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Pulse-Echo Ultrasonic Evaluation of the Integrity of Seams of Single-Ply Roofing Membranes: Laboratory Evaluation of a Prototype Test Apparatus

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ABSTRACT

The feasibility of using NDE (non-destructive evaluation) methods to detect voids in adhesive-bonded seams of single-ply membranes has been under investigation at the National Institute of Standards and Technology (NIST). This report covers the first phase of a two-part study to investigate the applicability of a pulse-echo ultrasonic method for this purpose. A prototype pulse-echo ultrasonic apparatus, called the field scanner and suitable for testing of single-ply seams in the field, was developed. A series of laboratory experiments was conducted using the field scanner to investigate: 1) optimal operating conditions, 2) sensitivity and practical limitations for detecting voids, and 3) variables affecting its response. The equipment was found to be effective in maintaining coupling between the transducer and seam specimens. Two 5-MHz transducers (focusing and non-focusing types) were selected as the most suitable for void detection in the seams. Voids incorporated in laboratory seam specimens were readily detected. The results of the Phase 1 investigation provided guidelines on the optimum conditions for use of the field scanner. Although not without limitations, encouraging evidence was obtained indicating that the field scanner should be applicable to inspections of EPDM seams in service. Consequently, field investigations are being conducted, as planned, in Phase 2 of the study.

Key words: adhesive-bonding, EPDM rubber, field inspection, membranes, nondestructive testing, pulse-echo method, roofing, seams, ultrasonics

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1. INTRODUCTION

1.1 Background

A critical parameter associated with the performance of single-ply roofing membranes is the waterproofing integrity of field-applied seams. The seams must be properly prepared and remain watertight over the service life of the roof. A failure of even a small length of one seam will result in a roof leak. Field experience based on NRCA's Project Pinpoint surveys [1] has shown unsatisfactory seam performance to be the major problem reported for single-ply membranes. Consequently, many studies have been conducted to investigate the factors affecting seam performance [2-9]. These studies have addressed both short-term bond strength tests and long-term creep rupture tests. However, few investigations have been performed regarding inspection methods for assessing the condition of in-place seams. In particular, no nondestructive evaluation (NDE) inspection procedure is presently available to determine if bond formation is complete in all sections of the seams [10].

An inspection is normally carried out visually by an inspector who checks for large bubbles, fishmouths, or lack of bond at the edge of the seam. The inspector may also probe along the seam edge using a blunt instrument or a fingernail to judge the extent of bond subjectively. Visual inspection does not usually detect voids or delaminated areas which can be hidden in the interior portions of seams and which may lead to seam failure. By definition for this study, voids are incorporated in seams at the time of fabrication because of the lack of complete adhesive application; delaminations occur through disbonding of the seam after fabrication [11].

Destructive methods, primarily peel tests, have been proposed as an indicator of whether a field seam has been properly prepared [6,7,12]. A shortcoming of such testing is that it evaluates only small portions of the entire seam. A complementary NDE method to evaluate the entire seam area is needed to assure the completeness of adhesive application and bond formation [10]. An additional benefit of an NDE method would be the availability of a tool to investigate possible seam delaminations during service.

Preliminary investigations have been conducted at the National Institute of Standards and Technology (NIST) on the feasibility of two NDE methods to detect voids in adhesive-bonded seams of single-ply membranes: infrared (IR) thermography and pulse-echo ultrasonics [10,11,13]. The results of these investigations indicated that infrared thermography was not practical for the general detection of voids and delaminations. Some such defects, purposely incorporated in laboratory seam specimens, were not found using the IR method in cases where the rubber sheets comprising the seam made contact with each other across the void area. In contrast, the pulse-echo ultrasonic method, using a wheel transducer that could scan continuously along the length of the seam specimen, was successful in detecting all voids incorporated in the adhesive layer. Thus, it was recommended that future study be directed at further investigations of the pulse-echo ultrasonic method, and in particular, towards the development of equipment for field use [10].

Ultrasonic NDE methods have been applied extensively to detecting voids or delaminations between sheet materials [14-18]. Most of these applications have been on adhesive-joints of rigid materials such as metals. A few have dealt with synthetic flexible membrane materials including geomembranes [19].

1.2 Objective and Scope of the Study

A two-phase study was conducted to investigate further the use of the pulse-echo ultrasonic method for detecting, in the field, voids and delaminations in seams of single-ply roofing membranes. This report presents the results of the first phase of the study. A prototype apparatus (herein called the field scanner) incorporating pulse-echo equipment was developed for inspecting seams in service. The prototype was investigated in the laboratory to determine: 1) its sensitivity and practical limitations for detecting voids, 2) optimal operating conditions, and 3) the influence of the properties of the seam (e.g., adhesive thickness) on void detection.

In the second phase of the study, the field scanner will be evaluated in the field. Adhesive-bonded seams of existing single-ply membranes, as well as those of roofs under construction, will be tested using the scanner. The procedure used for field testing will be based on the results of the laboratory investigations. Based on the results of both Phase 1 & 2, recommendations will be made on the use of the pulse-echo ultrasonic method for evaluating the integrity of seams of single-ply membranes.

2. PRINCIPLE OF THE METHOD AND FIELD SCANNER APPARATUS

2.1 Principle of the Pulse-Echo Ultrasonic Method

The principle of the pulse-echo ultrasonic method for detecting voids in single-ply roof membranes has been previously described [11]. Sound waves with a frequency above the audible range are induced in a seam by a piezoelectric transducer and waves reflected off discontinuities (e.g., voids and delaminations) and from interfaces (e.g., between membrane and thermal insulation or air) are recorded. A completely bonded seam would produce an echo signal that would pass through two membrane layers (Figure 1). If the region of the seam being inspected was unbonded, the echo would only pass through one layer. Therefore, the echo signal would require twice the time to pass through a bonded region as through an unbonded region of a seam.

The penetrating ability of the ultrasonic pulse and the minimum size of detectable flaws are influenced by the frequency of the generated waves. High-frequency waves (i.e., shorter wave length) have less penetrating ability, but better sensitivity in detecting small voids, than low-frequency waves (i.e., longer wave length). The frequency of the transducer is a factor investigated in the present study. Multiple reflections can occur when an ultrasonic wave is induced in a material, which complicates the interpretation of the echo pattern. For simplification of the method, only the first echoes (first-order echoes) were recorded.

2.2 Coupling Method for the Field Scanner

Reliable acoustic coupling of the transducer with the top surface of the seam of a single-ply membrane was a critical requirement in the development of the NDE field scanner [10,11]. A main concern was that field conditions such as unevenness of the roof membrane surface, and presence of dirt or other particles on the membrane surface could hamper effective coupling. Another consideration was the availability of sufficient amounts of water (a normal couplant) on the roof of a building under construction.

Figure 2 shows a schematic diagram of the technique selected to provide coupling of the transducer to the membrane surface using the field scanner. An immersible transducer was placed in a plastic cylindrical container (subsequently referred to here as the transducer holder) having a height and diameter of 4 and 3.5 in. (102 and 89 mm), respectively. The distance between the front surface of the immersible transducer and the top surface of the seam specimen was variable. The transducer holder was filled with water which was added through a small port sealed with a threaded screw plug.

The bottom of the holder is a flexible rubber (urethane) diaphragm, having a thickness of 0.03 in. (0.8 mm). A flexible bottom was selected to provide a conformable surface and, thus, help to keep continuous contact of the holder with irregular (i.e., uneven or non-planar) surfaces of the field seam specimens. When the holder was filled with water, the diaphragm bulged slightly, which also helped to maintain contact with the surfaces of test specimens. Water containing a wash detergent was used to couple the diaphragm and the seam surface acoustically. The rubber of the diaphragm was selected to have an acoustic impedance similar to that of water to minimize reflection of the ultrasonic echo at water-diaphragm interfaces [20], and also to have minimum attenuation of the signal passing through the diaphragm.

In the laboratory study, the transducer holder was set directly on a seam test specimen. Alternatively, for field applications, the transducer holder was mounted as part of the pulse-echo field scanner as described in the next section of the report. The field scanner with transducer holder were procured as a total system.

2.3 Description of the Field Scanner

Although not generally used in Phase 1, the description of the field scanner is presented because it was purchased at the outset of the study. Figure 3 shows a schematic of the field scanner. The basic components, typical of pulse-echo ultrasonic test equipment, are: the transducer (here incorporated in the holder), the pulser-receiver unit, and a couplant reservoir. The components are mounted on a wheeled luggage carrier to allow continuous scanning and maneuverability along lengths of seams in the field.

The transducer holder is attached to a plate at the bottom of the luggage carrier with a spring mechanism that allows for adjustment of the height of the holder above the roof surface. The couplant, whose flow can be adjusted using a plastic valve on the reservoir, is supplied to the seam in front of the transducer holder through a paint-brush pad. This brush pad is intended to drag across the seam surface during scanning to increase wetting of the surface with the couplant and to wipe away coarse particles.

The field scanner was provided by EMCO[1]. The pulser-receiver unit was Model no. DSL104 from Panametrics. It has an oscilloscope for detecting echoes and is compatible with transducers with nominal frequencies ranging from 1 to 10 MHz. The unit contains a rechargeable battery which may operate for eight hours and a 110 V AC can also be used. The operating controls include coarse and fine gain switches for adjusting the intensity of received echoes displayed on the oscilloscope. The coarse gain control provides adjustments in 20 decibel (dB) increments as follows: 0, 20, 40, 60, and 80 dB. The fine gain control allows adjustments in 2 dB increments from 0 to 20 dB.

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[1]Certain trade names or company products are mentioned in the text to specify adequately the experimental procedure and equipment used. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.

