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Environmental Geotechnics Report No. 94-2

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ABSTRACT

An ultrasonic nondestructive testing technique has been developed to assess the integrity of well seals. The pulse-echo inspection technique was used to evaluate the quality of the bond between a casing and a seal. The study was conducted in two phases. The first phase was conducted to develop a measurement algorithm. In this phase, a planar arrangement of casing materials and seals was employed. The second phase consisted of the design, construction, and evaluation of a probe for downhole testing.

Intact seals and seals containing defects were tested around a casing in both phases of the project. The seals tested were constructed with common sealants, bentonite and neat-cement. Defects introduced into the seals were filled with air or water. Results of the tests indicated that the presence of bentonite and neat-cement seals and defects filled with air or water at the casing-seal interface can be detected using the ultrasonic method.

ACKNOWLEDGMENT

Financial support for this research has been provided by the University of Wisconsin System Groundwater Research Advisory Council. Dr. Selcuk Sancar has provided technical expertise and general guidance for the project. His help is greatly appreciated.

The findings and opinions expressed in this report are solely those of the writers and are not necessarily consistent with the policies or opinions of the University of Wisconsin System Groundwater Research Advisory Council. This report has not been reviewed by the University of Wisconsin System Groundwater Research Advisory Council.

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SECTION ONE
INTRODUCTION

Numerous boreholes have been placed in the ground for geotechnical investigations, geologic and hydrogeologic exploration, monitoring and supply of groundwater, and for other investigation, testing, and monitoring purposes. Drilling boreholes is a common procedure in many disciplines ranging from highway construction to mine exploration. Proper installation and management of these boreholes is necessary to protect the subsurface environment.

When casings are placed in boreholes, an annular space is created between the casing and the surrounding soil. If not properly sealed, the annular space can be a potential path for transport of contaminants in the subsurface environment. Problems of cross-contamination, commingling of clean and contaminated groundwater, and groundwater loss can occur.

The most common materials used for seals are bentonite, cement, cement-bentonite mixtures, cement-sand mixtures, and concrete (Strata Engineering Corporation, 1991). Some regulations exist for preparation and placement of these seals. Regulations requiring an evaluation of seal integrity do not exist. A number of field methods used for the evaluation of cement-based seals surrounding casings are available. However, no in situ methods are currently available to evaluate both bentonite and cement-based seals.

The objective of this study is to develop a testing technique to verify the integrity of different types of seals placed around casings. An ultrasonic nondestructive method has been chosen for this purpose. Techniques used for ultrasonic nondestructive testing are being adapted for evaluation of seals. In particular, a technique is being developed to evaluate the quality of the bond between a casing and a seal. The project objective is being met by a three-phase research plan.

between a casing and a seal. The project objective was met by a two-phase research plan.

An initial phase of testing was conducted to develop a measurement algorithm. This phase employed a planar arrangement of casing materials and seals. Intact seals and seals with defects were tested. A second phase of the study consisted of the design and construction of a probe for downhole testing. The probe was constructed to fit into casings of diameters ranging from 50 mm to 100 mm. Tests were conducted with the probe in a borehole model consisting of a casing simulated by a stainless steel pipe and an annular space filled with different sealants. The algorithm developed during the planar arrangement tests was used. The method was found to be effective in detecting the presence of different seals and defects in the seals. The presence of bentonite and neat-cement seals and defects filled with air or water at the casing-seal interface can be detected.

SECTION TWO
BACKGROUND

2.1 IMPORTANCE OF PROPERLY SEALING CASINGS

The annular space between a casing and the surrounding soil is a potential pathway for advective and diffusive transport of contaminants. Contaminants from the surface can penetrate into deeper, uncontaminated layers. Alternatively, contamination in underlying aquifers can be carried to clean aquifers or to the surface. Groundwater can also be lost. The potential pathways for the transport of contaminants in the annular space are shown in Fig. 2.1.

Lutenegger and DeGroot (1993) suggest that seals should meet a number of criteria to protect the subsurface environment. In essence, all of the criteria, hydraulic conductivity, compatibility, instrumentation compatibility, length, and longevity are met to ensure that a low hydraulic conductivity seal is present which does not allow transport of contaminants. The most important criterion is that the seal have hydraulic conductivity at least one order of magnitude less than the surrounding native material. Any defects present in the seal that increase the hydraulic conductivity should be avoided.

Besides protecting the subsurface, a properly placed seal also protects the casing. The seal ensures structural integrity by insulating the casing against corrosion and chemical degradation that can be caused by the subsurface environment (Nielsen and Schalla 1991, Landry 1992).

Two recent case histories illustrate potential problems caused by improperly sealed casings. The first case history is described by Lesage et al. (1991). Liquid industrial wastes were injected from 1958 to 1975 into deep wells in Sarnia Valley (Ontario, Canada) at pressures up to 3.0 MPa. The

