0.313   | 0.001        | 0.329  | 0.015        | 0.314   | 0.000        | 0.318   | 0.004        | 0.335  | 0.021        | 0.318  | 0.004        | 0.301   | 0.013        |
| C3                                       | Flat Hole     | 0.314                    | 0.313   | 0.001        | 0.327  | 0.013        | 0.328   | 0.014        | 0.317   | 0.003        | 0.319  | 0.005        | 0.314   | 0.000        | 0.321   | 0.007        | 0.336  | 0.022        | 0.318  | 0.004        | 0.301   | 0.013        |
| C4                                       | Flat Hole     | 0.311                    | 0.312   | 0.001        | 0.327  | 0.016        | 0.329   | 0.018        | 0.313   | 0.002        | 0.317  | 0.006        | 0.318   | 0.007        | 0.321   | 0.010        | 0.34   | 0.029        | 0.36   | 0.049        | 0.301   | 0.010        |
| C5                                       | Flat Hole     | 0.31                     | 0.313   | 0.003        | 0.324  | 0.014        | 0.323   | 0.013        | 0.320   | 0.010        | 0.317  | 0.007        | 0.314   | 0.004        | 0.314   | 0.004        | 0.325  | 0.015        | Note 2   |              | Note 2  |              |
| D1                                       | Flat Hole     | 0.156                    | 0.159   | 0.003        | 0.162  | 0.006        | 0.172   | 0.016        | 0.158   | 0.002        | 0.150  | 0.006        | 0.163   | 0.007        | 0.142   | 0.014        | Note 1   |              | 0.161  | 0.005        | 0.155   | 0.001        |
| D2                                       | Flat Hole     | 0.157                    | 0.158   | 0.001        | 0.165  | 0.008        | 0.176   | 0.019        | 0.158   | 0.001        | 0.157  | 0.000        | 0.163   | 0.006        | 0.146   | 0.011        | Note 1   |              | 0.161  | 0.004        | 0.144   | 0.013        |
| D3                                       | Flat Hole     | 0.161                    | 0.159   | 0.002        | 0.165  | 0.004        | 0.174   | 0.013        | 0.158   | 0.003        | 0.162  | 0.001        | 0.16  | 0.001        | 0.142   | 0.019        | Note 1   |              | 0.161  | 0.000        | 0.161   | 0.000        |
| D4                                       | Flat Hole     | 0.155                    | 0.156   | 0.001        | 0.165  | 0.010        | 0.176   | 0.021        | 0.155   | 0.000        | 0.167  | 0.012        | 0.165   | 0.010        | 0.144   | 0.011        | Note 1   |              | Note 2   |              | Note 2  |              |
| D5                                       | Flat Hole     | 0.155                    | 0.157   | 0.002        | 0.158  | 0.003        | 0.158   | 0.003        | 0.155   | 0.000        | 0.167  | 0.012        | 0.16  | 0.005        | 0.134   | 0.021        | Note 1   |              | Note 2   |              | Note 2  |              |
| E1                                       | Shaped Hole   | 0.299                    | 0.298   | 0.001        | 0.302  | 0.003        | 0.313   | 0.014        | 0.284   | 0.015        | 0.290  | 0.009        | 0.3   | 0.001        | 0.283   | 0.016        | 0.347  | 0.048        | Note 2   |              | Note 2  |              |
| E2                                       | Shaped Hole   | 0.438                    | 0.442   | 0.004        | 0.446  | 0.008        | 0.450   | 0.012        | 0.439   | 0.001        | 0.436  | 0.002        | 0.441   | 0.003        | 0.453   | 0.015        | 0.415  | 0.023        | Note 2   |              | Note 2  |              |
| E3                                       | Shaped Hole   | 0.564                    | 0.597   | 0.033        | 0.558  | 0.006        | 0.564   | 0.000        | 0.601   | 0.037        | 0.597  | 0.033        | 0.566   | 0.002        | 0.488   | 0.076        | Note 2   |              | Note 2   |              | Note 2  |              |
| E4                                       | Shaped Hole   | 0.259                    | 0.329   | 0.070        | 0.327  | 0.068        | 0.255   | 0.004        | 0.327   | 0.068        | 0.252  | 0.007        | 0.328   | 0.069        | 0.307   | 0.048        | Note 2   |              | 0.275  | 0.016        | Note 2  |              |
|  | RMS Error     |                          |   | 0.016        |  | 0.016        |   | 0.011        |   | 0.016        |  | 0.011        |   | 0.014        |   | 0.021        |  | 0.026        |  | 0.018        |   | 0.011        |

Note 1: Ringdown of probe or interface reflection interfering with backwall signal.  
 Note 2: Could not resolve backwall signal(s) due to interference with background noise.  
 Note 3: Frequency too low to resolve backwall multiple reflections.  
 Note 4: Instrument indicated "invalid" measurement due to low signal amplitude or due to extra tape layer reflection.

**Table 3-3**  
**Ultrasonic thickness data collected on 16-mil coal tar epoxy specimen at 72°F**

| BLOCK 3 - Coal Tar Epoxy 16 mils @ 72° F |               |                          |  |              |   |              |  |              |  |              |   |              |  |              |  |              |   |              |   |              |  |              |
|--|---------------|--------------------------|--|--------------|---|--------------|--|--------------|--|--------------|---|--------------|--|--------------|--|--------------|---|--------------|---|--------------|--|--------------|
| Flaw ID                                  | Flaw Type     | AS-BUILT Ligament (inch) | Wall Thickness Measurements  |              |   |              |  |              |  |              |   |              |  |              |  |              |   |              |   |              |  |              |
|  |               |                          | TEST 1<br>38DL Plus Thru-Coat<br>SEM Technique<br>7906 Probe 5MHz Dual |              | TEST 2<br>PAUT<br>SEM Technique<br>5MHz w/ Delay Line |              | TEST 3<br>Flaw Detector<br>SEM Technique<br>5MHz w/ Delay Line |              | TEST 4<br>PAUT<br>MEM Technique<br>5MHz w/Delay Line |              | TEST 5<br>Flaw Detector<br>MEM Technique<br>5MHz w/o Delay Line |              | TEST 6<br>Flaw Detector<br>SEM Technique<br>7906 Probe 5MHz Dual |              | TEST 7<br>Flaw Detector<br>SEM Technique<br>1/2", 2.25MHz Dual |              | TEST 8<br>Flaw Detector<br>SEM Technique<br>1MHz 1/2" w/ Delay Line |              | TEST 9<br>Flaw Detector<br>MEM Technique<br>3/4" 2.25MHz Single |              | TEST 10<br>Flaw Detector<br>MEM Technique<br>1" 1.05MHz Single |              |
|  |               |                          | Measurement (inch)   | ERROR (inch) | Measurement (inch)                                    | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)                                   | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)   | ERROR (inch) |
| A1                                       | Square Pocket | 0.062                    | 0.064  | 0.002        | 0.050   | 0.012        | 0.061  | 0.001        | 0.072  | 0.010        | 0.061   | 0.001        | 0.06   | 0.002        | Note 1   | Note 1       |   | 0.063        | 0.001   | Note 3       |  |              |
| A2                                       | Square Pocket | 0.125                    | 0.125  | 0.000        | 0.118   | 0.007        | 0.117  | 0.008        | 0.126  | 0.001        | 0.120   | 0.005        | 0.123  | 0.002        | 0.101  | 0.024        | Note 1  |              | 0.118   | 0.007        | 0.126  | 0.001        |
| A3                                       | Square Pocket | 0.187                    | 0.188  | 0.001        | 0.175   | 0.012        | 0.180  | 0.007        | 0.187  | 0.000        | 0.192   | 0.005        | 0.185  | 0.002        | 0.179  | 0.008        | Note 1  |              | 0.203   | 0.016        | 0.19   | 0.003        |
| A4                                       | Square Pocket | 0.248                    | 0.250  | 0.002        | 0.246   | 0.002        | 0.244  | 0.004        | 0.251  | 0.003        | 0.239   | 0.009        | 0.251  | 0.003        | 0.25   | 0.002        | 0.239   | 0.009        | 0.241   | 0.007        | 0.249  | 0.001        |
| A5                                       | Square Pocket | 0.373                    | 0.375  | 0.002        | 0.379   | 0.006        | 0.366  | 0.007        | 0.373  | 0.000        | 0.373   | 0.000        | 0.375  | 0.002        | 0.373  | 0.000        | 0.383   | 0.010        | 0.357   | 0.016        | 0.374  | 0.001        |
| A6                                       | Square Pocket | 0.498                    | 0.500  | 0.002        | 0.500   | 0.002        | 0.495  | 0.003        | 0.499  | 0.001        | 0.499   | 0.001        | 0.502  | 0.004        | 0.493  | 0.005        | 0.502   | 0.004        | 0.482   | 0.016        | 0.505  | 0.007        |
| B1                                       | Flat Hole     | 0.469                    | 0.469  | 0.000        | 0.468   | 0.001        | 0.471  | 0.002        | 0.470  | 0.001        | 0.473   | 0.004        | 0.471  | 0.002        | 0.467  | 0.002        | 0.475   | 0.006        | 0.475   | 0.006        | 0.476  | 0.007        |
| B2                                       | Flat Hole     | 0.469                    | 0.469  | 0.000        | 0.464   | 0.005        | 0.471  | 0.002        | 0.470  | 0.001        | 0.473   | 0.004        | 0.471  | 0.002        | 0.467  | 0.002        | 0.474   | 0.005        | 0.475   | 0.006        | 0.464  | 0.005        |
| B3                                       | Flat Hole     | 0.472                    | 0.468  | 0.004        | 0.461   | 0.011        | 0.471  | 0.001        | 0.474  | 0.002        | 0.476   | 0.004        | 0.469  | 0.003        | 0.467  | 0.005        | 0.477   | 0.005        | 0.476   | 0.004        | 0.474  | 0.002        |
| B4                                       | Flat Hole     | 0.467                    | 0.468  | 0.001        | 0.464   | 0.003        | 0.469  | 0.002        | 0.470  | 0.003        | 0.469   | 0.002        | 0.469  | 0.002        | 0.462  | 0.005        | 0.473   | 0.006        | 0.453   | 0.014        | Note 2   |              |
| B5                                       | Flat Hole     | 0.465                    | 0.469  | 0.004        | 0.464   | 0.001        | 0.473  | 0.008        | 0.477  | 0.012        | 0.478   | 0.013        | 0.468  | 0.003        | 0.458  | 0.007        | 0.463   | 0.002        | Note 2  |              | Note 2   |              |
| C1                                       | Flat Hole     | 0.312                    | 0.313  | 0.001        | 0.304   | 0.008        | 0.307  | 0.005        | 0.323  | 0.011        | 0.314   | 0.002        | 0.313  | 0.001        | 0.314  | 0.002        | 0.325   | 0.013        | 0.30  | 0.012        | 0.318  | 0.006        |
| C2                                       | Flat Hole     | 0.314                    | 0.313  | 0.001        | 0.304   | 0.010        | 0.309  | 0.005        | 0.319  | 0.005        | 0.312   | 0.002        | 0.312  | 0.002        | 0.314  | 0.000        | 0.326   | 0.012        | 0.30  | 0.014        | 0.313  | 0.001        |
| C3                                       | Flat Hole     | 0.314                    | 0.313  | 0.001        | 0.300   | 0.014        | 0.314  | 0.000        | 0.323  | 0.009        | 0.314   | 0.000        | 0.312  | 0.002        | 0.314  | 0.000        | 0.326   | 0.012        | 0.30  | 0.016        | 0.318  | 0.004        |
| C4                                       | Flat Hole     | 0.311                    | 0.314  | 0.003        | 0.307   | 0.004        | 0.312  | 0.001        | 0.323  | 0.012        | 0.309   | 0.002        | 0.311  | 0.000        | 0.314  | 0.003        | 0.325   | 0.014        | 0.28  | 0.028        | Note 2   |              |
| C5                                       | Flat Hole     | 0.31                     | 0.313  | 0.003        | 0.300   | 0.010        | 0.314  | 0.004        | 0.319  | 0.009        | 0.316   | 0.006        | 0.309  | 0.001        | 0.307  | 0.003        | 0.326   | 0.016        | Note 2  |              | Note 2   |              |
| D1                                       | Flat Hole     | 0.156                    | 0.157  | 0.001        | 0.143   | 0.013        | 0.157  | 0.001        | 0.158  | 0.002        | 0.157   | 0.001        | 0.154  | 0.002        | 0.134  | 0.022        | Note 1  |              | 0.15  | 0.006        | 0.161  | 0.005        |
| D2                                       | Flat Hole     | 0.157                    | 0.157  | 0.000        | 0.150   | 0.007        | 0.157  | 0.000        | 0.165  | 0.008        | 0.155   | 0.002        | 0.154  | 0.003        | 0.137  | 0.020        | Note 1  |              | 0.15  | 0.007        | 0.161  | 0.004        |
| D3                                       | Flat Hole     | 0.161                    | 0.156  | 0.005        | 0.146   | 0.015        | 0.159  | 0.002        | 0.165  | 0.004        | 0.155   | 0.006        | 0.153  | 0.008        | 0.137  | 0.024        | Note 1  |              | 0.15  | 0.013        | Note 2   |              |
| D4                                       | Flat Hole     | 0.155                    | 0.156  | 0.001        | 0.146   | 0.009        | 0.155  | 0.000        | 0.158  | 0.003        | 0.157   | 0.002        | 0.153  | 0.002        | 0.142  | 0.013        | Note 1  |              | Note 2  |              | Note 2   |              |
| D5                                       | Flat Hole     | 0.155                    | 0.156  | 0.001        | 0.143   | 0.012        | 0.159  | 0.004        | 0.158  | 0.003        | 0.098   | 0.057        | 0.152  | 0.003        | 0.13   | 0.025        | Note 1  |              | Note 2  |              | Note 2   |              |
| E1                                       | Shaped Hole   | 0.299                    | 0.298  | 0.001        | 0.286   | 0.013        | 0.302  | 0.003        | 0.316  | 0.017        | 0.291   | 0.008        | 0.295  | 0.004        | 0.278  | 0.021        | 0.315   | 0.016        | Note 2  |              | Note 2   |              |
| E2                                       | Shaped Hole   | 0.438                    | 0.442  | 0.004        | 0.432   | 0.006        | 0.450  | 0.012        | 0.470  | 0.032        | 0.450   | 0.012        | 0.443  | 0.005        | 0.453  | 0.015        | 0.435   | 0.003        | Note 2  |              | Note 2   |              |
| E3                                       | Shaped Hole   | 0.564                    | 0.562  | 0.002        | 0.564   | 0.000        | 0.572  | 0.008        | 0.603  | 0.039        | 0.598   | 0.034        | 0.608  | 0.044        | 0.486  | 0.078        | Note 2  |              | Note 2  |              | Note 2   |              |
| E4                                       | Shaped Hole   | 0.259                    | 0.259  | 0.000        | 0.314   | 0.055        | 0.262  | 0.003        | 0.337  | 0.078        | 0.330   | 0.071        | 0.329  | 0.070        | 0.3  | 0.041        | Note 2  |              | 0.29  | 0.029        | Note 2   |              |
| RMS Error                                |               |                          |  | 0.002        |   | 0.014        |  | 0.005        |  | 0.020        |   | 0.020        |  | 0.017        |  | 0.022        |   | 0.010        |   | 0.014        |  | 0.004        |

Note 1: Ringdown of probe or interface reflection interfering with backwall signal.  
 Note 2: Could not resolve backwall signal(s) due to interference with background noise.  
 Note 3: Frequency too low to resolve backwall multiple reflections.  
 Note 4: Instrument indicated "invalid" measurement due to low signal amplitude or due to extra tape layer reflection.

**Table 3-4**  
**Ultrasonic thickness data collected on 16-mil coal tar epoxy specimen at 92°F**

| BLOCK 3 - Coal Tar Epoxy 16 mils @ 92° F |               |                  |  |                 |  |                 |  |                 |  |                 |  |                 |  |                 |   |                 |   |                 |   |                 |  |                 |
|--|---------------|------------------|--|-----------------|--|-----------------|--|-----------------|--|-----------------|--|-----------------|--|-----------------|---|-----------------|---|-----------------|---|-----------------|--|-----------------|
| Flaw ID                                  | Flaw Type     | AS-BUILT<br>Inch | Wall Thickness Measurements  |                 |  |                 |  |                 |  |                 |  |                 |  |                 |   |                 |   |                 |   |                 |  |                 |
|  |               |                  | TEST 1<br>38DL Plus Thru-Coat<br>SEM Technique<br>795K Probe 5MHz Dual |                 | TEST 2<br>PALUT<br>SEM Technique<br>5MHz w/ Delay Line |                 | TEST 3<br>Flaw Detector<br>SEM Technique<br>5MHz w/ Delay Line |                 | TEST 4<br>PALUT<br>MEM Technique<br>5MHz w/ Delay Line |                 | TEST 5<br>Flaw Detector<br>MEM Technique<br>5MHz w/ Delay Line |                 | TEST 6<br>Flaw Detector<br>SEM Technique<br>795K Probe 5MHz Dual |                 | TEST 7<br>Flaw Detector<br>SEM Technique<br>1/2" 2.25MHz Dual |                 | TEST 8<br>Flaw Detector<br>SEM Technique<br>1MHz 1/2" w/ Delay Line |                 | TEST 9<br>Flaw Detector<br>MEM Technique<br>3/4" 2.25MHz Single |                 | TEST 10<br>Flaw Detector<br>MEM Technique<br>1" 1.05MHz Single |                 |
|  |               |                  | Measurement<br>(Inch)  | ERROR<br>(Inch) | Measurement<br>(Inch)                                  | ERROR<br>(Inch) | Measurement<br>(Inch)  | ERROR<br>(Inch) | Measurement<br>(Inch)                                  | ERROR<br>(Inch) | Measurement<br>(Inch)  | ERROR<br>(Inch) | Measurement<br>(Inch)  | ERROR<br>(Inch) | Measurement<br>(Inch)   | ERROR<br>(Inch) | Measurement<br>(Inch)   | ERROR<br>(Inch) | Measurement<br>(Inch)   | ERROR<br>(Inch) | Measurement<br>(Inch)  | ERROR<br>(Inch) |
| A1                                       | Square Pocket | 0.062            | 0.067  | 0.005           | 0.068  | 0.006           | 0.058  | 0.004           | 0.064  | 0.002           | 0.060  | 0.002           | 0.06   | 0.002           | Note 1  |                 | Note 1  |                 | 0.066   | 0.004           | Note 3   |                 |
| A2                                       | Square Pocket | 0.125            | 0.128  | 0.003           | 0.129  | 0.004           | 0.117  | 0.008           | 0.125  | 0.000           | 0.126  | 0.001           | 0.123  | 0.002           | 0.111   | 0.014           | Note 1  |                 | 0.128   | 0.003           | 0.128  | 0.003           |
| A3                                       | Square Pocket | 0.187            | 0.190  | 0.003           | 0.186  | 0.001           | 0.194  | 0.007           | 0.186  | 0.001           | 0.202  | 0.015           | 0.186  | 0.001           | 0.165   | 0.022           | Note 1  |                 | 0.194   | 0.007           | 0.192  | 0.005           |
| A4                                       | Square Pocket | 0.248            | 0.251  | 0.003           | 0.254  | 0.006           | 0.250  | 0.002           | 0.254  | 0.006           | 0.256  | 0.008           | 0.249  | 0.001           | 0.233   | 0.015           | 0.252   | 0.004           | 0.256   | 0.008           | 0.251  | 0.003           |
| A5                                       | Square Pocket | 0.373            | 0.376  | 0.003           | 0.375  | 0.002           | 0.381  | 0.008           | 0.380  | 0.007           | 0.370  | 0.003           | 0.375  | 0.002           | 0.38  | 0.007           | 0.384   | 0.011           | 0.382   | 0.009           | 0.382  | 0.009           |
| A6                                       | Square Pocket | 0.498            | 0.502  | 0.004           | 0.500  | 0.002           | 0.505  | 0.007           | 0.507  | 0.009           | 0.510  | 0.012           | 0.505  | 0.007           | 0.502   | 0.004           | 0.502   | 0.004           | 0.509   | 0.011           | 0.507  | 0.009           |
| B1                                       | Flat Hole     | 0.469            | 0.470  | 0.001           | 0.479  | 0.010           | 0.477  | 0.008           | 0.475  | 0.006           | 0.480  | 0.011           | 0.472  | 0.003           | 0.465   | 0.004           | 0.467   | 0.002           | 0.479   | 0.010           | 0.474  | 0.005           |
| B2                                       | Flat Hole     | 0.469            | 0.469  | 0.000           | 0.471  | 0.002           | 0.477  | 0.008           | 0.475  | 0.006           | 0.480  | 0.011           | 0.472  | 0.003           | 0.46  | 0.009           | 0.466   | 0.003           | 0.476   | 0.007           | 0.469  | 0.000           |
| B3                                       | Flat Hole     | 0.472            | 0.471  | 0.001           | 0.471  | 0.001           | 0.479  | 0.007           | 0.475  | 0.003           | 0.477  | 0.005           | 0.474  | 0.002           | 0.46  | 0.012           | 0.468   | 0.004           | 0.462   | 0.010           | 0.462  | 0.010           |
| B4                                       | Flat Hole     | 0.467            | 0.469  | 0.002           | 0.468  | 0.001           | 0.474  | 0.007           | 0.471  | 0.004           | 0.477  | 0.010           | 0.471  | 0.004           | 0.462   | 0.005           | 0.467   | 0.000           | Note 2  |                 | Note 2   |                 |
| B5                                       | Flat Hole     | 0.465            | 0.469  | 0.004           | 0.471  | 0.006           | 0.477  | 0.012           | 0.482  | 0.017           | 0.489  | 0.024           | 0.471  | 0.006           | 0.455   | 0.010           | 0.414   | 0.051           | Note 2  |                 | Note 2   |                 |
| C1                                       | Flat Hole     | 0.312            | 0.315  | 0.003           | 0.321  | 0.009           | 0.315  | 0.003           | 0.308  | 0.004           | 0.324  | 0.012           | 0.314  | 0.002           | 0.302   | 0.010           | 0.325   | 0.013           | 0.318   | 0.006           | 0.318  | 0.006           |
| C2                                       | Flat Hole     | 0.314            | 0.314  | 0.000           | 0.304  | 0.010           | 0.318  | 0.004           | 0.308  | 0.006           | 0.321  | 0.007           | 0.314  | 0.000           | 0.297   | 0.017           | 0.322   | 0.008           | 0.32  | 0.006           | 0.315  | 0.001           |
| C3                                       | Flat Hole     | 0.314            | 0.316  | 0.002           | 0.318  | 0.004           | 0.315  | 0.001           | 0.315  | 0.001           | 0.303  | 0.011           | 0.314  | 0.000           | 0.314   | 0.000           | 0.32  | 0.006           | 0.318   | 0.004           | 0.318  | 0.004           |
| C4                                       | Flat Hole     | 0.311            | 0.313  | 0.002           | 0.321  | 0.010           | 0.318  | 0.007           | 0.312  | 0.001           | 0.300  | 0.011           | 0.311  | 0.000           | 0.311   | 0.000           | 0.322   | 0.011           | Note 2  |                 | Note 2   |                 |
| C5                                       | Flat Hole     | 0.31             | 0.315  | 0.005           | 0.329  | 0.019           | 0.318  | 0.008           | 0.320  | 0.010           | 0.298  | 0.012           | 0.311  | 0.001           | 0.307   | 0.003           | 0.376   | 0.066           | Note 2  |                 | Note 2   |                 |
| D1                                       | Flat Hole     | 0.156            | 0.159  | 0.003           | 0.161  | 0.005           | 0.159  | 0.003           | 0.159  | 0.003           | 0.143  | 0.013           | 0.154  | 0.002           | 0.144   | 0.012           | Note 1  |                 | 0.161   | 0.005           | 0.159  | 0.003           |
| D2                                       | Flat Hole     | 0.157            | 0.158  | 0.001           | 0.171  | 0.014           | 0.161  | 0.004           | 0.156  | 0.001           | 0.164  | 0.007           | 0.154  | 0.003           | 0.142   | 0.015           | Note 1  |                 | 0.161   | 0.004           | 0.161  | 0.004           |
| D3                                       | Flat Hole     | 0.161            | 0.160  | 0.001           | 0.175  | 0.014           | 0.164  | 0.003           | 0.159  | 0.002           | 0.164  | 0.003           | 0.154  | 0.007           | 0.142   | 0.019           | Note 1  |                 | 0.159   | 0.002           | 0.147  | 0.014           |
| D4                                       | Flat Hole     | 0.155            | 0.157  | 0.002           | 0.171  | 0.016           | 0.161  | 0.006           | 0.159  | 0.004           | 0.155  | 0.000           | 0.154  | 0.001           | 0.146   | 0.009           | Note 1  |                 | Note 2  |                 | Note 2   |                 |
| D5                                       | Flat Hole     | 0.155            | 0.157  | 0.002           | 0.179  | 0.024           | 0.161  | 0.006           | 0.167  | 0.012           | 0.164  | 0.009           | 0.151  | 0.004           | 0.134   | 0.021           | Note 1  |                 | Note 2  |                 | Note 2   |                 |
| E1                                       | Shaped Hole   | 0.299            | 0.298  | 0.001           | 0.311  | 0.012           | 0.308  | 0.009           | 0.312  | 0.013           | 0.301  | 0.002           | 0.297  | 0.002           | 0.307   | 0.008           | 0.321   | 0.022           | Note 2  |                 | Note 2   |                 |
| E2                                       | Shaped Hole   | 0.438            | 0.442  | 0.004           | 0.446  | 0.008           | 0.449  | 0.011           | 0.457  | 0.019           | 0.451  | 0.013           | 0.443  | 0.005           | 0.42  | 0.018           | 0.398   | 0.040           | Note 2  |                 | Note 2   |                 |
| E3                                       | Shaped Hole   | 0.564            | 0.599  | 0.035           | 0.568  | 0.004           | 0.582  | 0.018           | 0.601  | 0.037           | 0.592  | 0.028           | 0.609  | 0.045           | 0.509   | 0.055           | Note 2  |                 | Note 2  |                 | Note 2   |                 |
| E4                                       | Shaped Hole   | 0.259            | 0.330  | 0.071           | 0.318  | 0.059           | 0.280  | 0.021           | 0.308  | 0.049           | 0.326  | 0.067           | 0.326  | 0.067           | 0.302   | 0.043           | Note 2  |                 | 0.372   | 0.113           | Note 2   |                 |
|  | RMS Error     |                  | 0.016  |                 | 0.015  |                 | 0.009  |                 | 0.014  |                 | 0.018  |                 | 0.016  |                 | 0.019   |                 | 0.025   |                 | 0.029   |                 | 0.007  |                 |

Note 1: Ringdown of probe or interface reflection interfering with backwall signal.  
 Note 2: Could not resolve backwall signal(s) due to interference with background noise.  
 Note 3: Frequency too low to resolve backwall multiple reflections.  
 Note 4: Instrument indicated "invalid" measurement due to low signal amplitude or due to extra tape layer reflection.

**20-Mil Coal Tar Epoxy Specimen**

Tables 3-5 through 3-7 summarize the ultrasonic thickness data collected on the 20-mil coal tar epoxy coated specimen using ultrasonic Tests 1–10 for the three temperatures tested. Shaded areas on these tables indicate that a valid measurement was not possible. The results associated with this specimen were very similar to those observed on the 16-mil coal tar epoxy coating specimen. Technique performance was excellent for Tests 1–6, with RMS values ranging from 0.002 to 0.025 inch when the measured values were compared to the as-built dimensions. Test 7 also performed well, with the exception of not being able to measure the thinnest wall (0.062 inch) reflector as a result of operating at a lower frequency. In this case, the 2.25-MHz probe was not able to resolve the individual back wall multiple signals due to the larger wavelength of this transducer.

Tests 8, 9, and 10 did not perform as well on the 20-mil coating when compared to Tests 17. As observed with the 16-mil coal tar epoxy, deficiencies were related to the use of lower-frequency probes with larger element sizes. Signals related to small reflectors were not easily detected using the larger probes, and the lower-frequency probes were incapable of resolving the back wall signals associated with the thinner materials due to the larger wavelengths. The data

obtained on the 20-mil specimen indicated that the use of lower-frequency probes with large elements was not warranted, since attenuation associated with this coating did not prevent the use of smaller, higher-frequency probes with better resolution characteristics.

Temperature had no measureable effect on signal amplitude or measurement accuracy. All tests provided similar results regardless of the temperature of the specimen. The technique producing the most accurate measurements was the ultrasonic thickness gage (Test 1). The coal tar epoxy coating represented the exact configuration for which this specific instrument was designed. The coating provided minimal attenuation, resulting in strong interface reflections. The measurement algorithms used in the thickness gage have been optimized for time-of-flight accuracy using proprietary methodology, likely based on zero crossing reference points with high digital resolution.

In conclusion, it can be stated that the thickness of a pipe wall coated with 20-mil tape coal tar epoxy should be easily measured using ultrasonic techniques with excellent accuracies, assuming the integrity of the bond between the epoxy and the pipe outer surface is sufficient to permit a back wall signal. The results indicated that transducers operating at as high as 5 MHz with or without a delay line should be used with crystal sizes ranging from 0.25 to 0.5 inch in diameter. Both single- and dual-element conventional transducers, as well phased array techniques, performed well on this coating. Test results of this study indicated that lower-frequency transducers with large crystals are not needed to inspect this coating. These probes have limitations related to the detection of localized pitting and the capability to measure thin remaining wall thickness. However, it should be noted that the plates used for this investigation had coating that had not been exposed to environmental conditions and were not heavily corroded, a condition that may require the use of lower-frequency transducers.

**Table 3-5**  
**Ultrasonic thickness data collected on 20-mil coal tar epoxy specimen at 52°F**

| BLOCK 7 - Coal Tar Epoxy 20 mils @ 52° F |               |                          |  |              |   |              |  |              |  |              |   |              |  |              |  |              |   |              |   |              |  |              |
|--|---------------|--------------------------|--|--------------|---|--------------|--|--------------|--|--------------|---|--------------|--|--------------|--|--------------|---|--------------|---|--------------|--|--------------|
| Flaw ID                                  | Flaw Type     | AS-BUILT Ligament (inch) | Wall Thickness Measurements  |              |   |              |  |              |  |              |   |              |  |              |  |              |   |              |   |              |  |              |
|  |               |                          | TEST 1<br>38DL Plus Thru-Coat<br>SEM Technique<br>7906 Probe 5MHz Dual |              | TEST 2<br>PAUT<br>SEM Technique<br>5MHz w/ Delay Line |              | TEST 3<br>Flaw Detector<br>SEM Technique<br>5MHz w/ Delay Line |              | TEST 4<br>PAUT<br>MEM Technique<br>5MHz w/Delay Line |              | TEST 5<br>Flaw Detector<br>MEM Technique<br>5MHz w/o Delay Line |              | TEST 6<br>Flaw Detector<br>SEM Technique<br>7906 Probe 5MHz Dual |              | TEST 7<br>Flaw Detector<br>SEM Technique<br>1/2", 2.25MHz Dual |              | TEST 8<br>Flaw Detector<br>SEM Technique<br>1MHz 1/2" w/ Delay Line |              | TEST 9<br>Flaw Detector<br>MEM Technique<br>3/4" 2.25MHz Single |              | TEST 10<br>Flaw Detector<br>MEM Technique<br>1" 1.05MHz Single |              |
|  |               |                          | Measurement (inch)   | ERROR (inch) | Measurement (inch)                                    | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)                                   | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)   | ERROR (inch) |
| A1                                       | Square Pocket | 0.062                    | 0.065  | 0.003        | 0.047   | 0.015        | 0.075  | 0.013        | 0.061  | 0.001        | 0.062   | 0.000        | 0.055  | 0.007        | Note 1   |              | Note 5  |              | 0.059   | 0.003        | Note 3   |              |
| A2                                       | Square Pocket | 0.125                    | 0.127  | 0.002        | 0.122   | 0.003        | 0.132  | 0.007        | 0.122  | 0.003        | 0.145   | 0.020        | 0.117  | 0.008        | 0.125  | 0.000        | Note 5  |              | 0.128   | 0.003        | 0.124  | 0.001        |
| A3                                       | Square Pocket | 0.187                    | 0.190  | 0.003        | 0.187   | 0.000        | 0.192  | 0.005        | 0.201  | 0.014        | 0.202   | 0.015        | 0.179  | 0.008        | 0.189  | 0.002        | Note 5  |              | 0.192   | 0.005        | 0.18   | 0.007        |
| A4                                       | Square Pocket | 0.248                    | 0.250  | 0.002        | 0.245   | 0.003        | 0.250  | 0.002        | 0.248  | 0.000        | 0.264   | 0.016        | 0.248  | 0.000        | 0.245  | 0.003        | 0.294   | 0.046        | 0.251   | 0.003        | 0.239  | 0.009        |
| A5                                       | Square Pocket | 0.373                    | 0.375  | 0.002        | 0.374   | 0.001        | 0.374  | 0.001        | 0.374  | 0.001        | 0.379   | 0.006        | 0.367  | 0.006        | 0.37   | 0.003        | 0.373   | 0.000        | 0.376   | 0.003        | 0.357  | 0.016        |
| A6                                       | Square Pocket | 0.498                    | 0.500  | 0.002        | 0.500   | 0.002        | 0.499  | 0.001        | 0.500  | 0.002        | 0.498   | 0.000        | 0.5  | 0.002        | 0.498  | 0.000        | 0.502   | 0.004        | 0.506   | 0.008        | 0.485  | 0.013        |
| B1                                       | Flat Hole     | 0.469                    | 0.469  | 0.000        | 0.464   | 0.005        | 0.461  | 0.008        | 0.468  | 0.001        | 0.488   | 0.019        | 0.462  | 0.007        | 0.46   | 0.009        | 0.466   | 0.003        | 0.474   | 0.005        | 0.454  | 0.015        |
| B2                                       | Flat Hole     | 0.469                    | 0.469  | 0.000        | 0.464   | 0.005        | 0.462  | 0.007        | 0.471  | 0.002        | 0.476   | 0.007        | 0.464  | 0.005        | 0.458  | 0.011        | 0.467   | 0.002        | 0.474   | 0.005        | 0.451  | 0.018        |
| B3                                       | Flat Hole     | 0.472                    | 0.470  | 0.002        | 0.468   | 0.004        | 0.462  | 0.010        | 0.471  | 0.001        | 0.476   | 0.004        | 0.467  | 0.005        | 0.46   | 0.012        | 0.473   | 0.001        | 0.476   | 0.004        | 0.451  | 0.021        |
| B4                                       | Flat Hole     | 0.467                    | 0.468  | 0.001        | 0.471   | 0.004        | 0.463  | 0.004        | 0.468  | 0.001        | 0.476   | 0.009        | 0.464  | 0.003        | 0.458  | 0.009        | 0.471   | 0.004        | 0.472   | 0.005        | 0.452  | 0.015        |
| B5                                       | Flat Hole     | 0.465                    | 0.466  | 0.001        | 0.464   | 0.001        | 0.459  | 0.006        | 0.460  | 0.005        | 0.474   | 0.009        | 0.46   | 0.005        | 0.476  | 0.011        | 0.451   | 0.014        | Note 4  |              | Note 4   |              |
| C1                                       | Flat Hole     | 0.312                    | 0.315  | 0.003        | 0.309   | 0.003        | 0.311  | 0.001        | 0.317  | 0.005        | 0.319   | 0.007        | 0.307  | 0.005        | 0.304  | 0.008        | 0.312   | 0.000        | 0.318   | 0.006        | 0.298  | 0.014        |
| C2                                       | Flat Hole     | 0.314                    | 0.314  | 0.000        | 0.317   | 0.003        | 0.314  | 0.000        | 0.313  | 0.001        | 0.319   | 0.005        | 0.31   | 0.004        | 0.307  | 0.007        | 0.317   | 0.003        | 0.318   | 0.004        | 0.299  | 0.015        |
| C3                                       | Flat Hole     | 0.314                    | 0.314  | 0.000        | 0.317   | 0.003        | 0.315  | 0.001        | 0.313  | 0.001        | 0.321   | 0.007        | 0.307  | 0.007        | 0.311  | 0.003        | 0.317   | 0.003        | 0.315   | 0.001        | 0.298  | 0.016        |
| C4                                       | Flat Hole     | 0.311                    | 0.313  | 0.002        | 0.313   | 0.002        | 0.313  | 0.002        | 0.313  | 0.002        | 0.305   | 0.006        | 0.31   | 0.001        | 0.309  | 0.002        | 0.318   | 0.007        | 0.306   | 0.005        | 0.339  | 0.028        |
| C5                                       | Flat Hole     | 0.31                     | 0.312  | 0.002        | 0.309   | 0.001        | 0.307  | 0.003        | 0.309  | 0.001        | 0.317   | 0.007        | 0.307  | 0.003        | 0.33   | 0.020        | 0.317   | 0.007        | Note 4  |              | Note 4   |              |
| D1                                       | Flat Hole     | 0.156                    | 0.159  | 0.003        | 0.147   | 0.009        | 0.158  | 0.002        | 0.158  | 0.002        | 0.150   | 0.006        | 0.148  | 0.008        | 0.151  | 0.005        | Note 4  |              | 0.161   | 0.005        | 0.150  | 0.006        |
| D2                                       | Flat Hole     | 0.157                    | 0.158  | 0.001        | 0.155   | 0.002        | 0.163  | 0.006        | 0.158  | 0.001        | 0.160   | 0.003        | 0.15   | 0.007        | 0.153  | 0.004        | Note 4  |              | 0.161   | 0.004        | 0.150  | 0.007        |
| D3                                       | Flat Hole     | 0.161                    | 0.158  | 0.003        | 0.155   | 0.006        | 0.160  | 0.001        | 0.147  | 0.014        | 0.169   | 0.008        | 0.148  | 0.013        | 0.151  | 0.010        | Note 4  |              | 0.161   | 0.000        | 0.145  | 0.016        |
| D4                                       | Flat Hole     | 0.155                    | 0.155  | 0.000        | 0.151   | 0.004        | 0.157  | 0.002        | 0.155  | 0.000        | 0.169   | 0.014        | 0.288  | 0.133        | 0.151  | 0.004        | Note 4  |              | Note 1  |              | 0.19   | 0.035        |
| D5                                       | Flat Hole     | 0.155                    | 0.159  | 0.004        | 0.151   | 0.004        | 0.162  | 0.007        | 0.144  | 0.011        | 0.155   | 0.000        | 0.433  | 0.278        | 0.127  | 0.028        | Note 4  |              | Note 1  |              | Note 4   |              |
| E1                                       | Shaped Hole   | 0.299                    | 0.300  | 0.001        | 0.288   | 0.011        | 0.294  | 0.005        | 0.309  | 0.010        | 0.302   | 0.003        | 0.298  | 0.001        | 0.29   | 0.009        | 0.314   | 0.015        | Note 2  |              | Note 2   |              |
| E2                                       | Shaped Hole   | 0.438                    | 0.445  | 0.007        | 0.435   | 0.003        | 0.436  | 0.002        | 0.439  | 0.001        | 0.448   | 0.010        | 0.446  | 0.008        | 0.436  | 0.002        | 0.447   | 0.009        | Note 2  |              | Note 2   |              |
| E3                                       | Shaped Hole   | 0.564                    | 0.561  | 0.003        | 0.547   | 0.017        | 0.542  | 0.022        | 0.601  | 0.037        | 0.597   | 0.033        | 0.19   | 0.374        | 0.491  | 0.073        | Note 5  |              | Note 2  |              | Note 2   |              |
| E4                                       | Shaped Hole   | 0.259                    | 0.328  | 0.069        | 0.320   | 0.061        | 0.256  | 0.003        | 0.324  | 0.065        | 0.331   | 0.072        | 0.36   | 0.101        | 0.297  | 0.038        | 0.336   | 0.077        | 0.28  | 0.021        | Note 2   |              |
| RMS Error                                |               |                          | 0.014  |              | 0.014   |              | 0.007  |              | 0.016  |              | 0.018   |              | 0.099  |              | 0.019  |              | 0.023   |              | 0.007   |              | 0.017  |              |

Note 1: Ringdown of probe or interface reflection interfering with backwall signal.  
 Note 2: Could not resolve backwall signal(s) due to interference with background noise.  
 Note 3: Frequency too low to resolve backwall multiple reflections.  
 Note 4: Instrument indicated "invalid" measurement due to low signal amplitude or due to extra tape layer reflection.