3. EXPERIMENTAL

3.1 Materials Used for Preparation of Seam Specimens

The majority of the seam specimens were prepared using commercially available, non-reinforced, EPDM roofing membrane sheets. These rubber sheets had a talc-like release agent on both sides and a nominal thickness of either 0.045 or 0.060 in. (1.1 or 1.5 mm). For one experiment, the seam specimens were fabricated using a reinforced EPDM rubber having a nominal thickness of 0.060 in. (1.5 mm). Strands of the reinforcement were about 0.1 in. (3 mm) apart. The reinforcement produced a slight, yet noticeable, cross-hatched pattern of depressions in the surface of the rubber. Contact adhesives, typical for bonding EPDM roofing sheets, were commercially available, butyl-based or neoprene-based products. The adhesives were kept in small, closed containers until use and were thoroughly stirred before application.

3.2 Seam Specimen Preparation

The size of the specimens was generally 5 X 6 in. (130 X 150 mm) and each contained a 4-inch (100-mm) wide seam centered parallel to the long dimension. The preparation and curing of the seam specimens were carried out at ambient laboratory conditions, approximately 73°F (23°C) and 50-60% RH. The EPDM sheets were cut into pre-determined sizes, depending on the test to be conducted. Unless seam specimens prepared using uncleaned rubber were needed for experimentation, the EPDM sheets were cleaned by scrubbing both sides with soap and water, which was followed by rinsing with water, and then, wiping with a cloth saturated with heptane.

Voids of known size were incorporated in the adhesive layers of some seam specimens by placing masking tape on both EPDM sheet surfaces prior to application of the adhesive. The masking tape was removed prior to joining the sheets together to form a seam.

The adhesives were applied to the rubber sheets using a knife-coat method to provide uniformity to the adhesive layer at the designated thickness[2]. The sheets were joined together after an adequate open time, i.e., when the adhesive surfaces became dry-to-the-touch. Within 1 min. after joining, the seam specimens were pressed at 100 lbf/in^2 (0.69 MPa) for 5 to 10 s with a laboratory press. The seam specimens were then cured for a minimum of 2 weeks before testing. In cases where the thickness of the adhesive layer was a variable, it was measured after a 2-week cure using the method previously described [9].

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[2]The technique uses a draw-down blade or rod to control dispersion of the adhesive on the membrane. The distance between the blade edge and the membrane surface controls the adhesive thickness.

3.3 Echo Measurement Procedure

Before testing a seam specimen, the pulser-receiver was turned on with the transducer holder suspended in air. Two echoes having comparable intensity were observed on the oscilloscope. The first echo was associated with the interior water-diaphragm interface, whereas the second was due to the exterior air-diaphragm interface. When the transducer holder was acoustically coupled to a seam specimen, these echoes were still readily visible, but the second echo markedly decreased in intensity. In this case, the second echo was due to the interface between the diaphragm and the top surface of the seam. The decrease in intensity of the second echo provided a qualitative measure of coupling. Whenever coupling was not achieved, the second echo was generally as intense as the first echo associated with the interior water-diaphragm interface.

Figure 4 shows a schematic illustration of the echoes typically observed for seam specimens. Figure 4a is for a well-bonded seam which, for purposes of this paper, is one without voids or delaminations. Figure 4b depicts the echo pattern for a seam that contains a void (lack of adhesive) in the adhesive layer. In these figures, the X-axis represents relative time and the Y-axis represents the relative intensity of the echo. For both the well-bonded seam and void specimen, four echoes are usually observed, representing four interfaces from which the ultrasonic pulses are reflected. These four echoes have been designated as follows (Figure 4):

ED1: Echo from the water-diaphragm interface,

ED2: Echo from the diaphragm-specimen interface, (or in the absence of a specimen, the air-diaphragm interface),

EM1: Echo from the adhesive layer[3] in the seam, (or for a single sheet of membrane material, the echo from the interface of the sheet and its substrate), and

EM2: Echo from the seam specimen-substrate interface.

Note in Figure 4 the difference between the echo pattern for a well-bonded specimen and that for a specimen with a void. In the former case, the intensity of EM1 is relatively low and comparable to that of EM2. When a void is present, the relative intensity of EM1 greatly increases and that of EM2 becomes much weaker. In this case, the ultrasonic pulse is mainly reflected at the void (Figure 1).

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[3]The upper and lower surface of the adhesive layer in the seam did not show two corresponding echoes. Instead, only one signal having one peak was observed on the oscilloscope. In the following discussion, this reflected signal is named "EM1" and treated as an echo from the adhesive layer.

A quantitative measure of peak intensity was needed to analyze and compare the various echo patterns obtained as a function of the variables investigated during the study. The intensity of an individual echo was increased using the gain controls of the pulse-receiver unit until the peak height reached, but did not exceed, 100 percent of the relative intensity scale on the oscilloscope. The dB value at which maximum peak height was attained was recorded as the intensity of the echo. This technique was used in lieu of equipment that could directly measure echo intensity. Using this technique, the echo intensities were recorded as negative dB values, indicating that the original signals were amplified to reach maximum intensity. The larger the dB (absolute) value, the weaker was the intensity of the echo.

3.4 General Laboratory Procedure for Detecting Voids

Measurements were made under ambient laboratory conditions, approximately 73°F (23°C) and 50-60% RH. The general procedures used in the laboratory investigations were as follows: 1) spread couplant on the surface of the seam specimen, 2) slide the transducer holder, a minimum of 0.5 in. (13 mm), across the specimen surface locating the center of the transducer holder on the point of the specimen to be examined, and 3) record the intensities of the four echoes, while the transducer holder was setting stationary on the specimen.

4. RESULTS AND DISCUSSION

The laboratory tests conducted to evaluate the performance of the prototype field scanner were grouped into three categories:

(1) Optimization of Factors Critical to the Method. Two factors were included: coupling and transducer selection. Without adequate coupling and the proper transducer, the pulse-echo method will not provide the desired information.

(2) Void Detection. Before scanning seams of roofing in service, the operation of the scanner in the laboratory and its ability to locate known voids in adhesive layers needed to be studied.

(3) Variables Affecting Instrument Response. Before using the field scanner on roofs, it was necessary to examine variables that might adversely affect its performance. The variables investigated included: pressure applied to the transducer holder, orientation of the transducer holder, condition of the seam surface, membrane reinforcement, thickness of the membrane material and adhesive layer, adhesion of the seam specimen to the substrate, water under a loose-laid specimen, and scanning of the transducer holder across the specimen surface.

4.1 Optimization of Factors Critical to the Method

4.1.1 Coupling. Successful roof-top operation of the field scanner requires that proper acoustic coupling of the diaphragm with the surface of the seam be maintained. Improper coupling will reduce the transmission of the ultrasonic pulse across the diaphragm-seam interface. This, in turn, will reduce the intensity of the EM1 echo (as well as others), which is the indicator of voids. Under such circumstances, voids present in the adhesive layer might not be detected. Thus, for the laboratory tests in Phase 1, a quantitative measure of the degree of coupling was desirable.

As indicated previously, the intensity of the ED2 echo versus that of the ED1 echo decreased significantly when coupling was achieved. The difference of these echo intensities, ED2-ED1[4], was chosen as the quantitative indicator of a degree of coupling. The intensity of ED2 is inversely related to the ultrasonic energy transmitted into the seam specimen[5], while the ED1 echo effectively acts as a reference intensity. Since the difference value includes the ED1

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[4]Since the unit of echo intensity is decibels, which is logarithmic, ED2-ED1 represents the ratio of ED2 intensity to ED1 intensity in decibels.

[5]This depends not only on the degree of coupling but also on the acoustic properties of the membrane material comprising the seam. However, for this study where only EPDM rubber roofing sheets were used, constant acoustic properties were assumed.

echo intensity, which is not affected by coupling, it was considered to be a more appropriate indicator of coupling than the use of the intensity of the ED2 echo alone.

To provide an example of the difference values for proper and improper coupling, the transducer holder was first set on a seam specimen without couplant. In this case, ED2-ED1 was 2 dB. A small amount of a 0.2% aqueous detergent solution was added to the seam surface to moisten it slightly, but insufficient for proper coupling. In this case, ED2-ED1 was -8 dB. Finally, the surface of the specimen was well wetted with the detergent solution, resulting in a ED2-ED1 value of -15 dB. These values are for the specific example, and may change as other test parameters such as type and frequency of the transducer are varied.

Tap water, vaseline, and the 0.2% aqueous solution of detergent were compared as couplants by measuring ED1 and ED2 for five non-reinforced EPDM sheet materials. Two were new (unaged), and were well covered with the talc-like release agent. The other three were field samples cut from roofs in service. In the last case, the surfaces had little release agent, but were covered with some dirt. The results are given in Table 1.

The detergent solution had the lowest value of ED2-ED1, and could best wet the new sheet surfaces heavily covered with release agents. This was attributed to its reduced surface tension due to the existence of the surface active (detergent) agent. Based on the results of the comparison, it was decided to use the 0.2% detergent solution as the coupling agent in further experiments.

4.1.2 Transducer Selection. The variables related to the transducer were frequency, type, and the positioning of the transducer in the holder. Previous NIST studies [10,11,13] had indicated that frequencies of 1 and 2.25 MHz could be used for detecting voids in adhesive layers of single-ply seams using the pulse-echo method. Nevertheless, because the optimum transducer frequency for a specific application is often selected after empirical testing [18], the effect of varying the transducer frequency, as well as transducer type, was investigated.

As mentioned previously, a high frequency (i.e., shorter wave length) provides better sensitivity than a low frequency for detection of small voids and resolution of echoes from closely spaced voids or interfaces. In contrast, rubber materials greatly attenuate ultrasonic sound, especially high frequencies. Consequently, the transducer frequency selected for the field scanner must balance these opposing phenomena. As shown in table 2, transducer frequencies of 2.25, 5, and 10 MHz were included in the Phase 1 study.