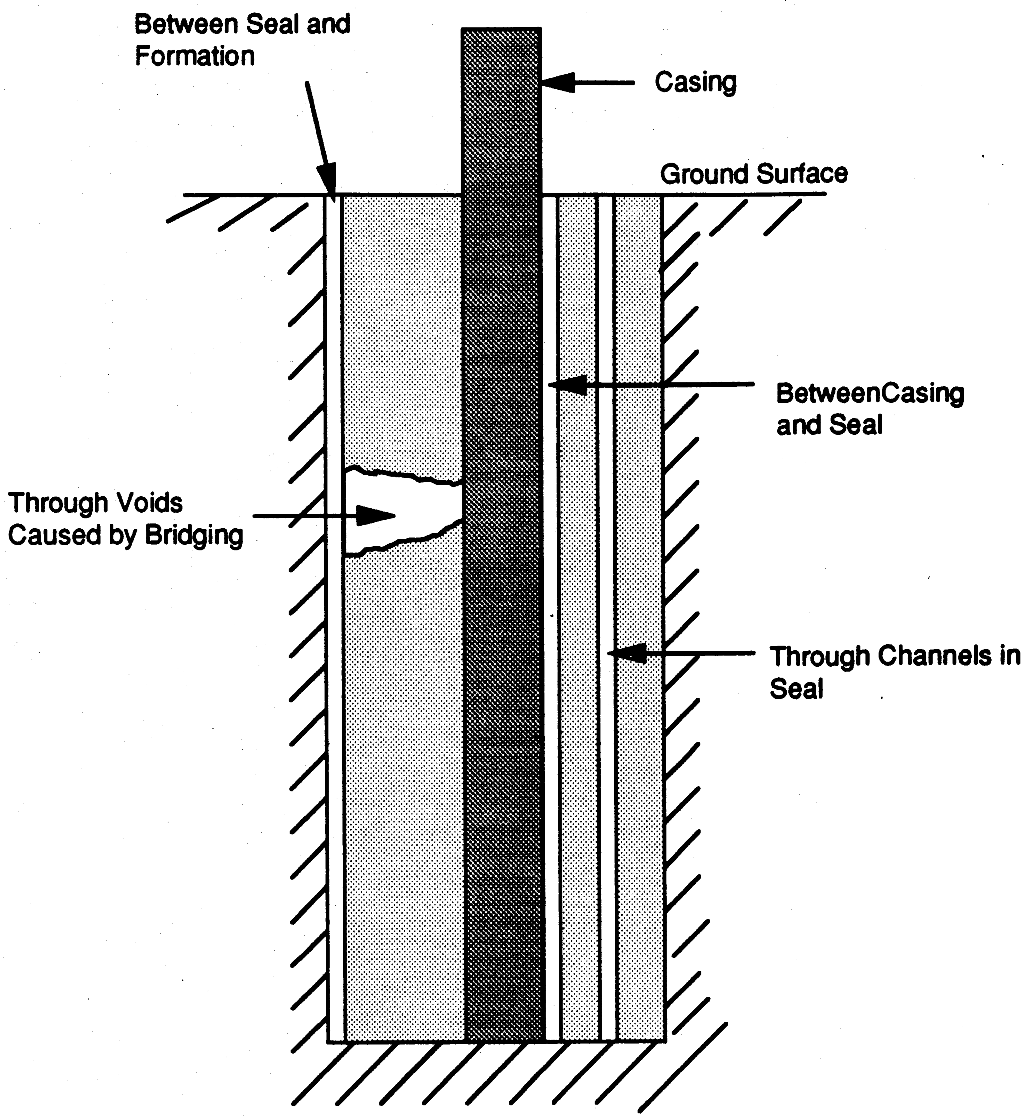


Fig. 2.1. Potential Pathways for Contaminant Transport in the Annular Space (adapted from Nielsen and Schalla, 1991)

wastes were injected into a dolomite bedrock formation. A freshwater aquifer lies above the bedrock. After injection began, bedrock formation fluids and liquids resembling the industrial wastes being injected were discharged to the surface from abandoned wells in the area. Since then, the wastes and formation fluids have contaminated the overlying aquifer. Potential paths for the upward migration of industrial wastes and formation fluids postulated by Lesage et al. are shown in Fig. 2.2. The improperly sealed injection well, abandoned oil wells, and fractured upper layers of the bedrock provided pathways for contaminants.

The second case history was reported by Meiri (1989). More than 20 soil borings and 23 monitoring wells were installed at a site that had several waste water impoundments. The stratigraphy of the site, from top to bottom, consisted of a fill layer at the surface, a fractured clay layer, an unfractured clay layer, a sand and gravel layer, and finally another unfractured clay layer at the bottom (Fig. 2.3). Contamination was primarily confined to the fractured clay layer directly below the surface fill because of isolation provided by the upper unfractured clay layer. However, contamination has been detected in one monitoring well in the sand and gravel layer. A tracer test conducted in the vicinity of this well indicated that wastewater migrated downward from the fractured clay along the monitoring well casing and into the sand and gravel aquifer.

2.2 EVALUATION OF CASING SEALS

2.2.1 Evaluation Before And During Placement

The physical properties of seals can be determined following ASTM and API procedures. Regulations in many states also exist regarding preparation

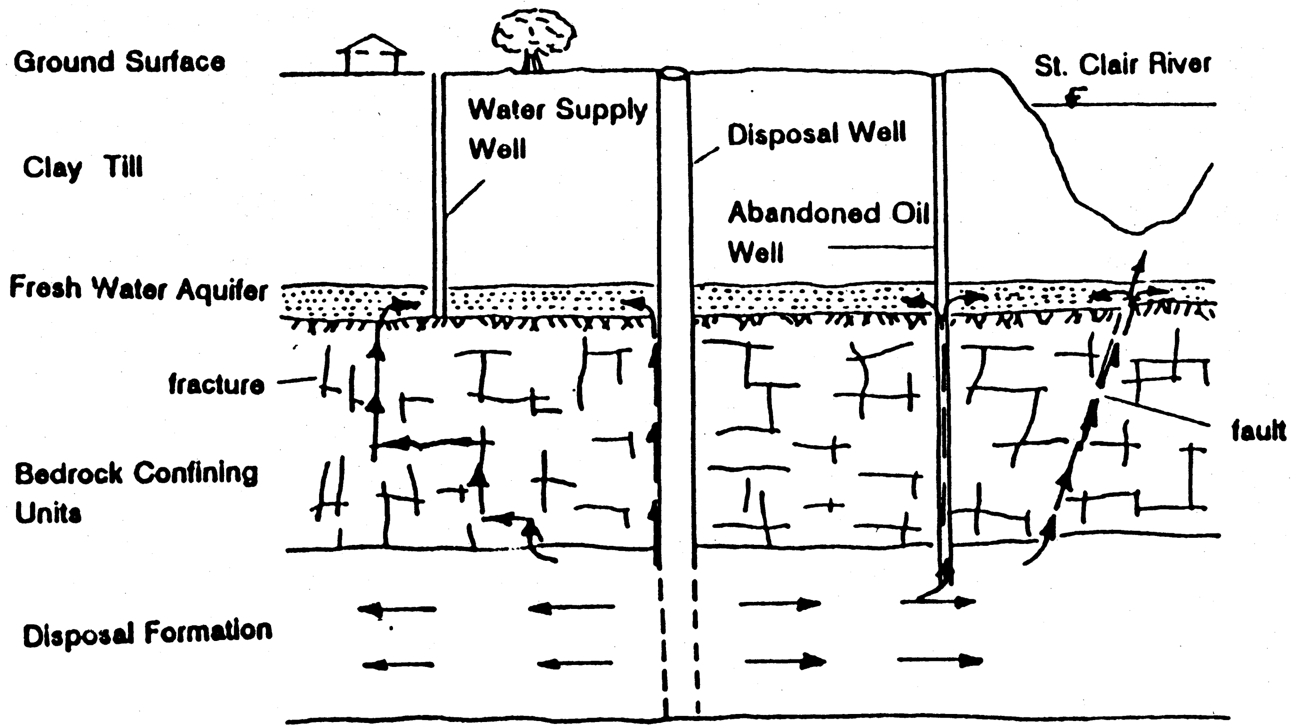


Fig. 2.2. Potential Paths for the Upward Migration of Liquid Industrial Waste (after Lesage et al. 1991)