**Table 3-6**  
**Ultrasonic thickness data collected on 20-mil coal tar epoxy specimen at 72°F**

| BLOCK 7 - Coal Tar Epoxy 20 mils @ 72° F |               |                          |  |              |   |              |  |              |  |              |   |              |  |              |  |              |   |              |   |              |  |              |
|--|---------------|--------------------------|--|--------------|---|--------------|--|--------------|--|--------------|---|--------------|--|--------------|--|--------------|---|--------------|---|--------------|--|--------------|
| Flaw ID                                  | Flaw Type     | AS-BUILT Ligament (inch) | Wall Thickness Measurements  |              |   |              |  |              |  |              |   |              |  |              |  |              |   |              |   |              |  |              |
|  |               |                          | TEST 1<br>38DL Plus Thru-Coat<br>SEM Technique<br>7906 Probe 5MHz Dual |              | TEST 2<br>PAUT<br>SEM Technique<br>5MHz w/ Delay Line |              | TEST 3<br>Flaw Detector<br>SEM Technique<br>5MHz w/ Delay Line |              | TEST 4<br>PAUT<br>MEM Technique<br>5MHz w/Delay Line |              | TEST 5<br>Flaw Detector<br>MEM Technique<br>5MHz w/o Delay Line |              | TEST 6<br>Flaw Detector<br>SEM Technique<br>7906 Probe 5MHz Dual |              | TEST 7<br>Flaw Detector<br>SEM Technique<br>1/2", 2.25MHz Dual |              | TEST 8<br>Flaw Detector<br>SEM Technique<br>1MHz 1/2" w/ Delay Line |              | TEST 9<br>Flaw Detector<br>MEM Technique<br>3/4" 2.25MHz Single |              | TEST 10<br>Flaw Detector<br>MEM Technique<br>1" 1.05MHz Single |              |
|  |               |                          | Measurement (inch)   | ERROR (inch) | Measurement (inch)                                    | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)                                   | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)   | ERROR (inch) |
| A1                                       | Square Pocket | 0.062                    | 0.063  | 0.001        | 0.036   | 0.026        | 0.063  | 0.001        | 0.075  | 0.013        | 0.047   | 0.015        | 0.06   | 0.002        | Note 1   | Note 1       | 0.061   | 0.001        | Note 3  |              |  |              |
| A2                                       | Square Pocket | 0.125                    | 0.125  | 0.000        | 0.121   | 0.004        | 0.122  | 0.003        | 0.133  | 0.008        | 0.127   | 0.002        | 0.122  | 0.003        | 0.12   | 0.005        | Note 1  |              | 0.126   | 0.001        | 0.13   | 0.005        |
| A3                                       | Square Pocket | 0.187                    | 0.188  | 0.001        | 0.182   | 0.005        | 0.180  | 0.007        | 0.197  | 0.010        | 0.180   | 0.007        | 0.186  | 0.001        | 0.182  | 0.005        | Note 1  |              | 0.19  | 0.003        | 0.187  | 0.000        |
| A4                                       | Square Pocket | 0.248                    | 0.249  | 0.001        | 0.239   | 0.009        | 0.246  | 0.002        | 0.258  | 0.010        | 0.248   | 0.000        | 0.248  | 0.000        | 0.238  | 0.010        | 0.244   | 0.004        | 0.249   | 0.001        | 0.253  | 0.005        |
| A5                                       | Square Pocket | 0.373                    | 0.374  | 0.001        | 0.368   | 0.005        | 0.370  | 0.003        | 0.384  | 0.011        | 0.377   | 0.004        | 0.375  | 0.002        | 0.363  | 0.010        | 0.37  | 0.003        | 0.379   | 0.006        | 0.381  | 0.008        |
| A6                                       | Square Pocket | 0.498                    | 0.500  | 0.002        | 0.493   | 0.005        | 0.502  | 0.004        | 0.510  | 0.012        | 0.506   | 0.008        | 0.505  | 0.007        | 0.483  | 0.015        | 0.498   | 0.000        | 0.505   | 0.007        | 0.502  | 0.004        |
| B1                                       | Flat Hole     | 0.469                    | 0.469  | 0.000        | 0.464   | 0.005        | 0.471  | 0.002        | 0.474  | 0.005        | 0.476   | 0.007        | 0.473  | 0.004        | 0.453  | 0.016        | 0.467   | 0.002        | 0.476   | 0.007        | 0.461  | 0.008        |
| B2                                       | Flat Hole     | 0.469                    | 0.469  | 0.000        | 0.471   | 0.002        | 0.473  | 0.004        | 0.474  | 0.005        | 0.476   | 0.007        | 0.473  | 0.004        | 0.453  | 0.016        | 0.465   | 0.004        | 0.474   | 0.005        | 0.473  | 0.004        |
| B3                                       | Flat Hole     | 0.472                    | 0.472  | 0.000        | 0.471   | 0.001        | 0.476  | 0.004        | 0.477  | 0.005        | 0.480   | 0.008        | 0.473  | 0.001        | 0.457  | 0.015        | 0.463   | 0.009        | 0.473   | 0.001        | 0.473  | 0.001        |
| B4                                       | Flat Hole     | 0.467                    | 0.469  | 0.002        | 0.464   | 0.003        | 0.473  | 0.006        | 0.474  | 0.007        | 0.478   | 0.011        | 0.472  | 0.005        | 0.45   | 0.017        | 0.465   | 0.002        | 0.473   | 0.006        | Note 2   |              |
| B5                                       | Flat Hole     | 0.465                    | 0.469  | 0.004        | 0.468   | 0.003        | 0.473  | 0.008        | 0.474  | 0.009        | 0.483   | 0.018        | 0.469  | 0.004        | 0.472  | 0.007        | 0.468   | 0.003        | Note 2  |              | Note 2   |              |
| C1                                       | Flat Hole     | 0.312                    | 0.314  | 0.002        | 0.307   | 0.005        | 0.307  | 0.005        | 0.319  | 0.007        | 0.321   | 0.009        | 0.314  | 0.002        | 0.3  | 0.012        | 0.32  | 0.008        | 0.322   | 0.010        | 0.312  | 0.000        |
| C2                                       | Flat Hole     | 0.314                    | 0.313  | 0.001        | 0.307   | 0.007        | 0.309  | 0.005        | 0.323  | 0.009        | 0.323   | 0.009        | 0.313  | 0.001        | 0.304  | 0.010        | 0.322   | 0.008        | 0.320   | 0.006        | 0.315  | 0.001        |
| C3                                       | Flat Hole     | 0.314                    | 0.314  | 0.000        | 0.311   | 0.003        | 0.309  | 0.005        | 0.323  | 0.009        | 0.328   | 0.014        | 0.313  | 0.001        | 0.304  | 0.010        | 0.321   | 0.007        | 0.315   | 0.001        | 0.308  | 0.006        |
| C4                                       | Flat Hole     | 0.311                    | 0.313  | 0.002        | 0.311   | 0.000        | 0.316  | 0.005        | 0.323  | 0.012        | 0.321   | 0.010        | 0.313  | 0.002        | 0.302  | 0.009        | 0.322   | 0.011        | Note 2  |              | Note 2   |              |
| C5                                       | Flat Hole     | 0.31                     | 0.313  | 0.003        | 0.307   | 0.003        | 0.312  | 0.002        | 0.319  | 0.009        | 0.328   | 0.018        | 0.31   | 0.000        | 0.307  | 0.003        | 0.313   | 0.003        | Note 2  |              | Note 2   |              |
| D1                                       | Flat Hole     | 0.156                    | 0.157  | 0.001        | 0.146   | 0.010        | 0.143  | 0.013        | 0.161  | 0.005        | 0.155   | 0.001        | 0.155  | 0.001        | 0.146  | 0.010        | Note 1  |              | 0.156   | 0.000        | 0.159  | 0.003        |
| D2                                       | Flat Hole     | 0.157                    | 0.156  | 0.001        | 0.150   | 0.007        | 0.150  | 0.007        | 0.158  | 0.001        | 0.150   | 0.007        | 0.155  | 0.002        | 0.125  | 0.032        | Note 1  |              | 0.156   | 0.001        | 0.154  | 0.003        |
| D3                                       | Flat Hole     | 0.161                    | 0.157  | 0.004        | 0.150   | 0.011        | 0.150  | 0.011        | 0.169  | 0.008        | 0.159   | 0.002        | 0.154  | 0.007        | 0.149  | 0.012        | Note 1  |              | 0.152   | 0.009        | 0.151  | 0.010        |
| D4                                       | Flat Hole     | 0.155                    | 0.157  | 0.002        | 0.150   | 0.005        | 0.148  | 0.007        | 0.158  | 0.003        | 0.155   | 0.000        | 0.15   | 0.005        | 0.144  | 0.011        | Note 1  |              | Note 2  |              | Note 2   |              |
| D5                                       | Flat Hole     | 0.155                    | 0.154  | 0.001        | 0.154   | 0.001        | 0.157  | 0.002        | 0.161  | 0.006        | 0.061   | 0.094        | 0.151  | 0.004        | 0.12   | 0.035        | Note 1  |              | Note 2  |              | Note 2   |              |
| E1                                       | Shaped Hole   | 0.299                    | 0.305  | 0.006        | 0.289   | 0.010        | 0.298  | 0.001        | 0.309  | 0.010        | 0.295   | 0.004        | 0.298  | 0.001        | 0.29   | 0.009        | 0.31  | 0.011        | Note 2  |              | Note 2   |              |
| E2                                       | Shaped Hole   | 0.438                    | 0.440  | 0.002        | 0.436   | 0.002        | 0.443  | 0.005        | 0.463  | 0.025        | 0.459   | 0.021        | 0.446  | 0.008        | 0.455  | 0.017        | 0.348   | 0.090        | Note 2  |              | Note 2   |              |
| E3                                       | Shaped Hole   | 0.564                    | 0.563  | 0.001        | 0.568   | 0.004        | 0.562  | 0.002        | 0.531  | 0.033        | 0.602   | 0.038        | 0.609  | 0.045        | 0.495  | 0.069        | Note 2  |              | Note 2  |              | Note 2   |              |
| E4                                       | Shaped Hole   | 0.259                    | 0.260  | 0.001        | 0.332   | 0.073        | 0.258  | 0.001        | 0.337  | 0.078        | 0.319   | 0.060        | 0.326  | 0.067        | 0.295  | 0.036        | Note 2  |              | 0.251   | 0.008        | Note 2   |              |
|  | RMS Error     |                          |  | 0.002        |   | 0.016        |  | 0.005        |  | 0.019        |   | 0.025        |  | 0.017        |  | 0.021        |   | 0.024        |   | 0.005        |  | 0.005        |

Note 1: Ringdown of probe or interface reflection interfering with backwall signal.  
 Note 2: Could not resolve backwall signal(s) due to interference with background noise.  
 Note 3: Frequency too low to resolve backwall multiple reflections.  
 Note 4: Instrument indicated "invalid" measurement due to low signal amplitude or due to extra tape layer reflection.

**Table 3-7**  
**Ultrasonic thickness data collected on 20-mil coal tar epoxy specimen at 92°F**

| BLOCK 7 - Coal Tar Epoxy 20 mils @ 92° F |               |                          |  |              |   |              |  |              |  |              |   |              |  |              |  |              |   |              |   |              |  |              |
|--|---------------|--------------------------|--|--------------|---|--------------|--|--------------|--|--------------|---|--------------|--|--------------|--|--------------|---|--------------|---|--------------|--|--------------|
| Flaw ID                                  | Flaw Type     | AS-BUILT Ligament (inch) | Wall Thickness Measurements  |              |   |              |  |              |  |              |   |              |  |              |  |              |   |              |   |              |  |              |
|  |               |                          | TEST 1<br>38DL Plus Thru-Coat<br>SEM Technique<br>7906 Probe 5MHz Dual |              | TEST 2<br>PAUT<br>SEM Technique<br>5MHz w/ Delay Line |              | TEST 3<br>Flaw Detector<br>SEM Technique<br>5MHz w/ Delay Line |              | TEST 4<br>PAUT<br>MEM Technique<br>5MHz w/Delay Line |              | TEST 5<br>Flaw Detector<br>MEM Technique<br>5MHz w/o Delay Line |              | TEST 6<br>Flaw Detector<br>SEM Technique<br>7906 Probe 5MHz Dual |              | TEST 7<br>Flaw Detector<br>SEM Technique<br>1/2", 2.25MHz Dual |              | TEST 8<br>Flaw Detector<br>SEM Technique<br>1MHz 3/2" w/ Delay Line |              | TEST 9<br>Flaw Detector<br>MEM Technique<br>3/4" 2.25MHz Single |              | TEST 10<br>Flaw Detector<br>MEM Technique<br>1" 1.05MHz Single |              |
|  |               |                          | Measurement (inch)   | ERROR (inch) | Measurement (inch)                                    | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)                                   | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)   | ERROR (inch) |
| A1                                       | Square Pocket | 0.062                    | 0.063  | 0.001        | 0.075   | 0.013        | 0.058  | 0.004        | 0.061  | 0.001        | 0.063   | 0.001        | 0.06   | 0.002        | Note 1   |              | Note 4  |              | 0.061   | 0.001        | Note 3   |              |
| A2                                       | Square Pocket | 0.125                    | 0.126  | 0.001        | 0.157   | 0.032        | 0.133  | 0.008        | 0.132  | 0.007        | 0.128   | 0.003        | 0.121  | 0.004        | 0.112  | 0.013        | Note 4  |              | 0.126   | 0.001        | 0.123  | 0.002        |
| A3                                       | Square Pocket | 0.187                    | 0.190  | 0.003        | 0.189   | 0.002        | 0.189  | 0.002        | 0.191  | 0.004        | 0.189   | 0.002        | 0.186  | 0.001        | 0.188  | 0.001        | Note 4  |              | 0.194   | 0.007        | 0.192  | 0.005        |
| A4                                       | Square Pocket | 0.248                    | 0.252  | 0.004        | 0.250   | 0.002        | 0.250  | 0.002        | 0.252  | 0.004        | 0.240   | 0.008        | 0.248  | 0.000        | 0.243  | 0.005        | 0.241   | 0.007        | 0.254   | 0.006        | 0.251  | 0.003        |
| A5                                       | Square Pocket | 0.373                    | 0.379  | 0.006        | 0.379   | 0.006        | 0.376  | 0.003        | 0.378  | 0.005        | 0.373   | 0.000        | 0.374  | 0.001        | 0.376  | 0.003        | 0.322   | 0.051        | 0.379   | 0.006        | 0.382  | 0.009        |
| A6                                       | Square Pocket | 0.498                    | 0.506  | 0.008        | 0.514   | 0.016        | 0.502  | 0.004        | 0.504  | 0.006        | 0.501   | 0.003        | 0.505  | 0.007        | 0.5  | 0.002        | 0.501   | 0.003        | 0.509   | 0.011        | 0.509  | 0.011        |
| B1                                       | Flat Hole     | 0.469                    | 0.476  | 0.007        | 0.471   | 0.002        | 0.470  | 0.001        | 0.471  | 0.002        | 0.468   | 0.001        | 0.473  | 0.004        | 0.471  | 0.002        | 0.467   | 0.002        | 0.476   | 0.007        | 0.461  | 0.008        |
| B2                                       | Flat Hole     | 0.469                    | 0.475  | 0.006        | 0.471   | 0.002        | 0.472  | 0.003        | 0.471  | 0.002        | 0.468   | 0.001        | 0.472  | 0.003        | 0.467  | 0.002        | 0.465   | 0.004        | 0.474   | 0.005        | 0.473  | 0.004        |
| B3                                       | Flat Hole     | 0.472                    | 0.473  | 0.001        | 0.475   | 0.003        | 0.470  | 0.002        | 0.471  | 0.001        | 0.470   | 0.002        | 0.473  | 0.001        | 0.474  | 0.002        | 0.463   | 0.009        | 0.495   | 0.023        | 0.476  | 0.004        |
| B4                                       | Flat Hole     | 0.467                    | 0.476  | 0.009        | 0.475   | 0.008        | 0.470  | 0.003        | 0.471  | 0.004        | 0.466   | 0.001        | 0.471  | 0.004        | 0.467  | 0.000        | 0.465   | 0.002        | 0.455   | 0.012        | Note 4   |              |
| B5                                       | Flat Hole     | 0.465                    | 0.473  | 0.008        | 0.486   | 0.021        | 0.474  | 0.009        | 0.478  | 0.013        | 0.470   | 0.005        | 0.467  | 0.002        | 0.464  | 0.001        | 0.468   | 0.003        | Note 1  |              | Note 4   |              |
| C1                                       | Flat Hole     | 0.312                    | 0.317  | 0.005        | 0.318   | 0.006        | 0.315  | 0.003        | 0.317  | 0.005        | 0.314   | 0.002        | 0.314  | 0.002        | 0.317  | 0.005        | 0.32  | 0.008        | 0.315   | 0.003        | 0.313  | 0.001        |
| C2                                       | Flat Hole     | 0.314                    | 0.316  | 0.002        | 0.321   | 0.007        | 0.313  | 0.001        | 0.313  | 0.001        | 0.324   | 0.010        | 0.312  | 0.002        | 0.317  | 0.003        | 0.322   | 0.008        | 0.318   | 0.004        | 0.310  | 0.004        |
| C3                                       | Flat Hole     | 0.314                    | 0.316  | 0.002        | 0.325   | 0.011        | 0.313  | 0.001        | 0.313  | 0.001        | 0.324   | 0.010        | 0.311  | 0.003        | 0.317  | 0.003        | 0.321   | 0.007        | 0.322   | 0.008        | 0.315  | 0.001        |
| C4                                       | Flat Hole     | 0.311                    | 0.316  | 0.005        | 0.329   | 0.018        | 0.311  | 0.000        | 0.313  | 0.002        | 0.321   | 0.010        | 0.311  | 0.000        | 0.317  | 0.006        | 0.322   | 0.011        | 0.275   | 0.036        | Note 4   |              |
| C5                                       | Flat Hole     | 0.31                     | 0.315  | 0.005        | 0.325   | 0.015        | 0.308  | 0.002        | 0.302  | 0.008        | 0.321   | 0.011        | 0.309  | 0.001        | 0.312  | 0.002        | 0.313   | 0.003        | Note 1  |              | Note 4   |              |
| D1                                       | Flat Hole     | 0.156                    | 0.159  | 0.003        | 0.168   | 0.012        | 0.157  | 0.001        | 0.164  | 0.008        | 0.156   | 0.000        | 0.154  | 0.002        | 0.136  | 0.020        | Note 4  |              | 0.159   | 0.003        | 0.161  | 0.005        |
| D2                                       | Flat Hole     | 0.157                    | 0.158  | 0.001        | 0.171   | 0.014        | 0.157  | 0.000        | 0.157  | 0.000        | 0.156   | 0.001        | 0.153  | 0.004        | 0.138  | 0.019        | Note 4  |              | 0.154   | 0.003        | 0.159  | 0.002        |
| D3                                       | Flat Hole     | 0.161                    | 0.158  | 0.003        | 0.164   | 0.003        | 0.154  | 0.007        | 0.164  | 0.003        | 0.156   | 0.005        | 0.154  | 0.007        | 0.138  | 0.023        | Note 4  |              | 0.159   | 0.002        | 0.156  | 0.005        |
| D4                                       | Flat Hole     | 0.155                    | 0.157  | 0.002        | 0.164   | 0.009        | 0.145  | 0.010        | 0.168  | 0.013        | 0.154   | 0.001        | 0.153  | 0.002        | 0.133  | 0.022        | Note 4  |              | Note 1  |              | Note 4   |              |
| D5                                       | Flat Hole     | 0.155                    | 0.155  | 0.000        | 0.168   | 0.013        | 0.152  | 0.003        | 0.175  | 0.020        | 0.165   | 0.010        | 0.151  | 0.004        | 0.136  | 0.019        | Note 4  |              | Note 1  |              | Note 4   |              |
| E1                                       | Shaped Hole   | 0.299                    | 0.300  | 0.001        | 0.304   | 0.005        | 0.299  | 0.000        | 0.313  | 0.014        | 0.285   | 0.014        | 0.298  | 0.001        | 0.312  | 0.013        | 0.31  | 0.011        | Note 2  |              | Note 2   |              |
| E2                                       | Shaped Hole   | 0.438                    | 0.448  | 0.010        | 0.450   | 0.012        | 0.456  | 0.018        | 0.446  | 0.008        | 0.430   | 0.008        | 0.446  | 0.008        | 0.45   | 0.012        | 0.348   | 0.090        | Note 2  |              | Note 2   |              |
| E3                                       | Shaped Hole   | 0.564                    | 0.569  | 0.005        | 0.575   | 0.011        | 0.554  | 0.010        | 0.612  | 0.048        | 0.566   | 0.002        | 0.607  | 0.043        | 0.594  | 0.030        | Note 5  |              | Note 2  |              | Note 2   |              |
| E4                                       | Shaped Hole   | 0.259                    | 0.265  | 0.006        | 0.329   | 0.070        | 0.271  | 0.012        | 0.329  | 0.070        | 0.327   | 0.068        | 0.327  | 0.068        | 0.269  | 0.010        | Note 4  |              | 0.306   | 0.047        | Note 2   |              |
|  | RMS Error     |                          |  | 0.005        |   | 0.019        |  | 0.006        |  | 0.018        |   | 0.015        |  | 0.016        |  | 0.013        |   | 0.027        |   | 0.016        |  | 0.005        |

Note 1: Reflector not distinguishable from back wall reflections.  
 Note 2: Second backwall multiple signal could not be resolved.  
 Note 3: Frequency too low to resolve backwall multiple reflections.  
 Note 4: Multiple back wall reflections associated with target not distinguishable from other reflections. Flaw size smaller than beam breating interference from backwall reflections.

### 50-Mil Tape Wrap Coating Specimen

Tables 3-8 through 3-10 summarize the ultrasonic thickness data collected on the 50-mil tape wrap specimen using ultrasonic Tests 1–10 for the three different temperatures tested. Shaded areas on these tables indicate that a valid measurement was not possible. Tests 2–7 all performed well on the 50-mil tape test block, with thickness measurement accuracies ranging from an RMS of 0.003 to 0.025 inch when values were compared to the as-built dimensions for all temperatures. In general, the attenuation created by the coating did not preclude the effective use of 5-MHz probes with relatively small apertures (0.25 to 0.5 inch), which provided the highest-accuracy measurements and ability to resolve small localized reflectors. Two techniques, Test 3 and Test 7, demonstrated a limitation on very thin steels (0.062 inch or less) due to two different causes. Test 3 used a 5-MHz transducer with a delay line where the ringing associated with the coating-to-metal interface signal interfered with the reception of the first back wall reflection, making a single back wall measurement impossible, as shown in Figure 3-20. Test 7 utilized the largest dual-element transducer tested in this investigation. This transducer had difficulty with very thin materials since the transmitter and receiver elements were spaced too far apart for proper straight line reception. A smaller dual-element transducer operated at a higher frequency, like that used in Test 6, performed very well on thin-wall materials, as shown in Figure 3-21.

Tests 8, 9, and 10 did not perform as well on the 50-mil coating when compared to Tests 2–7. The observed deficiencies were related to the use of lower-frequency probes with larger element sizes. Signals related to small reflectors were not easily detected using the larger probes, and the lower-frequency probes were incapable of resolving thinner material due to the larger wavelengths and signal ringing. The data obtained on the 50-mil specimen indicated that the use of lower-frequency probes with large elements was not warranted, since attenuation associated with this coating did not prevent the use of smaller, higher-frequency probes with better resolution characteristics.

Temperature did have some effect on this coating material, with moderate increase in sound attenuation with an increase in temperature. This was more notable with Test 1 using the thickness gage instrument. This technique relied on an algorithm for signal identification and thickness measurement. Although this technique functioned very well at ambient and lower temperatures, the reduction in signal amplitude experienced at the highest temperature (92°F) resulted in the instrument displaying an “invalid measurement” warning. This warning is provided by the instrument manufacturer when proper signal identification is in question, indicating that thickness readings are invalid. Temperature did not significantly impact the results of the remaining techniques tested. As a result, use of a thickness gage/probe combination like that used in Test 1 is not recommended for 50-mil tape wrap.

In conclusion, it can be stated that the thickness of a pipe wall coated with 50-mil tape wrap should be measureable ultrasonically with excellent accuracy as long as the integrity of the bond between the tape and the pipe outer surface has not degraded, allowing the sound to enter into the pipe wall. The 50-mil specimen exhibited good bond quality over the entire specimen. These results suggest that whenever possible, measurements should be performed in single-layer regions where the tape has not been overlapped. The results also suggested that transducers operating at as high as 5 MHz should be used with crystal sizes ranging from 0.25 to 0.5 inch in diameter. Both conventional and phased array techniques performed well on this coating. The use of lower-frequency probes using large crystal sizes should be considered as a last resort when penetration difficulties prevail. Finally, the use of thickness gages on this coating is not recommended. Overall, the 50-mil tape wrap coating is compatible for collecting wall thickness measurements without requiring removal under ideal conditions.

**Table 3-8**  
**Ultrasonic thickness data collected on 50-mil tape wrap specimen at 52°F**

| BLOCK 5 - Tape Wrap 50 mils @ 52 Degrees F |               |                          |  |              |   |              |  |              |   |              |   |              |  |              |   |              |   |              |   |              |  |              |
|--|---------------|--------------------------|--|--------------|---|--------------|--|--------------|---|--------------|---|--------------|--|--------------|---|--------------|---|--------------|---|--------------|--|--------------|
| Flaw ID                                    | Flaw Type     | AS-BUILT Ligament (inch) | Wall Thickness Measurements  |              |   |              |  |              |   |              |   |              |  |              |   |              |   |              |   |              |  |              |
|  |               |                          | TEST 1<br>38DL Plus Thru-Coat<br>SEM Technique<br>7906 Probe 5MHz Dual |              | TEST 2<br>PAUT<br>SEM Technique<br>5MHz w/ Delay Line |              | TEST 3<br>Flaw Detector<br>SEM Technique<br>5MHz w/ Delay Line |              | TEST 4<br>PAUT<br>MEM Technique<br>5MHz w/ Delay Line |              | TEST 5<br>Flaw Detector<br>MEM Technique<br>5MHz w/o Delay Line |              | TEST 6<br>Flaw Detector<br>SEM Technique<br>7906 Probe 5MHz Dual |              | TEST 7<br>Flaw Detector<br>SEM Technique<br>1/2" 2.25MHz Dual |              | TEST 8<br>Flaw Detector<br>SEM Technique<br>1MHz 3/2" w/ Delay Line |              | TEST 9<br>Flaw Detector<br>MEM Technique<br>3/4" 2.25MHz Single |              | TEST 10<br>Flaw Detector<br>MEM Technique<br>1" 1.05MHz Single |              |
|  |               |                          | Measurement (inch)   | ERROR (inch) | Measurement (inch)                                    | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)                                    | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)   | ERROR (inch) |
| A1   | Square Pocket | 0.062                    | 0.057  | 0.005        | 0.068   | 0.006        | Note 1   |              | 0.057   | 0.005        | 0.062   | 0.000        | 0.069  | 0.007        | Note 1  |              | Note 1  |              | 0.062   | 0.000        | Note 4   |              |
| A2   | Square Pocket | 0.125                    | 0.121  | 0.004        | 0.129   | 0.004        | 0.115  | 0.010        | 0.121   | 0.004        | 0.117   | 0.008        | 0.128  | 0.003        | 0.111   | 0.014        | Note 1  |              | 0.125   | 0.000        | 0.13   | 0.005        |
| A3   | Square Pocket | 0.187                    | 0.185  | 0.002        | 0.194   | 0.007        | 0.19   | 0.003        | 0.186   | 0.001        | 0.19  | 0.003        | 0.192  | 0.005        | 0.177   | 0.010        | Note 1  |              | 0.189   | 0.002        | 0.166  | 0.021        |
| A4   | Square Pocket | 0.248                    | 0.247  | 0.001        | 0.25  | 0.002        | 0.258  | 0.010        | 0.246   | 0.002        | 0.255   | 0.007        | 0.248  | 0.000        | 0.231   | 0.017        | 0.254   | 0.006        | 0.251   | 0.003        | 0.238  | 0.010        |
| A5   | Square Pocket | 0.373                    | 0.372  | 0.001        | 0.379   | 0.006        | 0.375  | 0.002        | 0.368   | 0.005        | 0.381   | 0.008        | 0.381  | 0.008        | 0.375   | 0.002        | 0.375   | 0.002        | 0.379   | 0.006        | 0.413  | 0.040        |
| A6   | Square Pocket | 0.498                    | 0.499  | 0.001        | 0.507   | 0.009        | 0.502  | 0.004        | 0.504   | 0.006        | 0.5   | 0.002        | 0.507  | 0.009        | 0.502   | 0.004        | 0.496   | 0.002        | 0.506   | 0.008        | 0.475  | 0.023        |
| B1   | Flat Hole     | 0.469                    | 0.469  | 0.000        | 0.471   | 0.002        | 0.47   | 0.001        | 0.468   | 0.001        | 0.479   | 0.010        | 0.478  | 0.009        | 0.483   | 0.014        | 0.493   | 0.024        | 0.474   | 0.005        | 0.455  | 0.014        |
| B2   | Flat Hole     | 0.469                    | 0.469  | 0.000        | 0.468   | 0.001        | 0.469  | 0.000        | 0.468   | 0.001        | 0.476   | 0.007        | 0.468  | 0.001        | 0.462   | 0.007        | 0.495   | 0.026        | 0.481   | 0.012        | 0.452  | 0.017        |
| B3   | Flat Hole     | 0.472                    | 0.472  | 0.000        | 0.468   | 0.004        | 0.456  | 0.016        | 0.471   | 0.001        | 0.479   | 0.007        | 0.466  | 0.006        | 0.483   | 0.011        | 0.486   | 0.014        | 0.474   | 0.002        | 0.45   | 0.022        |
| B4   | Flat Hole     | 0.467                    | 0.468  | 0.001        | 0.468   | 0.001        | 0.472  | 0.005        | 0.478   | 0.011        | 0.486   | 0.019        | 0.466  | 0.001        | 0.462   | 0.005        | 0.486   | 0.019        | 0.471   | 0.004        | 0.517  | 0.050        |
| B5   | Flat Hole     | 0.465                    | 0.467  | 0.002        | 0.471   | 0.006        | 0.468  | 0.003        | 0.464   | 0.001        | 0.486   | 0.021        | 0.466  | 0.001        | 0.46  | 0.005        | 0.442   | 0.023        | Note 2  |              | Note 2   |              |
| C1   | Flat Hole     | 0.312                    | 0.313  | 0.001        | 0.311   | 0.001        | 0.32   | 0.008        | 0.311   | 0.001        | 0.319   | 0.007        | 0.310  | 0.002        | 0.309   | 0.003        | Note 2  |              | 0.317   | 0.005        | 0.305  | 0.007        |
| C2   | Flat Hole     | 0.314                    | 0.313  | 0.001        | 0.311   | 0.003        | 0.321  | 0.007        | 0.311   | 0.003        | 0.329   | 0.015        | 0.310  | 0.004        | 0.307   | 0.007        | Note 2  |              | 0.317   | 0.003        | 0.299  | 0.015        |
| C3   | Flat Hole     | 0.314                    | 0.314  | 0.000        | 0.314   | 0.000        | 0.321  | 0.007        | 0.314   | 0.000        | 0.329   | 0.015        | 0.310  | 0.004        | 0.311   | 0.003        | Note 2  |              | 0.322   | 0.008        | 0.299  | 0.015        |
| C4   | Flat Hole     | 0.311                    | 0.312  | 0.001        | 0.311   | 0.000        | 0.322  | 0.011        | 0.307   | 0.004        | 0.329   | 0.018        | 0.312  | 0.001        | 0.311   | 0.000        | Note 2  |              | 0.345   | 0.034        | Note 2   |              |
| C5   | Flat Hole     | 0.31                     | 0.31   | 0.000        | 0.314   | 0.004        | 0.321  | 0.011        | 0.318   | 0.008        | 0.317   | 0.007        | 0.312  | 0.002        | 0.333   | 0.023        | Note 2  |              | Note 2  |              | Note 2   |              |
| D1   | Flat Hole     | 0.156                    | 0.154  | 0.002        | 0.157   | 0.001        | 0.171  | 0.015        | 0.154   | 0.002        | 0.15  | 0.006        | 0.158  | 0.002        | 0.13  | 0.026        | Note 1  |              | 0.161   | 0.005        | 0.153  | 0.003        |
| D2   | Flat Hole     | 0.157                    | 0.154  | 0.003        | 0.157   | 0.000        | 0.172  | 0.015        | 0.157   | 0.000        | 0.16  | 0.003        | 0.158  | 0.001        | 0.13  | 0.027        | Note 1  |              | 0.161   | 0.004        | 0.158  | 0.001        |
| D3   | Flat Hole     | 0.161                    | 0.157  | 0.004        | 0.157   | 0.004        | 0.173  | 0.012        | 0.161   | 0.000        | 0.162   | 0.001        | 0.158  | 0.003        | 0.134   | 0.027        | Note 1  |              | 0.161   | 0.000        | 0.155  | 0.006        |
| D4   | Flat Hole     | 0.155                    | 0.152  | 0.003        | 0.157   | 0.002        | 0.172  | 0.017        | 0.154   | 0.001        | 0.157   | 0.002        | 0.156  | 0.001        | 0.127   | 0.028        | Note 1  |              | 0.154   | 0.001        | Note 2   |              |
| D5   | Flat Hole     | 0.155                    | 0.151  | 0.004        | 0.157   | 0.002        | 0.169  | 0.014        | 0.164   | 0.009        | 0.157   | 0.002        | 0.156  | 0.001        | 0.127   | 0.028        | Note 1  |              | Note 2  |              | Note 2   |              |
| E1   | Shaped Hole   | 0.299                    | 0.296  | 0.003        | 0.293   | 0.006        | 0.303  | 0.004        | 0.289   | 0.010        | 0.3   | 0.001        | 0.304  | 0.005        | 0.302   | 0.003        | Note 2  |              | Note 2  |              | Note 2   |              |
| E2   | Shaped Hole   | 0.438                    | 0.451  | 0.013        | 0.436   | 0.002        | 0.433  | 0.005        | 0.435   | 0.003        | 0.457   | 0.019        | 0.438  | 0.000        | 0.434   | 0.004        | Note 2  |              | Note 2  |              | Note 2   |              |
| E3   | Shaped Hole   | 0.564                    | 0.602  | 0.038        | 0.564   | 0.000        | 0.552  | 0.012        | 0.601   | 0.037        | 0.614   | 0.050        | 0.565  | 0.001        | 0.495   | 0.069        | Note 2  |              | Note 2  |              | Note 2   |              |
| E4   | Shaped Hole   | 0.259                    | 0.326  | 0.067        | 0.325   | 0.066        | 0.263  | 0.004        | 0.327   | 0.068        | 0.333   | 0.074        | 0.329  | 0.070        | 0.325   | 0.066        | Note 2  |              | 0.336   | 0.077        | Note 2   |              |
|  | RMS Error     |                          |  | 0.016        |   | 0.014        |  | 0.010        |   | 0.016        |   | 0.020        |  | 0.015        |   | 0.025        |   | 0.017        |   | 0.020        |  | 0.021        |

Note 1: Ringdown of probe or interface reflection interfering with backwall signal.  
 Note 2: Could not resolve backwall signal(s) due to interference with background noise.  
 Note 3: Frequency too low to resolve backwall multiple reflections.  
 Note 4: Instrument indicated "invalid" measurement due to low signal amplitude or due to extra tape layer reflection.

**Table 3-9**  
**Ultrasonic thickness data collected on 50-mil tape wrap specimen at 72°F**

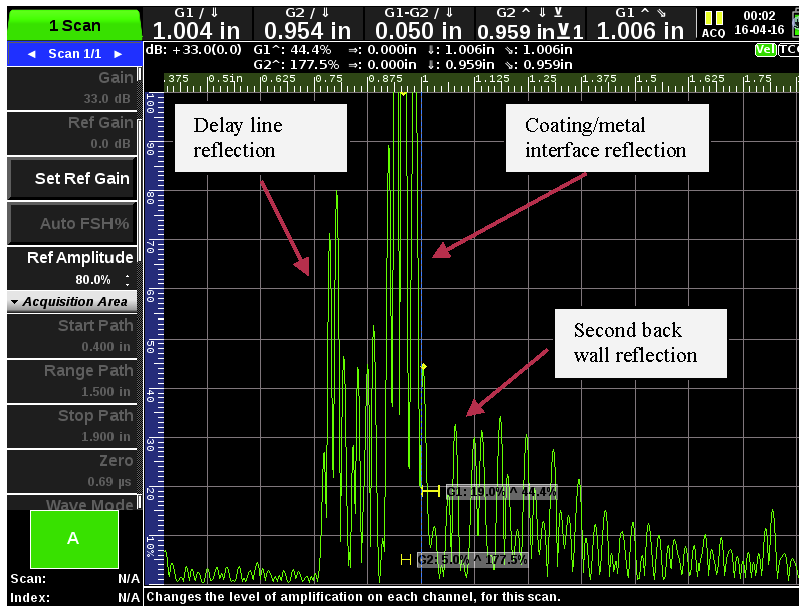
| BLOCK 5 - Tape Wrap 50 mils @ 72 Degrees F |               |                          |  |              |   |              |  |              |  |              |   |              |  |              |   |              |   |              |   |              |  |              |
|--|---------------|--------------------------|--|--------------|---|--------------|--|--------------|--|--------------|---|--------------|--|--------------|---|--------------|---|--------------|---|--------------|--|--------------|
| Flaw ID                                    | Flaw Type     | AS-BUILT Ligament (inch) | Wall Thickness Measurements  |              |   |              |  |              |  |              |   |              |  |              |   |              |   |              |   |              |  |              |
|  |               |                          | TEST 1<br>38DL Plus Thru-Coat<br>SEM Technique<br>7906 Probe 5MHz Dual |              | TEST 2<br>PAUT<br>SEM Technique<br>5MHz w/ Delay Line |              | TEST 3<br>Flaw Detector<br>SEM Technique<br>5MHz w/ Delay Line |              | TEST 4<br>PAUT<br>MEM Technique<br>5MHz w/Delay Line |              | TEST 5<br>Flaw Detector<br>MEM Technique<br>5MHz w/o Delay Line |              | TEST 6<br>Flaw Detector<br>SEM Technique<br>7906 Probe 5MHz Dual |              | TEST 7<br>Flaw Detector<br>SEM Technique<br>1/2" 2.25MHz Dual |              | TEST 8<br>Flaw Detector<br>SEM Technique<br>1MHz 3/2" w/ Delay Line |              | TEST 9<br>Flaw Detector<br>MEM Technique<br>3/4" 2.25MHz Single |              | TEST 10<br>Flaw Detector<br>MEM Technique<br>1" 1.05MHz Single |              |
|  |               |                          | Measurement (inch)   | ERROR (inch) | Measurement (inch)                                    | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)                                   | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)   | ERROR (inch) |
| A1   | Square Pocket | 0.062                    | 0.063  | 0.001        | 0.068   | 0.006        | Note 1   |              | 0.061  | 0.001        | 0.082   | 0.020        | 0.07   | 0.008        | Note 1  |              | Note 1  |              | 0.059   | 0.003        | Note 4   |              |
| A2   | Square Pocket | 0.125                    | 0.127  | 0.002        | 0.098   | 0.027        | 0.127  | 0.002        | 0.123  | 0.002        | 0.131   | 0.006        | 0.129  | 0.004        | 0.127   | 0.002        | Note 1  |              | 0.13  | 0.005        | 0.13   | 0.005        |
| A3   | Square Pocket | 0.187                    | 0.191  | 0.004        | 0.177   | 0.010        | 0.185  | 0.002        | 0.188  | 0.001        | 0.211   | 0.024        | 0.187  | 0.000        | 0.191   | 0.004        | Note 1  |              | 0.192   | 0.005        | 0.185  | 0.002        |
| A4   | Square Pocket | 0.248                    | 0.252  | 0.004        | 0.227   | 0.021        | 0.244  | 0.004        | 0.249  | 0.001        | 0.253   | 0.005        | 0.252  | 0.004        | 0.248   | 0.000        | 0.298   | 0.050        | 0.251   | 0.003        | 0.249  | 0.001        |
| A5   | Square Pocket | 0.373                    | 0.377  | 0.004        | 0.357   | 0.016        | 0.37   | 0.003        | 0.383  | 0.010        | 0.382   | 0.009        | 0.374  | 0.001        | 0.368   | 0.005        | 0.379   | 0.006        | 0.379   | 0.006        | 0.374  | 0.001        |
| A6   | Square Pocket | 0.498                    | 0.504  | 0.006        | 0.498   | 0.000        | 0.466  | 0.032        | 0.502  | 0.004        | 0.504   | 0.006        | 0.501  | 0.003        | 0.462   | 0.036        | 0.499   | 0.001        | 0.5   | 0.002        | 0.505  | 0.007        |
| B1   | Hole          | 0.469                    | 0.474  | 0.005        | 0.466   | 0.003        | 0.476  | 0.007        | 0.471  | 0.002        | 0.471   | 0.002        | 0.471  | 0.002        | 0.46  | 0.009        | 0.475   | 0.006        | 0.479   | 0.010        | 0.472  | 0.003        |
| B2   | Hole          | 0.469                    | 0.473  | 0.004        | 0.466   | 0.003        | 0.473  | 0.004        | 0.468  | 0.001        | 0.476   | 0.007        | 0.469  | 0.000        | 0.465   | 0.004        | 0.477   | 0.008        | 0.476   | 0.007        | 0.474  | 0.005        |
| B3   | Hole          | 0.472                    | 0.475  | 0.003        | 0.469   | 0.003        | 0.473  | 0.001        | 0.468  | 0.004        | 0.471   | 0.001        | 0.471  | 0.001        | 0.465   | 0.007        | 0.478   | 0.006        | 0.476   | 0.004        | 0.46   | 0.012        |
| B4   | Hole          | 0.467                    | 0.471  | 0.004        | 0.466   | 0.001        | 0.471  | 0.004        | 0.471  | 0.004        | 0.473   | 0.006        | 0.466  | 0.001        | 0.462   | 0.005        | 0.477   | 0.010        | 0.469   | 0.002        | Note 2   |              |
| B5   | Hole          | 0.465                    | 0.473  | 0.008        | 0.477   | 0.012        | 0.488  | 0.023        | 0.478  | 0.013        | 0.478   | 0.013        | 0.468  | 0.003        | 0.475   | 0.010        | 0.47  | 0.005        | Note 2  |              | Note 2   |              |
| C1   | Hole          | 0.312                    | 0.318  | 0.006        | 0.303   | 0.009        | 0.307  | 0.005        | 0.311  | 0.001        | 0.312   | 0.000        | 0.316  | 0.004        | 0.311   | 0.001        | Note 2  |              | 0.318   | 0.006        | 0.315  | 0.003        |
| C2   | Hole          | 0.314                    | 0.318  | 0.004        | 0.311   | 0.003        | 0.307  | 0.007        | 0.311  | 0.003        | 0.309   | 0.005        | 0.316  | 0.002        | 0.311   | 0.003        | Note 2  |              | 0.318   | 0.004        | 0.315  | 0.001        |
| C3   | Hole          | 0.314                    | 0.317  | 0.003        | 0.311   | 0.003        | 0.312  | 0.002        | 0.314  | 0.000        | 0.312   | 0.002        | 0.315  | 0.001        | 0.314   | 0.000        | Note 2  |              | 0.320   | 0.006        | 0.313  | 0.001        |
| C4   | Hole          | 0.311                    | 0.315  | 0.004        | 0.311   | 0.000        | 0.321  | 0.010        | 0.307  | 0.004        | 0.309   | 0.002        | 0.315  | 0.004        | 0.311   | 0.000        | Note 2  |              | Note 2  |              | Note 2   |              |
| C5   | Hole          | 0.31                     | 0.315  | 0.005        | 0.3   | 0.010        | 0.319  | 0.009        | 0.293  | 0.017        | 0.321   | 0.011        | 0.312  | 0.002        | 0.311   | 0.001        | Note 2  |              | Note 2  |              | Note 2   |              |
| D1   | Hole          | 0.156                    | 0.16   | 0.004        | 0.152   | 0.004        | 0.15   | 0.006        | 0.157  | 0.001        | 0.155   | 0.001        | 0.163  | 0.007        | 0.134   | 0.022        | Note 2  |              | 0.159   | 0.003        | 0.173  | 0.017        |
| D2   | Hole          | 0.157                    | 0.16   | 0.003        | 0.152   | 0.005        | 0.148  | 0.009        | 0.154  | 0.003        | 0.164   | 0.007        | 0.16   | 0.003        | 0.132   | 0.025        | Note 2  |              | 0.159   | 0.002        | 0.176  | 0.019        |
| D3   | Hole          | 0.161                    | 0.159  | 0.002        | 0.144   | 0.017        | 0.159  | 0.002        | 0.157  | 0.004        | 0.157   | 0.004        | 0.16   | 0.001        | 0.132   | 0.029        | Note 2  |              | 0.161   | 0.000        | Note 2   |              |
| D4   | Hole          | 0.155                    | 0.158  | 0.003        | 0.155   | 0.000        | 0.159  | 0.004        | 0.154  | 0.001        | 0.162   | 0.007        | 0.158  | 0.003        | 0.13  | 0.025        | Note 2  |              | Note 2  |              | Note 2   |              |
| D5   | Hole          | 0.155                    | 0.157  | 0.002        | 0.155   | 0.000        | 0.162  | 0.007        | 0.154  | 0.001        | 0.169   | 0.014        | 0.159  | 0.004        | 0.134   | 0.021        | Note 2  |              | Note 2  |              | Note 2   |              |
| E1   | Hole          | 0.299                    | 0.305  | 0.006        | 0.311   | 0.012        | 0.3  | 0.001        | 0.324  | 0.025        | 0.312   | 0.013        | 0.294  | 0.005        | 0.297   | 0.002        | Note 2  |              | Note 2  |              | Note 2   |              |
| E2   | Hole          | 0.438                    | 0.445  | 0.007        | 0.437   | 0.001        | 0.45   | 0.012        | 0.435  | 0.003        | 0.436   | 0.002        | 0.44   | 0.002        | 0.439   | 0.001        | Note 2  |              | Note 2  |              | Note 2   |              |
| E3   | Hole          | 0.564                    | 0.606  | 0.042        | 0.563   | 0.001        | 0.6  | 0.036        | 0.601  | 0.037        | 0.605   | 0.041        | 0.565  | 0.001        | 0.505   | 0.059        | Note 2  |              | Note 2  |              | Note 2   |              |
| E4   | Hole          | 0.259                    | 0.332  | 0.073        | 0.325   | 0.066        | 0.258  | 0.001        | 0.335  | 0.076        | 0.321   | 0.062        | 0.263  | 0.004        | 0.304   | 0.045        | Note 2  |              | 0.248   | 0.011        | Note 2   |              |
|  | RMS Error     |                          |  | 0.017        |   | 0.016        |  | 0.012        |  | 0.018        |   | 0.017        |  | 0.003        |   | 0.021        |   | 0.019        |   | 0.005        |  | 0.008        |

Note 1: Ringdown of probe or interface reflection interfering with backwall signal.  
 Note 2: Could not resolve backwall signal(s) due to interference with background noise.  
 Note 3: Frequency too low to resolve backwall multiple reflections.  
 Note 4: Instrument indicated "invalid" measurement due to low signal amplitude or due to extra tape layer reflection.