Two types of immersible transducers, flat-surfaced (non-focusing) and focusing were investigated. The latter type concentrates the ultrasonic energy at a focal point and thereby increases beam intensity (Figure 5) [18]. As a result, an echo from a discontinuity (e.g., void) near the focal point is magnified in intensity. An advantage of a focusing transducer is that it may be positioned in the holder such that its focal point is set within the adhesive layer of the seam specimen. A disadvantage is that, when the beam is focused, the examined area of the test specimen is small.

In comparison to the focusing transducer, the non-focusing type examines a larger test area, but echoes from discontinuities may be less intense. Also, the intensity of the ultrasonic pulse varies with the distance from the transducer face [20], but in a less degree for non-focusing than for focusing transducers. Thus, the non-focusing transducer should be positioned in the holder such that the maximum intensity of the pulse occurs in the adhesive layer of the seam.

Table 2 lists nine transducers used in the study. Three relatively wide non-focusing types (nos. 2, 6 & 9) were of interest because they would allow scanning of seam sections which would be at least 1 in. (25 mm) wide. However, preliminary investigations with these three transducers showed them to be insufficiently sensitive to analyzing seam specimens, and in particular, to providing reproducible and sufficiently intense EM1 and EM2 echoes. Consequently, these transducers were not used in further investigations and no data are reported for them.

Transducer effects were examined using a single sheet of an EPDM membrane material, and a well-bonded seam specimen. From an operational point of view regarding the pulse-echo method, a single sheet is akin to a void in a seam (Figure 1).

The first parameter determined was the optimum distance between the transducer and the inside surface of the diaphragm. The optimum distance was defined as the distance at which the intensity of the EM1 echo was maximum for a single sheet. The seam specimen was examined with each transducer to determine whether the EM2 echo could be readily determined at the optimum transducer distance.

Table 3 gives the optimum distance found for each transducer, and also the echo intensities determined for the single sheet and seam specimen at the optimum distance. Although an optimum distance was set for the non-focusing transducers (nos. 5 & 8), little variation in intensity of the EM1 echo was found with changes in distance.

For a given transducer, the intensity of the EM1 echo was less for the seam specimen than for the single-sheet. This finding was consistent with the principle of the method for detecting voids. Also, for a given transducer with the exception of no. 7, the intensities of the ED1 and ED2 echoes were comparable for the single sheet and seam specimen. This provided a check that the measurements of the single sheet and seam specimen were consistent. When transducer no. 7 was used, the echoes were too broad, with considerable noise, to allow determination of the peak intensities.

The 2.25-MHz, non-focusing transducer (no. 8) gave the strongest EM1 and EM2 echoes from the seam specimen. This was beneficial in terms of the sensitivity. On the other hand, the ED1 and ED2 echoes normally associated with the diaphragm were not resolvable, but appeared as one broad peak. This was also found for transducer no. 7. The non-resolution of the ED1 and ED2 echoes using the 2.25-MHz transducers was a major limitation because their difference, ED2-ED1, was used as a parameter of coupling.

The transducers nos. 1, 3, and 5 always gave distinctive and apparent echoes for both the single sheet and the well-bonded seam specimen. The EM1 echoes were less intense for the 5-MHz transducer no. 4 than for the other 5-MHz transducers (nos. 3 & 5). In addition, the echoes produced using transducer no. 4 were not sharp peaks, but displayed considerable noise.

The experiences in testing the various transducers lead to the development of the following desirable attributes of a transducer for effective NDE testing of seams using the field scanner:

1) Four echoes should be readily resolvable and sharp with little noise so that their intensities could be determined,

2) EM1 should be strong for a single sheet, and

3) EM1 should be relatively weak and EM2 should be relatively strong for a well-bonded seam specimen that is not adhered to the substrate.

Based on these characteristics and the results of the transducer screening, the 5-MHz, focusing transducer (no. 3) and the 5-MHz non-focusing transducer (no. 5) were considered to be most suitable for use in the field scanner. Hence, these two transducers were mainly used in the subsequent testing.

4.2 Void Detection

4.2.1 Echo Intensity. After optimizing the primary parameters affecting use of the instrument, the initial experiments conducted were a controlled series of measurements on detecting voids in the adhesive layer. The measurements were carried out using a large specimen[6] in which the majority of the seam was well-bonded, but contained six voids in the adhesive layer (Figure 6). The smallest void was 1 in. (25 mm) in diameter. The 5-MHz, non-focusing transducer (no. 5) with a 0.5 in. (13 mm) front face was used for these measurements. Since the effective width of an ultrasonic beam is generally smaller than the size of the transducer face [18], the ultrasonic beam in the measurement was considered to be smaller than the size of the voids.

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[6]This was the specimen described in a previous publication [10] reporting preliminary results on the use of the pulse-echo method for detecting voids in seams.

The intent of the measurements was to quantify differences in the intensities of the EM1 and EM2 echoes for the well-bonded sections of seams versus those sections having voids. The echo intensities were recorded (in triplicate) at twelve locations marked along the specimen: six points that were well-bonded and six points where voids were located. Each of the 12 locations were measured in turn once, after which two replicate series of 12 measurements were made.

Figure 7 is a plot of the intensities of the EM1 echoes versus those of the EM2 echoes. It is evident that the EM1 and EM2 intensities were readily distinguishable for the well-bonded and void sections of the specimen. In particular, the voids sections gave higher EM1 and lower EM2 intensities than those for well-bonded sections. This was as expected, based on preliminary investigations [10,11,13], and represents a quantification of the principle of the pulse-echo method (Figure 4) using the transducer holder of the field scanner.

Table 4 gives the mean and standard deviation values of the EM1 and EM2 echoes for both the well-bonded and void sections of the seam specimen. The average EM1 intensity for the voids was 17 dB greater than that for the well-bonded sections of the seams. In general, this difference was readily apparent when viewing the oscilloscope. This was advantageous, since it implied that viewing the oscilloscope of the field scanner during roof top inspections might normally provide adequate distinction between well-bonded and void sections of seams. Nevertheless, as is apparent in Figure 7, one data point for the EM1 echo due to a void overlapped with those of the well-bonded sections. This limited observation implied that, perhaps in a remote case, a void would not be distinguished from well-bonded seam sections of the roof using visual observation of the EM1 peak intensity alone. Whether or not such data scatter would limit the use of the field scanner was not further examined in Phase 1, but left to be addressed in Phase 2 of the study.

Figure 7 suggests that EM1-EM2 could provide a quantitative measure for enhancing the difference in the echo patterns between well-bonded seams and voids compared to using the EM1 intensities. The reason is that the presence of void increases the EM1 echo intensity and decreases the EM2 intensity. Calculated EM1-EM2 values are listed in Table 4. The average value for the well-bonded seam sections was -2 dB, and that for the voids was 27 dB. Thus, the difference between the EM1-EM2 value of the void sections versus the well-bond sections was greater than that of EM1 echoes alone for the well-bonded and void sections of the specimen (i.e., 17 dB).

In spite of the observation that the EM1-EM2 parameter enhances the difference between the echo patterns of the well-bonded and void sections for the data given in Figure 7, it is not a parameter that can be universally applied to distinguishing these types of specimens. The dependence of the EM1-EM2 parameter on the EM2 echo intensity is a practical limitation. In addition to being affected by the presence of voids, the EM2 intensity may be dependent on variables associated with the seam/substrate interface such as the presence of moisture (see Section 4.3.9). Such variables may be uncontrollable and unpredictable in the field, and consequently, it is felt that using a parameter incorporating EM2 could lead to erroneous interpretation of echo patterns.

Note in Table 4 that, when a void was in the adhesive layer, an EM2 echo was also present. Whether this echo was due to some transmission of the ultrasonic pulse across the void or a multiple reflection of the pulse within the top layer of rubber comprising the seam was not investigated. The data in Table 3, that a single-sheet shows no EM2 echo, may imply that an EM2 echo for a void in a seam is associated with some transmission of the ultrasonic pulse across the void. It may be that the upper rubber and lower rubber sheets, comprising the seam at the void, were in contact with each other due to the normal pressure applied by the transducer holder when set on the seam surface.

4.2.2 Void Size. Voids having a diameter of 1/8 in. (3 mm) were readily detected using the selected transducers (nos. 3 & 5). The practical ramifications of detecting small voids in seams in service (i.e., is an isolated small void of consequence) were not addressed in the laboratory phase of the study.

4.3 Variables Affecting the Instrument's Response

4.3.1 Pressure Applied to Transducer Holder. In pulse-echo NDE technology, echo intensity is generally dependent on the pressure applied to the transducer face [20]. This was found to be the case in the preliminary experiments conducted on seam specimens [10,11]. In the present study, tests were conducted to investigate the effect of pressure at the diaphragm of the transducer holder on echo intensity.

As held on the luggage carrier of the field scanner, the contact (downward) force of the transducer holder at the diaphragm, due to its mass alone, was 2.3 lbf (1.1 kgf). In one experiment, the intensities of the echoes at this force were compared to those obtained when the force was increased to 6.7 lbf (3.2 kgf) using weights. From a practical point of view, use of weights to create contact forces much greater than this amount were felt to be impractical for field investigations using the scanner. The 5-MHz non-focusing transducer (no. 5) was used in this test.

With the added force to the transducer holder, the intensity of each echo increased by 2 dB, which was the minimum sensitivity of the field scanner. One noticeable result of the increased force was that the echoes on the oscilloscope shifted left along the time axis. However, they were still readily resolvable. Apparently, the increased force on the transducer holder compressed the diaphragm, which shortened the travel distance of the pulses.

The practical conclusions from the experiment were:

1) Over the small range of pressure considered practical for field applications, the echo intensities were not influenced by pressure. In the laboratory, the design of the scanner appeared satisfactory to provide adequate contact of the diaphragm with the seam specimen. If subsequent field testing indicated that a slight increase in holder contact pressure was needed, it could be accommodated without significant change in the intensities and resolvability of the echoes.