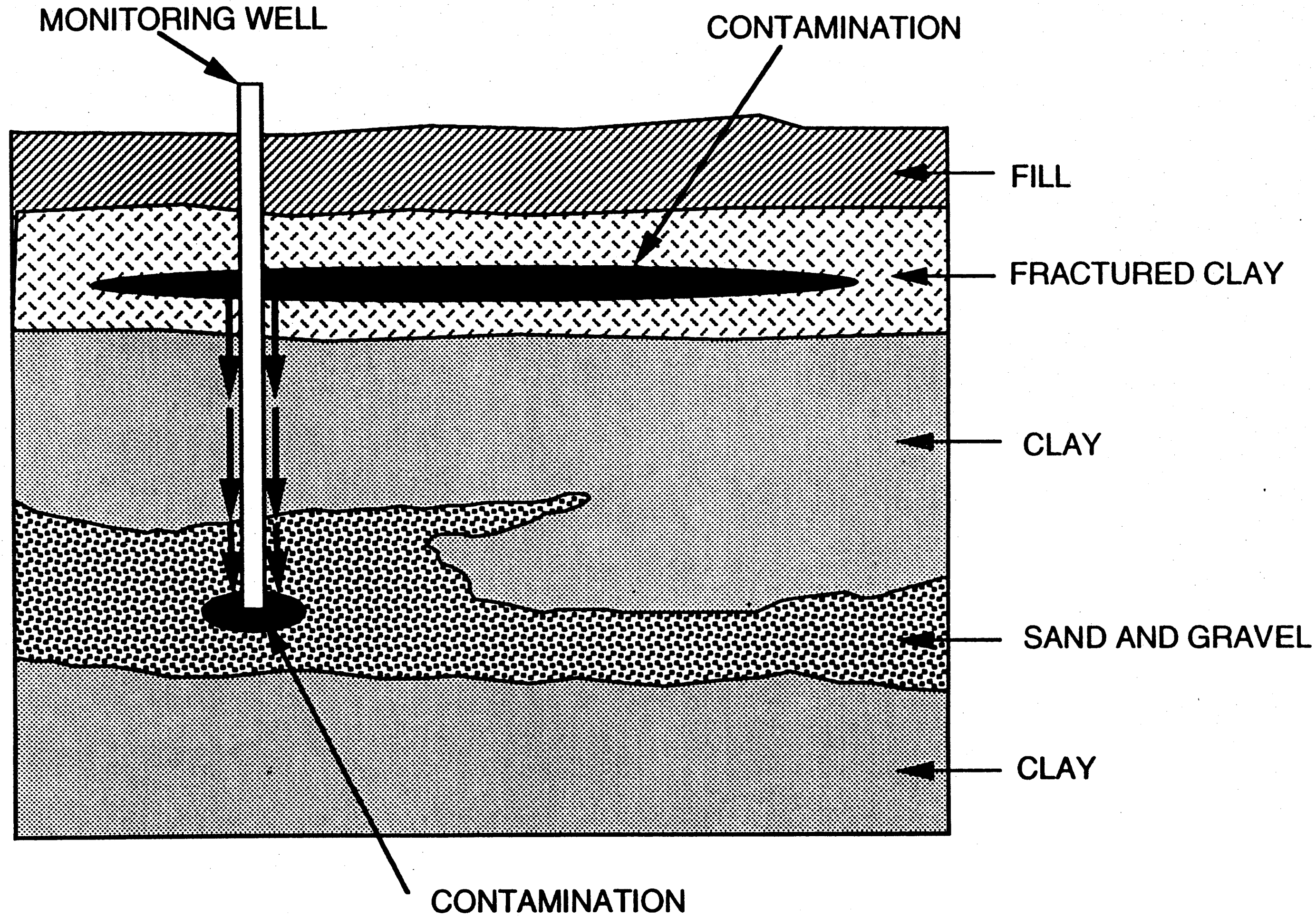


Fig. 2.3. Cross-Contamination Through the Monitoring Well Seal
(adapted from Meiri 1989)

and placement of seals. Properties commonly of interest include mud weight, viscosity, strength, filtration properties, volumetric sand content, shrinkage properties, and hydraulic conductivity. Methods to measure these physical properties are summarized in Table 2.1.

Strata Engineering Corporation (1991) conducted a survey regarding seal preparation and placement techniques among state departments of transportation, state geological surveys, state departments of environmental quality/protection, and state departments of natural resources. The results of this survey indicate that most states adopt regulations containing information about the type and proportions of material to be mixed when preparing the borehole seal. Some states also set criteria for mud weight, viscosity, and strength. Placement procedures for seals are also regulated in most states. Filling the annular space from bottom to top with a tremie pipe is the most commonly used placement technique. However, some states (including Michigan, North Dakota, and Utah) allow the placement of granular bentonite-based sealants by pouring from the ground surface.

2.2.2 Advantages and Disadvantages of Evaluation Before and During Placement

Mud weight, viscosity, gel strength, filtration properties, and volumetric sand content of bentonite-based sealants have the advantage of being properties that can easily be determined in field (Table 2.1). The instrumentation consists of small units that can easily be carried to field and the procedures for determination of these properties are simple and quick.