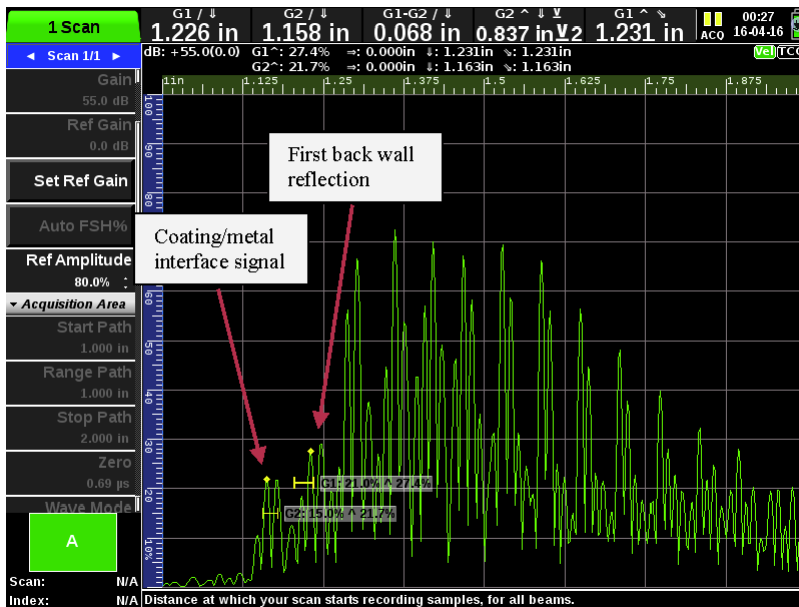
**Table 3-10**  
**Ultrasonic thickness data collected on 50-mil tape wrap specimen at 92°F**

| BLOCK 5 - Tape Wrap 50 mils @ 92 Degrees F |               |                          |  |              |  |              |  |              |  |              |  |              |  |              |   |              |   |              |   |              |  |              |
|--|---------------|--------------------------|--|--------------|--|--------------|--|--------------|--|--------------|--|--------------|--|--------------|---|--------------|---|--------------|---|--------------|--|--------------|
| Flaw ID                                    | Flaw Type     | AS-BUILT Ligament (inch) | Wall Thickness Measurements  |              |  |              |  |              |  |              |  |              |  |              |   |              |   |              |   |              |  |              |
|  |               |                          | TEST 1<br>38DL Plus Thru-Coat<br>SEM Technique<br>7995 Probe 5MHz Dual |              | TEST 2<br>PALUT<br>SEM Technique<br>5MHz w/ Delay Line |              | TEST 3<br>Flaw Detector<br>SEM Technique<br>5MHz w/ Delay Line |              | TEST 4<br>PALUT<br>MEM Technique<br>5MHz w/ Delay Line |              | TEST 5<br>Flaw Detector<br>MEM Technique<br>5MHz w/ Delay Line |              | TEST 6<br>Flaw Detector<br>SEM Technique<br>7995 Probe 5MHz Dual |              | TEST 7<br>Flaw Detector<br>SEM Technique<br>1/2" 2.25MHz Dual |              | TEST 8<br>Flaw Detector<br>SEM Technique<br>1MHz 1/2" w/ Delay Line |              | TEST 9<br>Flaw Detector<br>MEM Technique<br>3/4" 2.25MHz Single |              | TEST 10<br>Flaw Detector<br>MEM Technique<br>1" 1.05MHz Single |              |
|  |               |                          | Measurement (inch)   | ERROR (inch) | Measurement (inch)                                     | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)                                     | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)   | ERROR (inch) |
| A1   | Square Pocket | 0.062                    | Note 4   |              | 0.061  | 0.001        | Note 1   |              | 0.061  | 0.001        | 0.08   | 0.018        | 0.070  | 0.008        | Note 1  |              | Note 1  |              | 0.061   | 0.001        | Note 4   |              |
| A2   | Square Pocket | 0.125                    | Note 4   |              | 0.126  | 0.001        | 0.123  | 0.002        | 0.125  | 0.000        | 0.121  | 0.004        | 0.131  | 0.006        | 0.132   | 0.007        | Note 1  |              | 0.127   | 0.002        | 0.126  | 0.001        |
| A3   | Square Pocket | 0.187                    | Note 4   |              | 0.187  | 0.000        | 0.189  | 0.002        | 0.189  | 0.002        | 0.187  | 0.000        | 0.192  | 0.005        | 0.196   | 0.009        | Note 1  |              | 0.191   | 0.004        | 0.194  | 0.007        |
| A4   | Square Pocket | 0.248                    | Note 4   |              | 0.248  | 0.000        | 0.248  | 0.000        | 0.246  | 0.002        | 0.236  | 0.012        | 0.251  | 0.003        | 0.255   | 0.007        | 0.231   | 0.017        | 0.252   | 0.004        | 0.249  | 0.001        |
| A5   | Square Pocket | 0.373                    | Note 4   |              | 0.363  | 0.010        | 0.375  | 0.002        | 0.371  | 0.002        | 0.371  | 0.002        | 0.375  | 0.002        | 0.373   | 0.000        | 0.369   | 0.004        | 0.379   | 0.006        | 0.379  | 0.006        |
| A6   | Square Pocket | 0.498                    | Note 4   |              | 0.5  | 0.002        | 0.524  | 0.026        | 0.5  | 0.002        | 0.5  | 0.002        | 0.502  | 0.004        | 0.502   | 0.004        | 0.496   | 0.002        | 0.507   | 0.009        | 0.509  | 0.011        |
| B1   | Flat Hole     | 0.469                    | Note 4   |              | 0.468  | 0.001        | 0.476  | 0.007        | 0.471  | 0.002        | 0.47   | 0.001        | 0.472  | 0.003        | 0.465   | 0.004        | 0.472   | 0.003        | 0.476   | 0.007        | 0.472  | 0.003        |
| B2   | Flat Hole     | 0.469                    | Note 4   |              | 0.468  | 0.001        | 0.474  | 0.005        | 0.471  | 0.002        | 0.467  | 0.002        | 0.469  | 0.000        | 0.465   | 0.004        | 0.47  | 0.001        | 0.476   | 0.007        | 0.469  | 0.000        |
| B3   | Flat Hole     | 0.472                    | Note 4   |              | 0.468  | 0.004        | 0.476  | 0.004        | 0.471  | 0.001        | 0.47   | 0.002        | 0.471  | 0.001        | 0.467   | 0.005        | 0.467   | 0.005        | 0.474   | 0.002        | 0.462  | 0.010        |
| B4   | Flat Hole     | 0.467                    | Note 4   |              | 0.464  | 0.003        | 0.474  | 0.007        | 0.468  | 0.001        | 0.467  | 0.000        | 0.471  | 0.004        | 0.467   | 0.000        | 0.472   | 0.005        | 0.469   | 0.002        | Note 2   |              |
| B5   | Flat Hole     | 0.465                    | Note 4   |              | 0.475  | 0.010        | 0.5  | 0.035        | 0.478  | 0.013        | 0.467  | 0.002        | 0.469  | 0.004        | 0.469   | 0.004        | 0.468   | 0.003        | Note 2  |              | Note 2   |              |
| C1   | Flat Hole     | 0.312                    | Note 4   |              | 0.309  | 0.003        | 0.321  | 0.009        | 0.311  | 0.001        | 0.315  | 0.003        | 0.316  | 0.004        | 0.318   | 0.006        | Note 2  |              | 0.318   | 0.006        | 0.315  | 0.003        |
| C2   | Flat Hole     | 0.314                    | Note 4   |              | 0.313  | 0.001        | 0.318  | 0.004        | 0.311  | 0.003        | 0.313  | 0.001        | 0.316  | 0.002        | 0.314   | 0.000        | Note 2  |              | 0.32  | 0.006        | 0.308  | 0.006        |
| C3   | Flat Hole     | 0.314                    | Note 4   |              | 0.309  | 0.005        | 0.318  | 0.004        | 0.314  | 0.000        | 0.315  | 0.001        | 0.316  | 0.002        | 0.316   | 0.002        | Note 2  |              | 0.351   | 0.037        | 0.315  | 0.001        |
| C4   | Flat Hole     | 0.311                    | Note 4   |              | 0.313  | 0.002        | 0.321  | 0.010        | 0.311  | 0.000        | 0.311  | 0.000        | 0.315  | 0.004        | 0.318   | 0.007        | Note 2  |              | 0.341   | 0.030        | Note 2   |              |
| C5   | Flat Hole     | 0.31                     | Note 4   |              | 0.309  | 0.001        | 0.333  | 0.023        | 0.321  | 0.011        | 0.311  | 0.001        | 0.314  | 0.004        | 0.318   | 0.008        | Note 2  |              | Note 2  |              | Note 2   |              |
| D1   | Flat Hole     | 0.156                    | Note 4   |              | 0.152  | 0.004        | 0.16   | 0.004        | 0.157  | 0.001        | 0.15   | 0.006        | 0.163  | 0.007        | 0.139   | 0.017        | Note 1  |              | 0.161   | 0.005        | 0.168  | 0.012        |
| D2   | Flat Hole     | 0.157                    | Note 4   |              | 0.155  | 0.002        | 0.163  | 0.006        | 0.157  | 0.000        | 0.159  | 0.002        | 0.162  | 0.005        | 0.139   | 0.018        | Note 1  |              | 0.156   | 0.001        | 0.140  | 0.017        |
| D3   | Flat Hole     | 0.161                    | Note 4   |              | 0.155  | 0.006        | 0.165  | 0.004        | 0.157  | 0.004        | 0.157  | 0.004        | 0.162  | 0.001        | 0.139   | 0.022        | Note 1  |              | 0.161   | 0.000        | 0.152  | 0.009        |
| D4   | Flat Hole     | 0.155                    | Note 4   |              | 0.155  | 0.000        | 0.16   | 0.005        | 0.154  | 0.001        | 0.159  | 0.004        | 0.160  | 0.005        | 0.139   | 0.016        | Note 1  |              | 0.168   | 0.013        | Note 2   |              |
| D5   | Flat Hole     | 0.155                    | Note 4   |              | 0.187  | 0.032        | 0.179  | 0.024        | 0.157  | 0.002        | 0.159  | 0.004        | 0.160  | 0.005        | 0.142   | 0.013        | Note 1  |              | Note 2  |              | Note 2   |              |
| E1   | Shaped Hole   | 0.299                    | Note 4   |              | 0.313  | 0.014        | 0.307  | 0.008        | 0.275  | 0.024        | 0.255  | 0.044        | 0.297  | 0.002        | 0.323   | 0.024        | Note 2  |              | Note 2  |              | Note 2   |              |
| E2   | Shaped Hole   | 0.438                    | Note 4   |              | 0.468  | 0.030        | 0.448  | 0.010        | 0.439  | 0.001        | 0.404  | 0.034        | 0.441  | 0.003        | 0.448   | 0.010        | Note 2  |              | Note 2  |              | Note 2   |              |
| E3   | Shaped Hole   | 0.564                    | Note 4   |              | 0.582  | 0.018        | 0.606  | 0.042        | 0.604  | 0.040        | 0.608  | 0.044        | 0.566  | 0.002        | 0.517   | 0.047        | Note 2  |              | Note 2  |              | Note 2   |              |
| E4   | Shaped Hole   | 0.259                    | Note 4   |              | 0.321  | 0.062        | 0.27   | 0.011        | 0.342  | 0.083        | 0.333  | 0.074        | 0.271  | 0.012        | 0.314   | 0.055        | Note 2  |              | 0.341   | 0.082        | Note 2   |              |
|  | RMS Error     |                          | N/A  |              | 0.016  |              | 0.015  |              | 0.019  |              | 0.021  |              | 0.005  |              | 0.018   |              | 0.007   |              | 0.022   |              | 0.008  |              |

Note 1: Ringdown of probe or interface reflection interfering with backwall signal.  
 Note 2: Could not resolve backwall signal(s) due to interference with background noise.  
 Note 3: Frequency too low to resolve backwall multiple reflections.  
 Note 4: Instrument indicated "invalid" measurement due to low signal amplitude or due to extra tape layer reflection.



**Figure 3-20**  
 Signal obtained from 0.063-inch remaining wall showing first back wall signal no longer present due to ringing of interface signal



**Figure 3-21**  
 Signal obtained from 0.063-inch remaining wall showing first back wall signal when using 5-MHz dual-element probe used in Test 6

### **80-Mil Tape Wrap Coating Specimen**

Tables 3-11 through 3-13 summarize the ultrasonic thickness data collected on the 80-mil tape wrap specimen using ultrasonic Tests 1–10 for the three different temperatures tested. Shaded areas on these tables indicate that a valid measurement was not possible. The test results on the 80-mil specimen were similar to those observed on the 50-mil coatings (with the exception of Test 1 as discussed below), with Tests 2–7 providing good results, with thickness measurement accuracies ranging from an RMS of 0.005 to 0.034 inch. Aside from Test 1, the other notable difference between the 50- and 80-mil coatings was some difficulty in resolving reflections from shaped reflectors for probes with delay lines (Test 3 and Test 4) using either conventional or phased array transducers. The delay line was an additional layer of material and interface boundary through which the sound was required to pass. This boundary resulted in additional attenuation of back wall signals when using these probes. In ideal conditions, shaped reflectors produced weaker signals due to the topography of the reflecting surface. The additional attenuation created by the delay line components resulted in these signals no longer being detectable in some cases, especially at higher temperatures, as denoted in Table 3-13.

Tests 8, 9, and 10 did not perform as well on the 80-mil coating when compared to Tests 2–7. The observed deficiencies were related to the use of lower-frequency probes with larger element sizes. Signals related to small reflectors were not easily detected using the larger probes, and the lower-frequency probes were incapable of resolving thinner material due to the larger wavelengths. The data obtained on the 80-mil specimen indicated that the use of lower-frequency probes with large elements was not warranted, since attenuation associated with this coating did not prevent the use of smaller, higher-frequency probes with better resolution characteristics.

The most notable observation associated with the 80-mil tape coating was the inability of Test 1 to perform thickness measurements regardless of sample temperature. Test 1 was the thickness gage instrument using a 5-MHz probe. Thickness gages are commonly used when performing wall thickness measurements since they provide a numeric readout of the remaining wall thickness. However, thickness gages rely on algorithms that identify reflections and use these signals for thickness calculations. These algorithms also are designed to warn the operator if the reflections are suspect by indicating an invalid measurement. All measurements attempted on the 80-mil tape specimen were deemed invalid by the instrument. Two primary reasons were identified as causing this problem with the thickness gage measurements. First, the 80-mil tape wrap consisted of an additional tape layer. This layer produced an additional coating-related interface reflection, which created problems for the thickness gage algorithm, as shown in Figure 3-22. This additional boundary also significantly decreased the signal amplitude associated with all back wall reflections by decreasing the energy entering the steel block. In general, the signal amplitudes decreased an additional 6 dB (approximately  $\frac{1}{2}$  reduction in amplitude) for the 80-mil tape coating when compared to the 50-mil coating. The performance of the thickness gage (Test 1) was in stark contrast to the results obtained on the 50-mil specimen where it performed well at ambient and low temperatures. It should be stressed that the instrument did properly indicate invalid measurements. These results suggest that ultrasonic thickness gages should not be used on 80-mil tape wrap or in areas where thinner tape is overlapped, producing a double layer.

Temperature had a minor effect on the results obtained on this coating. There was some increase in sound attenuation observed with an increase in temperature. However, this change was not large enough to prevent a thickness measurement observed at lower temperatures from being repeated at a higher temperature. A small increase in measurement error was noted in some cases, although such changes were minor. In general, all techniques that functioned at low temperatures could also be applied at the higher temperature range.

In conclusion, it can be stated that the thickness of a pipe wall coated with 80-mil tape wrap can be measured with good accuracy in most cases. This assumes that the integrity of the bond between the tape and the pipe outer surface is sufficient to permit a signal of adequate amplitude permitting proper back wall signal identification. The 80-mil tape coating is composed of an additional tape layer, which decreased signal amplitude in all cases when compared to the single-ly 50-mil tape. The results indicated that transducers operating at as high as 5 MHz without a delay line with crystal sizes ranging from 0.25 to 0.5 inch in diameter provided good results. Both conventional and phased array techniques performed well on this coating. The use of lower-frequency probes with large crystal sizes should be considered as a last resort when penetration difficulties prevail. Finally, the use of ultrasonic thickness gages capable of performing measurements on coated surfaces is discouraged for double-layered tape wrap, since the additional coating interface signal coupled with lower signal amplitude would likely produce invalid measurements.

**Table 3-11**  
**Ultrasonic thickness data collected on 80-mil tape wrap specimen at 52°F**

| BLOCK 4 - Tape Wrap 80 mils @ 52°F |               |                          |   |              |   |              |  |              |   |              |  |              |  |              |   |              |   |              |   |              |  |              |
|------------------------------------|---------------|--------------------------|---|--------------|---|--------------|--|--------------|---|--------------|--|--------------|--|--------------|---|--------------|---|--------------|---|--------------|--|--------------|
| Flaw ID                            | Flaw Type     | AS-BUILT Ligament (inch) | Wall Thickness Measurements   |              |   |              |  |              |   |              |  |              |  |              |   |              |   |              |   |              |  |              |
|                                    |               |                          | TEST 1<br>3RD Plus Thru-Coat<br>SEM Technique<br>7905 Probe 5MHz Dual |              | TEST 2<br>PAUT<br>SEM Technique<br>5MHz w/ Delay Line |              | TEST 3<br>Flaw Detector<br>SEM Technique<br>5MHz w/ Delay Line |              | TEST 4<br>PAUT<br>MEM Technique<br>5MHz w/ Delay Line |              | TEST 5<br>Flaw Detector<br>MEM Technique<br>5MHz w/ Delay Line |              | TEST 6<br>Flaw Detector<br>SEM Technique<br>7905 Probe 5MHz Dual |              | TEST 7<br>Flaw Detector<br>SEM Technique<br>1/2" 2.25MHz Dual |              | TEST 8<br>Flaw Detector<br>SEM Technique<br>1MHz 1/2" w/ Delay Line |              | TEST 9<br>Flaw Detector<br>MEM Technique<br>3/4" 2.25MHz Single |              | TEST 10<br>Flaw Detector<br>MEM Technique<br>1" 1.05MHz Single |              |
|                                    |               |                          | Measurement (inch)  | ERROR (inch) | Measurement (inch)                                    | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)                                    | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)   | ERROR (inch) |
| A1                                 | Square Pocket | 0.062                    | Note 4  |              | 0.071   | 0.009        | Note 1   |              | 0.061   | 0.001        | 0.061  | 0.001        | 0.059  | 0.003        | Note 1  |              | Note 1  |              | 0.064   | 0.002        | Note 3   |              |
| A2                                 | Square Pocket | 0.125                    | Note 4  |              | 0.119   | 0.006        | 0.124  | 0.001        | 0.125   | 0.000        | 0.127  | 0.002        | 0.113  | 0.012        | 0.189   | 0.064        | Note 1  |              | 0.125   | 0.000        | 0.123  | 0.002        |
| A3                                 | Square Pocket | 0.187                    | Note 4  |              | 0.180   | 0.007        | 0.187  | 0.000        | 0.190   | 0.003        | 0.200  | 0.013        | 0.191  | 0.004        | 0.245   | 0.058        | Note 1  |              | 0.189   | 0.002        | 0.182  | 0.005        |
| A4                                 | Square Pocket | 0.248                    | Note 4  |              | 0.248   | 0.000        | 0.248  | 0.000        | 0.251   | 0.003        | 0.262  | 0.014        | 0.252  | 0.004        | 0.292   | 0.044        | Note 2  |              | 0.253   | 0.005        | 0.235  | 0.013        |
| A5                                 | Square Pocket | 0.373                    | Note 4  |              | 0.371   | 0.002        | 0.382  | 0.009        | 0.373   | 0.000        | 0.377  | 0.004        | 0.370  | 0.003        | 0.396   | 0.023        | Note 2  |              | 0.379   | 0.006        | 0.357  | 0.016        |
| A6                                 | Square Pocket | 0.498                    | Note 4  |              | 0.500   | 0.002        | 0.503  | 0.005        | 0.502   | 0.004        | 0.505  | 0.007        | 0.502  | 0.004        | 0.521   | 0.023        | 0.522   | 0.024        | 0.506   | 0.008        | 0.481  | 0.017        |
| B1                                 | Flat Hole     | 0.469                    | Note 4  |              | 0.461   | 0.008        | 0.468  | 0.001        | 0.468   | 0.001        | 0.476  | 0.007        | 0.476  | 0.007        | 0.476   | 0.007        | 0.501   | 0.032        | 0.473   | 0.004        | 0.447  | 0.022        |
| B2                                 | Flat Hole     | 0.469                    | Note 4  |              | 0.461   | 0.008        | 0.465  | 0.004        | 0.468   | 0.001        | 0.476  | 0.007        | 0.472  | 0.003        | 0.502   | 0.033        | 0.456   | 0.013        | 0.473   | 0.004        | 0.51   | 0.041        |
| B3                                 | Flat Hole     | 0.472                    | Note 4  |              | 0.461   | 0.011        | 0.463  | 0.009        | 0.464   | 0.008        | 0.462  | 0.010        | 0.469  | 0.003        | 0.502   | 0.030        | 0.457   | 0.015        | 0.476   | 0.004        | 0.526  | 0.054        |
| B4                                 | Flat Hole     | 0.467                    | Note 4  |              | 0.457   | 0.010        | 0.456  | 0.011        | 0.464   | 0.003        | 0.460  | 0.007        | 0.474  | 0.007        | 0.498   | 0.031        | 0.444   | 0.023        | 0.466   | 0.001        | Note 2   |              |
| B5                                 | Flat Hole     | 0.465                    | Note 4  |              | 0.468   | 0.003        | 0.472  | 0.007        | 0.471   | 0.006        | 0.460  | 0.005        | 0.467  | 0.002        | 0.495   | 0.030        | Note 2  |              | Note 2  |              | Note 2   |              |
| C1                                 | Flat Hole     | 0.312                    | Note 4  |              | 0.329   | 0.017        | 0.309  | 0.003        | 0.311   | 0.001        | 0.304  | 0.008        | 0.314  | 0.002        | 0.325   | 0.013        | Note 2  |              | 0.317   | 0.005        | 0.300  | 0.012        |
| C2                                 | Flat Hole     | 0.314                    | Note 4  |              | 0.325   | 0.011        | 0.314  | 0.000        | 0.311   | 0.003        | 0.304  | 0.010        | 0.316  | 0.002        | 0.328   | 0.014        | Note 2  |              | 0.317   | 0.003        | 0.295  | 0.019        |
| C3                                 | Flat Hole     | 0.314                    | Note 4  |              | 0.329   | 0.015        | 0.312  | 0.002        | 0.311   | 0.003        | 0.316  | 0.002        | 0.314  | 0.000        | 0.323   | 0.009        | Note 2  |              | 0.317   | 0.003        | 0.303  | 0.011        |
| C4                                 | Flat Hole     | 0.311                    | Note 4  |              | 0.321   | 0.010        | 0.306  | 0.005        | 0.307   | 0.004        | 0.314  | 0.003        | 0.311  | 0.000        | 0.323   | 0.012        | Note 2  |              | 0.317   | 0.006        | Note 2   |              |
| C5                                 | Flat Hole     | 0.31                     | Note 4  |              | 0.321   | 0.011        | 0.307  | 0.003        | 0.289   | 0.021        | 0.307  | 0.003        | 0.314  | 0.004        | 0.344   | 0.034        | Note 2  |              | Note 2  |              | Note 2   |              |
| D1                                 | Flat Hole     | 0.156                    | Note 4  |              | 0.168   | 0.012        | 0.159  | 0.003        | 0.157   | 0.001        | 0.158  | 0.002        | 0.158  | 0.002        | 0.167   | 0.011        | Note 1  |              | 0.156   | 0.000        | Note 2   |              |
| D2                                 | Flat Hole     | 0.157                    | Note 4  |              | 0.175   | 0.018        | 0.157  | 0.000        | 0.157   | 0.000        | 0.158  | 0.001        | 0.163  | 0.006        | 0.172   | 0.015        | Note 1  |              | 0.159   | 0.002        | Note 2   |              |
| D3                                 | Flat Hole     | 0.161                    | Note 4  |              | 0.171   | 0.010        | 0.158  | 0.003        | 0.157   | 0.004        | 0.170  | 0.009        | 0.160  | 0.001        | 0.17  | 0.009        | Note 1  |              | 0.159   | 0.002        | Note 2   |              |
| D4                                 | Flat Hole     | 0.155                    | Note 4  |              | 0.168   | 0.013        | 0.162  | 0.007        | 0.154   | 0.001        | 0.167  | 0.012        | 0.160  | 0.005        | 0.165   | 0.010        | Note 1  |              | 0.159   | 0.004        | Note 2   |              |
| D5                                 | Flat Hole     | 0.155                    | Note 4  |              | 0.154   | 0.001        | Note 2   |              | 0.164   | 0.009        | 0.153  | 0.002        | 0.149  | 0.006        | 0.163   | 0.008        | Note 1  |              | Note 2  |              | Note 2   |              |
| E1                                 | Shaped Hole   | 0.299                    | Note 4  |              | 0.317   | 0.018        | 0.317  | 0.018        | 0.279   | 0.020        | 0.297  | 0.002        | 0.297  | 0.002        | 0.342   | 0.043        | 0.387   | 0.088        | Note 2  |              | 0.33   | 0.031        |
| E2                                 | Shaped Hole   | 0.438                    | Note 4  |              | 0.464   | 0.026        | Note 2   |              | 0.436   | 0.002        | 0.462  | 0.024        | 0.446  | 0.008        | 0.481   | 0.043        | Note 2  |              | Note 2  |              | Note 2   |              |
| E3                                 | Shaped Hole   | 0.564                    | Note 4  |              | 0.576   | 0.012        | Note 2   |              | 0.586   | 0.022        | 0.614  | 0.050        | 0.551  | 0.013        | 0.542   | 0.022        | Note 2  |              | Note 2  |              | Note 2   |              |
| E4                                 | Shaped Hole   | 0.259                    | Note 4  |              | 0.338   | 0.079        | 0.322  | 0.063        | 0.325   | 0.066        | 0.333  | 0.074        | 0.326  | 0.067        | 0.342   | 0.083        | Note 2  |              | 0.367   | 0.108        | 0.326  | 0.067        |
|                                    | RMS Error     |                          | NA  |              | 0.020   |              | 0.015  |              | 0.015   |              | 0.020  |              | 0.014  |              | 0.034   |              | 0.021   |              | 0.004   |              | 0.030  |              |

Note 1: Ringdown of probe or interface reflection interfering with backwall signal.  
 Note 2: Could not resolve backwall signal(s) due to interference with background noise.  
 Note 3: Frequency too low to resolve backwall multiple reflections.  
 Note 4: Instrument indicated "invalid" measurement due to low signal amplitude or due to extra tape layer reflection.

**Table 3-12**  
**Ultrasonic thickness data collected on 80-mil tape wrap specimen at 72°F**

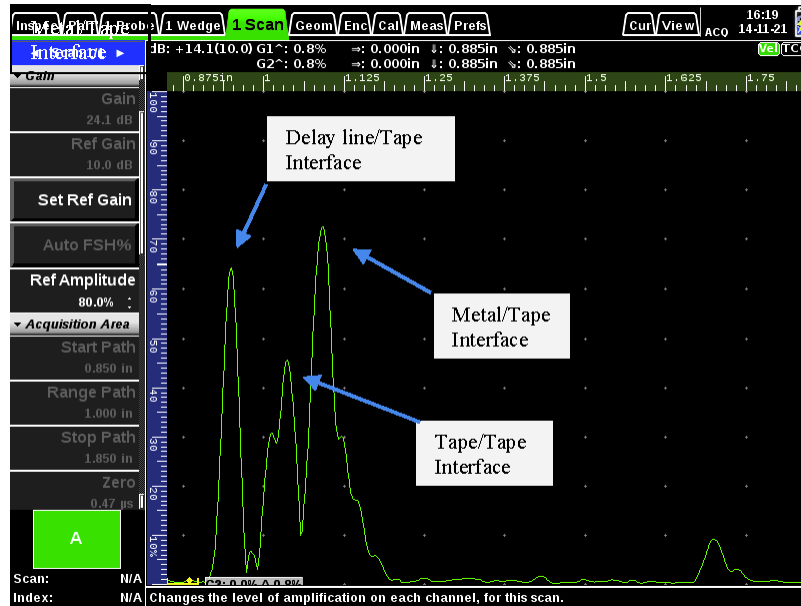
| BLOCK 4 - Tape Wrap 80 mils @ 72°F |               |                          |  |              |   |              |  |              |   |              |   |              |  |              |  |              |   |              |   |              |  |              |
|------------------------------------|---------------|--------------------------|--|--------------|---|--------------|--|--------------|---|--------------|---|--------------|--|--------------|--|--------------|---|--------------|---|--------------|--|--------------|
| Flaw ID                            | Flaw Type     | AS-BUILT Ligament (inch) | Wall Thickness Measurements  |              |   |              |  |              |   |              |   |              |  |              |  |              |   |              |   |              |  |              |
|                                    |               |                          | TEST 1<br>38DL Plus Thru-Coat<br>SEM Technique<br>7906 Probe 5MHz Dual |              | TEST 2<br>PAUT<br>SEM Technique<br>5MHz w/ Delay Line |              | TEST 3<br>Flaw Detector<br>SEM Technique<br>5MHz w/ Delay Line |              | TEST 4<br>PAUT<br>MEM Technique<br>5MHz w/ Delay Line |              | TEST 5<br>Flaw Detector<br>MEM Technique<br>5MHz w/o Delay Line |              | TEST 6<br>Flaw Detector<br>SEM Technique<br>7906 Probe 5MHz Dual |              | TEST 7<br>Flaw Detector<br>SEM Technique<br>1/2", 2.25MHz Dual |              | TEST 8<br>Flaw Detector<br>SEM Technique<br>1MHz 1/2" w/ Delay Line |              | TEST 9<br>Flaw Detector<br>MEM Technique<br>3/4" 2.25MHz Single |              | TEST 10<br>Flaw Detector<br>MEM Technique<br>1" 1.05MHz Single |              |
|                                    |               |                          | Measurement (inch)   | ERROR (inch) | Measurement (inch)                                    | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)                                    | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)   | ERROR (inch) |
| A1                                 | Square Pocket | 0.062                    | Note 4   |              | 0.064   | 0.002        | Note 1   |              | 0.061   | 0.001        | 0.098   | 0.036        | 0.071  | 0.009        | Note 1   |              | Note 1  |              | 0.061   | 0.001        | Note 3   |              |
| A2                                 | Square Pocket | 0.125                    | Note 4   |              | 0.123   | 0.002        | 0.113  | 0.012        | 0.123   | 0.002        | 0.131   | 0.006        | 0.132  | 0.007        | 0.142  | 0.017        | Note 1  |              | 0.123   | 0.002        | 0.135  | 0.010        |
| A3                                 | Square Pocket | 0.187                    | Note 4   |              | 0.184   | 0.003        | 0.183  | 0.004        | 0.177   | 0.010        | 0.166   | 0.021        | 0.192  | 0.005        | 0.2  | 0.013        | Note 1  |              | 0.19  | 0.003        | 0.187  | 0.000        |
| A4                                 | Square Pocket | 0.248                    | Note 4   |              | 0.261   | 0.013        | 0.264  | 0.016        | 0.248   | 0.000        | 0.239   | 0.009        | 0.252  | 0.004        | 0.267  | 0.019        | Note 2  |              | 0.251   | 0.003        | 0.249  | 0.001        |
| A5                                 | Square Pocket | 0.373                    | Note 4   |              | 0.379   | 0.006        | 0.375  | 0.002        | 0.376   | 0.003        | 0.373   | 0.000        | 0.375  | 0.002        | 0.384  | 0.011        | Note 2  |              | 0.377   | 0.004        | 0.37   | 0.003        |
| A6                                 | Square Pocket | 0.498                    | Note 4   |              | 0.502   | 0.004        | 0.502  | 0.004        | 0.516   | 0.018        | 0.492   | 0.006        | 0.501  | 0.003        | 0.505  | 0.007        | 0.494   | 0.004        | 0.507   | 0.009        | 0.5  | 0.002        |
| B1                                 | Flat Hole     | 0.469                    | Note 4   |              | 0.473   | 0.004        | 0.483  | 0.014        | 0.473   | 0.004        | 0.464   | 0.005        | 0.471  | 0.002        | 0.488  | 0.019        | 0.475   | 0.006        | 0.479   | 0.010        | 0.467  | 0.002        |
| B2                                 | Flat Hole     | 0.469                    | Note 4   |              | 0.477   | 0.008        | 0.473  | 0.004        | 0.459   | 0.010        | 0.466   | 0.003        | 0.472  | 0.003        | 0.476  | 0.007        | 0.465   | 0.004        | 0.479   | 0.010        | 0.47   | 0.001        |
| B3                                 | Flat Hole     | 0.472                    | Note 4   |              | 0.469   | 0.003        | 0.469  | 0.003        | 0.462   | 0.010        | 0.471   | 0.001        | 0.473  | 0.001        | 0.476  | 0.004        | 0.46  | 0.012        | 0.476   | 0.004        | 0.453  | 0.019        |
| B4                                 | Flat Hole     | 0.467                    | Note 4   |              | 0.469   | 0.002        | 0.464  | 0.003        | 0.473   | 0.006        | 0.471   | 0.004        | 0.471  | 0.004        | 0.472  | 0.005        | 0.457   | 0.010        | Note 2  |              | Note 2   |              |
| B5                                 | Flat Hole     | 0.465                    | Note 4   |              | 0.475   | 0.010        | 0.475  | 0.010        | 0.479   | 0.014        | 0.471   | 0.006        | 0.467  | 0.002        | 0.459  | 0.006        | Note 2  |              | Note 2  |              | Note 2   |              |
| C1                                 | Flat Hole     | 0.312                    | Note 4   |              | 0.318   | 0.006        | 0.309  | 0.003        | 0.307   | 0.005        | 0.277   | 0.035        | 0.317  | 0.005        | 0.325  | 0.013        | Note 2  |              | 0.318   | 0.006        | 0.323  | 0.011        |
| C2                                 | Flat Hole     | 0.314                    | Note 4   |              | 0.311   | 0.003        | 0.302  | 0.012        | 0.311   | 0.003        | 0.327   | 0.013        | 0.316  | 0.002        | 0.325  | 0.011        | Note 2  |              | 0.313   | 0.001        | 0.311  | 0.003        |
| C3                                 | Flat Hole     | 0.314                    | Note 4   |              | 0.307   | 0.007        | 0.312  | 0.002        | 0.314   | 0.000        | 0.274   | 0.040        | 0.314  | 0.000        | 0.323  | 0.009        | Note 2  |              | 0.322   | 0.008        | 0.306  | 0.008        |
| C4                                 | Flat Hole     | 0.311                    | Note 4   |              | 0.311   | 0.000        | 0.314  | 0.003        | 0.307   | 0.004        | 0.272   | 0.039        | 0.317  | 0.006        | 0.321  | 0.010        | Note 2  |              | 0.374   | 0.063        | Note 2   |              |
| C5                                 | Flat Hole     | 0.31                     | Note 4   |              | 0.314   | 0.004        | 0.323  | 0.013        | 0.292   | 0.018        | 0.244   | 0.066        | 0.316  | 0.006        | 0.323  | 0.013        | Note 2  |              | Note 2  |              | Note 2   |              |
| D1                                 | Flat Hole     | 0.156                    | Note 4   |              | 0.148   | 0.008        | 0.155  | 0.001        | 0.155   | 0.001        | 0.171   | 0.015        | 0.163  | 0.007        | 0.144  | 0.012        | Note 1  |              | 0.159   | 0.003        | Note 2   |              |
| D2                                 | Flat Hole     | 0.157                    | Note 4   |              | 0.157   | 0.000        | 0.162  | 0.005        | 0.157   | 0.000        | 0.173   | 0.016        | 0.163  | 0.006        | 0.149  | 0.008        | Note 1  |              | 0.156   | 0.001        | Note 2   |              |
| D3                                 | Flat Hole     | 0.161                    | Note 4   |              | 0.148   | 0.013        | 0.159  | 0.002        | 0.144   | 0.017        | 0.169   | 0.008        | 0.163  | 0.002        | 0.144  | 0.017        | Note 1  |              | 0.159   | 0.002        | Note 2   |              |
| D4                                 | Flat Hole     | 0.155                    | Note 4   |              | 0.137   | 0.018        | 0.155  | 0.000        | 0.159   | 0.004        | 0.159   | 0.004        | 0.165  | 0.010        | 0.142  | 0.013        | Note 1  |              | Note 2  |              | Note 2   |              |
| D5                                 | Flat Hole     | 0.155                    | Note 4   |              | 0.164   | 0.009        | Note 2   |              | 0.161   | 0.006        | 0.157   | 0.002        | 0.159  | 0.004        | 0.146  | 0.009        | Note 1  |              | Note 2  |              | Note 2   |              |
| E1                                 | Shaped Hole   | 0.299                    | Note 4   |              | 0.289   | 0.010        | 0.305  | 0.006        | 0.300   | 0.001        | 0.302   | 0.003        | 0.298  | 0.001        | 0.311  | 0.012        | 0.393   | 0.094        | Note 2  |              | 0.329  | 0.030        |
| E2                                 | Shaped Hole   | 0.438                    | Note 4   |              | 0.450   | 0.012        | Note 2   |              | 0.436   | 0.002        | 0.460   | 0.022        | 0.447  | 0.009        | 0.455  | 0.017        | Note 2  |              | Note 2  |              | Note 2   |              |
| E3                                 | Shaped Hole   | 0.564                    | Note 4   |              | 0.571   | 0.007        | Note 2   |              | 0.593   | 0.029        | 0.614   | 0.050        | 0.568  | 0.004        | 0.509  | 0.055        | Note 2  |              | Note 2  |              | Note 2   |              |
| E4                                 | Shaped Hole   | 0.259                    | Note 4   |              | 0.318   | 0.059        | 0.337  | 0.078        | 0.343   | 0.084        | 0.319   | 0.060        | 0.263  | 0.004        | 0.307  | 0.048        | Note 2  |              | 0.235   | 0.024        | 0.313  | 0.054        |
| MS Error                           |               |                          | NA   |              | 0.014   |              | 0.019  |              | 0.019   |              | 0.027   |              | 0.005  |              | 0.019  |              | 0.007   |              | 0.016   |              | 0.019  |              |

Note 1: Ringdown of probe or interface reflection interfering with backwall signal.  
 Note 2: Could not resolve backwall signal(s) due to interference with background noise.  
 Note 3: Frequency too low to resolve backwall multiple reflections.  
 Note 4: Instrument indicated "invalid" measurement due to low signal amplitude or due to extra tape layer reflection.