2) The shift of the echoes along the time axis of the oscilloscope with the change in contact pressure may be a limitation of the field scanner as designed. Changes in contact pressure in the field due to seam surface irregularities or other unforeseen factors may result in constant shifting of the echoes on the oscilloscope. In turn, this may make it difficult to interpret the echo signals while scanning larger segments of seams. In practice, data processing equipment may be needed to trace the echo peaks, if they shift along the time axis.

4.3.2 <u>Orientation of the Transducer Holder</u>. As designed, the transducer holder is oriented perpendicular to the surface of the seam specimen (i.e., the transducer face is parallel to the seam). It was considered that, in practice, unevenness of roofing system might slightly tilt the transducer holder in relation to the plane of the roof.

It was found in a brief experiment that tilting of the transducer holder by several degrees (up to 4°) had no noticeable affect on echo intensity, provided the transducer was properly aligned in the holder. This suggested that slight tilting of the transducer holder in relation to the seam surface, as would be likely to happen in practice, should not affect detection of voids in the seam.

4.3.3 <u>Condition of the Seam Surface</u>. Exposed surfaces of roofing membranes and seams in service are more than likely covered with release agents, dirt, or other particles. The concern was that such surface contamination, particularly coarse particles, could disrupt coupling. The possibility was investigated using a series of laboratory specimens which were comparable except for surface condition. These were a seam specimen with a cleaned surface (i.e., no release agent), a specimen with talc-like release agent on its surface, and a specimen which had sand slightly sprinkled across its surface. In addition, two seam specimens cut from roofs in service were examined. The effect of the condition was determined by comparing the recorded values of ED2-ED1 for each specimen (Table 5). The transducer no. 3 was used in these tests.

It was found that the release agent alone did not affect the coupling. ED2-ED1 was about the same for the cleaned and uncleaned specimens (Table 5). This implied that, in the case of many newly fabricated seams which would have release agents on their surfaces, the presence of these particles should not hinder coupling. Consistent with the results for these laboratory specimens, the uncleaned field seam specimens without coarse particles on the surface provided satisfactory coupling (ED2-ED1 was -14 to -18 dB).

In contrast, the sand particles of the laboratory specimens significantly reduced coupling. ED2-ED1 randomly ranged from -8 to -18 dB, as the transducer holder was slid across the specimen surface. The sand appeared, at times, to accumulate under the diaphragm and adversely affect the coupling. This raised the possibility that field tests using the scanner may require removal of particulate matter from the seam surfaces prior to their examination. However, the field scanner contains a paint-brush pad to sweep the surface in front of the transducer holder. Thus, the question of the effect of particles present on the seam surface was left for answering in Phase 2 of the study, when the use of the scanner (with the brush pad) would be investigated in the field.

4.3.4 Membrane Reinforcement. A reinforced membrane material has small depressions across its surface due to the reinforcement in the rubber. It was of interest to determine the effect of the reinforcement on the test method. Echo intensities from a single reinforced sheet and from a seam fabricated from the reinforced sheets were recorded and compared to the results obtained on similar specimens of non-reinforced sheet. The 5-MHz focusing transducer (no. 3) was used for this test.

The results (Table 6) indicated that, when the specimen contained reinforcement and the center of the transducer holder was set stationary on the mesh, an echo due to the reinforcement (ER) was present with an intensity of -60 dB. This was less intense than the EM1 echo from a single sheet, and comparable to that for a seam specimen made from non-reinforced membrane material. The ER echo was shifted left on the time axis relative to the position of the EM1 echo. This reflected the shorter travel distance required of the echo from the reinforcement. Also, when the specimen contained reinforcement and the center of the transducer holder was set on the mesh, EM1 and EM2 echoes were not found.

In contrast, with reinforcement present and the center of the transducer holder set on a depression between the mesh, the echo patterns for both the single sheet and seam specimens were typical of those obtained from the comparable non-reinforced specimen. Thus, with a focusing transducer, the reinforced specimens had two distinct echo patterns depending on whether the transducer holder was placed on the mesh or on a depression.

If the transducer holder was moved slowly across the surface of a reinforced specimen, the above two echo patterns appeared in turn. The constant shifting of the echo pattern for the reinforced membrane material was found to be a complexity in interpreting the echo pattern when visually watching the oscilloscope. This finding is another case where data processing equipment would facilitate analysis of the echo peaks.

4.3.5 Thickness of the Membrane Material. The intensity of EM1 was measured for three single sheets having measured thicknesses of 0.047, 0.058, and 0.125 in. (1.2, 1.5, and 3.2 mm). The thickest was a factory-made seam in a sheet having a nominal thickness of 0.060 in. (1.5 mm). Three transducers (nos. 3, 5 & 8) were used in this experiment.

The results are presented in Figure 8, which shows the intensity of the EM1 echo versus the sheet thickness for each of the transducers. At a given thickness, the EM1 echo intensity decreased as the frequency increased from 2.25 to 5.0 MHz. However, even for the thickest specimens at 5.0 MHz, the EM1 echo was readily visible. The regression lines (thickness in inches) in Figure 8 for each set of measurements were as follows:

$$EM1 = -185 \times (\text{thickness}) - 38 \quad \text{for transducer no. 3} \quad (R = 0.949) \quad \text{---- (1)}$$

$$EM1 = -232 \times (\text{thickness}) - 37 \quad \text{for transducer no. 5} \quad (R = 0.960) \quad \text{---- (2)}$$

$$EM1 = -105 \times (\text{thickness}) - 32 \quad \text{for transducer no. 8} \quad (R = 0.937), \quad \text{---- (3)}$$

where R is the correlation coefficient.

The coefficients of thickness in the equations represent the extent of attenuation of the ultrasonic pulses in the EPDM rubber, which was approximately twice as much at 5 MHz as it was at 2.25 MHz. This finding was in agreement with the general principle that ultrasonic waves having higher frequency are attenuated more in a material than lower frequency waves [20].

In general, EPDM membranes are fabricated from rubber sheets that are 0.045 and 0.060 in. (1.1 and 1.5 mm) thick. From Figure 8, the calculated difference between single sheets having these two thicknesses in the intensity of EM1 echo was approximately 3 dB. The pulse has twice the distance to travel in the seam specimen compared to the single sheet. By analogy, the difference in intensity of an EM2 echo should be approximately 6 dB for two seams made from rubbers of these two thicknesses. In practice, the differences in echo intensity due to thickness should be considered. These results suggested that, in the field, a reference seam specimen having about the same thickness as the membrane under inspection be used to calibrate the field scanner to compensate for the attenuation due to increased membrane material thickness.

In investigating the effect of membrane material thickness, the ultrasonic sound velocity in the EPDM rubber was measured. This was done by plotting the thicknesses of the three sheets versus relative times which elapsed between the ED1 and EM1 echoes for each sheet (Data not shown). The slope of the line was the sound velocity. The time axis on the oscilloscope was calibrated using the echoes of a steel block of known thickness and known sound velocity. A velocity of 1.8×10^3 m/s was found (Table 7) for the EPDM rubber. This compared favorably with published values of butyl rubber and neoprene rubber, which are 2.0 and 1.7×10^3 m/s, respectively (Table 7) [21]. As another point for comparison, a general value for vulcanized rubber given in a text book is 2.3×10^3 m/s [22].

Table 7 also includes acoustic impedance values, which is the product of sound velocity and density of a material. At the boundary of two materials, the difference in the acoustic impedance represents the resistance across the interface to the transmission of sound. Since the acoustic impedances of EPDM, butyl, and neoprene rubber are similar, in principle, ultrasonic pulses should not be reflected greatly at interfaces created by combinations of two of these materials [18]. This is important, because EPDM membranes incorporate primarily butyl or neoprene adhesive in the seams.

4.3.6 Thickness of the Adhesive Layer. The intensity of EM1 was measured for the well-bonded seam specimens having five levels of adhesive thickness which ranged from 0.002 to 0.022 in. (0.05 to 0.55 mm). The results for the 5-MHz, focusing (no. 3) and 2.25-MHz, non-focusing (no. 8) transducers are presented in Figure 9. Over the range of thicknesses from 0.002 to 0.012 in. (0.05 to 0.3 mm), the EM1 intensity was attenuated (for both frequencies) as the adhesive thickness increased. At the adhesive thickness of 0.022 in. (0.55 mm), the EM1 intensity was higher than that found for the 0.012 in. (0.3 mm) thickness. This observation was attributed to the presence of cavities formed in the adhesive layer of well-bonded seams when thick adhesive layers (of the order of 0.02 in. or 0.5 mm) are applied [9]. The ultrasonic pulse is reflected from these cavities, and consequently, the intensity of EM1 is increased.

The finding that thick adhesive layers with cavities increased the intensity of the EM1 echo implied a possible limitation of the field scanner. As previously indicated, voids and delaminations produce a relatively strong EM1 echo, whereas a well-bonded seam gives a relatively weak EM1 echo (for laboratory specimens without cavities). Using the scanner, false negatives would be produced if cavities in the adhesive layer increase the intensity of the EM1 echo to a level comparable to that for a seam void or delamination.

4.3.7 Adhesion of the Seam Specimen to the Substrate. In this experiment, the previously-described large specimen (Figure 6) with six voids incorporated in the adhesive layer was laid loose on a 0.5 in. (13 mm) thick fiberboard. Triplicate measurements of the intensities of the EM1 and EM2 echoes were made at 12 locations, which included six well-bonded sections and six sections with voids. Then, the specimen was adhered[7] to the board with a

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[7]Very often in practice, adhered EPDM systems incorporate fiberboard insulation immediately below the membrane.

commercially-available neoprene adhesive used for adhering EPDM sheets to insulation. The echoes were then re-measured.

The results are given in Table 8, where it is evident that the intensities for the EM1 and EM2 echoes for the adhered versus the loose-laid specimens were not significantly different (0.05 confidence level). Considering the scatter in the data, in this experiment, an interface created by a seam bonded to a porous fiberboard insulation of relatively low density reflected the ultrasonic pulse to the same extent as the interface of a loose-laid specimen.