A disadvantage is that some of the properties have to be determined in the laboratory. Sending samples to a laboratory for testing while a seal is being prepared in field is not as practical as tests conducted in field. The strength of cement-based sealants, shrinkage properties of bentonite-based sealants, and

Table 2.1. Evaluation of Physical Properties of Seals Before Placement

Property	Standard	Type of Sealant
Mud Weight	ASTM D 4380[1]	Bentonite-Based
Viscosity	API RP 13B-1[2]	Bentonite-Based
Gel Strength Cement Strength	API RP 13B-1 ASTM C 39-86[3] ASTM C 109-92[4]	Bentonite-Based Cement-Based
Filtration Properties	API 13B-1	Bentonite-Based
Volumetric Sand Content	ASTM D 4381[5]	Bentonite-Based
Shrinkage Properties	ASTM D 4943[6] ASTM D 427[7]	Bentonite-Based
Hydraulic Conductivity	Constant or Falling Head Tests[8]	Bentonite-Based Cement-Based

1 ASTM D 4380-84: Standard Test Method for Density of Bentonite Slurries

2 API RP 13B-1: Recommended Practice Standard Procedure for Field Testing Water-Based Drilling Fluids.

3 ASTM C 39-86: Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.

4 ASTM C 109-92: Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or 50-mm Cube Specimens).

5 ASTM D 4381: Standard Test Method for Sand Content by Volume of Bentonitic Slurries.

6 ASTM D 4943-89: Standard Test Method for Shrinkage Factors of Soils by the Vax Method.

7 ASTM D 427-93: Test Method for Shrinkage Factors of Soils by the Mercury Method.

8 Edil and Muhanna (1992), Banthia and Mindess (1989), Lutenegger and DeGroot (1993).

hydraulic conductivities of both cement-based and bentonite-based sealants have to be determined in the laboratory (Table 2.1). Strength and shrinkage property tests are quick. However, measuring the hydraulic conductivity of sealants is time consuming because sealants have low hydraulic conductivities.

Measuring all of the physical properties of sealants given in Table 2.1 provides an indication of the quality of the sealant. However, a high-quality sealant does not necessarily function well as a seal. A high- quality sealant can act poorly as a seal because of improper placement.

The procedures for sealant placement are included in regulations or described by sealant manufacturers. How closely these procedures are followed provides a means of seal evaluation. A primary disadvantage is that following placement procedures exactly does not guarantee an intact seal. Bridging may occur in small annular spaces in saturated zones when granular bentonite is dropped down the annular space. Bentonite may swell on descent before arriving at the previously sealed zone. Therefore, a gap may occur in the seal even though the granules are dropped down at pouring rates recommended by regulations or manufacturers.

A disadvantage of the evaluation techniques applied both before and during placement is that they do not provide any indication for the performance of the seal in time. The performance of a seal cannot be assessed after it is placed in an annular space with these methods.

2.2.3 Evaluation After Placement

Three widely accepted methods exist for in situ evaluation of cement-based seals around casings (Driscoll 1986): (1) water level monitoring; (2) pressure testing; and (3) cement bond logging. These methods are used primarily for water supply or oil wells having large casings. They are infrequently used for cased boreholes or monitoring wells.

In the first method, changes in the water or drilling fluid level are monitored in the casing. If the seal is intact, virtually no change in liquid level is expected. If the static water level in the casing is too high, the casing can be emptied and influx of water into the casing can be monitored. In this approach, influx is indicative of a defective seal.

The second method is used at locations where the subsurface is primarily rock. The well is pressurized under a pressure of 69 KPa for at least one hour after the cement has cured. If the seal is intact, virtually no drop in pressure occurs over time.

Finally, the third method, cement bond logging, uses sound waves to evaluate the condition of the seal. Cement bond logging is a nondestructive testing method that has long been used in the petroleum and gas industries to evaluate the integrity of cement seals around oil and gas pipes. Some recent applications include evaluation of the cement seals around waste disposal and deep water wells (Driscoll 1986, Landry 1992).

The integrity of casing-seal and seal-formation bonds can be determined with the cement bond logging method. The casing has to be filled with water for the transmission of ultrasonic waves. The travel time and amplitude of sound waves transmitted by a transducer inside the casing are monitored as they travel from a transmitter to one or more receivers (Fig. 2.4). The resulting waveform obtained by the receiver is a composite of the reflections from the fluid-casing, casing-seal, and seal-formation boundaries (Fig. 2.5). The differences in amplitude and arrival times of these reflections are examined to assess the quality of the seal.

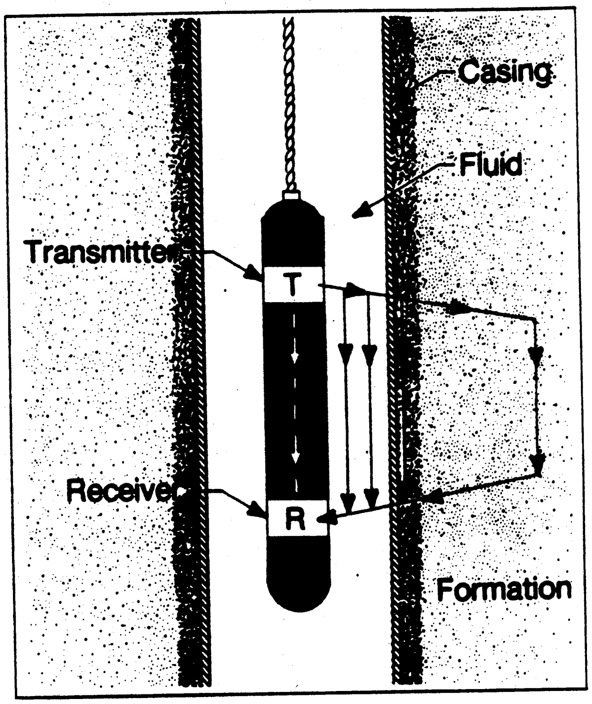


Fig. 2.4. Cement Bond Logging Tool and Wave Paths (after Driscoll, 1986)