**Table 3-13**  
**Ultrasonic thickness data collected on 80-mil tape wrap specimen at 92°F**

| BLOCK 4 - Tape Wrap 80 mils @ 92° F |               |                          |   |              |   |              |  |              |   |              |  |              |  |              |  |              |   |              |  |              |  |              |
|-------------------------------------|---------------|--------------------------|---|--------------|---|--------------|--|--------------|---|--------------|--|--------------|--|--------------|--|--------------|---|--------------|--|--------------|--|--------------|
| Flaw ID                             | Flaw Type     | AS-BUILT Ligament (inch) | Wall Thickness Measurements   |              |   |              |  |              |   |              |  |              |  |              |  |              |   |              |  |              |  |              |
|                                     |               |                          | TEST 1<br>3RD Plus Thru-Coat<br>SEM Technique<br>7905 Probe 5MHz Dual |              | TEST 2<br>PAUT<br>SEM Technique<br>5MHz w/ Delay Line |              | TEST 3<br>Flaw Detector<br>SEM Technique<br>5MHz w/ Delay Line |              | TEST 4<br>PAUT<br>MEM Technique<br>5MHz w/ Delay Line |              | TEST 5<br>Flaw Detector<br>MEM Technique<br>5MHz w/ Delay Line |              | TEST 6<br>Flaw Detector<br>SEM Technique<br>7905 Probe 5MHz Dual |              | TEST 7<br>Flaw Detector<br>SEM Technique<br>1/2", 2.25MHz Dual |              | TEST 8<br>Flaw Detector<br>SEM Technique<br>1MHz 1/2" w/ Delay Line |              | TEST 9<br>Flaw Detector<br>MEM Technique<br>3/4", 2.25MHz Single |              | TEST 10<br>Flaw Detector<br>MEM Technique<br>1" 1.05MHz Single |              |
|                                     |               |                          | Measurement (inch)  | ERROR (inch) | Measurement (inch)                                    | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)                                    | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)   | ERROR (inch) |
| A1                                  | Square Pocket | 0.062                    | Note 4  |              | 0.079   | 0.017        | Note 1   |              | 0.064   | 0.002        | 0.075  | 0.013        | 0.059  | 0.003        | Note 1   |              | Note 1  |              | 0.064  | 0.002        | Note 3   |              |
| A2                                  | Square Pocket | 0.125                    | Note 4  |              | 0.132   | 0.007        | 0.124  | 0.001        | 0.129   | 0.004        | 0.117  | 0.008        | 0.134  | 0.009        | 0.127  | 0.002        | Note 1  |              | 0.128  | 0.003        | 0.126  | 0.001        |
| A3                                  | Square Pocket | 0.187                    | Note 4  |              | 0.179   | 0.008        | 0.203  | 0.016        | 0.186   | 0.001        | 0.175  | 0.012        | 0.195  | 0.008        | 0.186  | 0.001        | Note 1  |              | 0.192  | 0.005        | 0.194  | 0.007        |
| A4                                  | Square Pocket | 0.248                    | Note 4  |              | 0.246   | 0.002        | 0.262  | 0.014        | 0.250   | 0.002        | 0.241  | 0.007        | 0.254  | 0.006        | 0.252  | 0.004        | Note 2  |              | 0.251  | 0.003        | 0.254  | 0.006        |
| A5                                  | Square Pocket | 0.373                    | Note 4  |              | 0.357   | 0.016        | 0.386  | 0.013        | 0.378   | 0.005        | 0.363  | 0.010        | 0.376  | 0.003        | 0.401  | 0.028        | Note 2  |              | 0.382  | 0.009        | 0.391  | 0.018        |
| A6                                  | Square Pocket | 0.498                    | Note 4  |              | 0.500   | 0.002        | 0.516  | 0.018        | 0.504   | 0.006        | 0.487  | 0.011        | 0.502  | 0.004        | 0.504  | 0.006        | 0.501   | 0.003        | 0.505  | 0.007        | 0.505  | 0.007        |
| B1                                  | Flat Hole     | 0.469                    | Note 4  |              | 0.468   | 0.001        | 0.463  | 0.006        | 0.475   | 0.006        | 0.461  | 0.008        | 0.472  | 0.003        | 0.476  | 0.007        | 0.431   | 0.038        | 0.476  | 0.007        | 0.472  | 0.003        |
| B2                                  | Flat Hole     | 0.469                    | Note 4  |              | 0.468   | 0.001        | 0.451  | 0.018        | 0.471   | 0.002        | 0.461  | 0.008        | 0.471  | 0.002        | 0.469  | 0.000        | 0.428   | 0.041        | 0.479  | 0.010        | 0.472  | 0.003        |
| B3                                  | Flat Hole     | 0.472                    | Note 4  |              | 0.468   | 0.004        | 0.472  | 0.000        | 0.475   | 0.003        | 0.464  | 0.008        | 0.476  | 0.004        | 0.465  | 0.007        | 0.423   | 0.049        | 0.481  | 0.009        | Note 2   |              |
| B4                                  | Flat Hole     | 0.467                    | Note 4  |              | 0.464   | 0.003        | 0.470  | 0.003        | 0.475   | 0.008        | 0.450  | 0.017        | 0.472  | 0.005        | 0.465  | 0.002        | 0.412   | 0.055        | 0.476  | 0.009        | Note 2   |              |
| B5                                  | Flat Hole     | 0.465                    | Note 4  |              | 0.464   | 0.001        | 0.460  | 0.005        | 0.479   | 0.014        | 0.447  | 0.018        | 0.468  | 0.003        | 0.488  | 0.023        | Note 2  |              | Note 2   |              | Note 2   |              |
| C1                                  | Flat Hole     | 0.312                    | Note 4  |              | 0.321   | 0.009        | 0.308  | 0.004        | 0.317   | 0.005        | 0.298  | 0.014        | 0.317  | 0.005        | 0.335  | 0.023        | Note 2  |              | 0.318  | 0.006        | 0.313  | 0.001        |
| C2                                  | Flat Hole     | 0.314                    | Note 4  |              | 0.311   | 0.003        | 0.320  | 0.006        | 0.317   | 0.003        | 0.303  | 0.011        | 0.317  | 0.003        | 0.34   | 0.026        | Note 2  |              | 0.318  | 0.004        | 0.320  | 0.006        |
| C3                                  | Flat Hole     | 0.314                    | Note 4  |              | 0.314   | 0.000        | 0.311  | 0.003        | 0.313   | 0.001        | 0.300  | 0.014        | 0.317  | 0.003        | 0.337  | 0.023        | Note 2  |              | 0.325  | 0.011        | 0.313  | 0.001        |
| C4                                  | Flat Hole     | 0.311                    | Note 4  |              | 0.311   | 0.000        | 0.306  | 0.005        | 0.324   | 0.013        | 0.304  | 0.007        | 0.314  | 0.003        | 0.344  | 0.033        | Note 2  |              | Note 2   |              | Note 2   |              |
| C5                                  | Flat Hole     | 0.31                     | Note 4  |              | 0.311   | 0.001        | 0.322  | 0.012        | 0.288   | 0.022        | 0.273  | 0.037        | 0.315  | 0.005        | 0.349  | 0.039        | Note 2  |              | Note 2   |              | Note 2   |              |
| D1                                  | Flat Hole     | 0.156                    | Note 4  |              | 0.146   | 0.010        | 0.173  | 0.017        | 0.154   | 0.002        | 0.147  | 0.009        | 0.163  | 0.007        | 0.167  | 0.011        | Note 1  |              | 0.159  | 0.003        | Note 2   |              |
| D2                                  | Flat Hole     | 0.157                    | Note 4  |              | 0.146   | 0.011        | 0.173  | 0.016        | 0.157   | 0.000        | 0.161  | 0.004        | 0.162  | 0.005        | 0.172  | 0.015        | Note 1  |              | 0.159  | 0.002        | Note 2   |              |
| D3                                  | Flat Hole     | 0.161                    | Note 4  |              | 0.154   | 0.007        | 0.173  | 0.012        | 0.157   | 0.004        | 0.152  | 0.009        | 0.163  | 0.002        | 0.167  | 0.006        | Note 1  |              | 0.156  | 0.005        | Note 2   |              |
| D4                                  | Flat Hole     | 0.155                    | Note 4  |              | 0.146   | 0.009        | 0.164  | 0.009        | 0.154   | 0.001        | 0.161  | 0.006        | 0.160  | 0.005        | 0.167  | 0.012        | Note 1  |              | 0.159  | 0.004        | Note 2   |              |
| D5                                  | Flat Hole     | 0.155                    | Note 4  |              | 0.157   | 0.002        | Note 3   |              | 0.154   | 0.001        | 0.178  | 0.023        | 0.159  | 0.004        | 0.167  | 0.012        | Note 1  |              | Note 2   |              | Note 2   |              |
| E1                                  | Shaped Hole   | 0.299                    | Note 4  |              | 0.304   | 0.005        | 0.304  | 0.005        | 0.299   | 0.000        | 0.302  | 0.003        | 0.302  | 0.003        | 0.34   | 0.041        | 0.341   | 0.042        | Note 2   |              | Note 2   |              |
| E2                                  | Shaped Hole   | 0.438                    | Note 4  |              | 0.450   | 0.012        | Note 1   |              | 0.435   | 0.003        | 0.460  | 0.022        | 0.446  | 0.008        | 0.479  | 0.041        | Note 2  |              | Note 2   |              | Note 2   |              |
| E3                                  | Shaped Hole   | 0.564                    | Note 4  |              | 0.568   | 0.004        | Note 1   |              | Note 1  |              | 0.614  | 0.050        | 0.568  | 0.004        | 0.535  | 0.029        | Note 2  |              | Note 2   |              | Note 2   |              |
| E4                                  | Shaped Hole   | 0.259                    | Note 4  |              | 0.321   | 0.062        | 0.337  | 0.078        | 0.324   | 0.065        | 0.319  | 0.060        | 0.274  | 0.015        | 0.337  | 0.078        | Note 2  |              | 0.339  | 0.080        | Note 2   |              |
| MS Error                            |               |                          | NA  |              | 0.014   |              | 0.020  |              | 0.015   |              | 0.021  |              | 0.006  |              | 0.026  |              | 0.041   |              | 0.020  |              | 0.007  |              |

Note 1: Ringdown of probe or interface reflection interfering with backwall signal.  
 Note 2: Could not resolve backwall signal(s) due to interference with background noise.  
 Note 3: Frequency too low to resolve backwall multiple reflections.  
 Note 4: Instrument indicated "invalid" measurement due to low signal amplitude or due to extra tape layer reflection.



**Figure 3-22**  
Two tape coating reflections associated with 80-mil tape wrap

### **130-Mil Coal Tar Enamel (TGF-3) Specimen**

Tables 3-14 through 3-16 summarize the ultrasonic thickness data collected on the 130-mil TGF-3 coated specimen. Shaded areas on these tables indicate that a valid measurement was not possible. When measurements were possible, RMS accuracies ranged from 0.008 to 0.044 inch when the measured values were compared to the as-built dimensions. The TGF-3 coating presented the most challenging of all coating types. The 130-mil coating was the thinnest of the two TGF-3 coatings tested and demonstrated to be compatible for performing thickness measurements in some locations. However, this specimen contained a large area where no ultrasonic back wall signals could be detected. Figures 3-23 and 3-24 are examples of two measurements taken on the same TGF-3 test block material where the thickness was similar with a flat, smooth back wall surface. Figure 3-23 shows both the coating/metal interface signal and the low-amplitude back wall reflection. The reception of the interface signal indicated that the sound was propagating through the coating material and reflecting off the coating/metal interface as well as the plate back wall surface. Figure 3-24 is a stark contrast, showing no coating/metal interface reflection or back wall signal. This measurement was taken at an adjacent location with no notable difference in coating appearance. This identical result was obtained with all other transducers tested, even lower-frequency units. The only significant variance between these two measurements was an apparent difference in the sound attenuation of the coating, since a disbond condition would have resulted in absence of the back wall reflection with little effect on the coating/metal interface reflection. The most probable cause of both the coating/metal interface signal and the back wall signal vanishing was a large increase in coating attenuation, most likely caused by a variation in the enamel-to-fiber ratio. The coating appeared to have a more fibrous surface texture when compared to other TGF-3 coating surfaces (see Figure 3-25). It is assumed that an inadequate quantity of enamel was used to fill all gaps between the fiberglass layers, creating a coating that had microvoids throughout its thickness. A mixture that lacked adequate enamel would result in a porous coating that would be highly attenuating to the transmission of

sound waves. Since the sample was prepared by a vendor that specialized in the application of these coatings, it is assumed that this condition could appear in buried piping. If this condition is encountered, any option of performing wall thickness measurements using a piezoelectric transducer is very unlikely. However, this coating condition was found to be compatible for inspection using electromagnetic acoustic transducers (EMATs), as discussed in Section 4.

A characteristic of all TGF-3 coatings was a significant increase in sound attenuation with an increase in temperature. This effect was observed in both the thick and thin TGF-3 specimens. Although temperature did not prevent the ability to collect data on the 130-mil specimen, it did have a significant effect on signal amplitude. A sound attenuation test was conducted on both the 130-mil and 189-mil specimens using the same 2.25-MHz dual-element contact transducer. The test involved setting the back wall signal from a ½-inch-thick square pocket and recording the gain required to maintain the signal peak amplitude to 50% full screen height as temperature was varied. The gain value was recorded over a range of temperatures from approximately 45°F to 108°F. Figure 3-26 is a plot of the results of this test. This plot can be used to estimate the expected change in signal amplitude when inspecting TGF-3 coated piping at different temperatures. For example, back wall signals measured through a 130-mil TGF-3 coating at a temperature of 100°F would require approximately 11 dB more signal amplification than if that same test was performed at 60°F. This equates to an increase in back wall signal amplitude of approximately of 3.5 times if the same test were performed at 60°F instead of 100°F. This test indicated that sound waves propagated through the 130-mil coating were attenuated 0.28 dB for every degree (F) increase in temperature. This is a significant difference, considering that back wall signals associated with TGF-3 can be very low-amplitude signals under ideal conditions and could make the difference in performing a successful inspection. These findings suggest that, in general, wall thickness inspections of TGF-3 should be performed at the low temperatures.

In locations where the coating-to-metal interface signal was observed, the inspection of the 130-mil TGF-3 coating was possible using Tests 2–10 in most cases. However, the poorest performing techniques were Test 8 and Test 10, both using a 1-MHz transducer. The lower-frequency probes were incapable of resolving thinner materials due to the larger wavelengths and element ringing. The data obtained on the 130-mil specimen indicated that the use of lower-frequency probes with large elements was not warranted, since attenuation associated with this coating did not prevent the use of smaller, higher-frequency probes with better resolution characteristics even at higher temperatures.

The use of an ultrasonic thickness gage (Test 1) was not possible on TGF-3 coatings due to low-amplitude signals. In no case did the thickness gage tested provide any useful information related to plate thickness.

In conclusion, it can be stated that the thickness of a pipe wall coated with 130-mil TGF-3 can be measured using ultrasonic techniques with excellent accuracies assuming the integrity of the bond between the epoxy and the pipe outer surface is sufficient to permit the detection of back wall signals. It was observed that the TGF-3 130-mil coating can be applied so that it has localized regions where penetration using a piezoelectric transducer-based technique is impossible. In such cases, the use of an electromagnetic acoustic transducer technique is advised (see Section 4). However, in the case where a coating/metal interface signal can be detected, transducers operating at as high as 5 MHz with or without a delay line should be used with crystal sizes ranging from 0.25 to 0.5 inch in diameter. Both single- and dual-element

conventional transducers, as well phased array techniques, performed well on the 130-mil TGF-3 coating. Lower-frequency transducers with large crystals are not needed to inspect the 130-mil TGF-3 coating and should be avoided unless warranted to avoid limitations related to the detection of corrosion and the resolution of thin walls.

**Table 3-14**  
**Ultrasonic thickness data collected on 130-mil coal tar enamel at 52°F**

| BLOCK 1 - Coal Tar Enamel (TGF3) 130 mils @ 52° F |               |                          |  |              |   |              |  |              |   |              |   |              |  |              |   |              |   |              |   |              |  |              |
|---|---------------|--------------------------|--|--------------|---|--------------|--|--------------|---|--------------|---|--------------|--|--------------|---|--------------|---|--------------|---|--------------|--|--------------|
| Flaw ID   | Flaw Type     | AS-BUILT Ligament (inch) | Wall Thickness Measurements  |              |   |              |  |              |   |              |   |              |  |              |   |              |   |              |   |              |  |              |
|   |               |                          | TEST 1<br>3BDL Plus Thru-Coat<br>SEM Technique<br>7905 Probe 30Hz Dual |              | TEST 2<br>PAUT<br>SEM Technique<br>5MHz w/ Delay Line |              | TEST 3<br>Flaw Detector<br>SEM Technique<br>5MHz w/ Delay Line |              | TEST 4<br>PAUT<br>MEM Technique<br>5MHz w/ Delay Line |              | TEST 5<br>Flaw Detector<br>MEM Technique<br>5MHz w/o Delay Line |              | TEST 6<br>Flaw Detector<br>SEM Technique<br>7905 Probe 30Hz Dual |              | TEST 7<br>Flaw Detector<br>SEM Technique<br>12"/ 2.25MHz Dual |              | TEST 8<br>Flaw Detector<br>SEM Technique<br>18MHz 12"/ Delay Line |              | TEST 9<br>Flaw Detector<br>MEM Technique<br>3 1/4" 2.25MHz Single |              | TEST 10<br>Flaw Detector<br>MEM Technique<br>1" 1.05MHz Single |              |
|   |               |                          | Measurement (inch)   | ERROR (inch) | Measurement (inch)                                    | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)                                    | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)   | ERROR (inch) |
| A1  | Square Pocket | 0.062                    | Note 4   |              | 0.076   | 0.014        | 0.051  | 0.011        | 0.061   | 0.001        | 0.062   | 0.000        | 0.075  | 0.013        | Note 1  |              | Note 3  |              | 0.059   | 0.003        | Note 3   |              |
| A2  | Square Pocket | 0.125                    | Note 4   |              | 0.126   | 0.001        | 0.111  | 0.014        | 0.126   | 0.001        | 0.126   | 0.001        | 0.121  | 0.004        | 0.119   | 0.006        | Note 1  |              | 0.099   | 0.026        | Note 2   |              |
| A3  | Square Pocket | 0.187                    | Note 4   |              | 0.205   | 0.018        | 0.187  | 0.000        | 0.187   | 0.000        | 0.179   | 0.008        | 0.181  | 0.006        | 0.186   | 0.001        | Note 1  |              | 0.189   | 0.002        | 0.175  | 0.012        |
| A4  | Square Pocket | 0.248                    | Note 4   |              | 0.245   | 0.003        | 0.252  | 0.004        | 0.248   | 0.000        | 0.252   | 0.004        | 0.26   | 0.012        | 0.243   | 0.005        | Note 2  |              | 0.248   | 0.000        | Note 2   |              |
| A5  | Square Pocket | 0.373                    | Note 4   |              | 0.385   | 0.012        | 0.361  | 0.012        | 0.374   | 0.001        | 0.379   | 0.006        | 0.371  | 0.002        | 0.371   | 0.002        | 0.411   | 0.038        | 0.374   | 0.001        | 0.36   | 0.013        |
| A6  | Square Pocket | 0.498                    | Note 4   |              | 0.511   | 0.013        | 0.492  | 0.006        | 0.5   | 0.002        | 0.507   | 0.009        | 0.507  | 0.009        | 0.502   | 0.004        | 0.522   | 0.024        | 0.504   | 0.006        | 0.538  | 0.040        |
| B1  | Flat Hole     | 0.469                    | Note 4   |              | 0.479   | 0.010        | 0.468  | 0.001        | 0.468   | 0.001        | 0.486   | 0.017        | 0.458  | 0.011        | 0.467   | 0.002        | Note 2  |              | 0.478   | 0.009        | Note 2   |              |
| B2  | Flat Hole     | 0.469                    | Note 4   |              | 0.468   | 0.001        | 0.471  | 0.002        | 0.453   | 0.016        | 0.474   | 0.005        | 0.475  | 0.006        | 0.443   | 0.026        | 0.452   | 0.017        | 0.473   | 0.004        | Note 2   |              |
| B3  | Flat Hole     | 0.472                    | Note 4   |              | 0.464   | 0.008        | 0.457  | 0.015        | 0.457   | 0.015        | 0.476   | 0.004        | 0.477  | 0.005        | 0.469   | 0.003        | Note 2  |              | 0.471   | 0.001        | Note 2   |              |
| B4  | Flat Hole     | 0.467                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | 0.476   | 0.009        | 0.487  | 0.020        | Note 2  |              | Note 2  |              | Note 2  |              | Note 2   |              |
| B5  | Flat Hole     | 0.465                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | 0.464   | 0.001        | 0.477  | 0.012        | Note 2  |              | Note 2  |              | Note 2  |              | Note 2   |              |
| C1  | Flat Hole     | 0.312                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2  |              | Note 2   |              |
| C2  | Flat Hole     | 0.314                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2  |              | Note 2   |              |
| C3  | Flat Hole     | 0.314                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2  |              | Note 2   |              |
| C4  | Flat Hole     | 0.311                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2  |              | Note 2   |              |
| C5  | Flat Hole     | 0.31                     | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2  |              | Note 2   |              |
| D1  | Flat Hole     | 0.156                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2  |              | Note 2   |              |
| D2  | Flat Hole     | 0.157                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | 0.157   | 0.000        | 0.169  | 0.012        | Note 2  |              | Note 2  |              | Note 2  |              | Note 2   |              |
| D3  | Flat Hole     | 0.161                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2  |              | Note 2   |              |
| D4  | Flat Hole     | 0.155                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2  |              | Note 2   |              |
| D5  | Flat Hole     | 0.155                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2  |              | Note 2   |              |
| E1  | Shaped Hole   | 0.299                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2  |              | Note 2   |              |
| E2  | Shaped Hole   | 0.438                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2  |              | Note 2   |              |
| E3  | Shaped Hole   | 0.564                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2  |              | Note 2   |              |
| E4  | Shaped Hole   | 0.259                    | Note 4   |              | 0.324   | 0.065        | 0.220  | 0.039        | 0.327   | 0.068        | 0.229   | 0.030        | 0.332  | 0.073        | Note 2  |              | 0.332   | 0.073        | Note 2  |              | Note 2   |              |
| RMS Error   |               |                          | NA   |              | 0.023   | 0.023        | 0.258  | 0.015        |   | 0.023        |   | 0.011        |  | 0.023        | 0.010   |              | 0.044   |              | 0.010   |              |  | 0.025        |

Note 1: Ringdown of probe or interface reflection interfering with backwall signal.  
 Note 2: Could not resolve backwall signal(s) due to interference with background noise.  
 Note 3: Frequency too low to resolve backwall multiple reflections.  
 Note 4: Instrument indicated "inwall" measurement due to low signal amplitude or due to extra tape layer reflection.

**Table 3-15**  
**Ultrasonic thickness data collected on 130-mil coal tar enamel at 72°F**

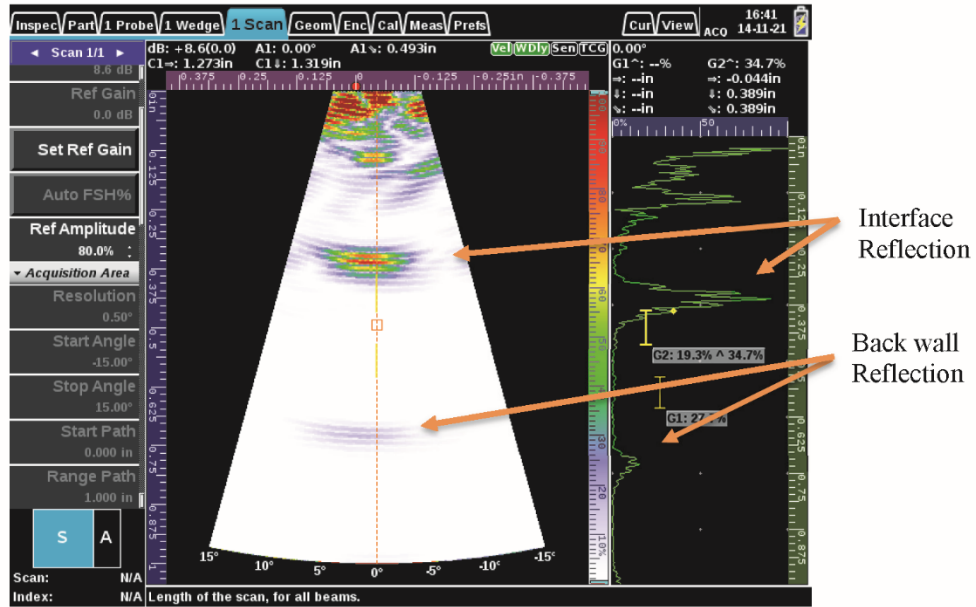
| BLOCK 1 - Coal Tar Enamel (TGF3) 130 mils @ 72° F |               |                          |  |              |   |              |  |              |   |              |   |              |  |              |  |              |   |              |   |              |  |              |
|---|---------------|--------------------------|--|--------------|---|--------------|--|--------------|---|--------------|---|--------------|--|--------------|--|--------------|---|--------------|---|--------------|--|--------------|
| Flaw ID   | Flaw Type     | AS-BUILT Ligament (inch) | Wall Thickness Measurements  |              |   |              |  |              |   |              |   |              |  |              |  |              |   |              |   |              |  |              |
|   |               |                          | TEST 1<br>38DL Plus Thru-Coat<br>SEM Technique<br>7906 Probe 5MHz Dual |              | TEST 2<br>PAUT<br>SEM Technique<br>5MHz w/ Delay Line |              | TEST 3<br>Flaw Detector<br>SEM Technique<br>5MHz w/ Delay Line |              | TEST 4<br>PAUT<br>MEM Technique<br>5MHz w/ Delay Line |              | TEST 5<br>Flaw Detector<br>MEM Technique<br>5MHz w/o Delay Line |              | TEST 6<br>Flaw Detector<br>SEM Technique<br>7906 Probe 5MHz Dual |              | TEST 7<br>Flaw Detector<br>SEM Technique<br>1/2", 2.25MHz Dual |              | TEST 8<br>Flaw Detector<br>SEM Technique<br>1MHz 1/2" w/ Delay Line |              | TEST 9<br>Flaw Detector<br>MEM Technique<br>3/4" 2.25MHz Single |              | TEST 10<br>Flaw Detector<br>MEM Technique<br>1" 1.05MHz Single |              |
|   |               |                          | Measurement (inch)   | ERROR (inch) | Measurement (inch)                                    | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)                                    | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)   | ERROR (inch) |
| A1  | Square Pocket | 0.062                    | Note 4   |              | 0.068   | 0.006        | 0.035  | 0.027        | 0.061   | 0.001        | 0.051   | 0.011        | 0.071  | 0.009        | Note 1   |              | Note 3  |              | 0.078   | 0.016        | Note 3   |              |
| A2  | Square Pocket | 0.125                    | Note 4   |              | 0.125   | 0.000        | 0.134  | 0.009        | 0.122   | 0.003        | 0.111   | 0.014        | 0.136  | 0.011        | 0.144  | 0.019        | Note 1  |              | 0.1218  | 0.003        | Note 2   |              |
| A3  | Square Pocket | 0.187                    | Note 4   |              | 0.204   | 0.017        | 0.218  | 0.031        | 0.187   | 0.000        | 0.169   | 0.018        | 0.196  | 0.009        | 0.158  | 0.029        | Note 1  |              | 0.216   | 0.029        | 0.197  | 0.010        |
| A4  | Square Pocket | 0.248                    | Note 4   |              | 0.261   | 0.013        | 0.248  | 0.000        | 0.259   | 0.011        | 0.259   | 0.011        | 0.257  | 0.009        | 0.252  | 0.004        | 0.269   | 0.021        | 0.254   | 0.006        | Note 2   |              |
| A5  | Square Pocket | 0.373                    | Note 4   |              | 0.375   | 0.002        | 0.417  | 0.044        | 0.327   | 0.046        | 0.380   | 0.007        | 0.376  | 0.003        | 0.377  | 0.004        | 0.376   | 0.003        | 0.379   | 0.006        | 0.368  | 0.005        |
| A6  | Square Pocket | 0.498                    | Note 4   |              | 0.511   | 0.013        | 0.514  | 0.016        | 0.507   | 0.009        | 0.505   | 0.007        | 0.504  | 0.006        | 0.5  | 0.002        | 0.502   | 0.004        | 0.476   | 0.022        | 0.503  | 0.005        |
| B1  | Flat Hole     | 0.469                    | Note 4   |              | 0.479   | 0.010        | 0.481  | 0.012        | 0.453   | 0.016        | 0.461   | 0.008        | 0.474  | 0.005        | 0.476  | 0.007        | 0.453   | 0.016        | 0.474   | 0.005        | Note 2   |              |
| B2  | Flat Hole     | 0.469                    | Note 4   |              | 0.479   | 0.010        | 0.472  | 0.003        | 0.471   | 0.002        | 0.463   | 0.006        | 0.475  | 0.006        | 0.488  | 0.019        | 0.484   | 0.015        | 0.474   | 0.005        | Note 2   |              |
| B3  | Flat Hole     | 0.472                    | Note 4   |              | 0.475   | 0.003        | 0.472  | 0.000        | 0.468   | 0.004        | 0.472   | 0.000        | 0.476  | 0.004        | 0.486  | 0.014        | 0.482   | 0.010        | 0.462   | 0.010        | Note 2   |              |
| B4  | Flat Hole     | 0.467                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | 0.471  | 0.004        | 0.483  | 0.016        | 0.478   | 0.011        | 0.455   | 0.012        | Note 2   |              |
| B5  | Flat Hole     | 0.465                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | 0.475  | 0.010        | Note 2   |              | 0.484   | 0.019        | Note 2  |              | Note 2   |              |
| C1  | Flat Hole     | 0.312                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| C2  | Flat Hole     | 0.314                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| C3  | Flat Hole     | 0.314                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| C4  | Flat Hole     | 0.311                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| C5  | Flat Hole     | 0.31                     | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| D1  | Flat Hole     | 0.156                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| D2  | Flat Hole     | 0.157                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| D3  | Flat Hole     | 0.161                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| D4  | Flat Hole     | 0.155                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| D5  | Flat Hole     | 0.155                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| E1  | Shaped Hole   | 0.299                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| E2  | Shaped Hole   | 0.438                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| E3  | Shaped Hole   | 0.564                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| E4  | Shaped Hole   | 0.259                    | Note 4   |              | 0.339   | 0.080        | 0.220  | 0.039        | 0.342   | 0.083        | 0.229   | 0.030        | 0.269  | 0.010        | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| RMS Error   |               |                          | NA   |              | 0.027   |              | 0.024  |              | 0.031   |              | 0.014   |              | 0.008  |              | 0.015  |              | 0.014   |              | 0.014   |              | 0.014  | 0.007        |

Note 1: Ringdown of probe or interface reflection interfering with backwall signal.  
 Note 2: Could not resolve backwall signal(s) due to interference with background noise.  
 Note 3: Frequency too low to resolve backwall multiple reflections.  
 Note 4: Instrument indicated "invalid" measurement due to low signal amplitude or due to extra tape layer reflection.

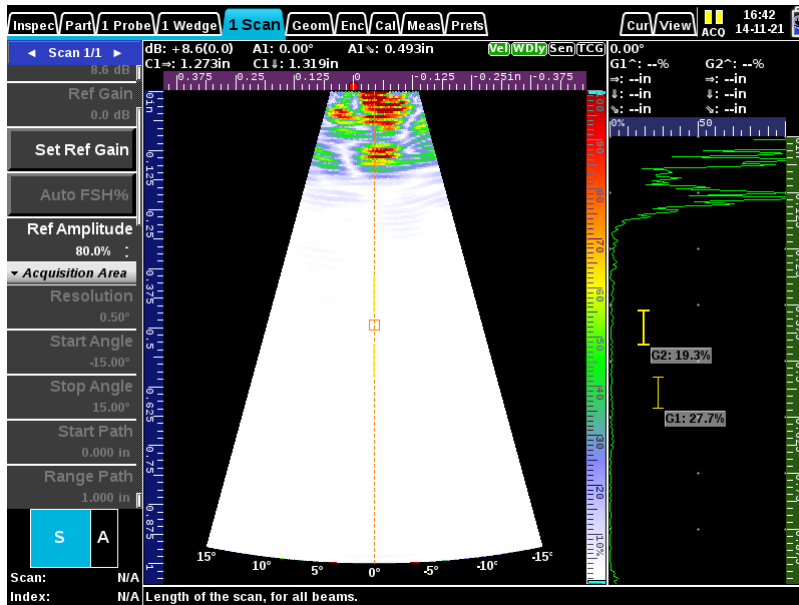
**Table 3-16**  
**Ultrasonic thickness data collected on 130-mil coal tar enamel at 92°F**

| BLOCK 1 - Coal Tar Enamel (TGF3) 130 mils @ 92° F |               |                          |  |              |   |              |  |              |   |              |   |              |  |              |  |              |   |              |   |              |  |              |
|---|---------------|--------------------------|--|--------------|---|--------------|--|--------------|---|--------------|---|--------------|--|--------------|--|--------------|---|--------------|---|--------------|--|--------------|
| Flaw ID   | Flaw Type     | AS-BUILT Ligament (inch) | Wall Thickness Measurements  |              |   |              |  |              |   |              |   |              |  |              |  |              |   |              |   |              |  |              |
|   |               |                          | TEST 1<br>38DL Plus Thru-Coat<br>SEM Technique<br>7906 Probe 5MHz Dual |              | TEST 2<br>PAUT<br>SEM Technique<br>5MHz w/ Delay Line |              | TEST 3<br>Flaw Detector<br>SEM Technique<br>5MHz w/ Delay Line |              | TEST 4<br>PAUT<br>MEM Technique<br>5MHz w/ Delay Line |              | TEST 5<br>Flaw Detector<br>MEM Technique<br>5MHz w/o Delay Line |              | TEST 6<br>Flaw Detector<br>SEM Technique<br>7906 Probe 5MHz Dual |              | TEST 7<br>Flaw Detector<br>SEM Technique<br>1/2", 2.25MHz Dual |              | TEST 8<br>Flaw Detector<br>SEM Technique<br>1MHz 1/2" w/ Delay Line |              | TEST 9<br>Flaw Detector<br>MEM Technique<br>3/4" 2.25MHz Single |              | TEST 10<br>Flaw Detector<br>MEM Technique<br>1" 1.05MHz Single |              |
|   |               |                          | Measurement (inch)   | ERROR (inch) | Measurement (inch)                                    | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)                                    | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)   | ERROR (inch) |
| A1  | Square Pocket | 0.062                    | Note 4   |              | 0.071   | 0.009        | 0.035  | 0.027        | 0.061   | 0.001        | 0.047   | 0.015        | 0.074  | 0.012        | Note 1   |              | Note 3  |              | 0.073   | 0.011        | Note 3   |              |
| A2  | Square Pocket | 0.125                    | Note 4   |              | 0.136   | 0.011        | 0.134  | 0.009        | 0.137   | 0.012        | 0.138   | 0.013        | 0.136  | 0.011        | 0.15   | 0.025        | Note 1  |              | 0.123   | 0.002        | 0.133  | 0.008        |
| A3  | Square Pocket | 0.187                    | Note 4   |              | 0.189   | 0.002        | 0.218  | 0.031        | 0.201   | 0.014        | 0.182   | 0.005        | 0.207  | 0.020        | 0.212  | 0.025        | Note 1  |              | 0.22  | 0.033        | 0.192  | 0.005        |
| A4  | Square Pocket | 0.248                    | Note 4   |              | 0.257   | 0.009        | 0.248  | 0.000        | 0.266   | 0.018        | 0.271   | 0.023        | 0.262  | 0.014        | 0.243  | 0.005        | Note 2  |              | 0.282   | 0.034        | 0.261  | 0.013        |
| A5  | Square Pocket | 0.373                    | Note 4   |              | 0.371   | 0.002        | 0.417  | 0.044        | 0.385   | 0.012        | 0.371   | 0.002        | 0.382  | 0.009        | 0.362  | 0.011        | Note 2  |              | 0.41  | 0.037        | 0.377  | 0.004        |
| A6  | Square Pocket | 0.498                    | Note 4   |              | 0.514   | 0.016        | 0.514  | 0.016        | 0.518   | 0.020        | 0.502   | 0.004        | 0.511  | 0.013        | 0.51   | 0.012        | 0.532   | 0.034        | 0.509   | 0.011        | 0.507  | 0.009        |
| B1  | Flat Hole     | 0.469                    | Note 4   |              | 0.479   | 0.010        | 0.481  | 0.012        | 0.464   | 0.005        | 0.451   | 0.018        | 0.482  | 0.013        | 0.476  | 0.007        | Note 2  |              | 0.479   | 0.010        | Note 2   |              |
| B2  | Flat Hole     | 0.469                    | Note 4   |              | 0.468   | 0.001        | 0.472  | 0.003        | 0.468   | 0.001        | 0.477   | 0.008        | 0.474  | 0.005        | 0.476  | 0.007        | Note 2  |              | 0.474   | 0.005        | Note 2   |              |
| B3  | Flat Hole     | 0.472                    | Note 4   |              | 0.464   | 0.008        | 0.472  | 0.000        | 0.478   | 0.006        | 0.498   | 0.026        | 0.478  | 0.006        | 0.483  | 0.011        | Note 2  |              | 0.476   | 0.004        | Note 2   |              |
| B4  | Flat Hole     | 0.467                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | 0.475  | 0.008        | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| B5  | Flat Hole     | 0.465                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | 0.475  | 0.010        | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| C1  | Flat Hole     | 0.312                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| C2  | Flat Hole     | 0.314                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| C3  | Flat Hole     | 0.314                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| C4  | Flat Hole     | 0.311                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| C5  | Flat Hole     | 0.31                     | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| D1  | Flat Hole     | 0.156                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| D2  | Flat Hole     | 0.157                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| D3  | Flat Hole     | 0.161                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| D4  | Flat Hole     | 0.155                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| D5  | Flat Hole     | 0.155                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| E1  | Shaped Hole   | 0.299                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| E2  | Shaped Hole   | 0.438                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| E3  | Shaped Hole   | 0.564                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| E4  | Shaped Hole   | 0.259                    | Note 4   |              | Note 2  |              | 0.220  | 0.039        | 0.342   | 0.083        | 0.229   | 0.030        | 0.336  | 0.077        | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| RMS Error   |               |                          | NA   |              | 0.009   |              | 0.024  |              | 0.029   |              | 0.014   |              | 0.025  |              | 0.015  |              | 0.034   |              | 0.021   |              | 0.008  |              |

Note 1: Ringdown of probe or interface reflection interfering with backwall signal.  
 Note 2: Could not resolve backwall signal(s) due to interference with background noise.  
 Note 3: Frequency too low to resolve backwall multiple reflections.  
 Note 4: Instrument indicated "invalid" measurement due to low signal amplitude or due to extra tape layer reflection.



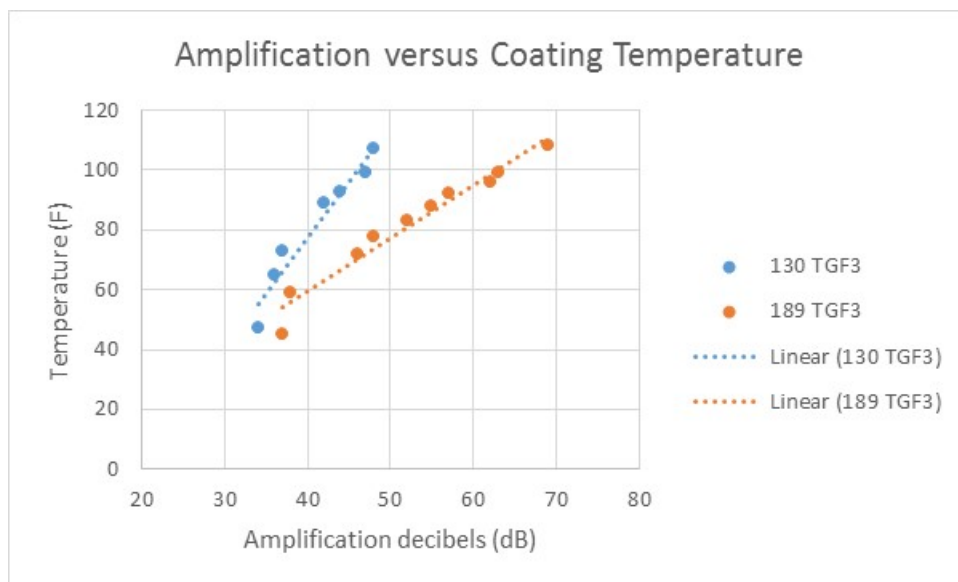
**Figure 3-23**  
 Back wall signal obtained at location where TGF-3 coating can be penetrated by a 5-MHz sound wave



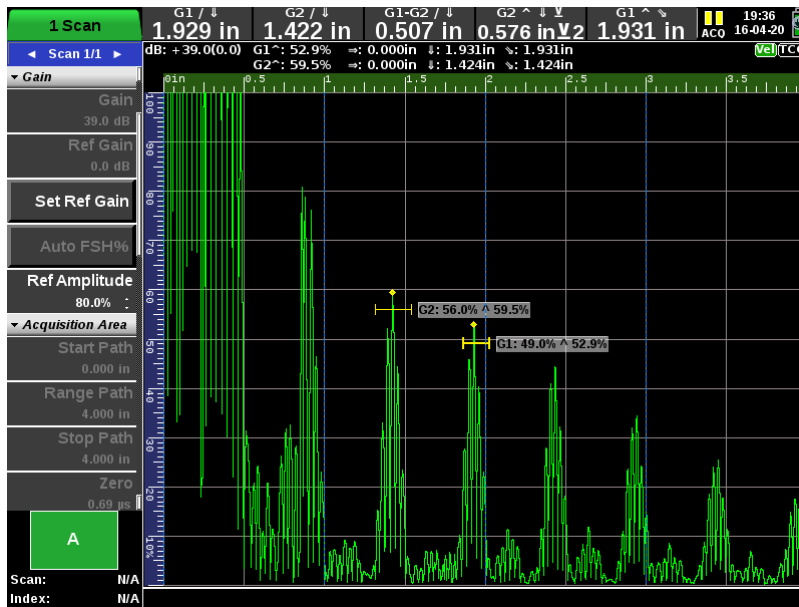
**Figure 3-24**  
 No back wall signal obtained at location where TGF-3 coating could not be penetrated by a 5-MHz sound wave



**Figure 3-25**  
**Photographs showing the contrast of TGF-3 surface finishes: fibrous and smooth**



**Figure 3-26**  
**Plot of gain required to maintain a 1/2-inch plate back wall signal over a range of temperatures using a 2.25-MHz dual-element contact transducer (like used in Test 7) for both TGF-3 specimens**



**Figure 3-27**

**Signal obtained using a 2.25-MHz,  $\frac{3}{4}$ -inch-diameter contact transducer using plate multiple reflections to determine thickness (Test 9) on 130 mils TGF-3 specimen**

### **189-Mil Coal Tar Enamel (TGF-3) Specimen**

Tables 3-17 through 3-19 summarize the ultrasonic thickness data collected on the thick 189-mil TGF-3 coated specimen. Shaded areas on these tables indicate that a valid measurement was not possible. When measurements were possible, RMS accuracies ranged from 0.007 to 0.042 inch when the measured values were compared to the as-built dimensions. The TGF-3 coating presented the most challenging of all coating types. The 189-mil coating was the thickest of the two TGF-3 coatings tested, with results indicating that performing thickness measurements through the coating was possible only under specific conditions. Unlike the 130-mil TGF-3 coating, this specimen did not have regions where the coating/metal interface signal was not detectable. This result suggested that the 189-mil coating makeup was consistent across the entire sample, with no localized regions of unusually high sound attenuation.

The effect of temperature on the sound attenuation properties of TGF-3 was very substantial for the 189-mil coating. Although this effect was observed in the 130-mil specimen, it proved to be an impediment for the successful use of piezoelectric transducer-based techniques on the 189-mil specimen. A signal attenuation test was conducted on both the 130-mil and 189-mil specimens using the same 2.25-MHz dual-element contact transducer. The test involved setting the back wall signal from a  $\frac{1}{2}$ -inch thick reflector and recording the gain required to set the peak amplitude to 50% full screen height. The gain value was recorded over a range of temperatures, from approximately 45°F to 108°F. Figure 3-26 is a plot of the results of this test. This plot can be used to estimate the expected change in signal amplitude when inspecting coated piping at different temperatures. For example, back wall signals measured through a 189-mil TGF-3 coating temperature at 100°F would require approximately 23 dB more signal amplification compared to the same test performed at 60°F. This equates to an increase in back wall signal amplitude of approximately 14 times if the same test were performed at 60°F instead of 100°F. Sound waves propagated through the 189-mil coating were attenuated 0.58 dB for every

degree (F) increase in temperature. This dependency on temperature is the primary reason that significant differences are observed in Tables 3-17 through 3-19 where many tests found useful at lower temperatures could no longer be applied at higher temperatures due to loss of signal. These findings suggest that, in general, wall thickness inspections of TGF-3 should always be performed at low temperatures (less than 60°F).

The inspection of the 189-mil TGF-3 coating was possible using Tests 2–10 when the TGF-3 coating temperature was in the 50–60°F range. Techniques that utilized delay line components became less effective when the coating was heated to approximately 70°F. This was due to the additional signal loss associated with the sound having to propagate through delay line material and interface boundaries. Finally, when the coating temperature reached approximately 90°F, only the tests that utilized the larger-element, lower-frequency transducers were effective (Tests 7–10). These probes produced more power and had better penetration capability. Out of these four tests, Test 7 and Test 9 performed best at higher temperatures. These tests employed 2.25-MHz probes that operated at a low enough frequency to penetrate the 189-mil coating, while still having some moderate lateral resolution capabilities for detecting smaller localized corrosion. Unlike the 1.0-MHz transducers, these probes had some ability to perform measurements on thin materials due to a smaller wavelength. It should be noted that both the single-echo method (SEM) and the multiple-echo method (MEM) were effective approaches when used with appropriate transducer types (SEM—dual-element; MEM—contact without delay line). Figure 43-28 is a screen shot of the MEM being used to measure a ½-inch thick plate through 189-mil TGF-3 at ambient temperature. The 189-mil TGF-3 coating was the only coating for which the use of lower-frequency transducers was required, especially when inspecting at higher temperatures.

The use of an ultrasonic thickness gage (Test 1) was not possible on TGF-3 coatings due to the lower-amplitude signals. In no case did the thickness gage tested provide any useful information related to plate thickness on the TGF-3 at any temperature.

In conclusion, it can be stated that the thickness of a pipe wall coated with 189 TGF-3 can be measured using ultrasonic techniques but the measurement should be performed using transducers no higher than 2.25 MHz using either dual- or single-element crystals. The TGF-3 coating was demonstrated to be highly sensitive to temperature, as its sound attenuation properties increased significantly with temperature. This effect is pronounced when inspecting thicker TGF-3 coatings. Since the thickness of a TGF-3 coating is not typically known, it is recommended that inspections be performed when the coatings are cool and should be avoided at elevated temperatures.