4.3.8 <u>Water under a Loose-Laid Specimen</u>. Field inspections of loose-laid and mechanically attached single-ply systems have occasionally found water present on the underside of the membrane [23]. This water would be expected to affect a pulse-echo analysis of seams, because it can acoustically couple the specimen and substrate. The result would be a reduction of the intensity of the EM2 echo.

A qualitative experiment was conducted to examine this phenomenon using a seam specimen containing voids and a polystyrene insulation board as a substrate. Comparisons were made of the echo patterns for sections of well-bonded seam and those with voids when the specimen/insulation interface was dry or contained water. When water was present, the intensities of the EM2 echoes for both well-bonded and void sections of the specimens were weak to the point that they were almost indistinguishable from the noise. In comparison, when the interface was dry (as previously discussed in Section 4.2), the EM2 echoes for the well-bonded section were considerably stronger than that for the void section. With regard to the EM1 echoes, as expected, no effect due to the water was found.

The practical significance of the effect of moisture at the specimen/substrate interface of a loose-laid system is that the intensity of the EM2 echo should not be used in an analysis procedure for detecting voids. EM2 could vary considerably for different areas of a roof depending upon moisture variations.

4.3.9 <u>Scanning of the Transducer Holder Across the Specimen</u>. The majority of the measurements made in Phase 1 of the study were conducted with the transducer holder resting stationary on the specimen surface. On a roof, the inspection of seams for voids and delaminations would be conducted by pushing the field scanner across the seam surface, and observing the echo patterns and intensities. Thus, it was of interest, in Phase 1 of the study, to have a laboratory determination of the effect of scanning the transducer holder across the seam on the operator's ability to interpret the echo patterns. This was examined qualitatively by pushing the transducer holder across the large seam specimen (Figure 6), in which the smallest void was 1 in. (25 mm) in diameter.

It was found that, in viewing the EM1 echo on the scope, the presence of a voids could be detected as long as the rate of scan was reasonably slow (about 90 ft/min or 27 m/min). The evidence of the void was a quick jump in intensity of the EM1 peak at the void location. This provided encouragement that field scanning could be conducted at a reasonable pace using visual observation as an indicator of the presence of voids. However, at the scan rate used, the intensities could not be recorded and the effect of the scanning on the intensity of the peaks versus those recorded for stationary measurements could not be made.

Thus, the effect of scanning on echo intensity was examined in a semi-quantitative test. A seam specimen without voids but with a cleaned surface (solvent washed) to assure adequate coupling was used. The echo intensities at predetermined points were measured when the transducer holder was placed stationary on the specimen. The transducer holder was then scanned across the specimen and a judgment was made whether the EM1 echoes at the pre-measured points were of comparable intensity. It was found that, to make the comparison of EM1 intensities, the rate of scan could not be greater about 0.25 in./s (6 mm/s), which was quite slow. At this rate, the results showed that the difference in the EM1 echo intensities appeared to be less than 2 dB (the resolution of the equipment) at each measured points. This indicated that the response of the field scanner was comparable for stationary measurements and those made at a low rate of scan.

5. SUMMARY AND CONCLUSIONS

This laboratory investigation was Phase 1 of a study on the development of an ultrasonic NDE method for evaluating the integrity of seams of single-ply roofing membranes. The method investigated was an application of the pulse-echo ultrasonic technique for detecting discontinuities in materials. A prototype pulse-echo test apparatus (the field scanner) was designed to scan across seams of roofs in service, while maintaining acoustic coupling to the seam surface. A series of laboratory experiments using the prototype field scanner was conducted to investigate: 1) optimal operating conditions, 2) its sensitivity and practical limitations for detecting voids, and 3) the variables affecting its response.

For the technique to be successful on a roof, one of the most critical requirements of the field scanner is to couple with the specimen. The design of the transducer holder considered this basic requirement. To provide coupling, an immersible transducer was placed in a water-filled cylindrical holder whose bottom surface consisted of a flexible rubber diaphragm. The intent was to have a conformable surface that could keep continuous contact between the holder and the field seams. Initial examinations of seams in the laboratory using the field scanner were positive in that voids could be distinguished from well-bonded sections of the specimen.

In Phase 1, the experiments were conducted using the transducer holder without mounting it on the field scanner, but placing it stationary on a test seam with an aqueous detergent solution as the couplant. The specimens were prepared using typical EPDM rubber sheets and butyl-based or neoprene-based adhesives. Measured intensities of the observed echoes were compared as a function of the variables investigated to judge the performance of the field scanner.

The following is a summary of the key laboratory findings:

<u>Optimization of Factors Critical to the Method</u>

- o The transducer holder, as designed, and the use of an aqueous detergent solution as the couplant produced satisfactory acoustic coupling to the seam specimens. The intensities of the echoes from the diaphragm interfaces provided an indicator for the adequacy of coupling.

- o Two 5-MHz transducers (a non-focusing and a focusing) were found to be most suitable (among those examined) for the seam analysis. They provided good resolution of the echo peaks with comparatively strong intensities.

Void Detection

- o Voids were readily detected in the adhesive layer of the laboratory seams. Quantitatively, the echo due to a void was, on the average, 17 dB more intense than the corresponding echo of a well-bonded specimen.

- o The results suggested that voids could be found in the field, if present in seams.

- o The laboratory data suggested that a parameter, based on the intensities of the echoes from the adhesive layers and specimen-substrate interface, could be used as a quantitative indicator of a void. However, the parameter was shown not to be universally applicable to all conditions of membrane use in the field.

Variables affecting instrument response

- o Pressure. Increased pressure on the transducer holder had little effect on echo intensity, but resulted in shifting of the echo pattern on the time-axis of the oscilloscope. This implied that data processing equipment might be needed to track echo shifts, if they occurred in the field.

- o Tilting of the Transducer Holder. Slight tilting of the transducer holder had no noticeable effect on the echo intensity. This suggested that the field scanner could tolerate some unevenness of roof surfaces that could result in tilting of the transducer.

- o Seam Surface Contamination. A particulate release agent on the seam surface did not affect coupling. This implied that, in the field, newly-fabricated surfaces generally should not have difficulty in coupling. Coarse sand particles significantly hindered coupling, indicating that they may have to be removed from seams during field investigations.

- o Membrane Reinforcement. Echoes due to the reinforcement were observed wherever the pulse focused on the mesh. These echoes disappeared when the pulse focused away from the mesh. The result was a complex echo pattern that could be difficult to interpret visually in the field. It provided further evidence that data processing equipment may be needed in the field.

- o Thickness of the Membrane Material. The intensity of the adhesive layer echo decreased with increasing membrane thickness due to attenuation of the ultrasonic pulse in the rubber. These results suggested that, in the field, a reference seam specimen having the same thickness as the membrane under inspection should be used to calibrate the field scanner to compensate for the attenuation due to increased membrane material thickness.

- Velocity of Ultrasonic Sound in EPDM Membrane Material. The velocity of ultrasonic sound in the EPDM rubber material was measured to be 1.8×10^3 m/s. This value compared favorably with published values for rubber materials. The acoustic impedance of the EPDM rubber membrane material was found to be similar to published values for those of butyl-based and neoprene-based rubbers. This implied that interfaces (such as seams between EPDM and butyl-based or neoprene-based rubbers) should give little reflection of the pulse.

- Adhesion of the Seam to a Substrate. Adhesion of seam specimens to a fiberboard insulation substrate had little effect on echo intensity compared to those obtained when the specimen was loose-laid on this substrate.

- Water Under a Loose-Laid Specimen. Water under the specimen eliminated the echo associated with the interface of the loose-laid membrane and its substrate. This indicated that the use of this interface echo in a quantitative procedure for void detection should not be done, because its intensity could be very variable.

- Scanning of the Transducer Holder. Voids could be detected qualitatively when the transducer holder was scanned across a seam specimen at a reasonable rate. This provided evidence that visual observation of the oscilloscope could serve as an indicator of voids during field inspections. Quantitatively, little difference in echo intensity was found when a seam was scanned at a slow rate or when the transducer holder was motionless on the specimen.

In summary, the laboratory testing provided guidance on the optimum conditions for use of the field scanner. Although not without limitations, encouraging evidence was obtained that the field scanner should be applicable to inspections of EPDM and related single-ply seams in service. Consequently, field investigations are being conducted, as planned, in Phase 2 of the study. The results will be published in a final report. It is noted at this time, however, that some preliminary field data have indicated that the method may yield false evidence of voids in seams in service. The reason for such observations is under study.

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Table 1. Results of couplant comparison

Specimen Type	Value of the Parameter, ED2-ED1, dB		
	Tap Water	Vaseline	Detergent Solution
New sheet	-14	-12	-18
New sheet	-16	-11	-19
Field sample	-12	-11	-18
Field sample	-13	-12	-17
Field sample	-12	-12	-17

Table 2. Transducers used in the study

No.	Frequency MHz	Type	Focal Point in. (mm)	Dimensions
1	10	Focusing	1 (25)	0.5 in. (13 mm) in diameter
2	10	Non-focusing	NA[a]	1.5 x 0.25 in. (39 x 6 mm)
3	5	Focusing	1 (25)	0.5 in. (13 mm) in diameter
4	5	Focusing	0.75 (19)	0.5 in. (13 mm) in diameter
5	5	Non-focusing	NA	0.5 in. (13 mm) in diameter
6	3.5	Non-focusing	NA	1 in. (25 mm) in diameter
7	2.25	Focusing	1 (25)	0.5 in. (13 mm) in diameter
8	2.25	Non-focusing	NA	0.5 in. (13 mm) in diameter
9	2.25	Non-focusing	NA	1 in. (25 mm) in diameter

[a]NA indicates not applicable.