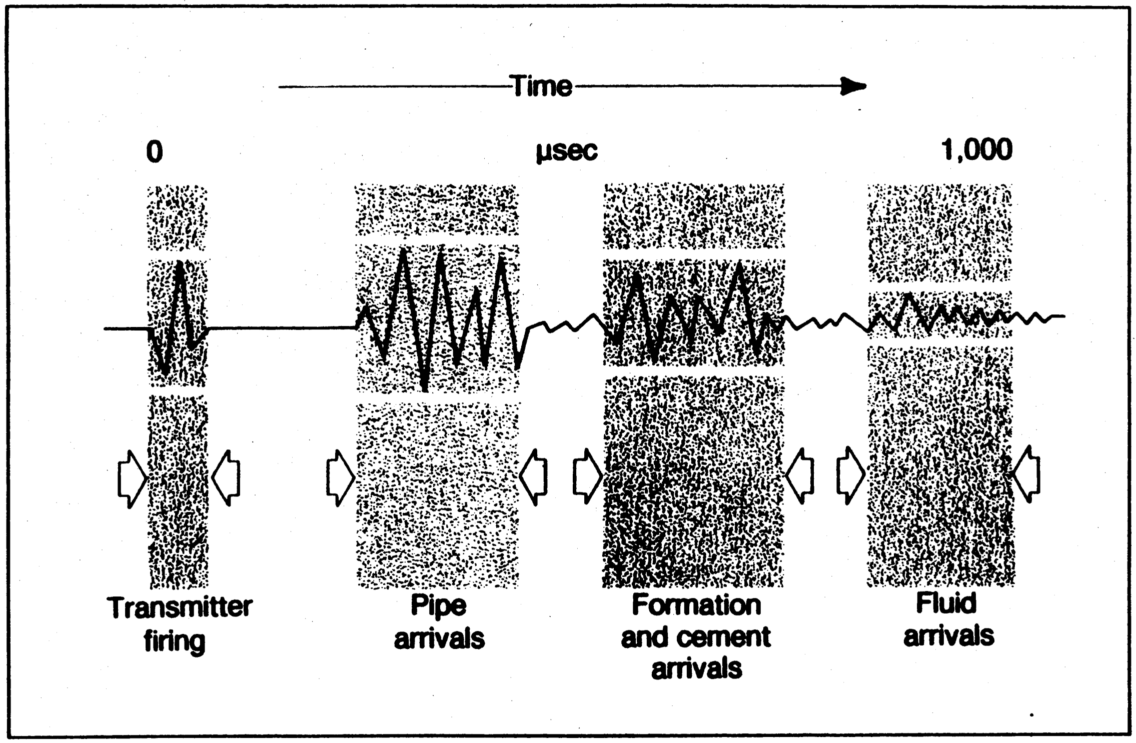


Fig. 2.5. Composite Waveform Obtained In Cement Bond Logging (after Driscoll 1986)

Data acquisition and analysis in cement bond logs require intensive computer systems. Most cement bond logs supply information about the seal integrity, as well as information regarding the subsurface and the casing. The "Cement Evaluation Tool" developed by Schlumberger Inc. (1989) provides information about the quality of the seal, measures the compressive strength of the cement, gives an indication of casing wear, and allows determination of oil and gas entry in the surrounding formation.

Two other less popular methods for evaluating cement seals are the temperature log and radioactive log (Driscoll 1986). The temperature log is conducted within the first 12 to 24 hours of seal placement. The casing is filled with water. The heat produced during setting of the cement is monitored by measuring the temperature of water inside the casing to determine if a seal exists around the casing. The amount of heat expected to be generated by a certain mass of cement is determined in the laboratory or in a field model. A lower temperature than the predetermined expected value in situ correspond to a bad seal. Same temperature with the predetermined expected value correspond to a good seal. This method cannot be applied after the cement has cured. The location of defects in a seal cannot be determined using this method.

In radioactive logging, a radioactive tracer is mixed into the cement prior to placement. Radioactivity is monitored to verify the position of the cement after the seal is placed in the annular space. This method is expensive and requires special procedures for handling of the radioactive material. In addition, the radioactive material affects the natural radioactivity of earth. This can result in misinterpretations of nuclear geophysical studies conducted in the vicinity of the casing.

2.2.4 Advantages and Disadvantages of Evaluation After Placement

Monitoring the water or fluid level change in a casing has the advantage of being easily conducted. It requires simple instrumentation and can be conducted repeatedly after seal placement to monitor the performance of the seal in time. However, the fluid level in the casing is a crude indication of the quality of the seal. Fluid level in the casing is not affected unless the defects in the seal are connected to the bottom of the casing. Arches formed in the seal cannot be detected. If poor performance is detected its location cannot be identified. Leaks at the bottom or top of the casing can be misinterpreted as defective seal.

Pressurizing the well can be conducted any time after curing of a cement seal. The performance of the seal can be monitored with respect to time, but a pressure source is required at the site. The main disadvantage of this method is that it is limited to locations where the subsurface is primarily rock. When soft formations exist around the casing, pressure changes do not necessarily reflect the integrity of a seal. The surrounding formations can be compressed and the pressure drop can be misinterpreted as a defective seal.

Cement bond logs are designed for use in the petroleum and gas industries. Several cement bond logging tools are available that fit into different diameter casings. The most important advantage of cement bond logs is that evaluation of both the cement seal-casing and cement seal-formation bonds is possible. The tool carrying the transmitter and receiver transducers is lowered inside a casing and a continuous record of cement-casing and cement formation bonds are obtained. The exact location of defects in a seal can be determined. Cement bond logging can also be conducted in a casing at different times, allowing for monitoring of the seal over time.

Disadvantages of cement bond logging procedures are the high cost and the need for skilled personnel. The main cost of cement bond evaluation systems is the electronic components. Intensive computer analysis methods in some cases require a truck containing all the electronic equipment (Schlumberger Inc. 1989, Hamilton and Myung 1973).

Currently, there are no existing regulations for the in situ assessment of borehole seals and there are no in situ testing methods for the evaluation of bentonite-based seals. For this reason, a seal-evaluation system is being developed at the University of Wisconsin which employs ultrasonic technology. The methods used in ultrasonic nondestructive testing of materials are being adapted to allow for testing seals around a casing. The ultrasonic method has been chosen because of its simplicity and its well established-theory. The seals are evaluated without disturbing the seal or the formation.

2.3 ULTRASONIC NONDESTRUCTIVE TESTING

2.3.1 Basic Principles

Ultrasonic testing methods are used in numerous disciplines such as agriculture, medicine, chemistry, metallurgy, and electronics. They are used to test a wide variety of materials ranging from concrete to beef. Applications of ultrasonics can be divided into two categories: low-intensity applications and high-intensity applications (Ensminger 1988).

(1) Low-intensity applications: The primary purpose of low-intensity applications is to send energy into a medium to "investigate" it or to pass "information through the medium" into another medium of interest. Examples of low-intensity applications include nondestructive testing of materials, medical applications, geophysical applications, and underwater applications.

(2) High-intensity applications: The primary purpose of high-intensity applications is to send energy into a medium to "produce an effect on the medium." Examples of high-intensity applications include atomization of liquids, cleaning, mixing of materials, homogenization of materials, and welding.