**Table 3-17**  
**Ultrasonic thickness data collected on 189-mil coal tar enamel at 52°F**

| BLOCK 2 - Coal Tar Enamel 189 mils @ 52° F |               |                          |  |              |   |              |  |              |   |              |   |              |  |              |  |              |   |              |   |              |  |              |
|--|---------------|--------------------------|--|--------------|---|--------------|--|--------------|---|--------------|---|--------------|--|--------------|--|--------------|---|--------------|---|--------------|--|--------------|
| Flaw ID                                    | Flaw Type     | AS-BUILT Ligament (inch) | Wall Thickness Measurements  |              |   |              |  |              |   |              |   |              |  |              |  |              |   |              |   |              |  |              |
|  |               |                          | TEST 1<br>38DL Plus Thru-Coat<br>SEM Technique<br>7906 Probe 5MHz Dual |              | TEST 2<br>PAUT<br>SEM Technique<br>5MHz w/ Delay Line |              | TEST 3<br>Flaw Detector<br>SEM Technique<br>5MHz w/ Delay Line |              | TEST 4<br>PAUT<br>MEM Technique<br>5MHz w/ Delay Line |              | TEST 5<br>Flaw Detector<br>MEM Technique<br>5MHz w/o Delay Line |              | TEST 6<br>Flaw Detector<br>SEM Technique<br>7906 Probe 5MHz Dual |              | TEST 7<br>Flaw Detector<br>SEM Technique<br>1/2", 2.25MHz Dual |              | TEST 8<br>Flaw Detector<br>SEM Technique<br>1MHz 1/2" w/ Delay Line |              | TEST 9<br>Flaw Detector<br>MEM Technique<br>3/4" 2.25MHz Single |              | TEST 10<br>Flaw Detector<br>MEM Technique<br>1" 1.05MHz Single |              |
|  |               |                          | Measurement (inch)   | ERROR (inch) | Measurement (inch)                                    | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)                                    | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)   | ERROR (inch) |
| A1   | Square Pocket | 0.062                    | Note 4   |              | 0.061   | 0.001        | 0.078  | 0.016        | 0.058   | 0.004        | 0.061   | 0.001        | 0.059  | 0.003        | Note 1   |              | Note 3  |              | 0.066   | 0.004        | Note 3   |              |
| A2   | Square Pocket | 0.125                    | Note 4   |              | 0.122   | 0.003        | 0.117  | 0.008        | 0.126   | 0.001        | 0.112   | 0.013        | 0.119  | 0.006        | 0.121  | 0.004        | Note 1  |              | 0.123   | 0.002        | Note 2   |              |
| A3   | Square Pocket | 0.187                    | Note 4   |              | 0.191   | 0.004        | 0.182  | 0.005        | 0.187   | 0.000        | 0.190   | 0.003        | 0.206  | 0.019        | 0.219  | 0.032        | Note 1  |              | 0.192   | 0.005        | 0.171  | 0.016        |
| A4   | Square Pocket | 0.248                    | Note 4   |              | 0.248   | 0.000        | 0.267  | 0.019        | 0.248   | 0.000        | 0.252   | 0.004        | 0.244  | 0.004        | 0.274  | 0.026        | Note 2  |              | 0.248   | 0.000        | 0.318  | 0.070        |
| A5   | Square Pocket | 0.373                    | Note 4   |              | 0.371   | 0.002        | 0.360  | 0.013        | 0.388   | 0.015        | 0.369   | 0.004        | 0.373  | 0.000        | 0.395  | 0.022        | 0.35  | 0.023        | 0.376   | 0.003        | 0.357  | 0.016        |
| A6   | Square Pocket | 0.498                    | Note 4   |              | 0.500   | 0.002        | 0.488  | 0.010        | 0.500   | 0.002        | 0.512   | 0.014        | 0.496  | 0.002        | 0.517  | 0.019        | 0.582   | 0.084        | 0.528   | 0.030        | 0.535  | 0.037        |
| B1   | Flat Hole     | 0.469                    | Note 4   |              | 0.468   | 0.001        | 0.452  | 0.017        | 0.468   | 0.001        | 0.467   | 0.002        | 0.463  | 0.006        | 0.49   | 0.021        | 0.458   | 0.011        | 0.466   | 0.003        | 0.498  | 0.029        |
| B2   | Flat Hole     | 0.469                    | Note 4   |              | 0.486   | 0.017        | 0.461  | 0.008        | 0.457   | 0.012        | 0.479   | 0.010        | 0.463  | 0.006        | 0.49   | 0.021        | 0.451   | 0.018        | 0.473   | 0.004        | 0.474  | 0.005        |
| B3   | Flat Hole     | 0.472                    | Note 4   |              | 0.486   | 0.014        | 0.464  | 0.008        | 0.471   | 0.001        | 0.486   | 0.014        | 0.479  | 0.007        | 0.49   | 0.018        | 0.453   | 0.019        | 0.499   | 0.027        | 0.526  | 0.054        |
| B4   | Flat Hole     | 0.467                    | Note 4   |              | 0.486   | 0.019        | 0.439  | 0.028        | 0.475   | 0.008        | 0.462   | 0.005        | 0.465  | 0.002        | 0.486  | 0.019        | Note 2  |              | 0.471   | 0.004        | 0.511  | 0.044        |
| B5   | Flat Hole     | 0.465                    | Note 4   |              | 0.489   | 0.024        | 0.495  | 0.030        | 0.464   | 0.001        | 0.437   | 0.028        | 0.458  | 0.007        | 0.481  | 0.016        | Note 2  |              | Note 2  |              | Note 2   |              |
| C1   | Flat Hole     | 0.312                    | Note 4   |              | 0.324   | 0.012        | 0.319  | 0.007        | 0.324   | 0.012        | 0.314   | 0.002        | 0.323  | 0.011        | 0.333  | 0.021        | Note 2  |              | 0.31  | 0.000        | 0.353  | 0.041        |
| C2   | Flat Hole     | 0.314                    | Note 4   |              | 0.335   | 0.021        | 0.315  | 0.001        | 0.320   | 0.006        | 0.331   | 0.017        | 0.311  | 0.003        | 0.326  | 0.012        | Note 2  |              | 0.312   | 0.061        | 0.3  | 0.014        |
| C3   | Flat Hole     | 0.314                    | Note 4   |              | 0.335   | 0.021        | 0.324  | 0.010        | 0.324   | 0.010        | 0.319   | 0.005        | 0.325  | 0.011        | 0.331  | 0.017        | Note 2  |              | 0.253   | 0.008        | 0.33   | 0.016        |
| C4   | Flat Hole     | 0.311                    | Note 4   |              | 0.320   | 0.009        | 0.329  | 0.018        | Note 2  |              | 0.319   | 0.008        | 0.309  | 0.002        | 0.329  | 0.018        | Note 2  |              | 0.322   | 0.011        | 0.299  | 0.012        |
| C5   | Flat Hole     | 0.31                     | Note 4   |              | Note 2  |              | 0.314  | 0.004        | Note 2  |              | 0.286   | 0.024        | 0.309  | 0.001        | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| D1   | Flat Hole     | 0.156                    | Note 4   |              | 0.155   | 0.001        | 0.152  | 0.004        | 0.155   | 0.001        | 0.152   | 0.004        | 0.152  | 0.004        | 0.181  | 0.025        | Note 2  |              | 0.154   | 0.002        | Note 2   |              |
| D2   | Flat Hole     | 0.157                    | Note 4   |              | 0.140   | 0.017        | 0.142  | 0.015        | 0.155   | 0.002        | 0.143   | 0.014        | 0.166  | 0.009        | 0.148  | 0.009        | Note 2  |              | 0.163   | 0.006        | Note 2   |              |
| D3   | Flat Hole     | 0.161                    | Note 4   |              | 0.147   | 0.014        | 0.129  | 0.032        | 0.165   | 0.004        | 0.160   | 0.001        | 0.152  | 0.009        | 0.181  | 0.020        | Note 2  |              | Note 2  |              | Note 2   |              |
| D4   | Flat Hole     | 0.155                    | Note 4   |              | Note 2  |              | 0.152  | 0.003        | Note 2  |              | 0.157   | 0.002        | 0.166  | 0.014        | 0.15   | 0.005        | Note 2  |              | Note 2  |              | Note 2   |              |
| D5   | Flat Hole     | 0.155                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | 0.169  | 0.135        | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| E1   | Shaped Hole   | 0.299                    | Note 4   |              | Note 2  |              | 0.285  | 0.014        | Note 2  |              | Note 2  |              | 0.290  | 0.009        | 0.324  | 0.025        | Note 2  |              | Note 2  |              | Note 2   |              |
| E2   | Shaped Hole   | 0.438                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | 0.36   | 0.078        | Note 2  |              | Note 2  |              | Note 2   |              |
| E3   | Shaped Hole   | 0.564                    | Note 4   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| E4   | Shaped Hole   | 0.259                    | Note 4   |              | 0.327   | 0.068        | Note 2   |              | Note 2  |              | 0.333   | 0.074        | 0.370  | 0.111        | 0.35   | 0.091        | Note 2  |              | 0.296   | 0.037        | Note 2   |              |
|  | RMS Error     |                          |  | NA           |   | 0.020        |  | 0.015        |   | 0.007        |   | 0.011        |  | 0.037        |  | 0.032        |   | 0.041        |   | 0.020        |  | 0.035        |

Note 1: Ringdown of probe or interface reflection interfering with backwall signal.  
 Note 2: Could not resolve backwall signal(s).  
 Note 3: Frequency too low to resolve backwall multiple reflections.  
 Note 4: Instrument indicated "invalid" measurement due to low signal amplitude or due to extra tape layer reflection.

**Table 3-18**  
**Ultrasonic thickness data collected on 189-mil coal tar enamel at 72°F**

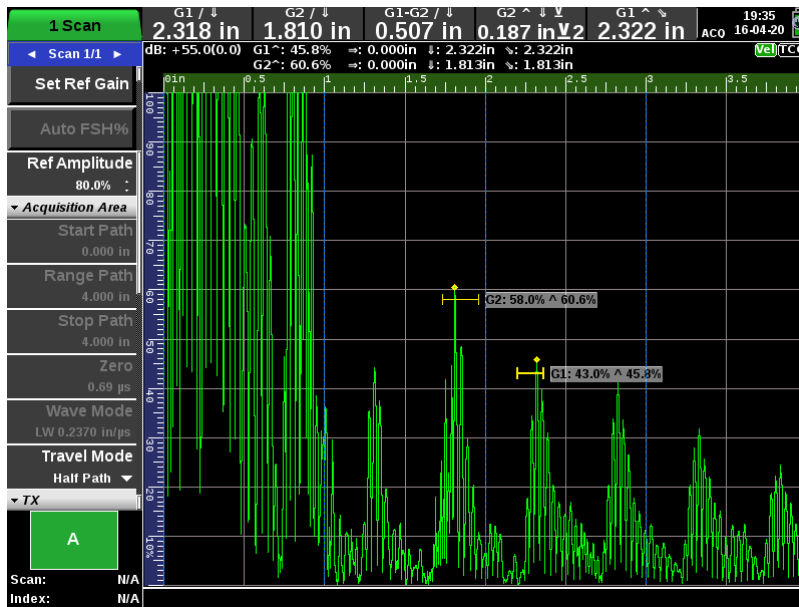
| BLOCK 2 - Coal Tar Enamel 189 mils @ 72 ° F |               |                          |  |              |   |              |  |              |   |              |  |              |  |              |  |              |   |              |   |              |  |              |
|---|---------------|--------------------------|--|--------------|---|--------------|--|--------------|---|--------------|--|--------------|--|--------------|--|--------------|---|--------------|---|--------------|--|--------------|
| Flaw ID                                     | Flaw Type     | AS-BUILT Ligament (inch) | Wall Thickness Measurements  |              |   |              |  |              |   |              |  |              |  |              |  |              |   |              |   |              |  |              |
|   |               |                          | TEST 1<br>38DL Plus Thru-Coat<br>SEM Technique<br>7906 Probe 5MHz Dual |              | TEST 2<br>PAUT<br>SEM Technique<br>5MHz w/ Delay Line |              | TEST 3<br>Flaw Detector<br>SEM Technique<br>5MHz w/ Delay Line |              | TEST 4<br>PAUT<br>MEM Technique<br>5MHz w/ Delay Line |              | TEST 5<br>Flaw Detector<br>MEM Technique<br>5MHz w/ Delay Line |              | TEST 6<br>Flaw Detector<br>SEM Technique<br>7906 Probe 5MHz Dual |              | TEST 7<br>Flaw Detector<br>SEM Technique<br>1/2", 2.25MHz Dual |              | TEST 8<br>Flaw Detector<br>SEM Technique<br>1MHz 1/2" w/ Delay Line |              | TEST 9<br>Flaw Detector<br>MEM Technique<br>3/4" 2.25MHz Single |              | TEST 10<br>Flaw Detector<br>MEM Technique<br>1" 1.05MHz Single |              |
|   |               |                          | Measurement (inch)   | ERROR (inch) | Measurement (inch)                                    | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)                                    | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)   | ERROR (inch) |
| A1  | Square Pocket | 0.062                    | Note 1   |              | 0.065   | 0.003        | Note 2   |              | 0.079   | 0.017        | Note 2   |              | 0.077  | 0.015        | Note 5   |              | Note 3  |              | 0.069   | 0.007        | Note 3   |              |
| A2  | Square Pocket | 0.125                    | Note 1   |              | 0.144   | 0.019        | Note 2   |              | 0.122   | 0.003        | 0.110  | 0.015        | 0.138  | 0.013        | 0.138  | 0.013        | Note 1  |              | 0.123   | 0.002        | Note 5   |              |
| A3  | Square Pocket | 0.187                    | Note 1   |              | 0.209   | 0.022        | Note 2   |              | 0.205   | 0.018        | 0.193  | 0.006        | 0.197  | 0.010        | 0.207  | 0.020        | Note 1  |              | 0.163   | 0.024        | 0.19   | 0.003        |
| A4  | Square Pocket | 0.248                    | Note 1   |              | 0.270   | 0.022        | Note 2   |              | 0.266   | 0.018        | 0.229  | 0.019        | 0.258  | 0.010        | 0.257  | 0.009        | 0.275   | 0.027        | 0.253   | 0.005        | 0.244  | 0.004        |
| A5  | Square Pocket | 0.373                    | Note 1   |              | 0.363   | 0.010        | Note 2   |              | 0.392   | 0.019        | 0.379  | 0.006        | 0.387  | 0.014        | 0.393  | 0.020        | 0.356   | 0.017        | 0.386   | 0.013        | 0.372  | 0.001        |
| A6  | Square Pocket | 0.498                    | Note 1   |              | 0.500   | 0.002        | Note 2   |              | 0.504   | 0.006        | 0.521  | 0.023        | 0.509  | 0.011        | 0.512  | 0.014        | 0.488   | 0.010        | 0.509   | 0.011        | 0.504  | 0.006        |
| B1  | Flat Hole     | 0.469                    | Note 1   |              | 0.471   | 0.002        | Note 2   |              | 0.468   | 0.001        | 0.440  | 0.029        | 0.483  | 0.014        | 0.419  | 0.050        | 0.459   | 0.010        | 0.497   | 0.028        | 0.467  | 0.002        |
| B2  | Flat Hole     | 0.469                    | Note 1   |              | Note 2  |              | Note 2   |              | Note 4  |              | 0.464  | 0.005        | 0.481  | 0.012        | 0.483  | 0.014        | 0.453   | 0.016        | 0.476   | 0.007        | 0.467  | 0.002        |
| B3  | Flat Hole     | 0.472                    | Note 1   |              | Note 2  |              | Note 2   |              | Note 4  |              | 0.486  | 0.014        | 0.48   | 0.008        | 0.471  | 0.001        | 0.446   | 0.026        | 0.48  | 0.008        | 0.474  | 0.002        |
| B4  | Flat Hole     | 0.467                    | Note 1   |              | Note 2  |              | Note 2   |              | Note 4  |              | Note 2   |              | 0.478  | 0.011        | Note 2   |              | 0.516   | 0.049        | 0.506   | 0.039        | Note 2   |              |
| B5  | Flat Hole     | 0.465                    | Note 1   |              | Note 2  |              | Note 2   |              | Note 4  |              | Note 2   |              | 0.473  | 0.008        | Note 2   |              | 0.468   | 0.003        | Note 2  |              | Note 2   |              |
| C1  | Flat Hole     | 0.312                    | Note 1   |              | 0.327   | 0.015        | Note 2   |              | 0.313   | 0.001        | 0.300  | 0.012        | 0.329  | 0.017        | 0.3  | 0.012        | Note 2  |              | 0.315   | 0.003        | 0.311  | 0.001        |
| C2  | Flat Hole     | 0.314                    | Note 1   |              | 0.320   | 0.006        | Note 2   |              | 0.327   | 0.013        | 0.330  | 0.016        | 0.322  | 0.008        | 0.302  | 0.012        | Note 2  |              | 0.315   | 0.001        | 0.315  | 0.001        |
| C3  | Flat Hole     | 0.314                    | Note 1   |              | 0.338   | 0.024        | Note 2   |              | 0.327   | 0.013        | 0.319  | 0.005        | 0.327  | 0.013        | 0.331  | 0.017        | Note 2  |              | 0.324   | 0.010        | 0.315  | 0.001        |
| C4  | Flat Hole     | 0.311                    | Note 1   |              | 0.313   | 0.002        | Note 2   |              | 0.324   | 0.013        | Note 2   |              | 0.323  | 0.012        | 0.329  | 0.018        | Note 2  |              | 0.336   | 0.025        | Note 2   |              |
| C5  | Flat Hole     | 0.31                     | Note 1   |              | Note 2  |              | Note 2   |              | Note 4  |              | Note 2   |              | 0.341  | 0.031        | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| D1  | Flat Hole     | 0.156                    | Note 1   |              | 0.158   | 0.002        | Note 2   |              | 0.147   | 0.009        | 0.157  | 0.001        | 0.165  | 0.009        | 0.179  | 0.023        | Note 2  |              | 0.147   | 0.009        | Note 2   |              |
| D2  | Flat Hole     | 0.157                    | Note 1   |              | 0.148   | 0.009        | Note 2   |              | 0.158   | 0.001        | Note 2   |              | 0.176  | 0.019        | 0.186  | 0.029        | Note 2  |              | 0.156   | 0.001        | Note 2   |              |
| D3  | Flat Hole     | 0.161                    | Note 1   |              | 0.176   | 0.015        | Note 2   |              | 0.158   | 0.003        | Note 2   |              | 0.176  | 0.015        | 0.181  | 0.020        | Note 2  |              | 0.161   | 0.000        | Note 2   |              |
| D4  | Flat Hole     | 0.155                    | Note 1   |              | 0.140   | 0.015        | Note 2   |              | 0.169   | 0.014        | Note 2   |              | 0.173  | 0.018        | 0.179  | 0.024        | Note 2  |              | Note 2  |              | Note 2   |              |
| D5  | Flat Hole     | 0.155                    | Note 1   |              | Note 2  |              | Note 2   |              | Note 4  |              | Note 2   |              | Note 2   |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| E1  | Shaped Hole   | 0.299                    | Note 1   |              | Note 2  |              | Note 2   |              | Note 4  |              | Note 2   |              | 0.322  | 0.023        | 0.293  | 0.006        | Note 2  |              | Note 2  |              | Note 2   |              |
| E2  | Shaped Hole   | 0.438                    | Note 1   |              | Note 2  |              | Note 2   |              | Note 4  |              | Note 2   |              | Note 2   |              | 0.46   | 0.022        | Note 2  |              | Note 2  |              | Note 2   |              |
| E3  | Shaped Hole   | 0.564                    | Note 1   |              | Note 2  |              | Note 2   |              | Note 4  |              | Note 2   |              | Note 2   |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| E4  | Shaped Hole   | 0.259                    | Note 1   |              | Note 2  |              | Note 2   |              | Note 4  |              | 0.333  | 0.074        | Note 2   |              | 0.329  | 0.070        | Note 2  |              | 0.303   | 0.044        | Note 2   |              |
|   | RMS Error     |                          |  | NA           | 0.014   |              | NA   |              | 0.012   |              | 0.025  |              | 0.015  |              | 0.019  |              | 0.024   |              | 0.018   |              | 0.003  |              |

Note 1: Ringdown of probe or interface reflection interfering with backwall signal.  
 Note 2: Could not resolve backwall signal(s).  
 Note 3: Frequency too low to resolve backwall multiple reflections.  
 Note 4: Instrument indicated "invalid" measurement due to low signal amplitude or due to extra tape layer reflection.

**Table 3-19**  
**Ultrasonic thickness data collected on 189-mil coal tar enamel at 92°F**

| BLOCK 2 - Coal Tar Enamel 189 mils @ 92° F |               |                          |  |              |   |              |  |              |   |              |   |              |  |              |  |              |   |              |   |              |  |              |
|--|---------------|--------------------------|--|--------------|---|--------------|--|--------------|---|--------------|---|--------------|--|--------------|--|--------------|---|--------------|---|--------------|--|--------------|
| Flaw ID                                    | Flaw Type     | AS-BUILT Ligament (inch) | Wall Thickness Measurements  |              |   |              |  |              |   |              |   |              |  |              |  |              |   |              |   |              |  |              |
|  |               |                          | TEST 1<br>38DL Plus Thru-Coat<br>SEM Technique<br>7906 Probe 5MHz Dual |              | TEST 2<br>PAUT<br>SEM Technique<br>5MHz w/ Delay Line |              | TEST 3<br>Flaw Detector<br>SEM Technique<br>5MHz w/ Delay Line |              | TEST 4<br>PAUT<br>MEM Technique<br>5MHz w/ Delay Line |              | TEST 5<br>Flaw Detector<br>MEM Technique<br>5MHz w/o Delay Line |              | TEST 6<br>Flaw Detector<br>SEM Technique<br>7906 Probe 5MHz Dual |              | TEST 7<br>Flaw Detector<br>SEM Technique<br>1/2", 2.25MHz Dual |              | TEST 8<br>Flaw Detector<br>SEM Technique<br>1MHz 1/2" w/ Delay Line |              | TEST 9<br>Flaw Detector<br>MEM Technique<br>3/4" 2.25MHz Single |              | TEST 10<br>Flaw Detector<br>MEM Technique<br>1" 1.05MHz Single |              |
|  |               |                          | Measurement (inch)   | ERROR (inch) | Measurement (inch)                                    | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)                                    | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)   | ERROR (inch) |
| A1   | Square Pocket | 0.062                    | Note 1   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 1   |              | Note 3  |              | 0.062   | 0.000        | Note 3   |              |
| A2   | Square Pocket | 0.125                    | Note 1   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 4  |              | Note 2   |              | 0.181  | 0.056        | Note 1  |              | 0.128   | 0.003        | Note 2   |              |
| A3   | Square Pocket | 0.187                    | Note 1   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 4  |              | Note 2   |              | 0.217  | 0.030        | Note 1  |              | 0.19  | 0.003        | 0.182  | 0.005        |
| A4   | Square Pocket | 0.248                    | Note 1   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 4  |              | Note 2   |              | 0.238  | 0.010        | Note 2  |              | 0.254   | 0.006        | Note 2   |              |
| A5   | Square Pocket | 0.373                    | Note 1   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 4  |              | Note 2   |              | 0.39   | 0.017        | 0.369   | 0.004        | 0.374   | 0.001        | 0.37   | 0.003        |
| A6   | Square Pocket | 0.498                    | Note 1   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 4  |              | Note 2   |              | 0.521  | 0.023        | 0.539   | 0.041        | 0.507   | 0.009        | 0.5  | 0.002        |
| B1   | Flat Hole     | 0.469                    | Note 1   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 4  |              | Note 2   |              | 0.443  | 0.026        | 0.496   | 0.027        | 0.457   | 0.012        | Note 2   |              |
| B2   | Flat Hole     | 0.469                    | Note 1   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 4  |              | Note 2   |              | 0.498  | 0.029        | 0.439   | 0.030        | 0.481   | 0.012        | Note 2   |              |
| B3   | Flat Hole     | 0.472                    | Note 1   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 4  |              | Note 2   |              | 0.49   | 0.018        | 0.452   | 0.020        | 0.479   | 0.007        | Note 2   |              |
| B4   | Flat Hole     | 0.467                    | Note 1   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 4  |              | Note 2   |              | 0.46   | 0.007        | Note 2  |              | Note 2  |              | Note 2   |              |
| B5   | Flat Hole     | 0.465                    | Note 1   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 4  |              | Note 2   |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| C1   | Flat Hole     | 0.312                    | Note 1   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 4  |              | Note 2   |              | 0.293  | 0.019        | Note 2  |              | 0.299   | 0.166        | Note 2   |              |
| C2   | Flat Hole     | 0.314                    | Note 1   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 4  |              | Note 2   |              | 0.331  | 0.017        | Note 2  |              | 0.318   | 0.006        | Note 2   |              |
| C3   | Flat Hole     | 0.314                    | Note 1   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 4  |              | Note 2   |              | 0.34   | 0.026        | Note 2  |              | 0.318   | 0.004        | Note 2   |              |
| C4   | Flat Hole     | 0.311                    | Note 1   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 4  |              | Note 2   |              | 0.307  | 0.004        | Note 2  |              | 0.313   | 0.001        | Note 2   |              |
| C5   | Flat Hole     | 0.31                     | Note 1   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 4  |              | Note 2   |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| D1   | Flat Hole     | 0.156                    | Note 1   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 4  |              | Note 2   |              | 0.183  | 0.027        | Note 2  |              | 0.161   | 0.005        | Note 2   |              |
| D2   | Flat Hole     | 0.157                    | Note 1   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 4  |              | Note 2   |              | 0.2  | 0.043        | Note 2  |              | 0.156   | 0.001        | Note 2   |              |
| D3   | Flat Hole     | 0.161                    | Note 1   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 4  |              | Note 2   |              | 0.181  | 0.020        | Note 2  |              | Note 2  |              | Note 2   |              |
| D4   | Flat Hole     | 0.155                    | Note 1   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 4  |              | Note 2   |              | 0.179  | 0.024        | Note 2  |              | Note 2  |              | Note 2   |              |
| D5   | Flat Hole     | 0.155                    | Note 1   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 4  |              | Note 2   |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| E1   | Shaped Hole   | 0.299                    | Note 1   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 4  |              | Note 2   |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| E2   | Shaped Hole   | 0.438                    | Note 1   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 4  |              | Note 2   |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| E3   | Shaped Hole   | 0.564                    | Note 1   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 4  |              | Note 2   |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              |
| E4   | Shaped Hole   | 0.259                    | Note 1   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 4  |              | Note 2   |              | Note 2   |              | Note 2  |              | 0.274   | 0.015        | Note 2   |              |
| RMS Error                                  |               |                          |  | NA           |   | N/A          |  | NA           |   | NA           |   | N/A          |  | N/A          |  | 0.026        |   | 0.027        |   | 0.042        |  | 0.004        |

Note 1: Ringdown of probe or interface reflection interfering with backwall signal.  
 Note 2: Could not resolve backwall signal(s).  
 Note 3: Frequency too low to resolve backwall multiple reflections.  
 Note 4: Instrument indicated "invalid" measurement due to low signal amplitude or due to extra tape layer reflection.



**Figure 3-28**  
 Signal obtained using a 2.25-MHz, 3/4-inch-diameter contact transducer using the multiple-echo method to determine thickness (Test 9) on 189-mil TGF-3 specimen at 1/2-inch plate thickness



# 4

## ELECTROMAGNETIC ACOUSTIC TRANSDUCER TESTS ON COATING SPECIMENS

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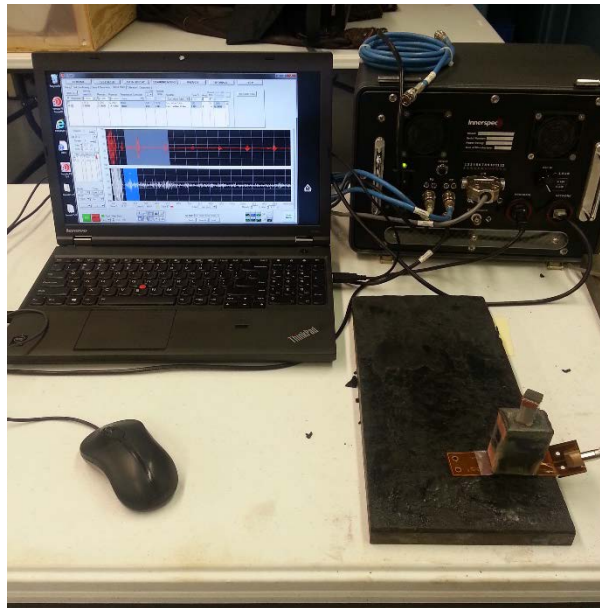
All data collected in the laboratory testing described in Section 3 utilized piezoelectric transducers for all plate thickness measurements. These tests required the round-trip transmission of sound through the coating material and across the coating/metal interface before thickness measurements could be performed. Although the technique was effective in most cases, results indicated that both the 130-mil and 189-mil TGF-3 coatings were difficult to penetrate, especially at higher temperatures. An alternative technology using electromagnetic acoustic transducers (EMATs), which did not require through-coating transmission of sound waves, was also investigated. This approach, which could be used as a supplement to piezoelectric-based techniques, is described in this section.

The objectives of the activities described in this section were to fabricate an EMAT specifically designed for use on thick coatings and to perform thickness measurements on all coated specimens. This investigation was conducted using a commercially available EMAT system and sensor designed to accommodate large lift-off testing conditions like those presented by non-conductive coating on carbon steel pipe.

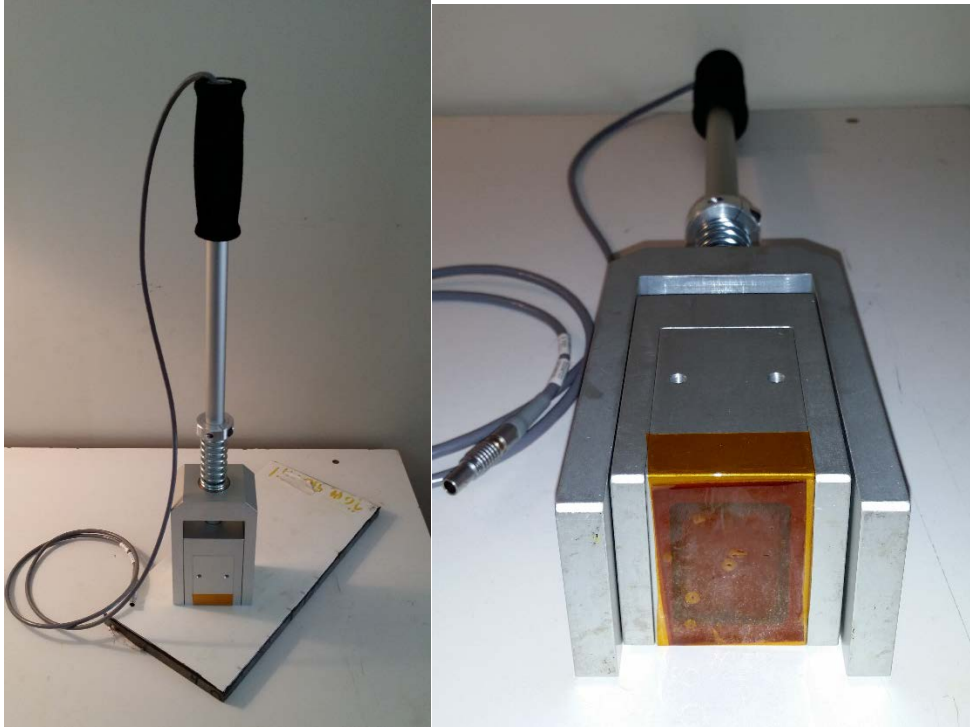
EMATs differ from piezoelectric-based ultrasonic transducers primarily in the method by which sound is generated and detected. Piezoelectric transducers generate sound waves in the body of the transducer, which is coupled to the material being inspected through an accessible surface. In the case of coated piping, the piezoelectric transducer is coupled to the OD surface, requiring sound to transmit through the coating layer and coating/metal interface in order to determine pipe wall thickness. This can be problematic if the coating represents a sound-insulating boundary with very high attenuation properties or if the bond to the pipe has failed. In contrast, an EMAT couples to the pipe wall electromagnetically, resulting in the creation of sound waves on the conductive pipe outer surface. The EMAT generates electric and magnetic fields that interact with a conductive material by generating an alternating Lorentz force. This alternating force generates a sound wave in the conductive material that propagates in a direction and frequency determined by the EMAT coil design. EMATs do require that the conductive material be in close proximity to the EMAT coil for sound to be generated. The efficiency of the EMAT is inversely related to the separation distance (that is, lift-off) between the EMAT coil and the metallic material. In the case of a buried piping, the coal tar epoxy, coal tar enamel, and tape wrap coatings have no significant electrical conductivity and thus represent only a lift-off condition for the EMAT. Thicker coatings will result in weaker signals due to the increased separation distance between the EMAT coil and pipe OD surface. The amount of permissible lift-off varies depending on the EMAT electric coil design, drive frequency used to excite the EMAT coil, and magnet design. Other external factors such as the power output of the signal used to excite the

EMAT coil can have some effect on signal strength. Therefore, the ability of the EMAT to measure wall thickness is expected to decrease with coating thickness—not because of sound attenuation properties of the coating or potential dis-bond conditions, but rather because of the increase in lift-off created by the coating.

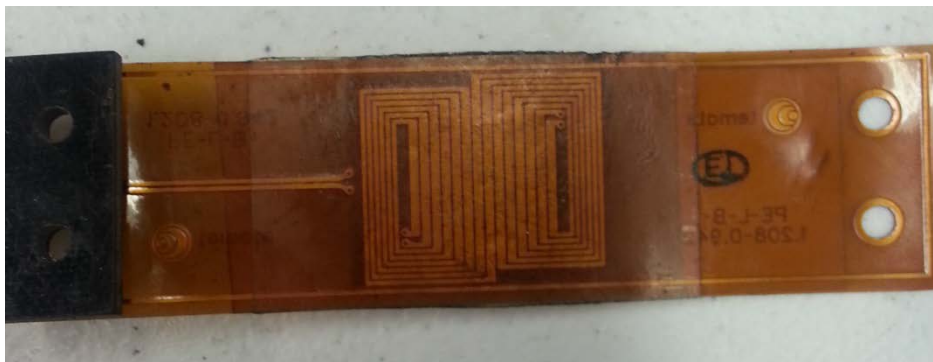
Figure 4-1 is a photograph of the EMAT system used for data collection for this investigation, and Figure 4-2 is a photograph of the high lift-off EMAT fabricated for the investigation by a company that specializes in EMAT systems. The EMAT operated at a frequency of 1.0 MHz and incorporated a large neodymium boron iron permanent magnet. Neodymium boron iron magnets are the strongest permanent magnet readily available, and the magnet was a key component in the EMAT design. The coil was a 1.5-inch x 1.0-inch butterfly design, with one side used for transmitting and the opposing side for receiving. Figure 4-3 is an example of a “butterfly” coil similar to the one in the EMAT used in this investigation. A large coil and magnet assembly was critical in maximizing performance at relatively large lift-off distances. The EMAT was fabricated to operate with lift-off distances up to approximately 0.2 inch. All thickness measurements were performed using an auto-correlation analysis feature found in the EMAT data analysis software or manually using A-scan peak-to-peak cursors (when signal-to-noise levels were too low for the auto-correlation algorithms to function). The EMAT was equipped with an adjustable spring-loaded mechanism that provided a counter force for the assistance of probe removal when testing magnetic materials. The strong permanent magnet was capable of generating significant attractive forces, especially on samples with very thin coating thicknesses.



**Figure 4-1**  
**EMAT system used for testing**



**Figure 4-2**  
High lift-off EMAT fabricated for coating inspection



**Figure 4-3**  
EMAT butterfly coil similar to the one used in the high lift-off EMAT

The results of the EMAT tests for all coating samples are provided in Table 4-1. Shaded areas on this table indicate that a valid measurement was not possible. Figures 4-4 through 4-9 are A-scan presentations of wall thickness multiples observed when testing the 1/2-inch-thick square pocket reflector from each specimen. These figures provide a representative example of signal waveforms generated by the EMAT for each coating when inspecting large flat reflectors.

The EMAT was tested using all coated specimens with thicknesses (lift-off distances) ranging from 0.016 to 0.189 inch. The EMAT was capable of providing accurate thickness readings on the full range of coatings when testing large reflectors. The EMAT was not able to detect the 0.2-inch-diameter flat-bottom holes or shaped reflectors due to its inability to detect multiple wall reflections. The EMAT had a large coil, resulting in a limited ability to resolve small

reflectors due to a low energy density of the transmitted sound wave. As a result, reflections from small reflectors were below the noise threshold of the probe. Also, the “dead zone” of the probe caused by the ringing of the initial pulse prevented measuring wall thickness less than approximately 0.45 inches using the first back wall reflection (SEM technique). As a result, multiple back wall reflections were needed for thin wall measurements (that is, the MEM technique). This caused problems with reflectors such as the shaped-bottom holes where reception of multiple thickness reflections was not possible. Since only the first back wall reflection could be used for detection, these flaws were not detected due to interference with the initial pulse.

The EMAT was useful for measuring wall thickness on larger reflectors covering a wide range of thicknesses for all specimen coatings. The EMAT was capable of measuring wall thickness on the 189-mil TGF-3 specimen for these type of reflectors. It should be noted that coating thickness did have an adverse effect on the signal amplitude due to lift-off. To better understand this effect, signals were compared on the ½-inch wall thickness square pocket reflector for each specimen with the amplification required to normalize the signals recorded. Figure 4-10 is a plot of this data, illustrating the amount of signal loss caused by increased distance between the EMAT coil and the component surface. This distance, or lift-off, is created by the thickness of the coating since the coatings tested in this investigation were not conductive and had no magnetic properties. In summary, the signals associated with the 189-mil coating were approximately 40 times lower in amplitude than those detected on the 16-mil coating. This reduction in wall thickness amplitude was a direct result of two effects. First, the magnitude of the eddy current flow on the component surface decreased exponentially as the component was moved toward the outer limits of the electrical field generated by the coil. Similarly, the carbon steel drew less magnetic flux from the permanent magnet as the separation was increased. These two effects resulted in a significant decrease in signal amplitude on thicker coated specimens. The 189-mil specimen was the most challenging specimen for the EMAT. Wall thickness measurements were limited to large flat reflectors only, with difficulties associated with wall thickness less than 1/8 inch.

The EMAT was the only probe capable of measuring wall thickness on the high attenuation areas noted in Section 3 on the 130-mil TGF-3 specimen where coating conditions prevented the use piezoelectric transducers. It was hypothesized that these areas did not have as much tar enamel in the coating composition, which led to the creation of small voids that prevented sound transmission. Since the EMAT did not require the transmission of sound through the coating, it was not adversely affected by this condition. In this case, the EMAT provided an effective complementary inspection tool to the piezoelectric techniques by providing thickness measurements where no other techniques proved to be possible.

In conclusion, the high-lift-off EMAT was capable of acquiring wall thickness measurements on all coating type specimens (coal tar enamel, tape wrap, and coal tar epoxy) and thickness ranges. The EMAT was limited to measurement of thickness on larger areas, with significant limitations on measuring small localized reflectors, shaped reflectors, and very thin-walled regions, especially on the thickest coating. The data supports the use of the EMAT testing for accessing pipe wall thickness in cases where corrosion is generally uniform over larger areas (that is, 1 square inch and larger). The probe does not require couplant like piezoelectric transducers do and can be moved from location to location with minimal effort. The EMAT may be useful

where coating surface conditions prevent the coupling of piezoelectric transducers, where coating-to-pipe bonding is insufficient to support sound transmission, and where coating composition creates very high attenuation for the transmission of sound.