Table 3. Comparison of six transducers investigated

Transducer No.	Optimum Distance in. (mm)	Typical Echo Intensity, dB — Single Sheet ED1	ED2	EM1	Seam Specimen ED1	ED2	EM1	EM2
1	0.6 (15)	-50	-68	-62	(not conducted)			
3	0.6 (15)	-40	-54	-44	-40	-56	-62	-58
4	0.4 (15)	-60	-70	-70	-58	-70	-78	-88
5	0.2 (5)	-40	-58	-46	-40	-54	-58	-60
7	0.8 (20)	(-56)[a]		-56	(too weak to measure)			
8	1.6 (20)	(-34)[a]		-30	(-32)[a]		-40	-36

[a]The intensities of ED1 and ED2 echoes were not obtained separately because the echoes from the diaphragm were not resolvable.

Table 4. Intensities of EM1 and EM2 echoes for well-bonded and void sections of a seam specimen

Echo Designation	Echo Intensity[a], dB — Well-bonded MEAN	S.D.[c]	Void MEAN	S.D.[c]	Difference[b]
EM1	-68	4	-51	4	+17
EM2	-66	3	-78	2	-12
(EM1-EM2)	-2	4	+27	4	

[a]The results of triplicate measurement at six points are given.
[b]Subtraction of mean echo intensity for void section from that for well-bonded section.
[c]S.D. indicates the standard deviation.

Table 5. Range of the parameter, ED2-ED1, for various conditions of specimen surface

Specimen	Surface Condition	ED2-ED1, dB
Laboratory 1	Cleaned, no release agent	-18
Laboratory 2	Uncleaned, release agent present	-16 to -18
Laboratory 3	Cleaned with some sand present	-8 to -18
Field 1	Uncleaned, some dirt, but no coarse particles apparent	-14 to -18
Field 2	Uncleaned, some dirt, but no coarse particles apparent	-14 to -18

Table 6. Effect of the reinforcement in the membrane material on echo intensity

Spec. Type	Reinforced	Location of Transducer[a]	Typical Echo Intensity, dB				
			ED1	ED2	ER[b]	EM1	EM2
Single-sheet	No		-40	-54	--[c]	-44	--[d]
	Yes	Between meshes	-40	-54	--[e]	-46	--[d]
	Yes	On mesh	-40	-54	-60	--[d]	--[d]
Seam	No		-40	-56	--[c]	-62	-58
	Yes	Between meshes	-40	-56	--[e]	-66	-62
	Yes	On mesh	-40	-56	-60	--[d]	--[d]

[a]Refers to the location where the transducer was set on the specimen in relation to the reinforcement in the sheet.
[b]ER indicates echo from the reinforcement.
[c]Not applicable since the specimen was not reinforced.
[d]Echo not present or too weak to measure its intensity.
[e]Echo not present since the transducer was placed on the surface away from the reinforcement.

Table 7. Acoustic properties of materials used in the study

Material	Density g/cm^3	Sound Velocity 10^3 m/s, at 5MHz	Impedance 10^5 g/cm.s
EPDM rubber[a]	1.16	1.8	2.1
Butyl rubber[b]	1.13	2.0	2.3
Neoprene rubber[b]	1.42	1.7	2.4
Water	1	1.5	1.5
Air	0.001	0.33	0.0033

[a]Measured in the present study.
[b]Measured by Hartmann [21].

Table 8. EM2-echo intensities as affected by adhesion of the seam specimen to the substrate

Specimen Type	Intensity of EM2, dB			
	Well-bonded		Void	
	Mean	S.D.[a]	Mean	S.D.[a]
Loose-Laid	-65	3	-78	1
Adhered	-70	4	-77	4

[a]S.D. indicates the standard deviation

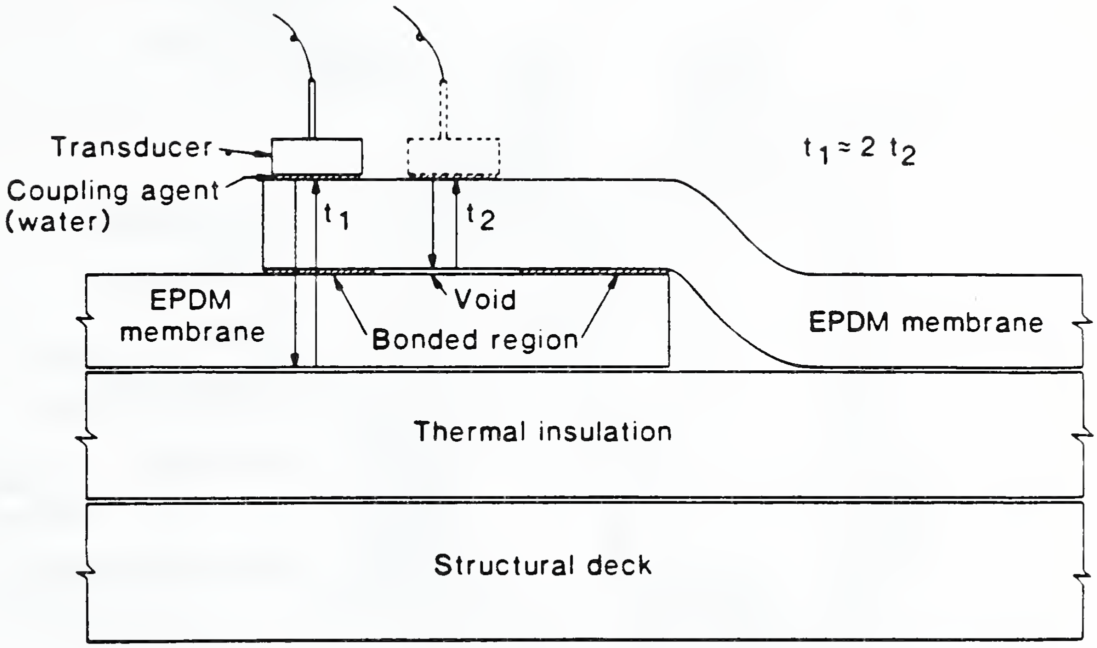


Figure 1. Pulse-echo ultrasonic method [11].

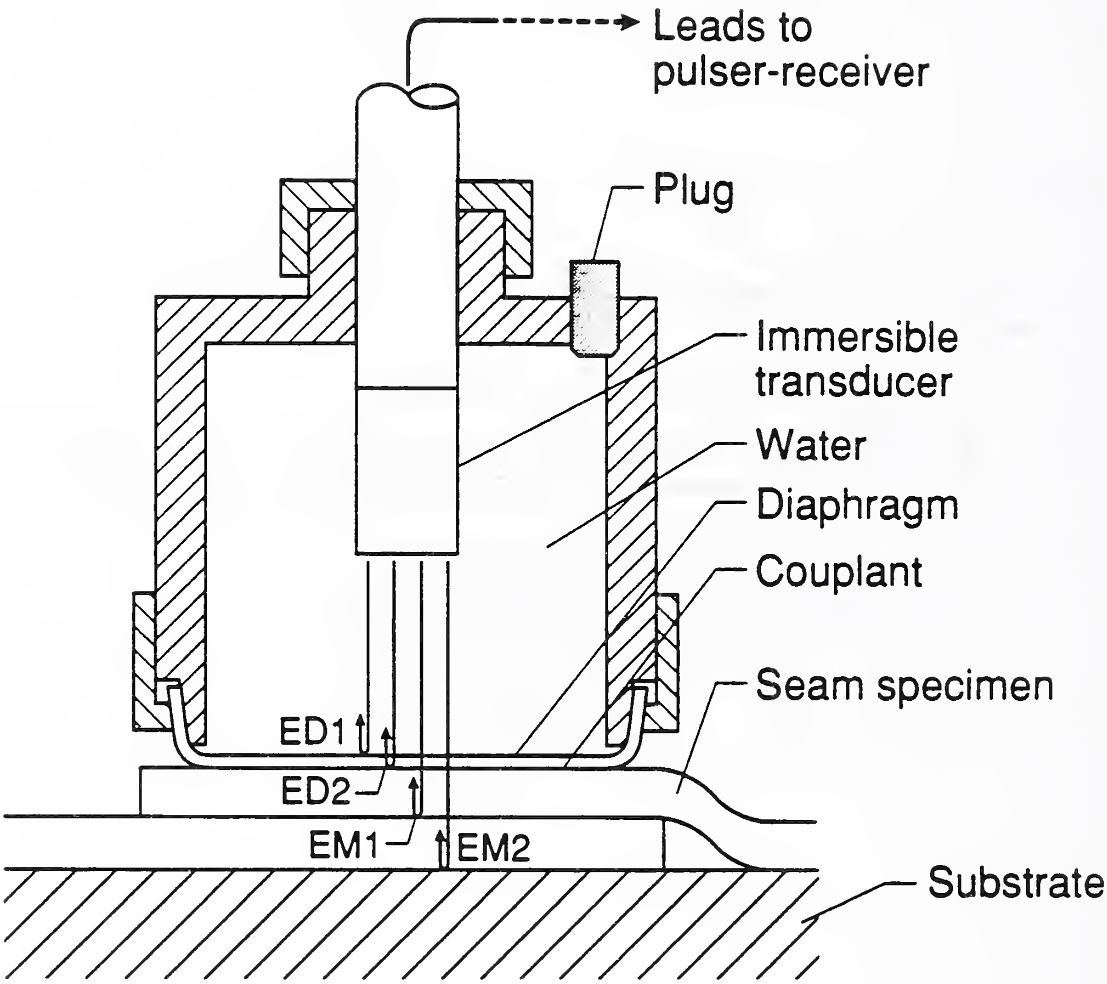


Figure 2. Schematic illustration of the transducer holder acoustically coupled to a seam specimen. (Reflections of the ultrasonic pulse from the various interfaces are also illustrated, and are designated as ED1, ED2, EM1, and EM2.)