Ultrasonic nondestructive testing techniques applicable to evaluating seals are low intensity applications, where testing is conducted without causing any change in material properties or performance.

The use of ultrasonics in nondestructive testing evolved from old acoustic methods. The method of striking an object with a hammer and observing the change in the "ringing" sound has long been used to detect large internal defects (Bray and McBride 1992, Krautkramer and Krautkramer 1983). Ultrasonic methods work in a similar manner. However, in ultrasonics the frequency of the sound being used is higher than audible limits (Fig 2.6). Ultrasonic waves used in nondestructive testing usually have frequencies ranging from 200 kHz to 20 MHz (Bray and McBride 1992). Furthermore, generating and receiving ultrasonic waves require more advanced technology than striking an object with a hammer and listening to the resulting sound.

Waves sent into the medium of interest (gas, liquid, or solid). during ultrasonic testing refract and reflect when they encounter a velocity discontinuity. Reflections from the boundaries between the test material and another medium are then analyzed to investigate the integrity and properties of the test material. Differences in the impedances (velocity x density) of the test material and the other medium affect the energy content of reflections from the boundary between the test material and the other medium.

Ultrasonics in nondestructive testing can be used to detect flaws, determine elastic and metallurgical material properties, and to measure

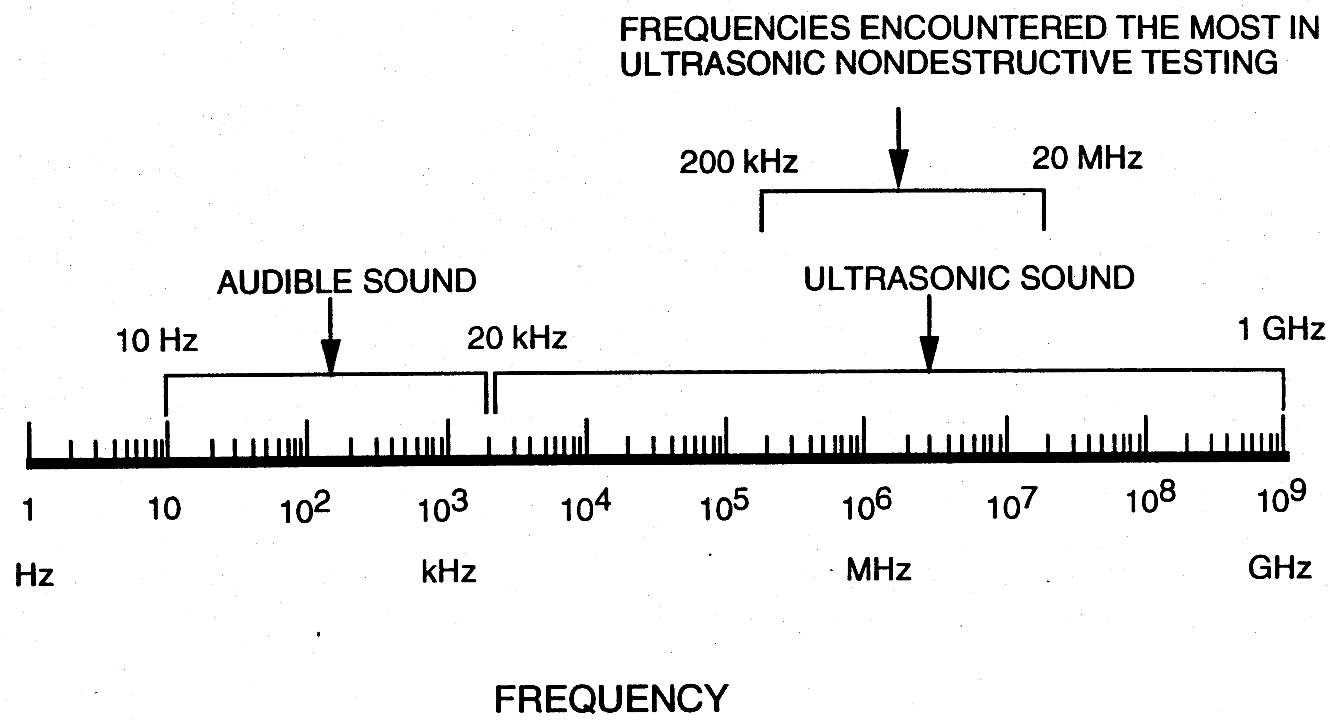


Fig. 2.6. Sound Frequency

thickness, stress, and material degradation. "Cracks, voids, and any other abrupt discontinuity or lack of homogeneity in metallic, nonmetallic, and composite materials" can be detected (Bray and McBride 1992).

A typical example of flaw detection in a material, adapted from Banks et al. (1962), is shown in Fig. 2.7. In case (a), where the test object is intact, the reflection from the base of the object (B) arrives at the receiver at time T having amplitude A. However, when there is a crack or defect present in the test object (Fig. 2.7b), the reflection from the crack (F) arrives at the receiver at time t which is earlier than T. The reflection also has amplitude smaller than A. The location and size of the crack or defect are determined by analysis of the arrival time and amplitude of the crack reflection (F).

2.3.2 Ultrasonic Testing Techniques

There are three main ultrasonic testing techniques: pulse-echo inspection, through-transmission inspection, and the pitch-catch and delta technique (Bray and McBride 1992).

(1) Pulse-Echo Inspection: In the pulse-echo method, waves are sent into the medium of interest and received back either by the transmitting transducer or another transducer. The transmitting and receiving transducers are located on the same surface of the test material. Most ultrasonic instruments operate in the pulse-echo mode.