**Table 4-1**  
**Summary of EMAT results on all plates**

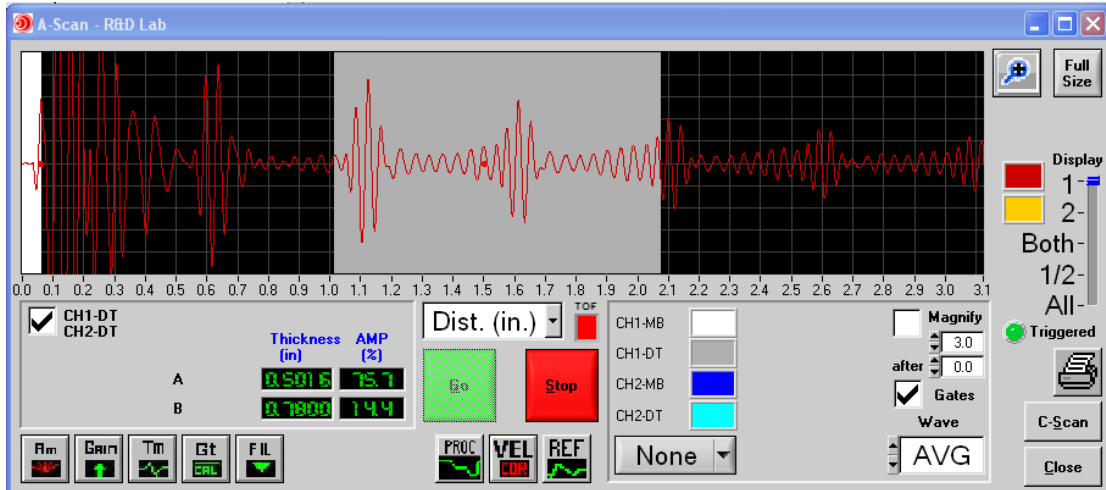
| EMAT Tests - 1.0 MHz, 0°, SH-wave |               |                               |                               |              |                               |              |                          |              |                          |              |                                 |              |                                 |              |
|-----------------------------------|---------------|-------------------------------|-------------------------------|--------------|-------------------------------|--------------|--------------------------|--------------|--------------------------|--------------|---------------------------------|--------------|---------------------------------|--------------|
| Flaw ID                           | Flaw Type     | AS-BUILT Ligament inch (inch) | Wall Thickness Measurements   |              |                               |              |                          |              |                          |              |                                 |              |                                 |              |
|                                   |               |                               | 16 Mil Coal Tar Epoxy Coating |              | 20 Mil Coal Tar Epoxy Coating |              | 50 Mil Tape Wrap Coating |              | 80 Mil Tape Wrap Coating |              | 130 Mil Coal Tar Enamel Coating |              | 189 Mil Coal Tar Enamel Coating |              |
|                                   |               |                               | Measurement (inch)            | ERROR (inch) | Measurement (inch)            | ERROR (inch) | Measurement (inch)       | ERROR (inch) | Measurement (inch)       | ERROR (inch) | Measurement (inch)              | ERROR (inch) | Measurement (inch)              | ERROR (inch) |
| A1                                | Square Pocket | 0.062                         | 0.061                         | 0.001        | 0.06                          | 0.002        | 0.061                    | 0.001        | 0.059                    | 0.003        | Note 3                          |              | Note 3                          |              |
| A2                                | Square Pocket | 0.125                         | 0.125                         | 0.000        | 0.126                         | 0.001        | 0.125                    | 0.000        | 0.124                    | 0.001        | 0.125                           | 0.000        | Note 3                          |              |
| A3                                | Square Pocket | 0.187                         | 0.187                         | 0.000        | 0.188                         | 0.001        | 0.188                    | 0.001        | 0.187                    | 0.000        | 0.188                           | 0.001        | 0.187                           | 0.000        |
| A4                                | Square Pocket | 0.248                         | 0.248                         | 0.000        | 0.248                         | 0.000        | 0.249                    | 0.001        | 0.248                    | 0.000        | 0.247                           | 0.001        | 0.249                           | 0.001        |
| A5                                | Square Pocket | 0.373                         | 0.374                         | 0.001        | 0.373                         | 0.000        | 0.375                    | 0.002        | 0.373                    | 0.000        | 0.372                           | 0.001        | 0.371                           | 0.002        |
| A6                                | Square Pocket | 0.498                         | 0.501                         | 0.003        | 0.5                           | 0.002        | 0.503                    | 0.005        | 0.5                      | 0.002        | 0.5                             | 0.002        | 0.501                           | 0.003        |
| B1                                | Flat Hole     | 0.469                         | 0.469                         | 0.000        | 0.47                          | 0.001        | 0.473                    | 0.004        | 0.47                     | 0.001        | 0.467                           | 0.002        | 0.467                           | 0.002        |
| B2                                | Flat Hole     | 0.469                         | 0.47                          | 0.001        | 0.47                          | 0.001        | 0.472                    | 0.003        | 0.47                     | 0.001        | 0.467                           | 0.002        | Note 3                          |              |
| B3                                | Flat Hole     | 0.472                         | 0.479                         | 0.007        | 0.47                          | 0.002        | 0.456                    | 0.016        | 0.456                    | 0.016        | 0.456                           | 0.016        | Note 3                          |              |
| B4                                | Flat Hole     | 0.467                         | 0.456                         | 0.011        | 0.46                          | 0.007        | 0.464                    | 0.003        | 0.456                    | 0.011        | 0.448                           | 0.019        | Note 3                          |              |
| B5                                | Flat Hole     | 0.465                         | Note 1                        |              | Note 1                        |              | Note 1                   |              | Note 1                   |              | Note 1                          |              | Note 3                          |              |
| C1                                | Flat Hole     | 0.312                         | 0.314                         | 0.002        | 0.313                         | 0.001        | 0.314                    | 0.002        | 0.311                    | 0.001        | 0.312                           | 0.000        | 0.313                           | 0.001        |
| C2                                | Flat Hole     | 0.314                         | 0.313                         | 0.001        | 0.31                          | 0.004        | 0.311                    | 0.003        | 0.31                     | 0.004        | 0.311                           | 0.003        | Note 3                          |              |
| C3                                | Flat Hole     | 0.314                         | Note 2                        |              | Note 2                        |              | Note 2                   |              | Note 2                   |              | Note 2                          |              | Note 3                          |              |
| C4                                | Flat Hole     | 0.311                         | Note 2                        |              | Note 2                        |              | Note 2                   |              | Note 2                   |              | Note 2                          |              | Note 3                          |              |
| C5                                | Flat Hole     | 0.31                          | Note 1                        |              | Note 1                        |              | Note 1                   |              | Note 1                   |              | Note 1                          |              | Note 3                          |              |
| D1                                | Flat Hole     | 0.156                         | 0.156                         | 0.000        | 0.157                         | 0.001        | 0.158                    | 0.002        | 0.156                    | 0.000        | 0.154                           | 0.002        | 0.155                           | 0.001        |
| D2                                | Flat Hole     | 0.157                         | 0.157                         | 0.000        | 0.159                         | 0.002        | 0.159                    | 0.002        | 0.157                    | 0.000        | 0.156                           | 0.001        | Note 3                          |              |
| D3                                | Flat Hole     | 0.161                         | 0.157                         | 0.004        | 0.158                         | 0.003        | 0.157                    | 0.004        | 0.158                    | 0.003        | 0.156                           | 0.005        | Note 3                          |              |
| D4                                | Flat Hole     | 0.155                         | 0.155                         | 0.000        | 0.156                         | 0.001        | 0.154                    | 0.001        | 0.155                    | 0.000        | Note 3                          |              | Note 3                          |              |
| D5                                | Flat Hole     | 0.155                         | Note 1                        |              | Note 1                        |              | Note 1                   |              | Note 1                   |              | Note 1                          |              | Note 3                          |              |
| E1                                | Shaped Hole   | 0.299                         | Note 4                        |              | Note 4                        |              | Note 4                   |              | Note 4                   |              | Note 4                          |              | Note 3                          |              |
| E2                                | Shaped Hole   | 0.438                         | Note 3                        |              | Note 3                        |              | Note 3                   |              | Note 3                   |              | Note 3                          |              | Note 3                          |              |
| E3                                | Shaped Hole   | 0.564                         | Note 3                        |              | Note 3                        |              | Note 3                   |              | Note 3                   |              | Note 3                          |              | Note 3                          |              |
| E4                                | Shaped Hole   | 0.259                         | 0.362                         | 0.103        | 0.362                         | 0.103        | 0.354                    | 0.095        | 0.317                    | 0.058        | 0.319                           | 0.060        | Note 3                          |              |
| RMS Error                         |               |                               |                               | 0.025        |                               | 0.025        |                          | 0.023        |                          | 0.015        |                                 | 0.017        |                                 | 0.002        |

Note 1: Reflector too small to be detected.

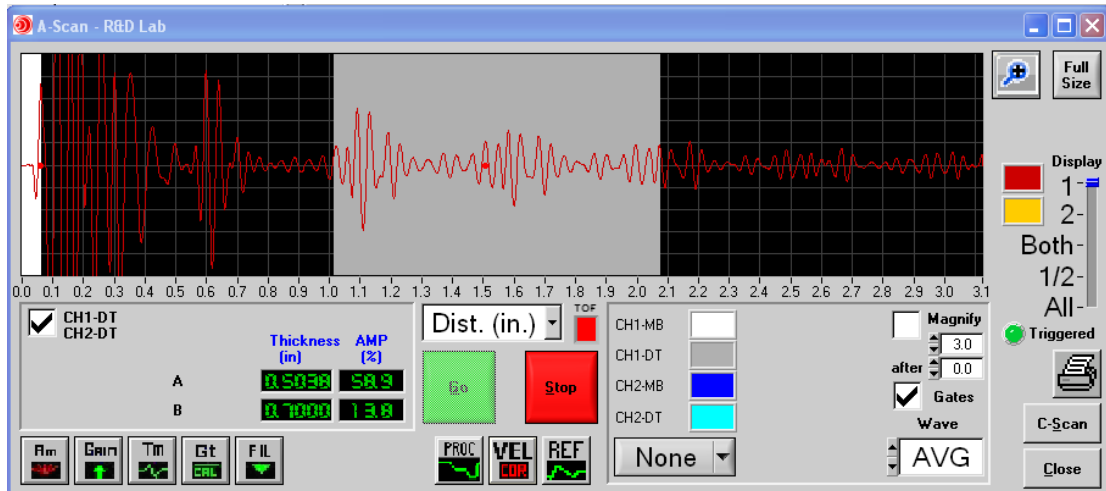
Note 2: Reflector signal interfered with plate backwall signals.

Note 3: Signal too weak to be resolved likely due to lift-off and/or reflector size.

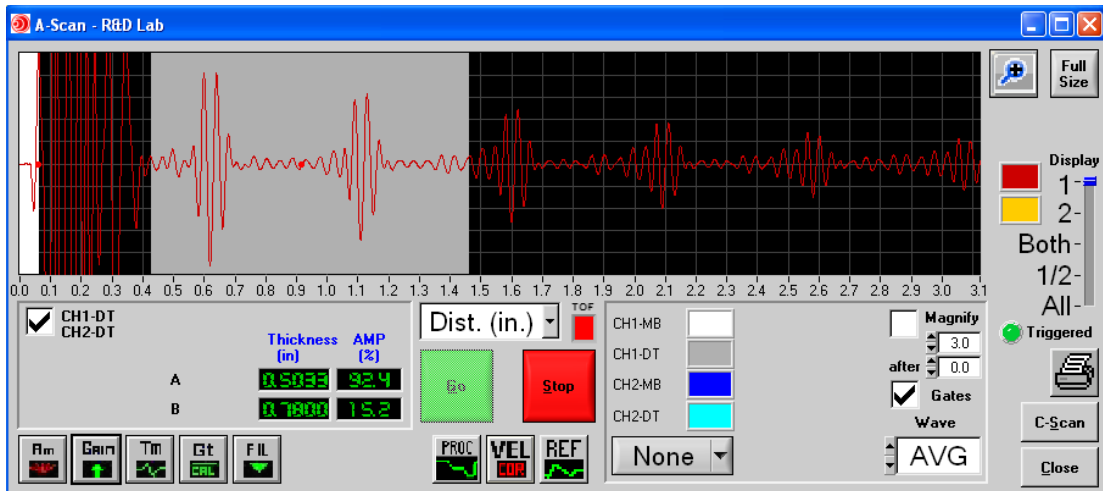
Note 4: Reflector signal in dead zone of probe: No multiple reflections possible due to shape of reflector.



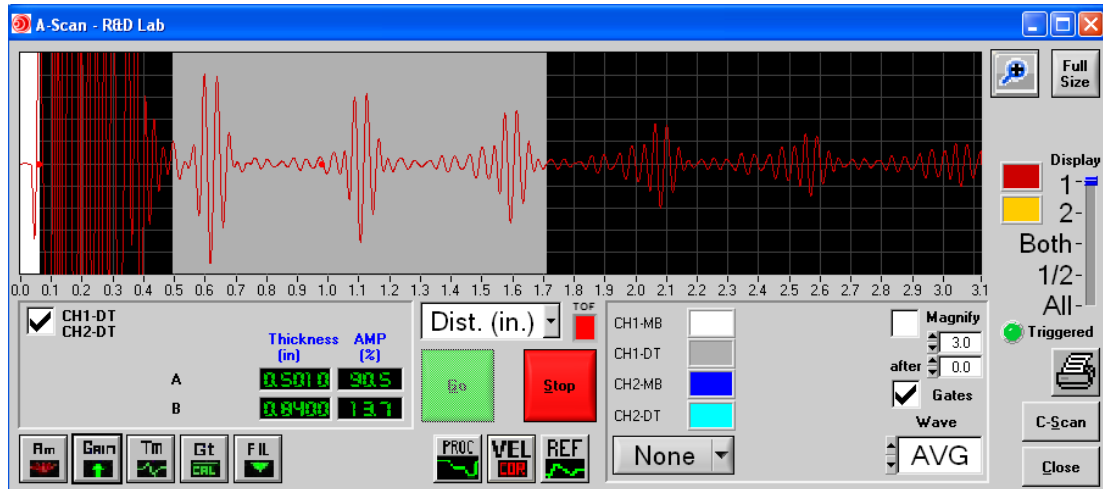
**Figure 4-4**  
Back wall multiples collected when testing 16-mil coal tar epoxy specimen at 0.500-inch wall thickness



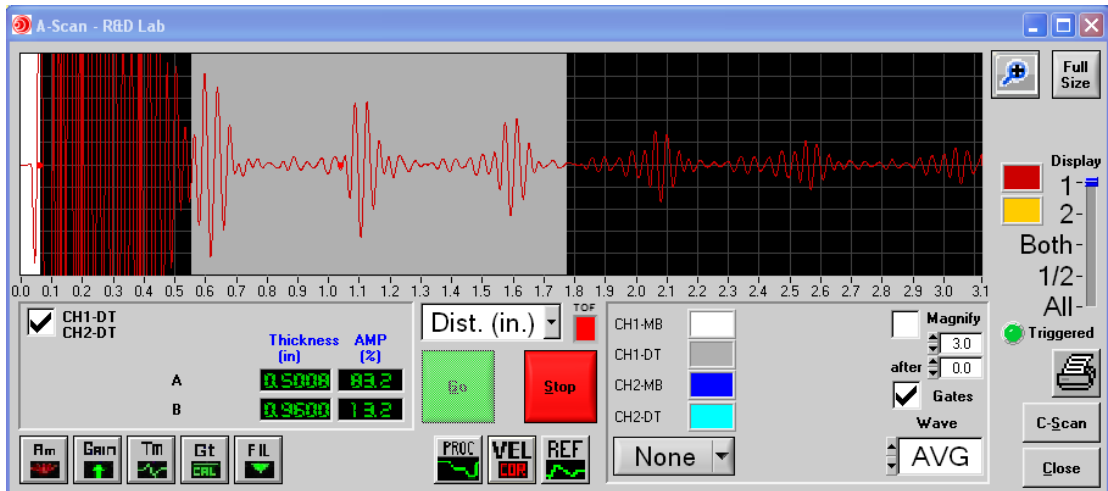
**Figure 4-5**  
Back wall multiples collected when testing 20-mil coal tar epoxy specimen at 0.500-inch wall thickness



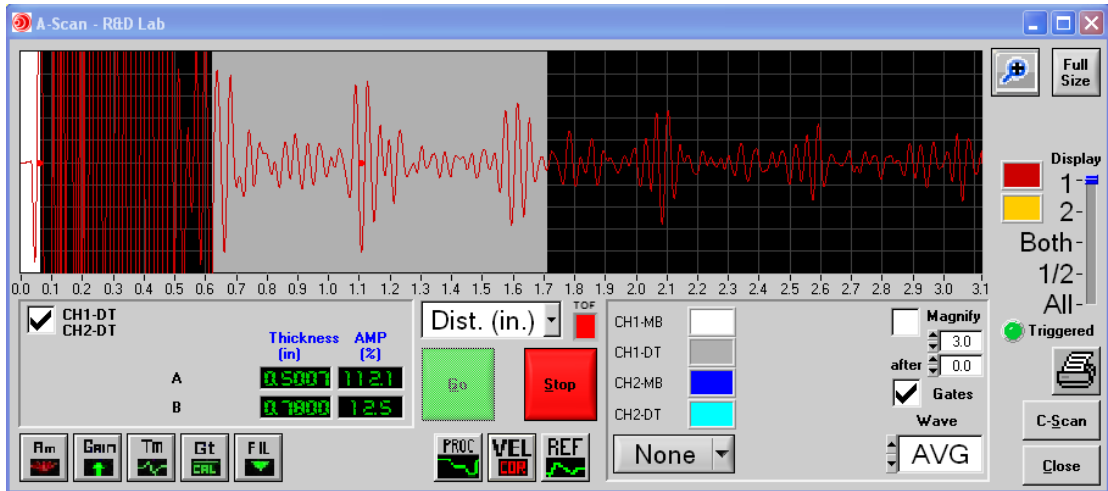
**Figure 4-6**  
Back wall multiples collected when testing 50-mil tape wrap specimen at 0.500-inch wall thickness



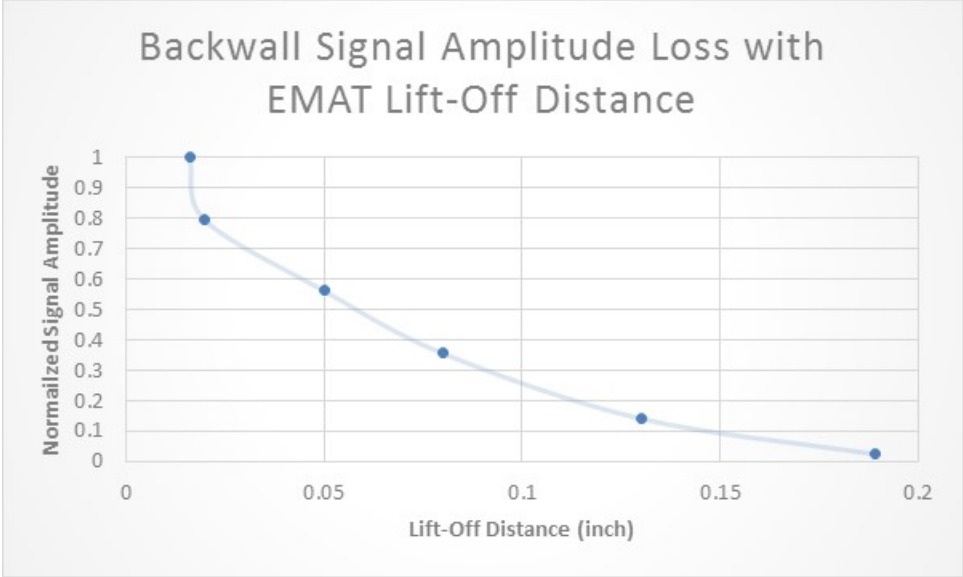
**Figure 4-7**  
Back wall multiples collected when testing 80-mil tape wrap specimen at 0.500-inch wall thickness



**Figure 4-8**  
Back wall multiples collected when testing 130-mil coal tar enamel specimen at 0.500-inch wall thickness



**Figure 4-9**  
Back wall multiples collected when testing 189-mil coal tar enamel specimen at 0.500-inch wall thickness



**Figure 4-10**  
Signal loss measured using the high lift-off EMAT on a 1/2-inch-thick carbon steel material



# 5

## ULTRASONIC MEASUREMENT OF PIPE THICKNESS THROUGH STRUCTURAL COATING

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A new type of structural coating was identified during this investigation that was not used during the construction of existing nuclear facilities but has potential use for life extension purposes. This section was added to provide the reader with insights on the compatibility of ultrasonic methods for the inspection of coated piping through this type of structural coating.

### Background

Structural coatings are designed not only to provide a corrosion-resistant barrier but also to add to the strength of the original pipe. Structural coatings are designed to restore the functionality of a degraded parent piping system but can also be engineered to increase the original design flow and operational pressures of the system. These coatings are applied to either the ID or OD surfaces of larger-diameter piping (30 inches or greater), with the coating thickness calculated based on targeted strength specifications. Structural coatings are a two-phase composite material consisting of a high-strength fiber material surrounded by a resin matrix phase. The fiber is typically carbon or fiberglass weave, which provides load-bearing characteristics. Once cured, the matrix resin material transfers the load between individual fibers and serves as the bonding agent securing the fiber relative positions. The thickness of the structural coating depends on the number of layers of fiber material that are applied. The more layers of fiber weave used, the stronger the resulting coating. Therefore, the thickness of the applied coating can vary depending on each unique application. Typical coating thicknesses range from approximately ½ to 1 inch in thickness, according to the manufacturer.

The coating tested in this investigation was a composite layup consisting of a high-strength carbon fiber weave that was saturated in a resin matrix material. Figure 5-1 provides photographs of this specimen. To prepare the sample for testing, the coating applicator was provided with a steel plate, which was flat on one side while the other side had a series of prenotched holes that varied in depth and width. The applicator abrasively (sponge) blasted the steel plate to a near white metal (SSPC-10) and blew down/wiped the surface clean. A series of glass fiber reinforced polymer (GFRP) composite and carbon fiber reinforced polymer (CFRP) composite layers were installed with the following sequence:

1. Prime the surface with neat epoxy
2. Install a thin layer of thickened epoxy
3. Install a layer of 0.034-inch-thick bidirectional GFRP as a dielectric barrier
4. Install a thin layer of thickened epoxy
5. Install a vertical/hoop layer of 0.08-inch unidirectional CFRP
6. Install a thin layer of thickened epoxy

7. Install a horizontal/longitudinal layer of 0.08-inch unidirectional CFRP
8. Install a thin layer of thickened epoxy
9. Install a layer of 0.034-inch-thick bidirectional GFRP for water tightness
10. Install a thin layer of thickened epoxy
11. Install a vertical/hoop layer of 0.08-inch unidirectional CFRP
12. Install a thin layer of thickened epoxy top coating

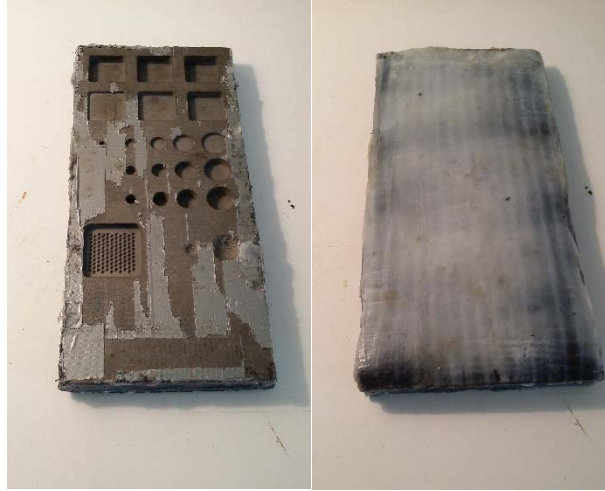
Each layer was troweled out to ensure uniformity and absence of entrapped air pockets. Thickened epoxy was equally and uniformly placed between successive layers of GFRP/CFRP materials. The layers of GFRP and CFRP were saturated with epoxy using a calibrated mechanical saturator to ensure proper impregnation of the fabrics with epoxy resin. The plate and materials were cured in a controlled environment to ensure proper cure prior to shipment to EPRI for testing.

Once applied, the coating cured to a durable epoxy-like surface with a final thickness of approximately 0.45 inch with some tapering at the edges. The surface was hard, with some localized ridges and bumps associated primarily with the troweling process used during application. Surface roughness was considered typical, and no attempt was made to modify it mechanically through machining.

The sample was subjected to the same testing as all other coated specimens described in this investigation including all piezoelectric techniques as well as the EMAT technique. Testing was performed at three temperatures: 52°F, 72°F, and 92°F (+/- 5°F). The results of these tests can be found in Tables 5-1 through 5-3.

The results of these tests suggest that the structural coating greatly attenuated the sound waves as they propagated between the outer surface and the coating/steel interface. Only two techniques provided some limited thickness measurement capability. The 2.25-MHz, 0.75-inch-diameter transducer and the 1.0-MHz, 1-inch-diameter transducer both produced similar results, allowing for the measurement of plate thickness only on the largest reflectors (square pockets). These transducers represented the largest aperture size as well as the two lowest frequencies. The large aperture assured maximum total energy input into the material while limiting the ability to detect smaller reflectors. The lower frequencies produced sound waves with relatively large wavelengths, which increased penetration capabilities. Both of these probes produced significantly large-amplitude coating-related signals immediately following the initial pulsing of the transducers. These signals were created by reflections from within the coating material, likely from interactions with the carbon weave layers, as shown in Figure 5-2. The reflections shown in this figure were collected using the 2.25-MHz transducer on a 1½-inch-square pocket reflector at a gain of 20 dB. This signal did not appear to contain any plate-thickness-related signals. However, an additional 40 dB of amplification (60 dB total gain) did produce a series of thickness multiple reflections, as shown in Figure 5-3. This large amount of gain was indicative of the amount of energy loss resulting from having traversed the coating material. This high gain requirement also increased the effect of low-amplitude coating-related reflections by amplifying them to levels equal to or greater than the thickness reflection. As a result, the first and second

back wall thickness multiples could not be resolved reliably. This required that back wall multiple reflections farther out in time be used in order to obtain accurate plate thickness measurements. A similar observation was noted using the 1-MHz transducer, although the lower frequency required less signal amplification, as shown in Figure 5-4.



**Figure 5-1**  
Carbon fiber mat epoxy structural coating applied to test specimen

**Table 5-1**  
Test results for epoxy carbon mat coating at 52°F

| Epoxy Carbon Fiber Mat Coating @ 52F |               |                          |   |              |  |              |   |              |  |              |   |              |   |              |  |              |  |              |  |              |   |              |
|--------------------------------------|---------------|--------------------------|---|--------------|--|--------------|---|--------------|--|--------------|---|--------------|---|--------------|--|--------------|--|--------------|--|--------------|---|--------------|
| Flaw ID                              | Flaw Type     | AS-BUILT Ligament (inch) | Wall Thickness Measurements   |              |  |              |   |              |  |              |   |              |   |              |  |              |  |              |  |              |   |              |
|                                      |               |                          | TEST 1<br>38DL Plus Thru-Coat SEM Technique<br>7506 Probe 5MHz Dual |              | TEST 2<br>PAUT SEM Technique<br>5MHz w/ Delay Line |              | TEST 3<br>Flaw Detector SEM Technique<br>5MHz w/ Delay Line |              | TEST 4<br>PAUT MEM Technique<br>5MHz w/ Delay Line |              | TEST 5<br>Flaw Detector MEM Technique<br>5MHz w/ Delay Line |              | TEST 6<br>Flaw Detector SEM Technique<br>7506 Probe 5MHz Dual |              | TEST 7<br>Flaw Detector SEM Technique<br>1/2" 2.25MHz Dual |              | TEST 8<br>Flaw Detector SEM Technique<br>3/4" 2.25MHz Single |              | TEST 9<br>Flaw Detector MEM Technique<br>3/4" 1.05MHz Single |              | TEST 10<br>Flaw Detector MEM Technique<br>1" 1.05MHz Single |              |
|                                      |               |                          | Measurement (inch)  | ERROR (inch) | Measurement (inch)                                 | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)                                 | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)  | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)   | ERROR (inch) | Measurement (inch)  | ERROR (inch) |
| A1                                   | Square Pocket | 0.062                    | Note 1  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | Note 3  |              |
| A2                                   | Square Pocket | 0.125                    | Note 1  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | Note 3  |              |
| A3                                   | Square Pocket | 0.187                    | Note 1  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | 0.225  | 0.038        | Note 3  |              |
| A4                                   | Square Pocket | 0.248                    | Note 1  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | 0.251  | 0.003        | Note 3  |              |
| A5                                   | Square Pocket | 0.373                    | Note 1  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | 0.319  | 0.054        | 0.353   | 0.020        |
| A6                                   | Square Pocket | 0.498                    | Note 1  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | 0.447  | 0.051        | 0.498   | 0.000        |
| B1                                   | Flat Hole     | 0.469                    | Note 1  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | 0.468  | 0.001        | 0.47  | 0.001        |
| B2                                   | Flat Hole     | 0.469                    | Note 1  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | 0.463   | 0.006        |
| B3                                   | Flat Hole     | 0.472                    | Note 1  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | 0.536   | 0.064        |
| B4                                   | Flat Hole     | 0.467                    | Note 1  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | Note 3  |              |
| B5                                   | Flat Hole     | 0.465                    | Note 1  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | Note 3  |              |
| C1                                   | Flat Hole     | 0.312                    | Note 1  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | Note 3  |              |
| C2                                   | Flat Hole     | 0.314                    | Note 1  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | Note 3  |              |
| C3                                   | Flat Hole     | 0.314                    | Note 1  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | Note 3  |              |
| C4                                   | Flat Hole     | 0.311                    | Note 1  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | Note 3  |              |
| C5                                   | Flat Hole     | 0.31                     | Note 1  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | Note 3  |              |
| D1                                   | Flat Hole     | 0.156                    | Note 1  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | Note 3  |              |
| D2                                   | Flat Hole     | 0.157                    | Note 1  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | Note 3  |              |
| D3                                   | Flat Hole     | 0.161                    | Note 1  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | Note 3  |              |
| D4                                   | Flat Hole     | 0.155                    | Note 1  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | Note 3  |              |
| D5                                   | Flat Hole     | 0.155                    | Note 1  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | Note 3  |              |
| E1                                   | Shaped Hole   | 0.209                    | Note 1  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | Note 3  |              |
| E2                                   | Shaped Hole   | 0.438                    | Note 1  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | Note 3  |              |
| E3                                   | Shaped Hole   | 0.564                    | Note 1  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | Note 3  |              |
| E4                                   | Shaped Hole   | 0.229                    | Note 1  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2  |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | Note 3  |              |
| RMS Error                            |               |                          |   | NA           |  | NA           |   | N/A          |  | NA           |   | NA           |   | NA           |  | NA           |  | N/A          |  | 0.037        |   | 0.030        |

Note 1: Instrument indicated "invalid" measurement due to low signal amplitude.  
 Note 2: First backwall reflection could not be positively identified.  
 Note 3: Multiple backwall reflection could not be positively identified.

Ultrasonic Measurement of Pipe Thickness Through Structural Coating

**Table 5-2**  
**Test results for epoxy carbon mat coating at 72°F**

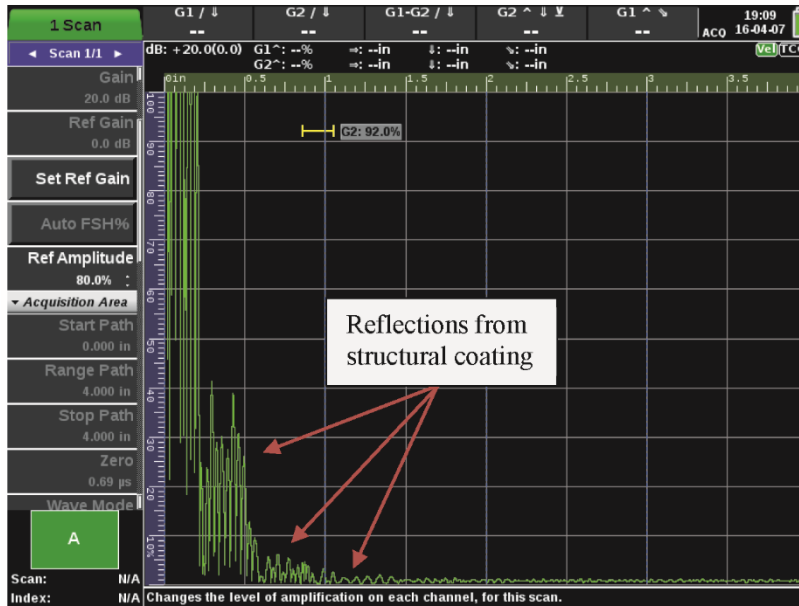
| Epoxy Carbon Fiber Mat Coating @ 72F |               |                          |  |              |  |              |   |              |   |              |  |              |   |              |  |              |  |              |  |              |  |              |
|--------------------------------------|---------------|--------------------------|--|--------------|--|--------------|---|--------------|---|--------------|--|--------------|---|--------------|--|--------------|--|--------------|--|--------------|--|--------------|
| Flaw ID                              | Flaw Type     | AS-BUILT Ligament (inch) | Wall Thickness Measurements                              |              |  |              |   |              |   |              |  |              |   |              |  |              |  |              |  |              |  |              |
|                                      |               |                          | TEST 1   |              | TEST 2                                   |              | TEST 3  |              | TEST 4                                  |              | TEST 5   |              | TEST 6  |              | TEST 7   |              | TEST 8   |              | TEST 9   |              | TEST 10  |              |
|                                      |               |                          | 3RD Plus Thru-Coat SEM Technique<br>7906 Probe 5MHz Dual | ERROR (inch) | PAUT SEM Technique<br>5MHz w/ Delay Line | ERROR (inch) | Flaw Detector SEM Technique<br>5MHz w/ Delay Line | ERROR (inch) | PAUT MEM Technique<br>5MHz w/Delay Line | ERROR (inch) | Flaw Detector MEM Technique<br>5MHz w/o Delay Line | ERROR (inch) | Flaw Detector SEM Technique<br>7906 Probe 5MHz Dual | ERROR (inch) | Flaw Detector SEM Technique<br>1/2" 2.25MHz Dual | ERROR (inch) | Flaw Detector SEM Technique<br>1MHz 1/2" w/ Delay Line | ERROR (inch) | Flaw Detector MEM Technique<br>3/4" 2.25MHz Single | ERROR (inch) | Flaw Detector MEM Technique<br>1" 1.05MHz Single | ERROR (inch) |
| A1                                   | Square Pocket | 0.062                    | Note 1   |              | Note 2                                   |              | Note 2  |              | Note 2                                  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | Note 3   |              |
| A2                                   | Square Pocket | 0.125                    | Note 1   |              | Note 2                                   |              | Note 2  |              | Note 2                                  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | Note 3   |              |
| A3                                   | Square Pocket | 0.187                    | Note 1   |              | Note 2                                   |              | Note 2  |              | Note 2                                  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2   |              | 0.187  | 0.000        | Note 3   |              |
| A4                                   | Square Pocket | 0.248                    | Note 1   |              | Note 2                                   |              | Note 2  |              | Note 2                                  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2   |              | 0.251  | 0.003        | Note 3   |              |
| A5                                   | Square Pocket | 0.373                    | Note 1   |              | Note 2                                   |              | Note 2  |              | Note 2                                  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2   |              | 0.336  | 0.037        | 0.38   | 0.007        |
| A6                                   | Square Pocket | 0.498                    | Note 1   |              | Note 2                                   |              | Note 2  |              | Note 2                                  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2   |              | 0.478  | 0.020        | 0.498  | 0.000        |
| B1                                   | Flat Hole     | 0.469                    | Note 1   |              | Note 2                                   |              | Note 2  |              | Note 2                                  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | 0.513  | 0.044        |
| B2                                   | Flat Hole     | 0.469                    | Note 1   |              | Note 2                                   |              | Note 2  |              | Note 2                                  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | 0.505  | 0.036        |
| B3                                   | Flat Hole     | 0.472                    | Note 1   |              | Note 2                                   |              | Note 2  |              | Note 2                                  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | Note 3   |              |
| B4                                   | Flat Hole     | 0.467                    | Note 1   |              | Note 2                                   |              | Note 2  |              | Note 2                                  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | Note 3   |              |
| B5                                   | Flat Hole     | 0.465                    | Note 1   |              | Note 2                                   |              | Note 2  |              | Note 2                                  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | Note 3   |              |
| C1                                   | Flat Hole     | 0.312                    | Note 1   |              | Note 2                                   |              | Note 2  |              | Note 2                                  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | Note 3   |              |
| C2                                   | Flat Hole     | 0.314                    | Note 1   |              | Note 2                                   |              | Note 2  |              | Note 2                                  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | Note 3   |              |
| C3                                   | Flat Hole     | 0.314                    | Note 1   |              | Note 2                                   |              | Note 2  |              | Note 2                                  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | Note 3   |              |
| C4                                   | Flat Hole     | 0.311                    | Note 1   |              | Note 2                                   |              | Note 2  |              | Note 2                                  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | Note 3   |              |
| C5                                   | Flat Hole     | 0.31                     | Note 1   |              | Note 2                                   |              | Note 2  |              | Note 2                                  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | Note 3   |              |
| D1                                   | Flat Hole     | 0.156                    | Note 1   |              | Note 2                                   |              | Note 2  |              | Note 2                                  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | Note 3   |              |
| D2                                   | Flat Hole     | 0.157                    | Note 1   |              | Note 2                                   |              | Note 2  |              | Note 2                                  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | Note 3   |              |
| D3                                   | Flat Hole     | 0.161                    | Note 1   |              | Note 2                                   |              | Note 2  |              | Note 2                                  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | Note 3   |              |
| D4                                   | Flat Hole     | 0.155                    | Note 1   |              | Note 2                                   |              | Note 2  |              | Note 2                                  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | Note 3   |              |
| D5                                   | Flat Hole     | 0.155                    | Note 1   |              | Note 2                                   |              | Note 2  |              | Note 2                                  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | Note 3   |              |
| E1                                   | Shaped Hole   | 0.299                    | Note 1   |              | Note 2                                   |              | Note 2  |              | Note 2                                  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | Note 3   |              |
| E2                                   | Shaped Hole   | 0.438                    | Note 1   |              | Note 2                                   |              | Note 2  |              | Note 2                                  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | Note 3   |              |
| E3                                   | Shaped Hole   | 0.564                    | Note 1   |              | Note 2                                   |              | Note 2  |              | Note 2                                  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | Note 3   |              |
| E4                                   | Shaped Hole   | 0.259                    | Note 1   |              | Note 2                                   |              | Note 2  |              | Note 2                                  |              | Note 2   |              | Note 2  |              | Note 2   |              | Note 2   |              | Note 3   |              | Note 3   |              |
|                                      | RMS Error     |                          | NA   |              | N/A                                      |              | N/A   |              | N/A                                     |              | N/A  |              | N/A   |              | N/A  |              | N/A  |              | N/A  |              | 0.021  | 0.029        |

Note 1: Instrument indicated "invalid" measurement due to low signal amplitude.  
 Note 2: First backwall reflection could not be positively identified.  
 Note 3: Second backwall reflection could not be positively identified.

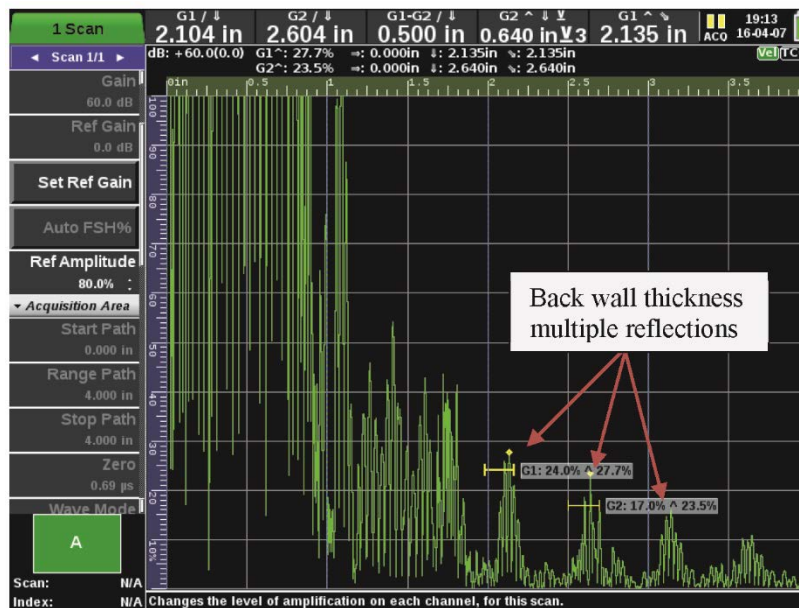
**Table 5-3**  
**Test results for epoxy carbon mat coating at 92°F**

| Epoxy Carbon Fiber Mat Coating @ 92F |               |                          |                                  |                      |                    |                    |                             |                    |                    |                    |                             |                     |                      |                             |                   |                             |                         |                             |                     |                             |                   |                             |                   |
|--------------------------------------|---------------|--------------------------|----------------------------------|----------------------|--------------------|--------------------|-----------------------------|--------------------|--------------------|--------------------|-----------------------------|---------------------|----------------------|-----------------------------|-------------------|-----------------------------|-------------------------|-----------------------------|---------------------|-----------------------------|-------------------|-----------------------------|-------------------|
| Flaw ID                              | Flaw Type     | AS-BUILT Ligament (inch) | Wall Thickness Measurements      |                      |                    |                    |                             |                    |                    |                    |                             |                     |                      |                             |                   |                             |                         |                             |                     |                             |                   |                             |                   |
|                                      |               |                          | TEST 1                           |                      | TEST 2             |                    | TEST 3                      |                    | TEST 4             |                    | TEST 5                      |                     | TEST 6               |                             | TEST 7            |                             | TEST 8                  |                             | TEST 9              |                             | TEST 10           |                             |                   |
|                                      |               |                          | 3RD Plus Thru-Coat SEM Technique | 7906 Probe 5MHz Dual | PAUT SEM Technique | 5MHz w/ Delay Line | Flaw Detector SEM Technique | 5MHz w/ Delay Line | PAUT MEM Technique | 5MHz w/Delay Line  | Flaw Detector MEM Technique | 5MHz w/o Delay Line | 7906 Probe 5MHz Dual | Flaw Detector SEM Technique | 1/2" 2.25MHz Dual | Flaw Detector SEM Technique | 1MHz 1/2" w/ Delay Line | Flaw Detector MEM Technique | 3/4" 2.25MHz Single | Flaw Detector MEM Technique | 1" 1.05MHz Single | Flaw Detector MEM Technique | 1" 1.05MHz Single |
| Measurement (inch)                   | ERROR (inch)  | Measurement (inch)       | ERROR (inch)                     | Measurement (inch)   | ERROR (inch)       | Measurement (inch) | ERROR (inch)                | Measurement (inch) | ERROR (inch)       | Measurement (inch) | ERROR (inch)                | Measurement (inch)  | ERROR (inch)         | Measurement (inch)          | ERROR (inch)      | Measurement (inch)          | ERROR (inch)            | Measurement (inch)          | ERROR (inch)        | Measurement (inch)          | ERROR (inch)      |                             |                   |
| A1                                   | Square Pocket | 0.062                    | Note 1                           |                      | Note 2             |                    |                             | Note 2             |                    |                    | Note 2                      |                     |                      | Note 2                      |                   |                             | Note 2                  |                             |                     | Note 3                      |                   | Note 2                      |                   |
| A2                                   | Square Pocket | 0.125                    | Note 1                           |                      | Note 2             |                    |                             | Note 2             |                    |                    | Note 2                      |                     |                      | Note 2                      |                   |                             | Note 2                  |                             |                     | Note 3                      |                   | Note 2                      |                   |
| A3                                   | Square Pocket | 0.187                    | Note 1                           |                      | Note 2             |                    |                             | Note 2             |                    |                    | Note 2                      |                     |                      | Note 2                      |                   |                             | Note 2                  |                             |                     | 0.187                       | 0.000             | Note 2                      |                   |
| A4                                   | Square Pocket | 0.248                    | Note 1                           |                      | Note 2             |                    |                             | Note 2             |                    |                    | Note 2                      |                     |                      | Note 2                      |                   |                             | Note 2                  |                             |                     | 0.251                       | 0.003             | 0.251                       | 0.003             |
| A5                                   | Square Pocket | 0.373                    | Note 1                           |                      | Note 2             |                    |                             | Note 2             |                    |                    | Note 2                      |                     |                      | Note 2                      |                   |                             | Note 2                  |                             |                     | 0.348                       | 0.025             | 0.384                       | 0.011             |
| A6                                   | Square Pocket | 0.498                    | Note 1                           |                      | Note 2             |                    |                             | Note 2             |                    |                    | Note 2                      |                     |                      | Note 2                      |                   |                             | Note 2                  |                             |                     | 0.471                       | 0.027             | 0.498                       | 0.000             |
| B1                                   | Flat Hole     | 0.469                    | Note 1                           |                      | Note 2             |                    |                             | Note 2             |                    |                    | Note 2                      |                     |                      | Note 2                      |                   |                             | Note 2                  |                             |                     | 0.45                        | 0.019             | 0.455                       | 0.014             |
| B2                                   | Flat Hole     | 0.469                    | Note 1                           |                      | Note 2             |                    |                             | Note 2             |                    |                    | Note 2                      |                     |                      | Note 2                      |                   |                             | Note 2                  |                             |                     | Note 3                      |                   | 0.472                       | 0.003             |
| B3                                   | Flat Hole     | 0.472                    | Note 1                           |                      | Note 2             |                    |                             | Note 2             |                    |                    | Note 2                      |                     |                      | Note 2                      |                   |                             | Note 2                  |                             |                     | Note 3                      |                   | Note 2                      |                   |
| B4                                   | Flat Hole     | 0.467                    | Note 1                           |                      | Note 2             |                    |                             | Note 2             |                    |                    | Note 2                      |                     |                      | Note 2                      |                   |                             | Note 2                  |                             |                     | Note 3                      |                   | Note 2                      |                   |
| B5                                   | Flat Hole     | 0.465                    | Note 1                           |                      | Note 2             |                    |                             | Note 2             |                    |                    | Note 2                      |                     |                      | Note 2                      |                   |                             | Note 2                  |                             |                     | Note 3                      |                   | Note 2                      |                   |
| C1                                   | Flat Hole     | 0.312                    | Note 1                           |                      | Note 2             |                    |                             | Note 2             |                    |                    | Note 2                      |                     |                      | Note 2                      |                   |                             | Note 2                  |                             |                     | Note 3                      |                   | Note 2                      |                   |
| C2                                   | Flat Hole     | 0.314                    | Note 1                           |                      | Note 2             |                    |                             | Note 2             |                    |                    | Note 2                      |                     |                      | Note 2                      |                   |                             | Note 2                  |                             |                     | Note 3                      |                   | Note 2                      |                   |
| C3                                   | Flat Hole     | 0.314                    | Note 1                           |                      | Note 2             |                    |                             | Note 2             |                    |                    | Note 2                      |                     |                      | Note 2                      |                   |                             | Note 2                  |                             |                     | Note 3                      |                   | Note 2                      |                   |
| C4                                   | Flat Hole     | 0.311                    | Note 1                           |                      | Note 2             |                    |                             | Note 2             |                    |                    | Note 2                      |                     |                      | Note 2                      |                   |                             | Note 2                  |                             |                     | Note 3                      |                   | Note 2                      |                   |
| C5                                   | Flat Hole     | 0.31                     | Note 1                           |                      | Note 2             |                    |                             | Note 2             |                    |                    | Note 2                      |                     |                      | Note 2                      |                   |                             | Note 2                  |                             |                     | Note 3                      |                   | Note 2                      |                   |
| D1                                   | Flat Hole     | 0.156                    | Note 1                           |                      | Note 2             |                    |                             | Note 2             |                    |                    | Note 2                      |                     |                      | Note 2                      |                   |                             | Note 2                  |                             |                     | Note 3                      |                   | Note 2                      |                   |
| D2                                   | Flat Hole     | 0.157                    | Note 1                           |                      | Note 2             |                    |                             | Note 2             |                    |                    | Note 2                      |                     |                      | Note 2                      |                   |                             | Note 2                  |                             |                     | Note 3                      |                   | Note 2                      |                   |
| D3                                   | Flat Hole     | 0.161                    | Note 1                           |                      | Note 2             |                    |                             | Note 2             |                    |                    | Note 2                      |                     |                      | Note 2                      |                   |                             | Note 2                  |                             |                     | Note 3                      |                   | Note 2                      |                   |
| D4                                   | Flat Hole     | 0.155                    | Note 1                           |                      | Note 2             |                    |                             | Note 2             |                    |                    | Note 2                      |                     |                      | Note 2                      |                   |                             | Note 2                  |                             |                     | Note 3                      |                   | Note 2                      |                   |
| D5                                   | Flat Hole     | 0.155                    | Note 1                           |                      | Note 2             |                    |                             | Note 2             |                    |                    | Note 2                      |                     |                      | Note 2                      |                   |                             | Note 2                  |                             |                     | Note 3                      |                   | Note 2                      |                   |
| E1                                   | Shaped Hole   | 0.299                    | Note 1                           |                      | Note 2             |                    |                             | Note 2             |                    |                    | Note 2                      |                     |                      | Note 2                      |                   |                             | Note 2                  |                             |                     | Note 3                      |                   | Note 2                      |                   |
| E2                                   | Shaped Hole   | 0.438                    | Note 1                           |                      | Note 2             |                    |                             | Note 2             |                    |                    | Note 2                      |                     |                      | Note 2                      |                   |                             | Note 2                  |                             |                     | Note 3                      |                   | Note 2                      |                   |
| E3                                   | Shaped Hole   | 0.564                    | Note 1                           |                      | Note 2             |                    |                             | Note 2             |                    |                    | Note 2                      |                     |                      | Note 2                      |                   |                             | Note 2                  |                             |                     | Note 3                      |                   | Note 2                      |                   |
| E4                                   | Shaped Hole   | 0.259                    | Note 1                           |                      | Note 2             |                    |                             | Note 2             |                    |                    | Note 2                      |                     |                      | Note 2                      |                   |                             | Note 2                  |                             |                     | Note 3                      |                   | Note 2                      |                   |
|                                      | RMS Error     |                          | NA                               |                      | N/A                |                    |                             | NA                 |                    |                    | NA                          |                     |                      | N/A                         |                   |                             | N/A                     |                             |                     | N/A                         |                   | 0.019                       | 0.008             |
|                                      |               |                          |                                  |                      |                    |                    |                             |                    |                    |                    |                             |                     |                      |                             |                   |                             |                         |                             |                     |                             |                   |                             |                   |
|                                      |               |                          |                                  |                      |                    |                    |                             |                    |                    |                    |                             |                     |                      |                             |                   |                             |                         |                             |                     |                             |                   |                             |                   |
|                                      |               |                          |                                  |                      |                    |                    |                             |                    |                    |                    |                             |                     |                      |                             |                   |                             |                         |                             |                     |                             |                   |                             |                   |

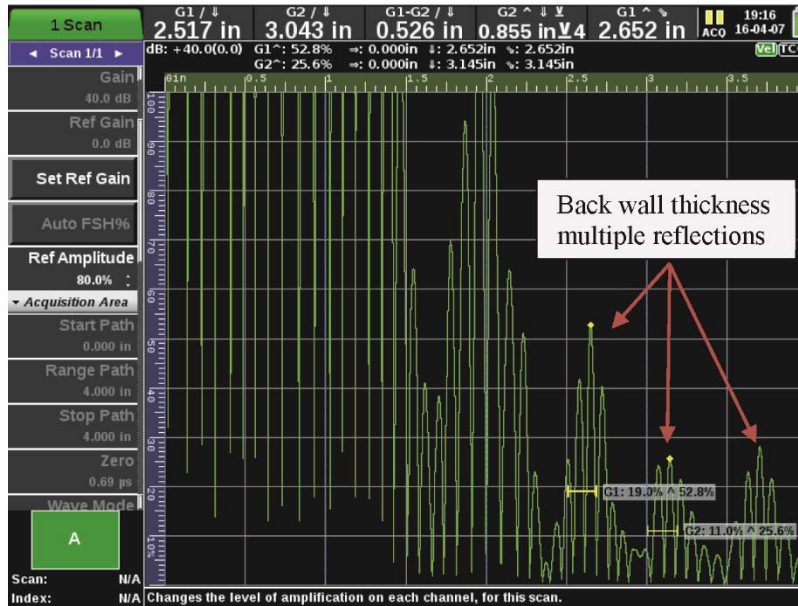
Note 1: Instrument indicated "invalid" measurement due to low signal amplitude.  
 Note 2: First backwall reflection could not be positively identified.  
 Note 3: Second backwall multiple signal could not be resolved.