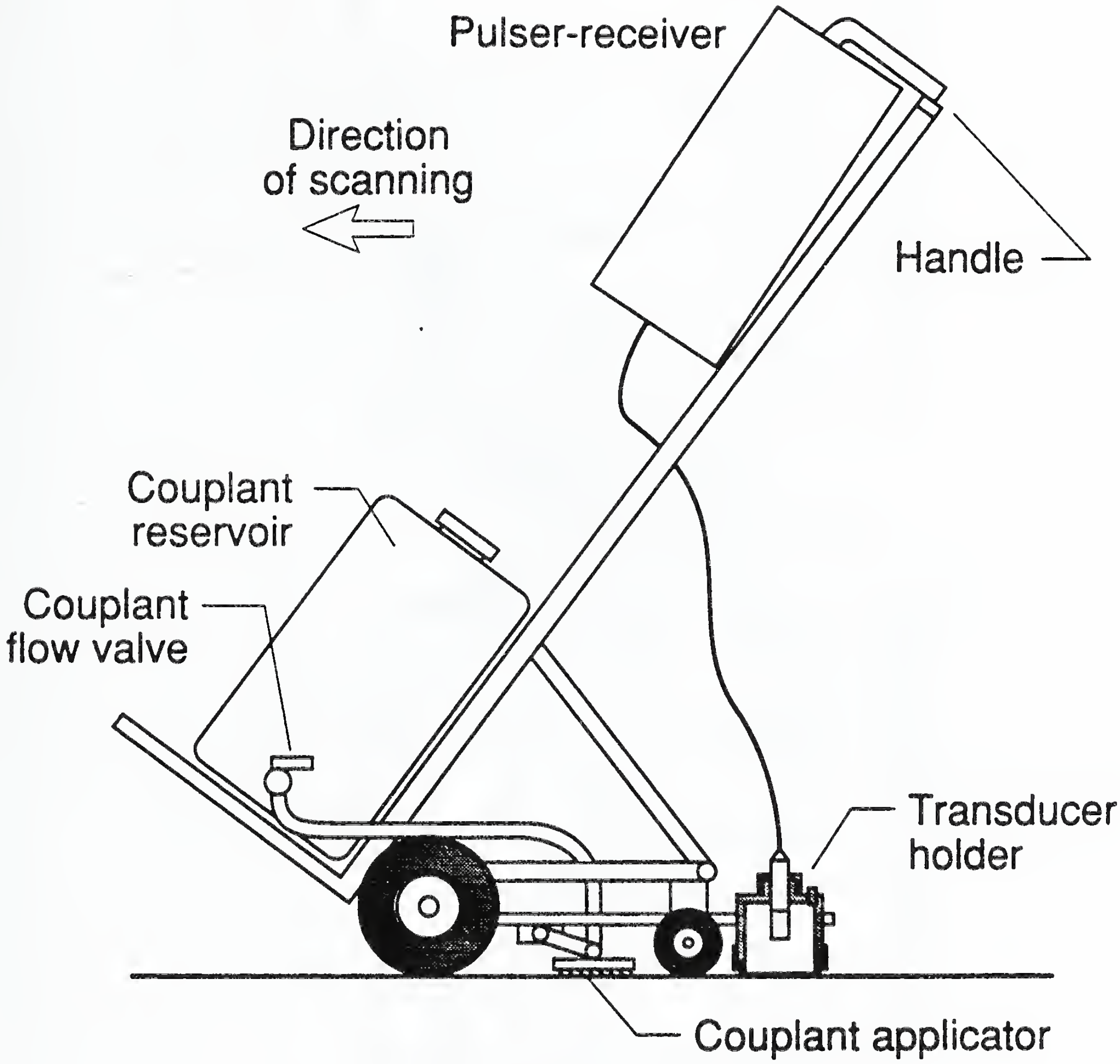


Figure 3. Prototype field scanner used in the study.
(The detail of the transducer holder is presented in Figure 2.)

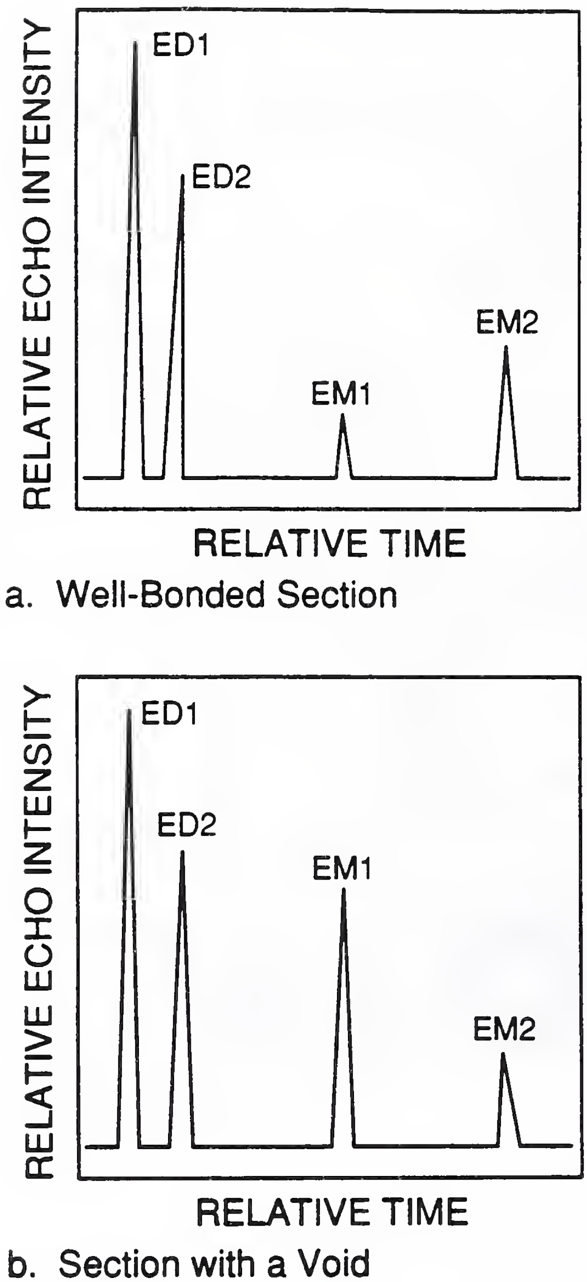


Figure 4. Scheme of echo patterns for a well-bonded section of a seam and a seam section with a void.

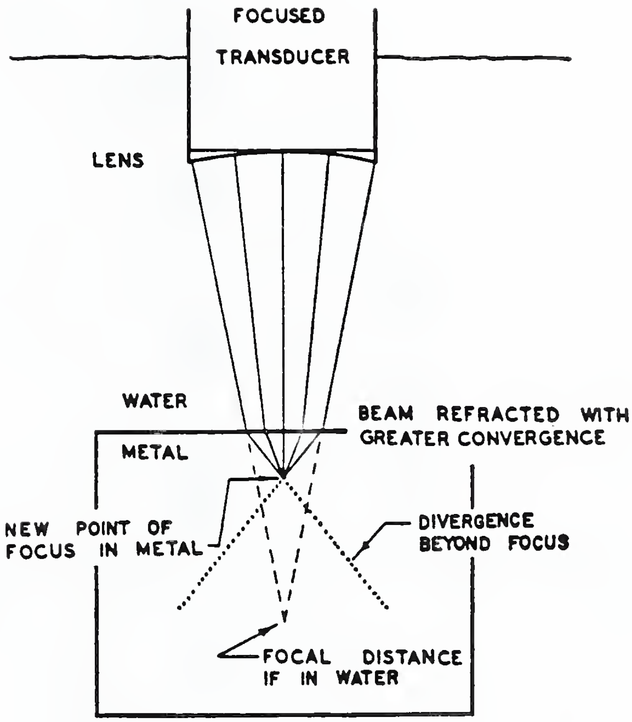


Figure 5. Focusing transducer and its focal distance [20].

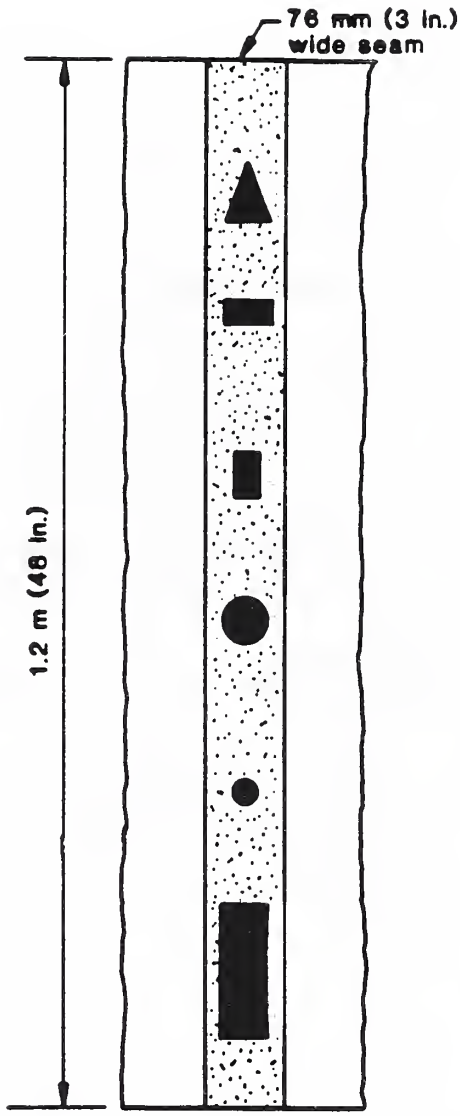


Figure 6. Seam specimen with voids incorporated in the adhesive layer.