(2) Through-Transmission Inspection: Through transmission is used for materials that strongly attenuate ultrasonic waves. Waves are sent by a transmitting transducer placed on the surface of test material and are received by a receiving transducer located on the opposite surface. The waves travel from one surface of the material to the opposite one, half the

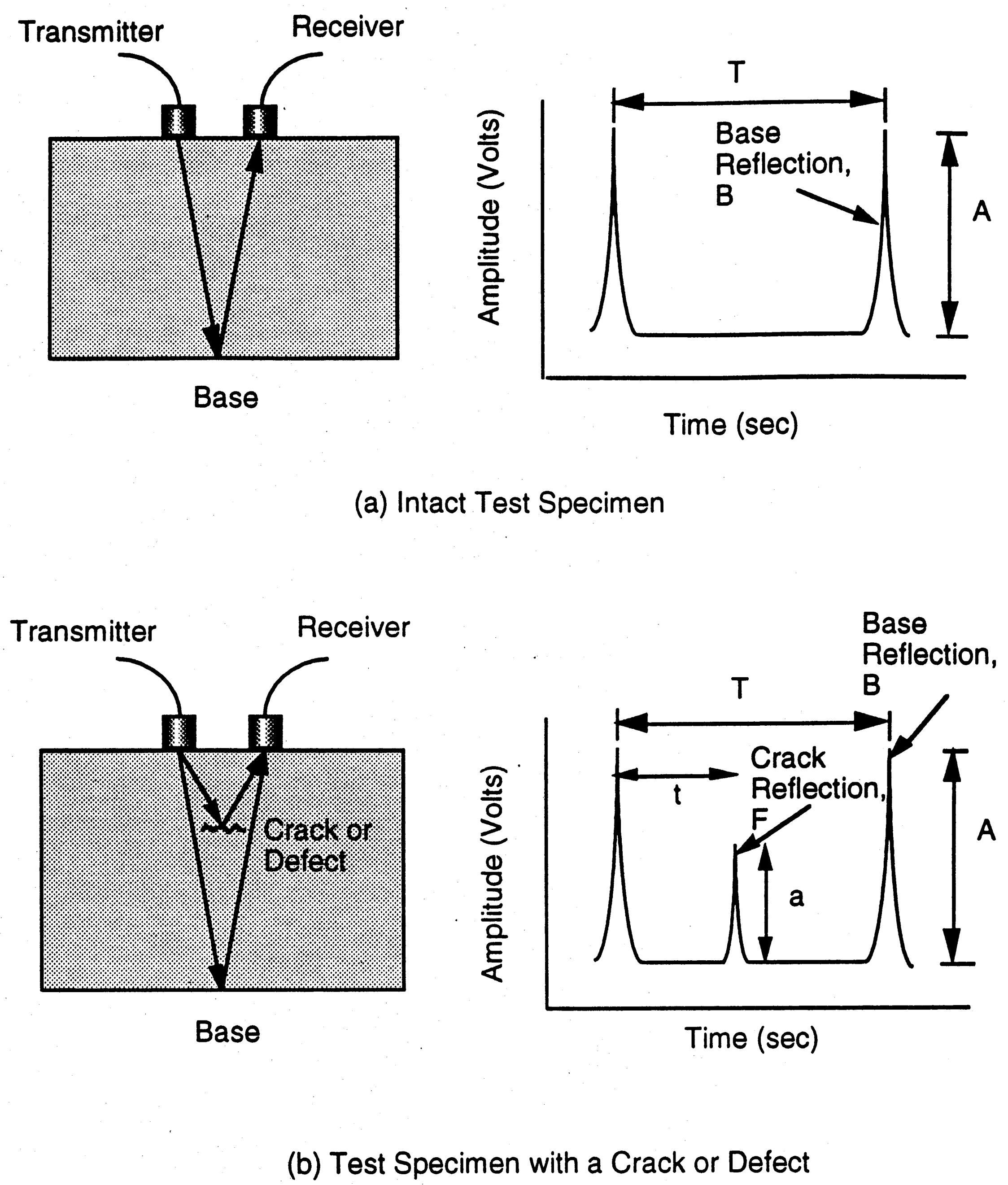


Fig. 2.7. Ultrasonic Flaw Detection in an Intact and Defective Test Specimen (adapted from Banks et al. 1962)

distance waves travel when using the pulse-echo method. Because the travel distance is smaller in through-transmission, less energy is attenuated.

(3) Pitch-Catch And Delta Technique: The pitch-catch technique is mostly used in testing welds. In this method, the distance between the transmitter and receiver units is large compared relative to the pulse-echo and through-transmission techniques. Also, the faces of the transducers are not parallel to the surface of the test material. The transmitter and the receiver transducers are inclined with respect to the normal of the surface. The delta technique is a variation of the pitch-catch method where only the transmitting transducer is inclined at an angle to the normal. The transmitter is adjusted to generate shear waves in the material while the face of the receiver is placed parallel to the surface of the test material.

The pulse-echo method was chosen for evaluation of seals for this research project. This method allows for the testing to be done on one side of the material being tested. This aspect becomes important in testing seals around casings in that a seal is evaluated from within a casing. Another reason for choosing the pulse-echo method is that it employs planar waves. Inspection using plane waves is more simple compared to the use of other wave modes (shear, Rayleigh, Stoneley, or Lamb).

SECTION THREE
ULTRASONIC SEAL EVALUATION: PLANAR TESTS

3.1 ULTRASONIC SEAL EVALUATION

Ultrasonic testing was selected because it has the following advantages: (1) the condition of a seal (bentonite or cement-based) can be evaluated without disturbing the seal or formation, (2) separations in the order of micrometers between the seal and casing can be detected, (3) defects having an area as small as 2.50 cm^2 can be located, (4) the location of a defect is determined with an accuracy of few millimeters, and (5) most importantly, the simplicity of data analysis.

The ultrasonic nondestructive testing method developed for evaluating borehole seals uses a single transducer and commercially available hardware for data acquisition and analysis. The transducer is used to send and receive ultrasonic energy, which is transmitted through a coupling material (water or rubber) into the steel plate (planar tests) or casing (borehole tests) to be tested. Reflections from the boundary between the plate or casing and seal are received by the same transducer. Differences in the acoustic properties of mediums present behind the plate or the casing cause differences in the reflected wave energies. Analysis of these reflected waves indicates the presence of different mediums (seal or defects filled with air or water in a seal) behind a steel plate or a casing. The acoustic properties of the different materials used in the study are given in Table 3.1.