**Figure 5-2**  
 2.25-MHz probe testing through a structural coating attempting to measure a ½-inch-thick plate at 20 dB gain. Note the significant coating noise with no thickness multiple visible at this gain value.



**Figure 5-3**  
 2.25-MHz probe testing through a structural coating attempting to measure a ½-inch-thick plate at 60 dB gain. Note the significant coating noise, creating a dead zone out to approximately 2 inches. Weak thickness reflections were detected at high gain values.



**Figure 5-4**  
**1.0-MHz probe testing through a structural coating attempting to measure a ½-inch-thick plate at 40 dB gain. Note the significant coating noise, creating a dead zone out to approximately 2 inches. Weak thickness reflections were detected at high gain values.**

The EMAT results on the structural coating were negative and indicated that plate thickness measurements were not possible. The structural coating provided two conditions that prevented the EMAT from providing plate thickness information: lift-off and conductivity. The structural coating thickness was nearly ½ inch, which was much greater than the operational limitation of the transducer. The high-liftoff EMAT was only capable of acquiring plate reflections at liftoff distances up to 0.2 inch. However, similar structural coatings with much thinner profiles would also have similar negative results due to the use of carbon fiber weave embedded in the coating material. Although it is a non-metal, carbon fiber does have electrical conductivity properties, effectively acting as an electrical shield. The structural coating prevents the electric field generated by the EMAT from reaching the carbon steel plate. Component thickness measurements underneath structural coatings fabricated using fiberglass instead of carbon fiber and having a thickness no greater than 0.2 inches may be possible. This coating was not available for testing during this investigation.

## Conclusion and Recommendations Regarding Structural Coatings

Structural coatings not only provide a protective barrier from corrosive environments and materials but also add strength equaling or exceeding that of the original parent component. This requires the use of a high concentration of load-supporting fibers, typically made from carbon or fiberglass embedded in the coating, which are applied to a thickness ranging from ½ to 1 inch. Tests were performed to assess the ability to measure wall thickness on coated material using a sample with a carbon fiber coating with thickness of approximately ½ inch. These results suggest that the inspection of components coated with structural coatings is difficult due to the high sound attenuation properties and large thicknesses. Although some thickness measurements were obtainable, their acquisition was limited to large areas of uniform corrosion, and the ability to resolve localized pitting was lacking. The coating generated significant internal reflections that

also hampered testing by creating dead zones that were exacerbated by the need for very high amplification. The results indicated that wall thickness measurements using piezoelectric transducers require frequencies at or below 2.25 MHz using multiple wall thickness reflections. Tests showed that the use of EMATs on typical structural coatings was not possible due to excessive thickness (greater than 0.2 inches). Also, it was postulated that the electrical conductivity characteristics of carbon fiber shielded the electrical field from the metallic component, preventing the generation of sound. The use of EMATs on structural coatings is not recommended.

# 6

## CONCLUSION AND RECOMMENDATIONS

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The objective of this project was to produce a comprehensive document focused on the measurement of remaining wall thickness of carbon steel piping through protective coatings. This project was limited to the application of the ultrasonic method of nondestructive testing whereby wall thickness measurements were performed through different coating systems like that applied to the OD (outer diameter) surface of buried low-carbon steel piping used in nuclear facilities. Discussions and testing were focused exclusively on the assessment of wall loss caused by corrosion located on the ID (inner diameter) surface.

In addition to documenting the testing performed in the project, this report provides background information on the methodologies used to ultrasonically measure wall thickness on a coated pipe using piezoelectric transducers. Information on ultrasonic transducer types and techniques including signal identification is provided, along with discussion of the theoretical effects of various testing conditions and inspection parameters on wall thickness measurements. This information is meant to provide a basis of understanding for all readers regardless of their prior knowledge or experience with ultrasonic testing. This material is presented in Appendix A of the report.

Section 1 provides an overview of buried piping in nuclear facilities including its use and how it is assessed. Ground contamination due to compromised buried piping has become a significant issue in the industry, and a better understanding of nondestructive techniques used for the evaluation of pipe integrity without requiring coating removal is needed.

Section 2 provides information on the protective coatings used during the construction of existing nuclear power facilities and how these coatings were replicated on samples used in this study. Three coating types—coal tar epoxy, coal tar enamel (TGF-3), and tape wrap—were identified through a survey of utility representatives and are the basis for data collection described in subsequent chapters in this report. Two samples were manufactured for each type of coating, representing the thinnest and thickest configurations when applied per specification.

Section 3 provides a detailed description of machined test blocks and reflectors used to assess the resolution capabilities of different ultrasonic measurement techniques. Ten techniques were selected for evaluation of the fabricated specimens coated with coal tar epoxy, coal tar enamel, and tape wrap. The ultrasonic techniques described in this section all used piezoelectric transducers but differed in the probe types (phased array, monolithic crystal, dual-element, and so on), crystal sizes, frequency, ultrasonic instruments, and methodology used for measuring wall thickness. All testing was performed with the test blocks held at 52°F, 72°F, and 92°F in an effort to simulate field conditions. The results were mostly positive, with the coal tar epoxy being very compatible for performing thickness measurements using high-frequency transducers. Similar results were also obtained on tape wrap coatings, although some limitations were noted due to the increase in sound attenuation caused by the tape material. The most difficult were the coal tar enamel (TGF-3) coatings. This coating had some localized areas where no testing could

be performed due to an undefined coating condition. However, many locations were compatible for collecting ultrasonic thickness measurements but required lower-frequency probes (2.25 MHz and lower) with larger element sizes. The TGF-3 coatings were the only coating type that demonstrated a significant increase in sound attenuation with an increase in temperature. This relationship was so significant that a recommendation is made to avoid inspections of TGF-3 coating at higher temperatures. Numerous tables are provided that detail the types of flaws and thicknesses that can be detected, including measurement accuracies using various ultrasonic techniques for each coating type for three coating temperatures. Generally, thickness accuracies were very good (less than 0.040 inch) when coating attenuation did not prevent testing.

Section 4 describes the use of a specially designed high lift-off EMAT for the measurement of wall thickness on coal tar epoxy, coal tar enamel, and tape wrap coatings. The EMAT measurement capabilities were limited to larger reflectors due to the large aperture size, with significant limitations on measuring small localized thinning like that associated with pitting. Data supported the use of the EMAT testing for measuring wall thickness in cases where corrosion is generally uniform over larger areas (that is, 1 square inch and larger). The EMAT was capable of measuring wall thickness on all coatings and in areas where piezoelectric transducers could not penetrate (130-mil coating). The probe did not require couplant as piezoelectric transducers do, and could be moved from location to location with minimal effort. Overall, the results of testing described in Section 4 were positive, showing the capabilities as well as limitations of the EMAT technique.

Finally, Section 5 focuses on the ultrasonic measurement of component thickness through a structural coating. A specimen was fabricated, coated with a structural coating consisting of carbon fiber and epoxy mixture with a 0.4-inch thickness. It was concluded that the inspection of components coated with structural coatings is difficult due to the high sound attenuation properties and large thicknesses. Although some thickness measurements were obtainable, their acquisition was limited to large, uniform areas, and the ability to resolve localized pitting was lacking. The coating generated significant internal reflections that also hampered testing by creating dead zones that were worsened by the need for very high amplification. The results indicated that wall thickness measurement using piezoelectric transducers requires frequencies at or below 2.25 MHz using multiple wall thickness multiple reflections. Tests showed that the use of EMATs on typical structural coatings was not possible due to excessive thickness (greater than 0.2 inches) as well as electrical shielding created by the electrical conductivity characteristics of carbon fiber.

# 7

## REFERENCES

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1. NEI Presentation, “Underground Piping and Tanks Initiative – Update,” J. Riley and J. Sears, October 9, 2013.
2. Report to Congressional Requesters, “Oversight of Underground Piping Systems Commensurate with Risk, but Proactive Measures Could Help Address Future Leaks,” GAO Report GAO-11-563, June 2011.
3. AWWA C203, “Coal-Tar Protective Coatings and Linings for Steel Water Pipe,” American Water Works Association, 2015 Edition, June 7, 2015.
4. AWWA C210, “Liquid-Epoxy Coatings and Linings for Steel Water Pipe and Fittings,” American Water Works Association, 2015 Edition, June 7, 2015.
5. AWWA C214, “Tape Coatings for Steel Water Pipe,” American Water Works Association, 2014 Edition, 2015.



# A

## WALL THICKNESS MEASUREMENT USING PIEZOELECTRIC ULTRASONIC TRANSDUCERS— BACKGROUND INFORMATION

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### Objective

The objective of this appendix is to provide the reader with background information on the methodologies used to ultrasonically measure wall thickness on a coated pipe using piezoelectric transducers. Additional information is provided regarding the theoretical effects of various testing conditions and inspection parameters on wall thickness measurements. The information provided in this appendix is meant to provide a basis of understanding for all readers regardless of their prior knowledge or experience with ultrasonic testing. The appendix does not provide detailed information on specific hardware, testing procedures, or related data.

The information in this appendix is directed toward the use of piezoelectric-based transducers on coated piping.

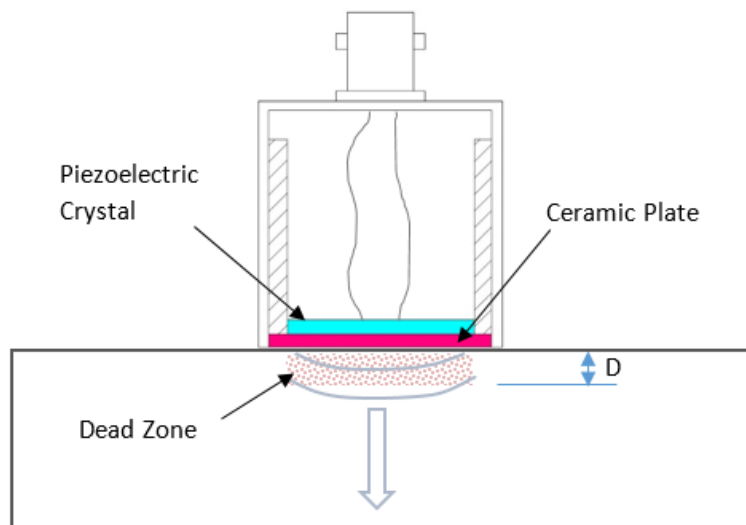
### Piezoelectric Transducers

The majority of ultrasonic transducers used for inspections are based on a design in which a piezoelectric crystal is used to generate and receive high-frequency sound waves. The piezoelectric effect occurs in certain types of materials where electrical current is transformed into a physical displacement. Ultrasonic transducers contain one or more wafers of such material, which is excited by an electrical pulse generated by the ultrasonic instrument. The wafer responds by vibrating at its natural resonant frequency defined by its thickness, creating a vibration that propagates internally to a designated surface on the transducer. These high-frequency vibrations, or sound waves, will remain confined to the sensor housing unless coupled to another material. It is important to note that ultrasonic sound waves do not propagate efficiently in air due to the small wavelengths involved. In order to transfer the sound energy to another material, a fluid or gel-like material (couplant) is used. The efficiency of the transfer of energy from the transducer to the component is dependent upon factors such as contact area with the probe surface, roughness of the material being inspected, contact force, and coupling media used. The use of piezoelectric-based transducers for pipe wall thickness measurements on coated piping requires that the sound energy pass through the coating for all measurements, since the coating lies between the transducer and the pipe. Any effects on the ultrasonic signal by the coating layer, such as increased attenuation and time-of-flight, must be considered when using a piezoelectric-based transducer.

Three basic configurations of piezoelectric ultrasonic transducers can be applicable for use in measuring pipe wall thickness. Thickness transducers can be classified as contact probes, delay line probes, and dual-element probes.

### Single-Element Contact Transducers

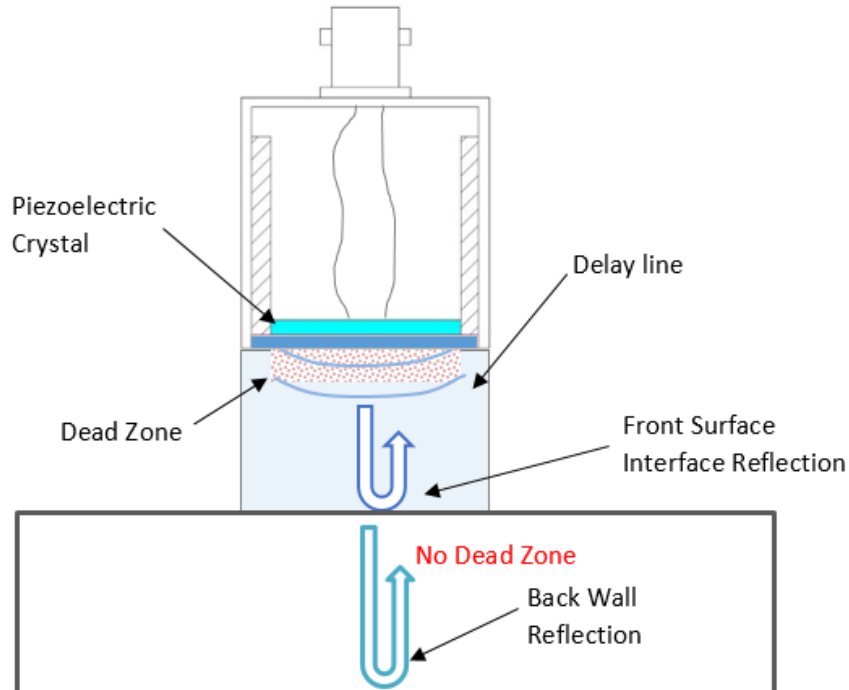
The most common ultrasonic probe used for thickness measurements is typically referred to as a *contact transducer*. As the name implies, the probe is coupled directly to the part without the use of a delay line component (see the section “Delay Line Transducers”), as illustrated in Figure A-1. The single-element contact transducer consists of a single piezoelectric crystal used for both transmitting and receiving sound waves in a “pulse-echo” mode. The sound-producing crystal is bonded to a thin ceramic plate, which serves as the wear-resistant surface that contacts the component being tested. Single-element contact transducers are relatively low in cost compared to other types, due to the simple design of this transducer. An important disadvantage of this type of transducer is its inability to detect reflectors that are located in a region close to the test surface. This region, commonly referred to as the “dead zone,” has a depth “D” as shown in Figure A-1 that is unique to a specific probe design. The dead zone is created by the high-voltage spike used to drive the piezoelectric crystal. This high-voltage signal saturates the receiving electronic circuitry, which takes time to recover. Also, the piezoelectric crystal must finish resonating before it can effectively detect a low-amplitude ultrasonic reflection. In the case of a single-element contact probe, any reflections with travel times that do not exceed the ring-down time of the initial pulse will not be detected. As a result, single-element contact probes are not effective in measuring the thickness of thin materials or any other reflector close to the contact surface. Another disadvantage of this type of probe is the difficulty in contouring the ceramic contact wear surface. The use of a flat probe on a curved surface can reduce coupling efficiency and change beam profile characteristics, depending on the radius of surface curvature and the size of the transducer.



**Figure A-1**  
Basic construction of a contact transducer where a piezoelectric crystal is bonded to a wear plate that contacts the component being inspected

## Delay Line Transducers

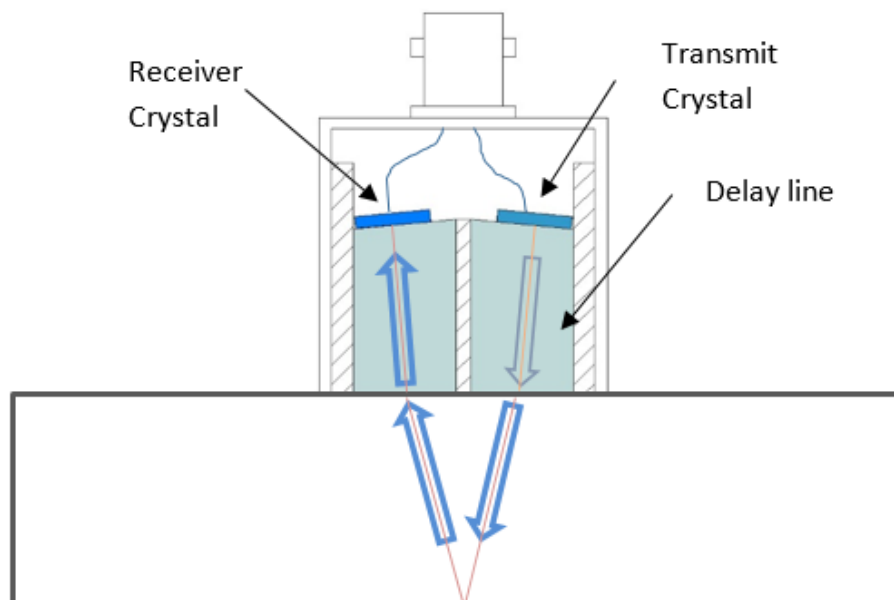
The delay line probe is similar to a single-element contact transducer, with the addition of a cylinder of plastic, epoxy, or fused silica that is coupled between the transducer housing and the part being inspected, as illustrated in Figure A-2. The primary purpose of this cylinder, or delay line, is to separate the initial pulse signal from the signal produced by the front surface interface reflection. The thickness of the delay line should be large enough that multiple reflections within the delay line do not interfere with pipe wall signals. Although a dead zone associated with the initial pulse does exist with a delay line transducer, it is contained in the delay line material, where it has no deleterious effects on the detection of near-surface reflectors. The delay line also provides a medium for the transmitted sound wave to properly form into a coherent wave front prior to entering the component. Large variations in energy exist across the width of a sound wave immediately beneath a transmitting crystal due to constructive and destructive interference of the forming wave front. The *far field* is the minimum distance from the transmitting crystal that reflectors should be positioned for optimum thickness measurement results. This depth is dependent on the material, probe size, and frequency and should be considered when selecting a transducer. The primary advantage of using a delay line transducer on coated pipe is for the measurement of thin wall thicknesses. It may also be possible to directly measure the coating thickness through detection of the coating/OD surface interface reflection. The delay line material can also be machined to fit the curvature of a pipe OD surface, which can assist with the inspection of smaller-diameter piping. It should be noted that the delay line is an additional layer of material through which the sound must propagate, and it will reduce the amplitude of pipe wall reflections.



**Figure A-2**  
**Basic construction of a delay line transducer where polymer material that is coupled between the component and the transducer eliminates dead zone effects, allowing near-surface inspection**

### Dual-Element Transducers

The third type of ultrasonic probe that is applicable for coated pipe wall thickness measurement is the dual-element contact transducer. This transducer is fabricated using two piezoelectric crystals, each bonded to its own acoustically isolated delay line, as illustrated in Figure A-3. One crystal/delay line serves as the transmitter, with the second element/delay line acting as the receiver. This dual arrangement eliminates the “dead zone” effect, since a separate piezoelectric crystal is used for receiving all ultrasonic signals, and it is not affected by the high-voltage transmit pulse. Also, any internal reflections that may exist in the delay line resulting from the transmitted sound wave are not received in the acoustically isolated receiver delay line. This type of probe typically has minimal baseline acoustic noise, making it more sensitive to low-amplitude reflections like those associated with a heavily corroded back wall signal. The transmitter and receiver delay lines can be designed with a small machined cut angle, commonly referred to as the *roof angle*, which concentrates the sound energy at a targeted material depth. The width of the sound beam and the angle of beam spread define the practical range of depth for which the probe should be used, depending on its design. These probes are very useful for heavily corroded pipes where the back wall signals are weak. These probes tend to be slightly less accurate for measuring wall thickness since the angle of propagation of the reflected wave changes with depth. This results in a nonlinear wall time-of-flight calibration, which is not accounted for when calibrating the time base of a typical ultrasonic instrument. However, this limitation is minimized by ensuring that the measured thicknesses are encompassed in the minimum and maximum thickness of the calibration standard. Dual-element probes can be less effective for performing thickness measurements where wall thickness multiples are required, due to the small propagation angle of the transmitted sound beam. Dual-element probes can be contoured for use on curved surfaces.



**Figure A-3**  
Basic construction of a dual-element transducer where separate transmit and receive piezoelectric crystals are bonded to two acoustically isolated delay lines designed to optimize sensitivity at a specific depth

## Transducer Frequency

The term *ultrasonic* refers to sound waves with a frequency higher than that detectable by human hearing, or greater than 20 kHz. For industrial nondestructive applications, the majority of ultrasonic testing is performed in a frequency range from 1.0 MHz to 10 MHz. The frequency of an ultrasonic transducer is an essential parameter that can have a profound effect on test measurements or even the ability to perform a test. Frequency is a measure of the number of vibrations or cycles that are produced by the transducer every second. For example, a 1-MHz transducer produces a one million vibrations every second that the probe is energized. Related to frequency is the wavelength of the sound wave. The wavelength is a peak-to-peak distance measurement between each cycle. If one were to measure the wavelength of waves in the ocean, the distance would be in meters. In contrast, the wavelength of a typical ultrasonic wave would be measured in millimeters. As the frequency increases, the wavelength decreases. The wavelength for a sound wave of a given frequency can be calculated using Equation A-1.

$$\lambda = \frac{C}{f} \qquad \text{Eq. A-1}$$

where

$\lambda$  = wavelength

C = sound velocity for the wave mode being used

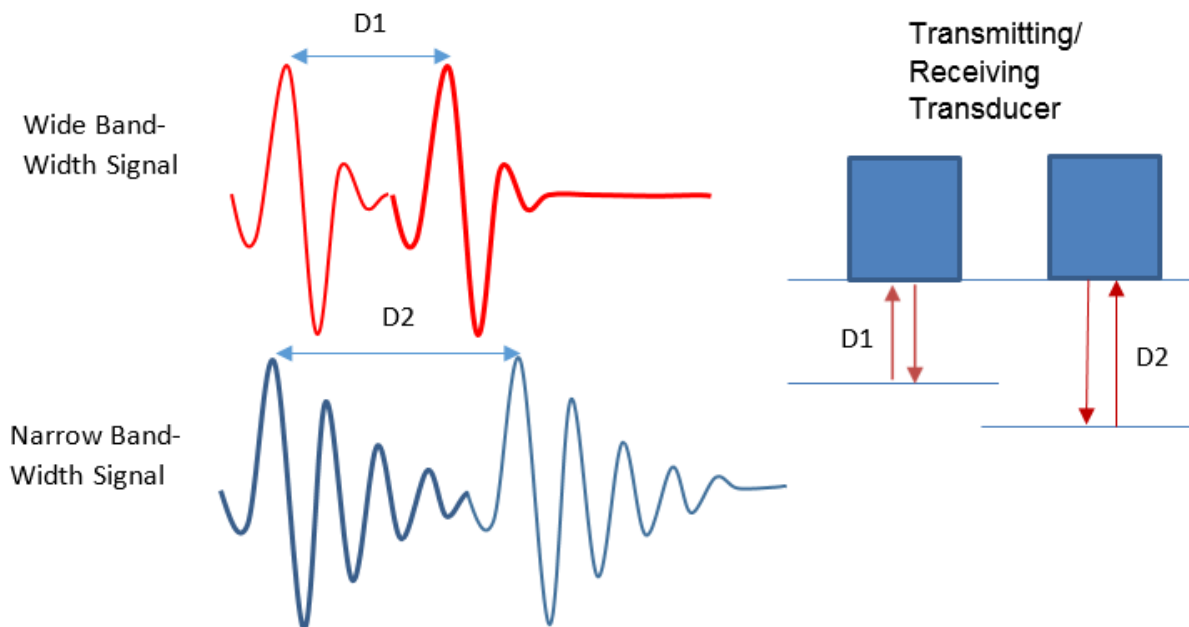
f = frequency of the sound waves generated

An important factor when performing wall thickness measurements is reflector resolution. Resolution is the ability to resolve two reflections that arrive very close in time. High-frequency transducers have better resolution since the total time to complete one cycle is less, due in part to the smaller wavelength. This is important when testing thin wall piping or coatings, since the arrival times of wall-related reflections are very close in time. However, high-frequency sound waves are more sensitive to material imperfections and microstructural inconsistencies that can attenuate the signal. For example, higher-frequency techniques are not typically used on austenitic materials due to the large crystallographic grains, which can significantly increase the apparent attenuation of propagated sound waves. Sound attenuation is of particular concern when inspecting coated piping since the coating can attenuate the sound. Multiphase coatings such as coal tar enamel (TFG-3) can be of significant challenge to the high-frequency sound waves, especially if the wavelength approaches the dimension of the tape fiber. Coatings that are semi-ridged, exhibiting some rubber-like qualities, will tend to absorb the sound energy. In these examples, more power may be required to perform the inspection. Lower-frequency sound waves exhibit more power and thus have a better ability to penetrate. (An example of this phenomenon in everyday life is the situation in which only the bass notes of amplified music in a closed car penetrate through the vehicle to be heard by people outside the car.) Therefore, the selection of an appropriate frequency can be a compromise between penetrability and resolution. It should be noted that additional factors such as near-field distance (natural focus location) and the amount of beam divergence of a sound beam generated by a transducer are also influenced by frequency.

## Transducer Bandwidth

The bandwidth of an ultrasonic transducer is another important parameter that can affect the ability to successfully measure remaining wall thickness on a coated pipe. All ultrasonic transducers have a frequency designation that is an indication of the center resonant frequency of the probe's piezoelectric crystal. The frequency bandwidth of a transducer is influenced by the amount of dampening material applied to the piezoelectric crystal during production. A lightly dampened transducer will produce signals that take many cycles to dissipate. The “ringing” of the crystal occurs at its primary natural resonant frequency, which is directly related to its thickness. With minimal dampening the resonant frequency of the crystal dominates the frequency content of the sound wave generated, resulting in a very narrow band response. In contrast, if the transducer is heavily dampened, the resulting signal amplitude dissipates very quickly, like that shown in Figure A-4. Heavily dampened probes have a minimum pulse width of approximately 1½ cycles. The dampening of the crystal reduces the amplitude of the resulting signal, while broadening the frequency response of the transducer.

Transducers used for thickness measurements are typically wide-band transducers in order to improve spatial resolution and measurement accuracy needed for thinner-walled components. However, these highly dampened (wide-band) transducers may lack the power to penetrate through some coating materials. In such cases, a transducer with more narrow frequency response may be required to penetrate the coating material, even though limitations on minimum wall thickness will exist.



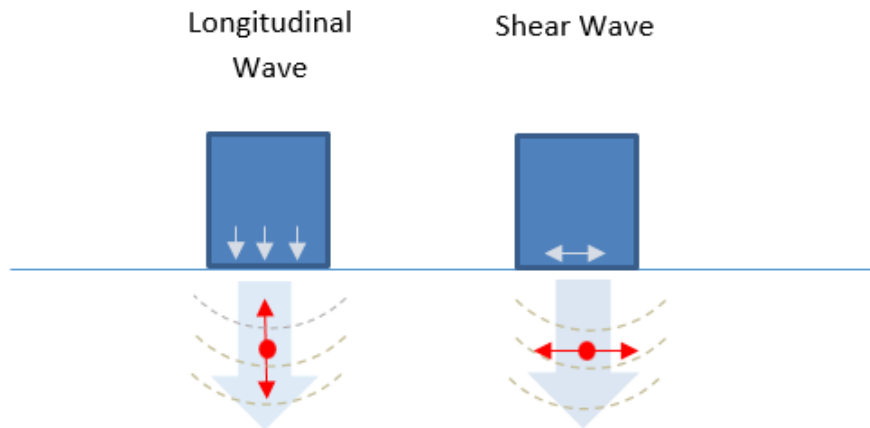
**Figure A-4**  
Illustration of how the ring-down of signals produced by a transducer with a narrow bandwidth limits the minimum wall thickness that can be measured when compared to a transducer with a wider bandwidth

## Wave Mode

The propagation of ultrasonic waves through solid media can occur in many different modes, depending on the excitation forces and surrounding boundary conditions. Wave modes are usually described by the motion imposed on the material as the wave front passes. For example, the majority of ultrasonic thickness measurements are performed using a longitudinal wave mode. Longitudinal waves are unique in that the material movement is parallel to the direction of the wave front as illustrated in Figure A-5. This wave mode has the best penetration capability through materials with high attenuation, making it the best choice for thick, pliable coatings. Longitudinal waves also propagate at a velocity higher than any other sound wave mode. The high velocity could be a disadvantage when testing thin materials, since the difference in arrival times of closely spaced reflectors, like wall thickness multiples, will be minimized. Longitudinal waves can be transmitted using couplant materials such as silicone gel or oil, making the implementation simple.

The second wave mode used for localized thickness measurements is the shear wave mode. Although this wave mode is rarely used for thickness measurements with piezoelectric-based techniques, it is commonly utilized when performing thickness measurements using electromagnetic acoustic transducers (EMATs). This mode produces a material motion that is perpendicular to the direction of wave propagation. The velocity of the shear wave is approximately half that of the longitudinal wave, resulting in a smaller wave length (see Equation A-1) for a transducer of comparable frequency. The slower velocity also increases the time separation of reflections associated with thin materials. Shear waves are not typically used with piezoelectric transducers, since the couplant required must be capable of transferring shearing forces. Shear waves are not supported in fluids. Therefore, the couplant used with a piezoelectric normal beam shear wave transducer must be highly viscous. This involves a couplant with the viscosity of molasses or a similar substance, making lateral movements of the transducer nearly impossible. In the case of EMAT-based thickness measurement systems, such a couplant restriction above does not apply, since EMATs do not require the use of couplant.

*Plate waves*, another type of ultrasonic waves, have a velocity that varies depending on the thickness of the material. Although this wave mode is limited to thinner materials, it can be used to detect general areas of wall thinning. Techniques deploying plate waves are not suitable for localized measurements and have accuracies much less than that associated with a typical ultrasonic thickness method.



**Figure A-5**  
Longitudinal and shear wave modes used for localized thickness measurements where material motion is either parallel or perpendicular to the wave propagation direction

## Ultrasonic Instrumentation

Ultrasonic instrumentation typically used for coated pipe wall thickness measurements ranges from standard flaw detectors to instruments designed specifically for taking thickness measurements, commonly called *thickness gages* or *T-gages*. These instruments all have one feature in common: an adjustable time base that must be calibrated properly, allowing it to directly display material thickness in the units required. Instrument calibration typically involves the use of a calibration standard of known thickness made from an acoustically similar material as that being tested. Flaw detectors and thickness gages are functionally very similar. They differ primarily in the process by which measurements are made, and in their levels of versatility.

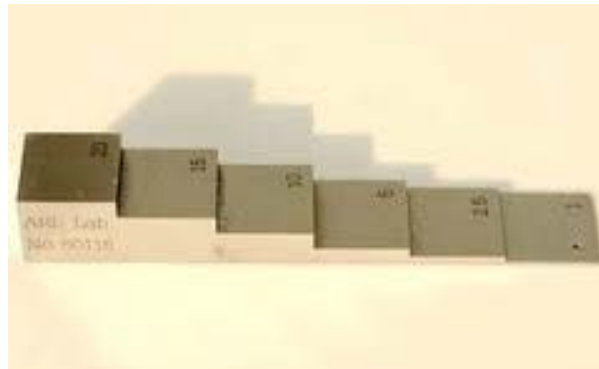
An ultrasonic flaw detector is an instrument used for various applications such as flaw detection to determine dimensional measurements. The conventional flaw detector is based around the A-scan display, which is typically sized so that it encompasses the majority of the instrument face. The A-scan is the amplitude vs time display that is commonly associated with an oscilloscope. Unlike an oscilloscope, which is internally calibrated to display absolute time very accurately, the time base of the flaw detector A-scan is designed to be manipulated so that it can provide a distance measurement using material velocity as the conversion factor. When using the device for thickness measurements, the operator manually adjusts one or more measurement gates over the signal(s) of interest. The thickness is typically calculated based on a converted time value that corresponds to the location on the signal that breaks the gate threshold or signal peak value. The thickness values obtained using a flaw detector may not be as precise as those obtained using a thickness gage, since the thickness measurement algorithms used may not be as robust. However, flaw detectors provide a clear indication and control over what signals are used for thickness measurements. Such control may be important when performing a thickness measurement on coated pipe.

An ultrasonic thickness gage, or T-gage, is typically a very compact instrument that may or may not be equipped with an A-scan display. Very basic models provide only a digital readout of measured thickness. Basic gages will likely provide measurements that are in error when used on coated pipe, since there is no option to compensate for the additional time-of-flight provided by the coating layer. However, more advanced T-gages do exist that are designed for use on coated

materials. When used with special probes, these instruments have the potential to detect both the coating/pipe interface signal and the pipe back wall reflection. In such a case, the instrument may be capable of providing both the coating thickness and the pipe wall thickness using two separate velocity values for the two materials. These advanced T-gages typically provide a small A-scan display allowing the operator to observe what signals are being used for thickness determination. T-gages also use propriety algorithms designed specifically for obtaining dimensional measurements. These algorithms minimize any effect that signal amplitude may have on measurement accuracy, such as the use of zero crossing or auto-correlation function.

## Instrumentation Calibration

Ultrasonic instruments such as portable flaw detectors and thickness gages cannot simply be turned on and used without first checking or adjusting parameters that are critical for accurate measurements. The process followed for setting up an instrument to perform an inspection is called *calibration* and is described in the inspection procedure. Procedures are an important part of all ultrasonic inspections, since they describe essential aspects of the test, assuring results that are consistent and repeatable between different users. Although steps for setting up an instrument may vary, all require the use of a calibration block that is machined to known dimensions. A step block like the one shown in Figure A-6 is typically used when calibrating for a thickness measurement. A step block consists of several different sections, each closely machined to a designated thickness. A range of thickness steps is selected that encompasses the expected component thickness targeted for inspection. It is important that the step block be fabricated from a material that has the same sound velocity for the wave mode used for the material to be inspected.



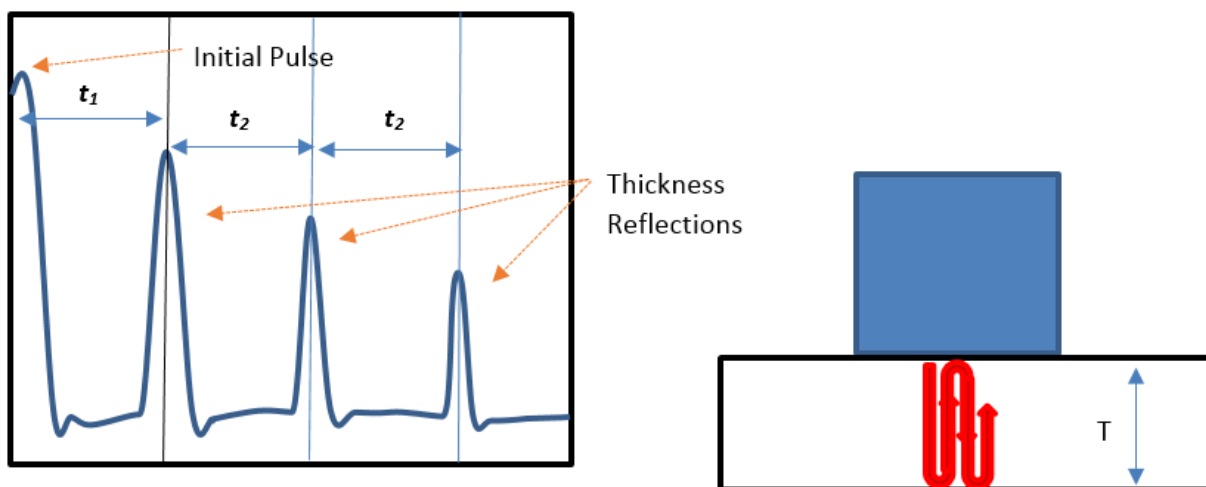
**Figure A-6**  
**Typical step calibration block**

The calibration of an ultrasonic instrument involves the adjustment of three primary parameters: material velocity, system delay, and signal amplitude. The following is an overview of these parameters and how they are typically adjusted.

### **Velocity Adjustment**

A conventional ultrasonic instrument is similar to an oscilloscope in that both are capable of displaying signals in an A-scan format where time (x-axis) is plotted against amplitude (y-axis). Unlike an oscilloscope, the ultrasonic instrument is designed to display the x-axis not in units of time, but in units of distance. This is performed internally in the instrument through a simple

mathematical conversion (see Equation A-2 in the section “Time-of-Flight”) using the sound velocity of the material being inspected. Therefore, it is critical that the appropriate sound velocity value be entered into the ultrasonic instrument prior to testing. The accuracy of all thickness measurements will be limited by the accuracy of this value. If the precise sound velocity value for a material is not known, then it can be determined through the use of a step block that is fabricated from that material. Figure A-7 is a typical A-scan signal obtained from a step calibration block. There are two types of signals represented on the illustrated A-scan: the initial pulse, and thickness multiple reflections as indicated in Figure 7. The initial pulse represents the start of a firing cycle when the transducer is excited with a high-voltage spike. Arrival times of subsequent detected signals are measured relative to the start of this signal. The time required for the first back wall signal to be detected is affected by both the material velocity and a time delay that can be caused by many factors, as discussed in the next section. However, the relative time separating the thickness multiple reflections ( $t_2$  in Figure A-7) is influenced solely by the material velocity value entered into the ultrasonic instrument. During the calibration procedure, the operator can manually adjust the material velocity value until the displayed distance separating two consecutive back wall reflections is equal to the step block thickness. Most ultrasonic instruments have built-in algorithms that will perform this function automatically once the appropriate signals are positioned in designated time gates. With the velocity value properly established, the delay setting can be adjusted.



**Figure A-7**  
Typical A-scan signal response from a step calibration block

### **Delay Adjustment**

The delay parameter is a critical parameter, found on every ultrasonic instrument, that must be properly adjusted to achieve accurate wall thickness measurements. This parameter is especially important for any technique that uses only the first back wall reflection to determine wall thickness. The delay parameter is a measure of the time difference between the generation of the high-voltage pulse used to excite the transducer ( $t=0$ ) and the moment when the sound actually exits the bottom of the transducer. A factor that contributes to this time delay is associated with the finite time required for the high-voltage signal to be generated and reach the ultrasonic

transducer. Although small, this time can be significant when longer cable lengths are used. The most significant contributor to this parameter is related to the use of delay lines like those illustrated in Figures A-2 and A-3. In these types of transducers, the time delay contributed by these internal components can be significant.