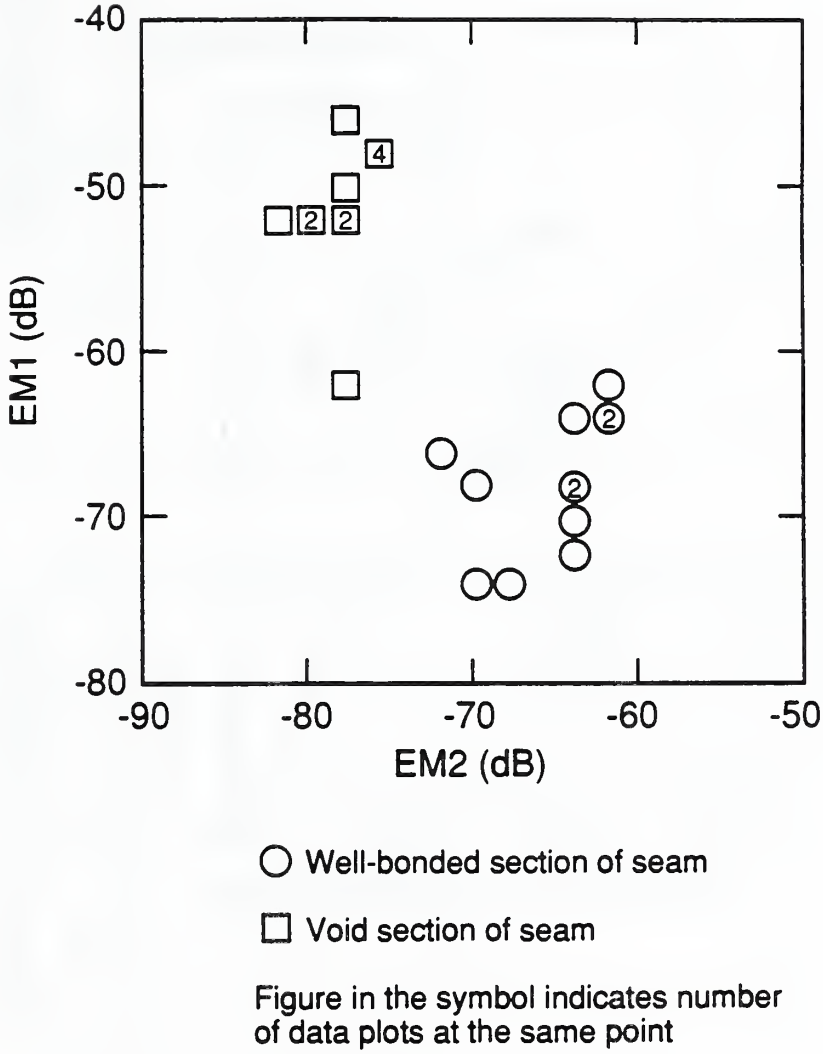


Figure 7. Intensities of EM1 and EM2 echoes for well-bonded and void sections of seams.

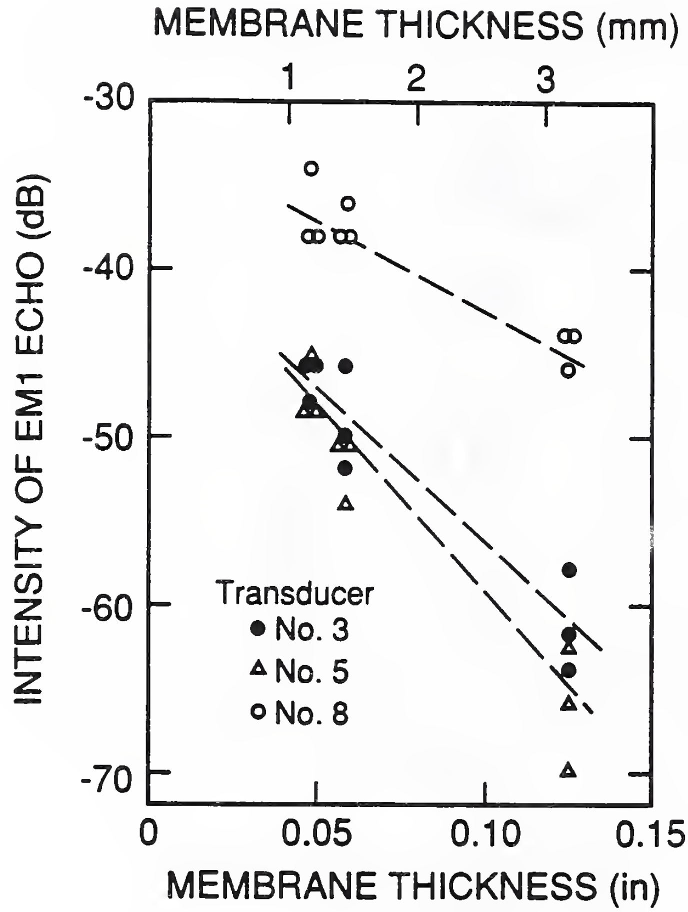
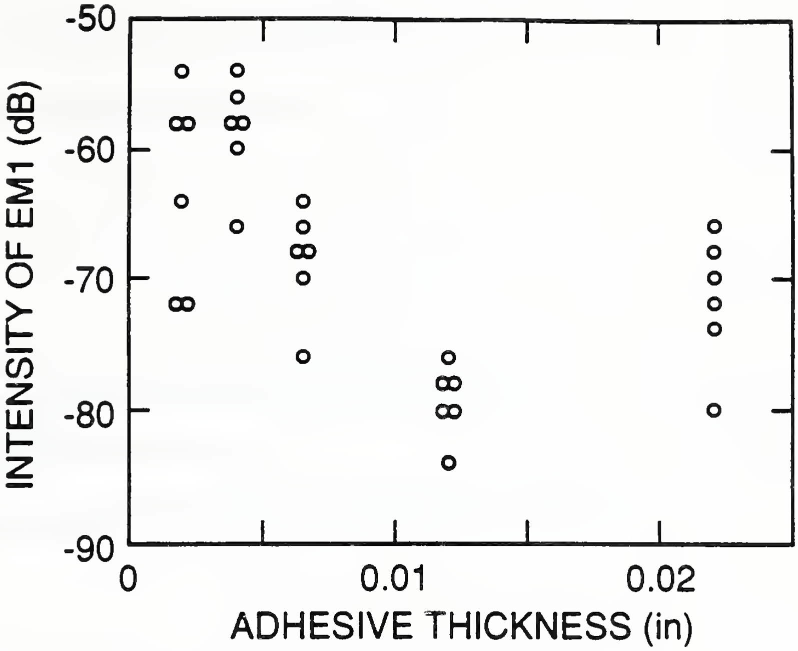
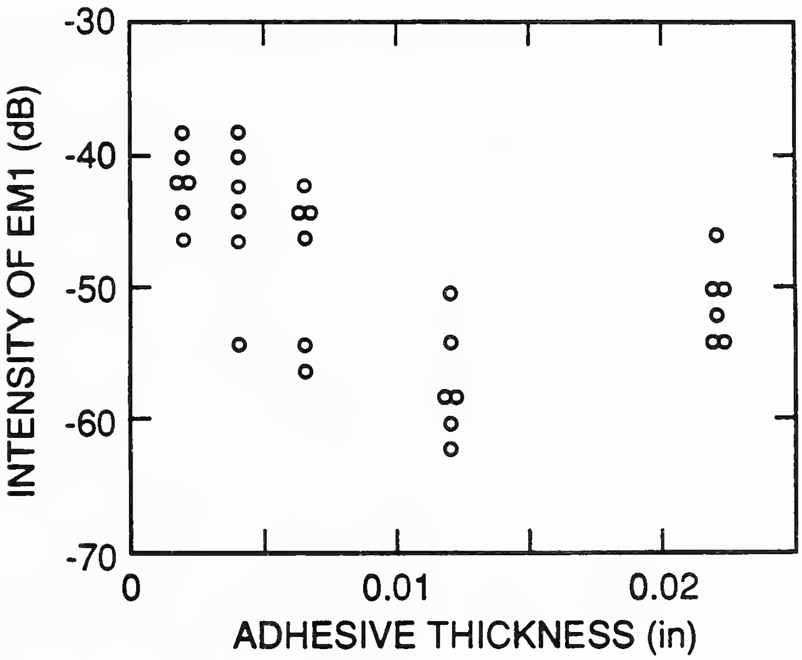


Figure 8. Dependence of EM1 echo intensity on thickness of EPDM rubber membrane materials. (Three data sets for the measurements using three different transducers are presented with their regression lines.)



9a. 5-MHz Focusing Transducer (No. 3)



9b. 2.25 MHz Non-Focusing Transducer (No. 8)

Figure 9. Dependence of EM1 echo intensity on thickness of the adhesive layer in the seam.

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The feasibility of using NDE (non-destructive evaluation) methods to detect voids in adhesive-bonded seams of single-ply membranes has been under investigation at the National Institute of Standards and Technology (NIST). This report covers the first phase of a two-part study to investigate the applicability of a pulse-echo ultrasonic method for this purpose. A prototype pulse-echo ultrasonic apparatus, called the field scanner and suitable for testing of single-ply seams in the field, was developed. A series of laboratory experiments was conducted using the field scanner to investigate: 1) optimal operating conditions, 2) sensitivity and practical limitations for detecting voids, and 3) variables affecting its response. The equipment was found to be effective in maintaining coupling between the transducer and seam specimens. Two 5-MHz transducers (focusing and non-focusing types) were selected as the most suitable for void detection in the seams. Voids incorporated in laboratory seam specimens were readily detected. The results of the Phase 1 investigation provided guidelines on the optimum conditions for use of the field scanner. Although not without limitations, encouraging evidence was obtained indicating that the field scanner should be applicable to inspections of EPDM seams in service. Consequently, field investigations are being conducted, as planned, in Phase 2 of the study.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)
adhesive-bonding; EPDM rubber; field inspection; membranes; nondestructive testing; pulse-echo method; roofing; seams; ultrasonics.

13. AVAILABILITY

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