The time delay parameter is determined during calibration by coupling the probe to a location on a step block with a known thickness dimension. The first back wall reflection is then identified; this may be the first signal detected, as illustrated in Figure A-7. It is important to note that when using a delay line transducer, an entry reflection may be present, and this should not be misinterpreted for the first back wall signal. The time delay value can be determined by manually altering the delay adjustment until the displayed distance for the first back wall reflection is equal to the step block thickness. Most ultrasonic instruments have built-in algorithms that will perform this function automatically once the first back wall signal is positioned in designated time gate.

### **Gain Adjustment**

The third parameter that is typically adjusted during a thickness measurement is system amplification or gain. The signal produced by an ultrasonic probe is characteristically very weak and must be amplified. Too much amplification will saturate the system electronics and possibly compromise resulting measurements. Not enough gain may have equally deleterious effects, with insufficient signal amplitude to properly perform a measurement. The test procedure should provide adequate guidance on the appropriate gain to be used for different test conditions. However, there are circumstances when the signal amplitude is not strong enough to perform a thickness measurement. In such cases the inspection should not be performed.

### **Coating Compatibility for Piezoelectric Testing**

The ability to measure the remaining wall thickness of a coated pipe is directly dependent upon the ability to detect the sound reflections off the ID surface of the pipe being inspected. For this to occur, the sound wave must be able to successfully negotiate a round trip through two interfaces, propagate through two different materials, and reflect off the inner surface of the pipe back in the direction of the receiving transducer. Not all coated piping can be inspected using a conventional ultrasonic transducer. The purpose of this section is to provide some guidance in determining whether a coated pipe is compatible for inspection using a conventional ultrasonic technique.

The first step in assessing a coated pipe is to closely inspect the exposed coating surface. Since many coated pipes are inspected following excavation, a thorough visual inspection of the pipe is important. To the extent possible, the coating should be free of foreign material (such as soil), to improve the ability of the transducer to couple to the component. Once the surface is clean, the integrity of the coating should be evaluated. A coating that is no longer bonded to the pipe or has signs of delamination cannot be inspected using a conventional ultrasonic method. High-frequency sound waves are not capable of propagating across an air boundary. It is important that the coating be well adhered to the pipe wall. A coating that has localized areas of disbonding may not be obvious visually, but they may sound different when tapped using a small object.

Any corrosive product that is trapped between the coating and the pipe outer surface will also prevent the use of a piezoelectric-based technique. Severe OD surface pipe corrosion will tend to expand underneath the coating, creating a localized swelling that may be observable.

Another potential problem that could prevent inspection is surface roughness of the coating. A coating that exhibits a very rough outer surface may prevent the transducer from coupling properly to the pipe surface. Any reduction in the contact surface between the pipe and transducer will reduce the energy that is available for the wall thickness measurement. Ideally the transducer should be coupled in a smooth area that allows for the entire probe surface to contact the coating surface. Surface contour irregularities created by tape overlaps or dried coating runs are examples of places where coupling could be compromised.

The primary method for determining inspection compatibility is to couple the transducer to the pipe surface and observe the presence or amplitude of the inner surface reflection. It is important to have a properly calibrated instrument prior to performing this initial evaluation so that the appropriate location of the back wall on the A-scan display reflection is known and there is assurance that the hardware is operating correctly. The inability to detect any back wall reflection is a decisive indication that the use of a piezoelectric-based technique cannot be used at the inspection location. The reasons for a lack of signal can be numerous, including inadequate coating-to-pipe bond, improper coupling of the transducer to the coating material, severely corroded inner pipe surface, impenetrable coating material, or an issue with the probe being used (that is, frequency). A weak but discernable back wall reflection may permit a less accurate measurement of the wall thickness. Thickness gages require a minimal signal amplitude in order for measurement algorithms to function properly. Thickness measurements using a back wall reflection with a signal-to-noise ratio of 2:1 or less should be avoided. In all cases where back wall signal amplitude is preventing accurate measurements, recoupling of the transducer should be attempted as well as additional testing at adjacent locations. Testing at multiple locations will help identify whether a problem is localized or potentially global to the entire piping system.

## **Time-of-Flight**

A dimensional measurement, such as wall thickness, is attained by accurately measuring the time-of-flight (TOF) required for a sound wave to travel a path that defines the dimension of interest. With the TOF known, the distance traveled by the sound wave can be calculated using the simple relationship expressed in Equation A-2.

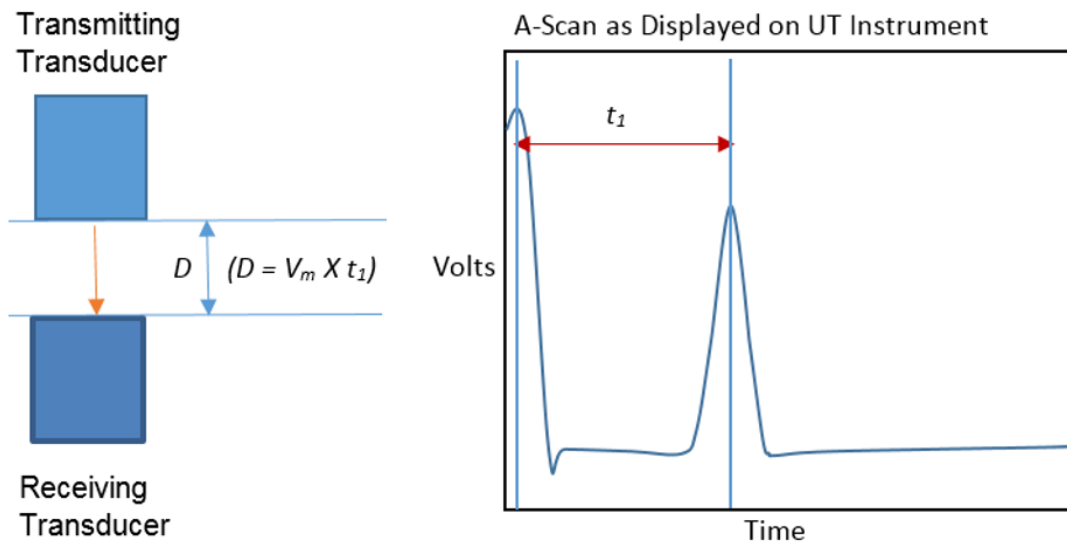
$$\text{Distance} = \text{Material Velocity} \times \text{TOF} \qquad \text{Eq. A-2}$$

As denoted in the equation, knowledge of the sound velocity value is required in order to convert the time-of-flight value measured on the ultrasonic instrument to distance. Sound velocity varies depending on the material being tested as well as the wave mode used. Also required is an understanding of the path taken during the measurement. Instances where the sound wave travels through multiple media (that is, coatings) or where the propagation angle is not orthogonal to the pipe surface can result in inaccuracies in the dimensional measurement if they are not compensated for.

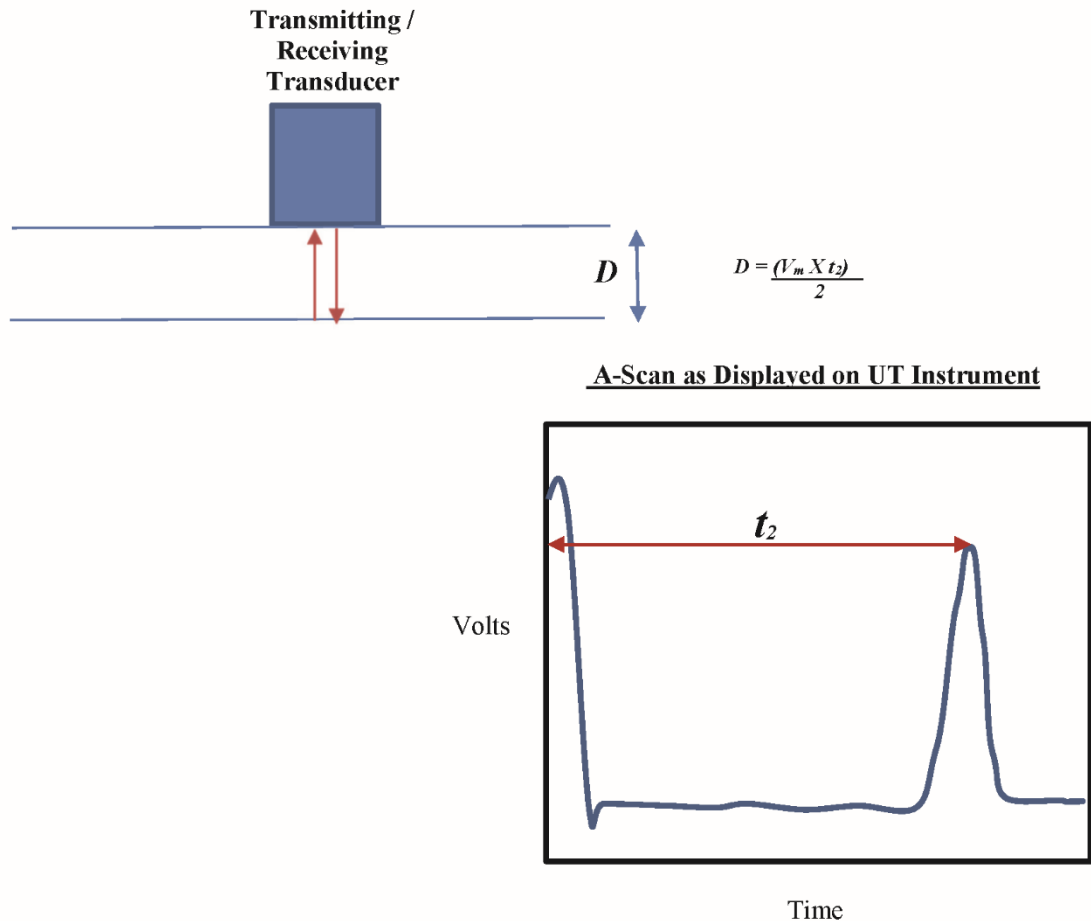
Figure A-8 is an illustration of a flat plate with two parallel surfaces with a thickness  $D$ . An ultrasonic transducer is coupled to both surfaces of the plate, with the sound wave propagated in an orthogonal direction so that it takes the shortest path across the plate thickness. In this case no reflections off the plate surfaces are required, since the sound wave travels through the thickness of the plate from one transducer to the other. In this example of a through-transmission test, the thickness is directly proportional to the product of the velocity and the TOF value measured by the ultrasonic instrument, as indicated in Equation A-2.

In a pulse-echo examination, the transmission and reception of sound are performed on the same side of the plate, as shown in Figure A-9. In this configuration the sound wave must propagate through the thickness twice, since a reflection is required from the opposite surface in order to make the thickness measurement. As a result, the TOF value of the measured signal is twice that of the through-transmission example (Figure A-8). Therefore, in this pulse-echo example the plate thickness  $D$  is calculated by dividing the velocity and TOF product by a factor of two, as indicated in Figure A-9.

The two examples provided are for uncoated materials where the transducer is coupled directly to the component of interest. The following discussion will be applicable to a coated structure where the ultrasonic probe is coupled to the coating surface, requiring transmission through the layer. The coating layer adds complexity to the wall thickness measurement since it adds additional boundary reflections and an additional material having its own unique velocity. For this discussion it is assumed that the coating is capable of supporting the transmission of high-frequency sound waves and that adequate signal amplitudes are present. Two different approaches to wall thickness measurements on coating structures are addressed: the *single-echo method (SEM)* and the *multiple-echo method (MEM)*.



**Figure A-8**  
**Illustration showing that thickness is directly proportional to the velocity and TOF product for a through-transmission test**



**Figure A-9**  
Illustration showing that thickness is directly proportional to one-half the velocity and TOF product since the sound has traveled through the thickness twice for the pulse-echo test

## Single-Echo Method (SEM)

### **Reflection Identification**

The single-echo method (SEM) requires the reception of two ultrasonic reflections for each inspection location. The first reflection originates from the coating/OD surface interface, and the second originates from the pipe ID surface. No other reflections are needed for the implementation of this technique. This approach is very useful, especially on heavily corroded pipe where multiple ID surface reflections cannot be detected.

### **Applicable Ultrasonic Transducers**

The best types of ultrasonic transducers for use with the SEM are the *delay line transducer* and the *dual-element transducer*. The *single-element contact transducer* should be avoided when using this technique. This probe does not utilize a delay line component, resulting in the possible interference of the initial pulse with the coating/OD interface reflection signal. Single-element contact transducers may be effective on thick coatings, depending on the amount of dampening

used during the construction of the transducer to reduce signal ringing. However, this type of probe will not be capable of measuring remaining pipe wall thickness when using the SEM approach for a full range of coating thicknesses. The following discussion does include all three probe types.

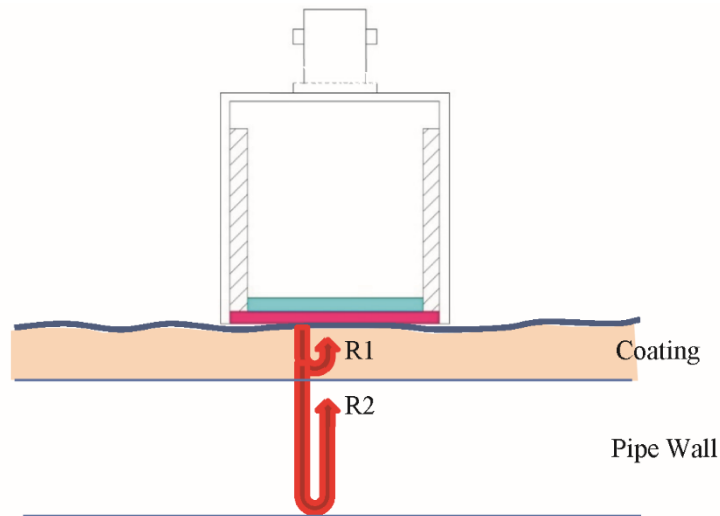
### ***Signal Recognition Using a Single-Element Contact Transducer***

The first signal following the initial pulse when using a single-element contact probe is the reflection of the coating/pipe OD surface interface, which is denoted as R1 in Figure A-10. This signal arrives immediately following the initial pulse. The initial pulse is the large signal associated with the high-voltage spike used to drive the piezoelectric crystal that creates the ultrasonic sound wave. The R1 signal may not be detectable when using single-element contact transducers, especially if the thickness of the coating is thin. Such probes tend to display an initial pulse with width (in time) that encompasses the R1 signal. In such case, the initial pulse produces a “dead zone” starting at the sound entry location and extending into the depth of the material. Signals from near-surface reflectors that are inside this dead zone depth will not be detected. If the coating is too thin so that the travel time of the R1 reflection does not exceed the width of the initial pulse, it will not be detected. Therefore, it is important that a highly dampened probe be used and the thickness of the coating be large enough so that an interface signal can be detected. If an interface signal cannot be detected, then the SEM technique cannot be used.

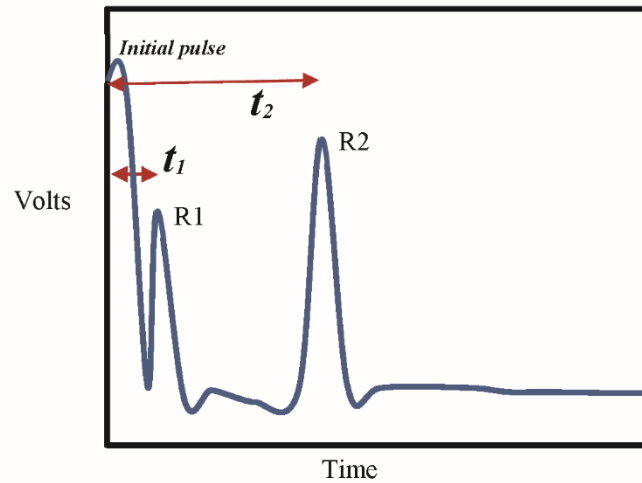
The second reflection required for an SEM measurement is the R2 reflection as illustrated in Figure A-10. This signal is the direct reflection from the pipe ID surface. Unlike the R1 reflection, this signal can be detected with most single-element contact transducers.

$$\text{Wall Thickness} = \frac{(t_2 - t_1) \times V_m}{2}$$

where  $V_m$  = sound velocity of pipe material



**A-Scan as Displayed on UT Instrument**



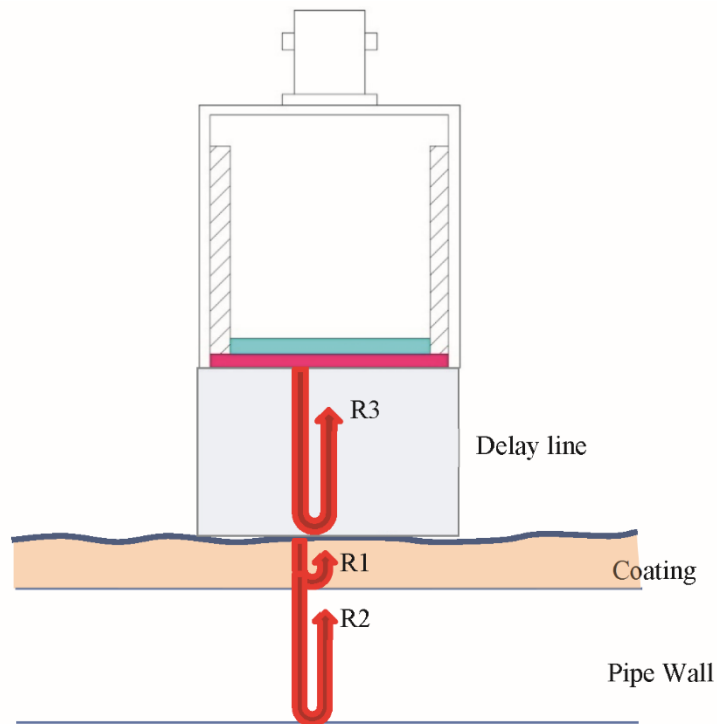
**Figure A-10**  
Signal recognition using a single-element contact transducer when performing the SEM technique

### **Signal Recognition Using a Delay Line Transducer**

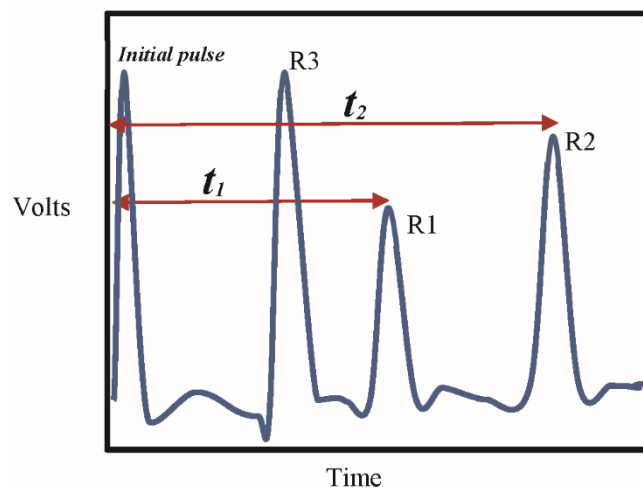
*Delay line transducers* are similar to single-element contact probes with the addition of a delay line component. This component adds an additional reflection that originates from the bottom surface of the delay line, denoted as R3 in Figure A-11. Once the ultrasonic wave exits the bottom surface of the delay line, it enters the coating layer. As a result, the next signal to be detected by the transducer is the reflection off the coating/pipe OD surface interface, which is denoted as R1 in Figure A-11. This signal should always follow the delay line reflection, which then is followed in time by the pipe back wall reflection, labeled as R2 in Figure A-11. Since all pipe-related signals are delayed in time by use of a delay line, any negative effects (dead zone) caused by the initial pulse are eliminated. It should be noted that all reflections have a finite amount of ringing that is related to the dampening of the transducer crystal, which can interfere when measuring very thin coatings even when using a delay line probe. This effect is minimized by using highly dampened transducers.

$$\text{Wall Thickness} = \frac{(t_2 - t_1) \times V_m}{2}$$

where  $V_m$  = sound velocity of pipe material



**A-Scan as Displayed on UT Instrument**



**Note:** A-scan is displayed with no delay added.

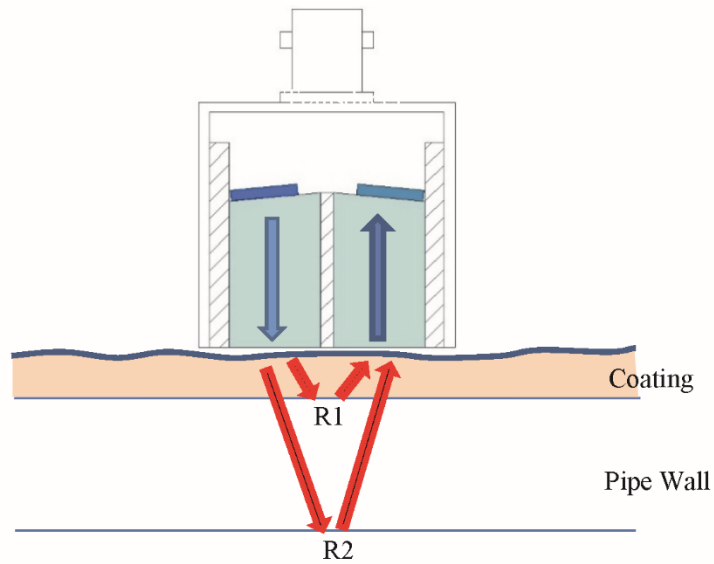
**Figure A-11**  
Signal recognition using a delay line contact transducer when performing the SEM technique

### **Signal Recognition Using a Dual-Element Transducer**

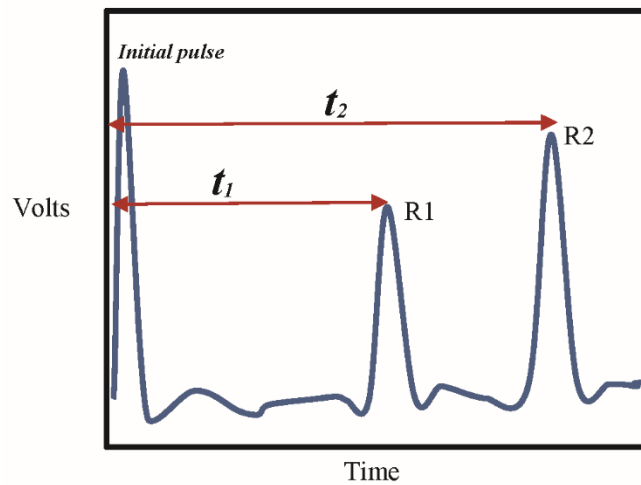
*Dual-element transducers* are unique in that they operate using separate transmitting and receiving piezoelectric crystals, both typically containing dedicated delay line components. This arrangement results in an acoustic isolation between the transmitter and receiver sides of the transducer. As a result, reflections from the delay line bottom surface are not detected by the receiver, since these signals are constrained to the transmitter side of the probe. Figure A-12 illustrates a typical signal presentation when testing a coated pipe using a dual-element transducer. Both the coating-to-pipe interface signal (R1) and the pipe ID surface reflection (R2) should be displayed on the A-scan display if an appropriate probe has been selected. Unlike other thickness transducers, dual-element probes are made for a specific range of thickness applications. This is a result of a slight angle machined on both the transmitter and receiver delay line components. This “roof angle” is designed to create a focal zone underneath the transducer where the transmitted and received elements are focused through refraction. The larger the roof angle, the closer to the surface the probe can be to detect reflections. Even though the transducer is designed for optimum sensitivity at a prescribed depth, the probe can be used over a range of depths due to beam width and divergence effects. These effects allow for possible simultaneous detection of both the coating-to-pipe interface and the pipe inner surface reflections. The reception of coating/pipe interface signal (R1) will always precede the pipe inner surface reflection (R2).

$$\text{Wall Thickness} = \frac{(t_2 - t_1) \times V_m}{2}$$

where  $V_m$  = sound velocity of pipe material



**A-Scan as Displayed on UT Instrument**



**Note:** A-scan is displayed with no delay added.

**Figure A-12**  
Signal recognition using a dual-element transducer when performing the SEM technique

### **Measurement Approach Using TOF Readings**

This section describes implementation of the SEM when using an instrument capable of providing calibrated time-of-flight values for displayed signals. This includes some commercially available digital flaw detectors capable of displaying signal horizontal position in units of time (that is,  $\mu\text{s}$ ). Alternatively, an ultrasonic pulser/receiver instrument used in conjunction with a calibrated oscilloscope can be used. What is required is the ability to directly measure the absolute time-of-flight of ultrasonic signals.

The first step in implementing the SEM approach is to properly identify the coating/OD surface interface signal (R1) and the pipe ID surface reflection (R2) on the instrument's A-scan display. The remaining wall thickness of the pipe is calculated by first subtracting the TOF associated with the R1 reflection from that measured for the R2 reflection. Since the sound wave must propagate through the coating thickness, additional time that has no relation to the wall thickness value is added to both signals. The resulting difference in TOF is directly related to the pipe wall thickness, which can be converted to a wall thickness dimension by multiplying by the appropriate sound velocity and dividing this value by 2 (pulse/echo test).

### **Measurement Approach Using Distance-Based Readings**

This section describes implementation of the SEM when using a UT instrument that is calibrated to display reflector position as a unit of distance (depth), as described in the "Instrument Calibration" section of this appendix. All commercially available digital flaw detectors, both analog and digital, are capable of displaying reflector depth (inch or mm) when properly calibrated.

Once calibrated, the transducer is coupled to the OD surface of the coated pipe so that both the coating/pipe OD interface (R1) and pipe ID surface (R2) reflections are observed simultaneously on the A-scan display. A prerequisite to using this technique is the ability to observe both the coating/OD interface and pipe ID surface reflections at the same test location. Pipe wall thickness is determined by measuring the difference in depth displayed on the UT instrument between the R1 and R2 signals. This can be determined by subtracting the displayed depth of the R1 signal (interface signal) from the depth associated with the R2 signal (ID surface). Alternatively, the UT instrument may have the capability to provide a delta depth value directly between these two signals. It should be stressed that the absolute depth readings associated with either the interface signal or the ID surface reflection are not an accurate reading of true depth for either of these reflectors. Each individual measurement has an unknown time delay created by the coating through which the sound passes. This time delay affects both the interface and ID surface reflections equally since both measurements are taken at the same location. Inaccuracies in depth caused by this time delay are factored out when the difference of the two signals is considered. As a result, only the delta between the interface and ID surface depths can be used to determine an accurate measure of pipe wall thickness.

### **Measurement Error**

The SEM requires the use of both the ID surface reflection and the coating/OD interface signals to produce an accurate wall thickness measurement. Use of both signals provides an accurate wall thickness measurement, since the additional time delay imposed by the coating thickness is factored out. In the event that a coating interface reflection is not detected, the operator may be

tempted to measure wall thickness of a coated pipe by only using the displayed depth of the first pipe ID surface reflection. Such a measurement should not be performed, since there would be significant error associated with this value. The amount of error is dependent upon the thickness of the coating at the measurement location. In such cases, the wall thickness measurement will always measure to be thicker than its actual value. Table A-1 is provided in order to demonstrate typical errors associated with the use of an absolute depth measurement of the pipe ID reflection on a coated pipe when depth is used to represent wall thickness. In other words, if the same UT thickness technique typically used on uncoated piping were to be used on a coated pipe, errors such as those described would be possible. The values provided in Table A-1 are based on a coating velocity of 1.0E5 inches/second, which may not correspond to all coatings. Therefore, this table is provided as an example and should not be used for any other purposes. It is evident that nonconservative measurements are the result of this error and could have negative consequences for the current and future reliability of the component.

**Table A-1**  
**Typical measured wall thickness without coating TOF compensation**

| Typical Measured Wall Thickness Without Coating TOF Compensation (Inch) |       |                                 |      |      |      |      |
|---|-------|---------------------------------|------|------|------|------|
|   |       | Actual Coating Thickness (Inch) |      |      |      |      |
|   |       | 0.05                            | 0.1  | 0.15 | 0.2  | 0.25 |
| Actual Wall Thickness (Inch)  | 0.125 | 0.24                            | 0.35 | 0.46 | 0.58 | 0.69 |
|   | 0.25  | 0.36                            | 0.48 | 0.59 | 0.70 | 0.82 |
|   | 0.5   | 0.61                            | 0.73 | 0.84 | 0.95 | 1.07 |
|   | 0.75  | 0.86                            | 0.98 | 1.09 | 1.20 | 1.32 |

**Note:** Table provides an example of measured wall thickness values when only the pipe ID reflection is used without compensating for the additional time added by the coating thickness. (Velocities used: Steel L-wave at 2.26E5 inch/sec; Coating at 1.0E5 inch/sec)

## Multiple-Echo Method (MEM)

### Reflection Identification

The MEM requires the reception of any two multiple reflections associated with the pipe wall thickness. These can be either the first, second, or third set of echoes as long as the echo pair represents only one plate thickness. This technique does not require the detection of the coating/pipe interface reflection as discussed in the section on the SEM approach. The pipe wall structure can serve as an efficient body through which sound waves can reverberate. Multiple reflections occur when an ID surface-reflected sound wave reflects off the OD surface, returning back to the ID surface, with the cycle continuing until the sound dissipates. On a pipe that has little or no surface corrosion, this reverberation of the sound wave within the pipe wall can occur many times. However, if the pipe is heavily corroded, a lesser amount of sound energy is reflected back into the pipe wall as a coherent wave front. Instead, a greater portion of the sound is scattered or absorbed by the rough surface, resulting in a significant reduction in amplitude of subsequent wall thickness reflections, making their reception difficult. It is common that multiple

wall thickness reflections cannot be detected in cases of severe corrosion or in localized regions of heavy pitting. The MEM approach can only be utilized where two or more back wall reflections can be detected. If only one back wall reflection is available, then an SEM approach must be utilized.

### ***Applicable Ultrasonic Transducers***

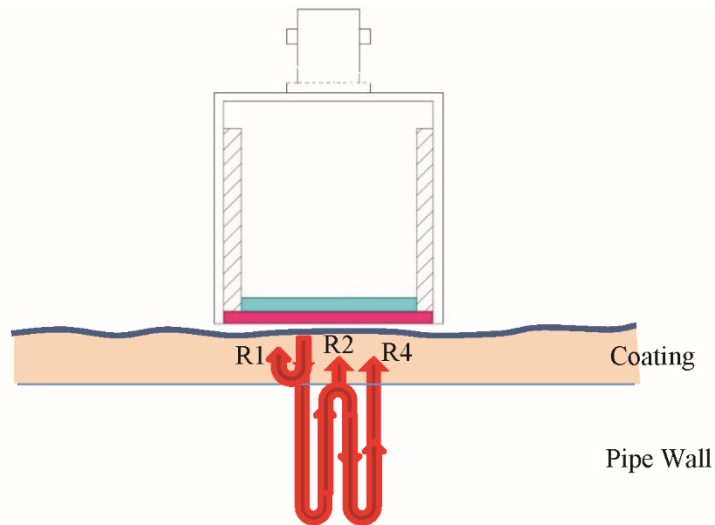
The most appropriate types of ultrasonic transducers for use with the SEM are the single-element contact transducer and the delay line transducer. The dual-element transducer is not likely to produce strong multiple reflections on thick wall piping due to the refracted angle of the transmitted beam. This small refracted angle tends to direct the sound away from the receiving transducer as it reverberates in the pipe wall. This effect is magnified with the increase in thickness of the pipe wall inspected. The dual-element transducer may be effective on thinner wall thicknesses but is mostly used when deploying the SEM approach for heavily corroded pipe. The following discussion does include all three probe types.

### ***Signal Recognition Using a Single-Element Contact Transducer***

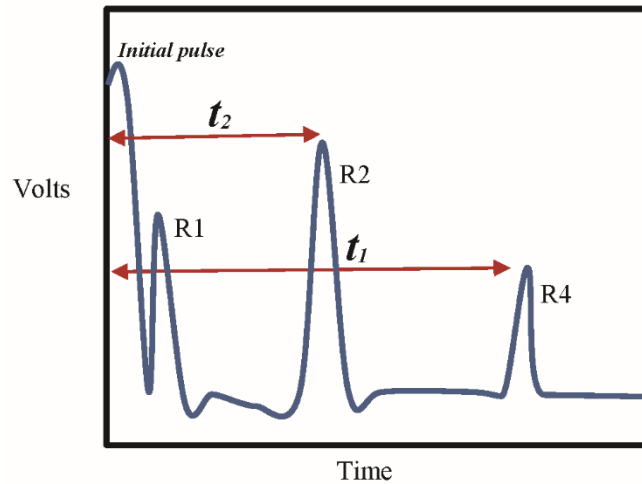
Figure A-13 is an illustration of the typical signal presentation associated with the use of a single-element contact transducer. The two primary signals used for this technique are the first and second back wall reflections, denoted on this figure as R2 and R4. Additional wall thickness reflections that are not shown in Figure A-13 may also be detected. All wall thickness multiple reflections will be equally spaced with descending amplitude. The first signal following the initial pulse when using a single-element contact probe may be the reflection of the coating/pipe OD surface interface, which is denoted as R1. However, this signal may not be detectable, since it may be obscured by the initial pulse. In such a case, the wall thickness multiples will be the first two signals detected following the initial pulse. The MEM approach can only be utilized where two multiple back wall reflections can be detected. If only one back wall reflection is available, then an SEM approach must be utilized.

$$\text{Wall Thickness} = \frac{(t_2 - t_1) \times V_m}{2}$$

where  $V_m$  = sound velocity of pipe material



A-Scan as Displayed on UT Instrument



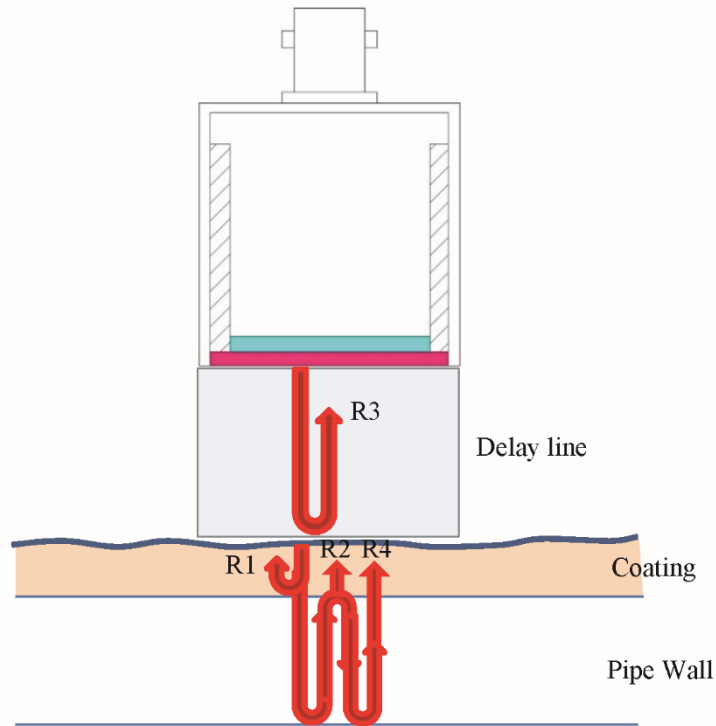
**Figure A-13**  
Signal recognition using a single-element contact transducer when performing the MEM technique

### **Signal Recognition Using a Delay Line Transducer**

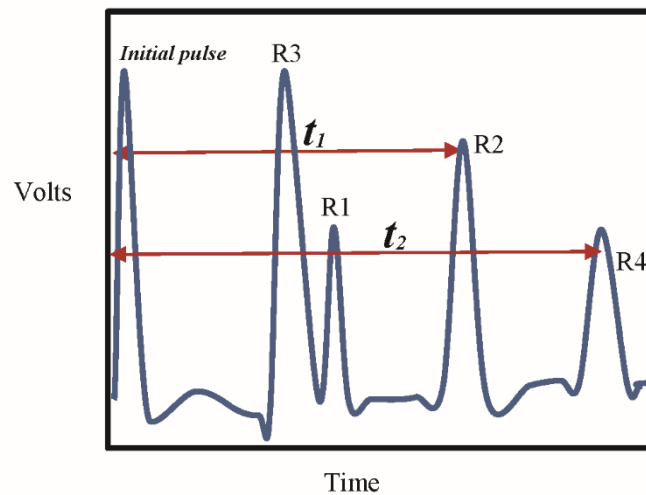
Delay line transducers are similar to single-element contact probes with the addition of a delay line component as described in the section titled “Delay Line Transducers.” This component adds an additional reflection that originates from the bottom surface of the delay line, denoted as R3 in Figure A-14. The MEM technique uses the first and second back wall reflections off the pipe inner diameter surface. These two signals, denoted as R2 and R4 in Figure A-14, will appear following the coating interface reflection (R1), which should be detected immediately after the delay line bottom reflection. A potential problem will occur if the delay line component is not sufficiently sized so that the second delay line multiple reflection is detected before the second back wall multiple. This cannot occur if the length of the delay line component is sized appropriately considering the maximum pipe wall thickness. The MEM approach can only be utilized where two multiple back wall reflections can be detected. If only one back wall reflection is available, then an SEM approach must be utilized.

$$\text{Wall Thickness} = \frac{(t_2 - t_1) \times V_m}{2}$$

where  $V_m$  = sound velocity of pipe material



**A-Scan as Displayed on UT Instrument**



**Note:** A-scan is displayed with no delay added.

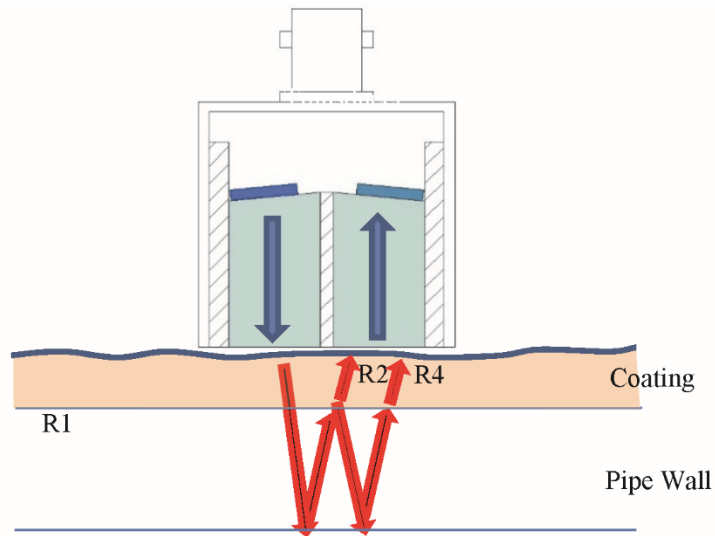
**Figure A-14**  
Signal recognition using a delay line contact transducer when performing the MEM technique

### **Signal Recognition Using a Dual-Element Transducer**

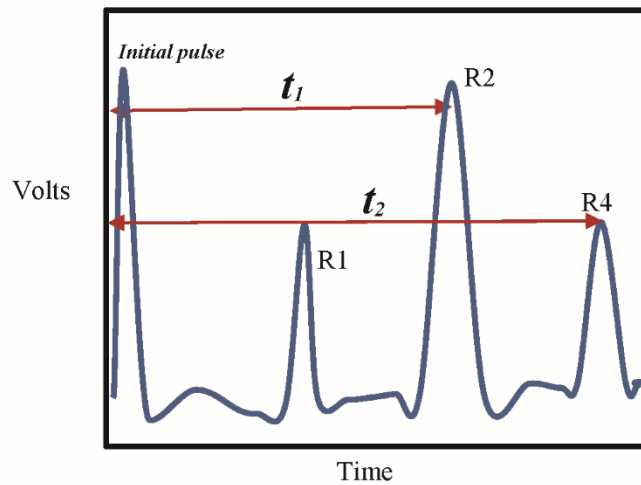
Dual-element transducers are unique in that they operate using separate transmitting and receiving piezoelectric crystals, both with dedicated delay line components. This arrangement results in an acoustic isolation between the transmitting and receiver sides of the transducer. As a result, reflections from the delay line bottom surface are not detected by the receiver, since these signals are constrained to the transmitter side of the probe. Dual-element probes are not well suited for use with an MEM technique, due to the small angle imposed on the transmitted beam making it difficult to detect multiple thickness reflections. Figure A-15 illustrates a signal presentation when testing a coated pipe using a dual-element transducer where two thickness reflections are detected. In this case the wall thickness is small enough to permit the detection of the second back wall reflection. The MEM approach can only be utilized where two multiple back wall reflections can be detected. If only one back wall reflection is available, then an SEM approach must be utilized.

$$\text{Wall Thickness} = \frac{(t_2 - t_1) \times V_m}{2}$$

where  $V_m$  = sound velocity of pipe material



**A-Scan as Displayed on UT Instrument**



**Note:** A-scan is displayed with no delay added.

**Figure A-15**  
Signal recognition using a dual-element transducer when performing the MEM technique

### **Measurement Approach Using TOF Readings**

This section describes implementation of the MEM when using an instrument capable of providing calibrated time-of-flight values for displayed signals. This includes some commercially available digital flaw detectors capable of displaying signal horizontal position in units of time (that is,  $\mu\text{s}$ ). Alternatively, an ultrasonic pulser/receiver instrument used in conjunction with a calibrated oscilloscope can be used. What is required is the ability to directly measure the absolute time-of-flight of ultrasonic signals.

The first step in implementing the MEM approach is to properly identify the first and second back wall reflection (R2 and R4) on the instrument's A-scan display, or any two multiple reflections associated with the pipe wall thickness. These can be either the first, second, or third set of echoes as long as the sound transition represents only one thickness. The wall thickness value is calculated by subtracting the TOF associated with the second back wall reflection (R4) from the TOF associated with first back wall reflection (R2). The resulting difference in TOF is directly related to the pipe wall thickness, which can be converted to a distance measurement by multiplying by the appropriate sound velocity and dividing this value by 2 (pulse/echo test).

### **Measurement Approach Using Distance-Based Readings**

This section describes implementation of the MEM when using a UT instrument that is calibrated to display reflector position as a unit of distance (depth) as described in the "Instrument Calibration" section of this appendix. All commercially available digital flaw detectors, both analog and digital, are capable of displaying reflector depth (inch or mm) when properly calibrated.

Once calibrated, the transducer is coupled to the OD surface of the coated pipe so that the first and second back wall reflections (R2 and R4), or other wall thickness multiple pair, are observed simultaneously on the A-scan display. A prerequisite to using this technique is the ability to observe a minimum of two back wall reflections at the same test location. Pipe wall thickness is determined by measuring the difference in depth displayed on the UT instrument between the R2 and R4 signals. This can be determined by subtracting the displayed depth of the R4 signal (second back wall reflection) from the depth associated with the R2 signal (first back wall reflection). Alternatively, the UT instrument may have the capability to provide a delta depth value directly between these two signals. It should be stressed that the absolute depth readings associated with either of the back wall reflections are not an accurate measurement of wall thickness. Each individual measurement has an unknown time delay created by the coating through which the sound passes. This time delay affects both the interface and ID surface reflections equally, since both measurements are taken at the same location. Inaccuracies in depth caused by this time delay are factored out when the difference of the two signals is considered. As a result, only the delta depth between the two wall thickness multiples can be used to determine an accurate measure of pipe wall thickness.





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