Table 3.1. Acoustic Properties of the Materials Used in the Study

Material	Density, ρ 10^3 (kg/m^3)	Velocity, c (m/s)	Impedance, $z = \rho x c$ 10^6 (kg/m^{2}s)
Steel[1]	7.70	5900	4.50
Rubber[1]	0.9 - 1.2	1480 - 2300	0.11 - 0.24
Air (STP)[2]	0.00121	343	4.15×10^{-4}
Water (STP)[2]	0.998	1483	1.48
Dry Sand (Medium)[3]	1.61	1700	2.74
Bentonite[4]	1.15 - 1.17	2100 - 2700	2.42 - 3.16
Concrete[3]	2.60	3100	8.10

1 Bray and Stanley (1989).

2 Ensminger (1988).

3 Sancar (1992).

4 Measured in borehole model tests.

3.2 PLANAR SETUP

The pulse-echo method was first evaluated using a planar arrangement of casing material and sealant (steel plate placed over a sealant). The test specimens were prepared in rectangular containers having dimensions of 420 mm x 300 mm x 50 mm. The steel plates used were 200 mm x 200 mm x 3.2 mm. Tests were performed with intact seals and seals that included purposely induced defects. Defects were constructed using a porous building insulation material.

Measurements were made on "test areas" located in the mid-section of the plates. A grid was placed on the plate in the test area to provide a coordinate system. The transducer was placed at intersections of the grid points. At these locations, ultrasonic waves were transmitted to interrogate the contact between the plate and seal. Grids 102 mm x 102 mm in cross-sectional area that were partitioned into 16-cells (25.5 mm x 25.5 mm spacing) were used for testing the intact seals. Finer grids having 121 cells (12.7 mm x 12.7 mm spacing) were used for testing specimens with defects.

The transducer was coupled to the steel plate using a 76 mm x 76 mm square soft neoprene rubber sheet that was 12.7 mm thick (Fig. 3.1). Rubber was used as the couplant in the planar arrangement tests because originally the transducer was to be coupled to the casing with a dry contact. The soft rubber (durometer hardness between 5-10) was expected to provide contact between the transducer and casing wall without leaving any air gaps. Nevertheless, water was placed between the transducer and the rubber sheet and the rubber sheet and the plate to ensure perfect coupling. Dry contact could not be implemented successfully, and thus was abandoned.

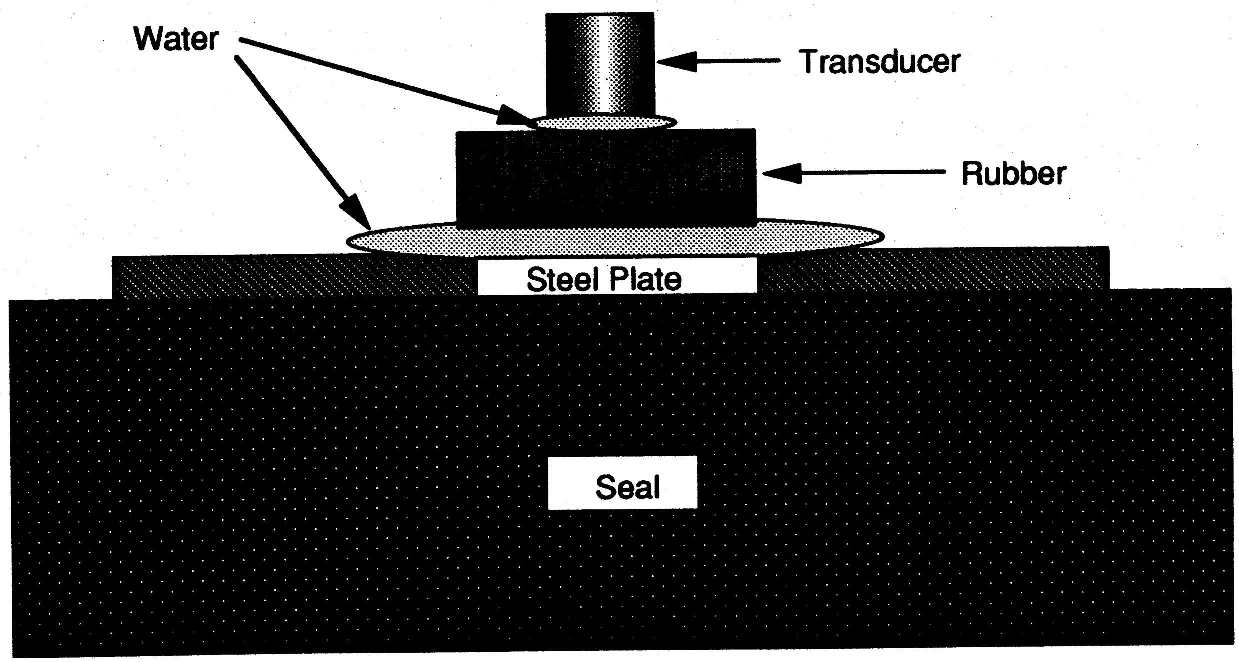


Fig. 3.1. Arrangement of Materials Used in Planar Tests

3.3 MATERIALS EVALUATED IN PLANAR TESTS

The backing materials used in the tests were air, water, bentonite, neat-cement, and sand. Air and water represent defects. Bentonite and neat-cement are the most common types of sealants used in sealing applications. Sand was used in the preparation of bentonite seals. It was also used alone as a formation material.

The bentonite seals were prepared with bentonite, sand, and water using a recipe given by Edil and Muhanna (1992). The recipe resulted in a slurry composed of 6.7% bentonite (Quik Gel®), 10% sand (Portage sand), and 83.3% water by weight. Quik Gel® is a finely ground sodium bentonite manufactured by Baroid Drilling Fluids Inc. to be used as a viscosifier which yields high viscosity slurries in drilling applications. However, it is also used in sealing wells and instrument casings (Edil and Muhanna 1992). Portage sand is a medium sand with round particles and a uniform particle size distribution. The neat-cement seals were prepared using a ratio 2 kg Type-I Portland cement to 1 L of water. This recipe for neat-cement is used in field applications for sealing casings (Edil et al. 1992, Strata Engineering Corporation 1991). Portage sand is also used as the formation material.

3.4 ELECTRONIC APPARATUS

Ultrasonic waves are transmitted to the test specimens by a piezoelectric transducer (Series A103-Panametrics). The transducer is actuated by a pulser-receiver (Ultrasonic Pulser-Receiver - Panametrics) unit which is connected to a waveform analyzer (Universal Waveform Analyzer with Data 6000 Mainframe and Model 620-1 Plug-In - Analogic Data Precision) for analysis.

3.4.1 Transducer

A piezoelectric transducer is used in the tests. Piezoelectricity is the mechanical vibration of certain materials under the effect of an electrical potential and, conversely, creation of an electrical potential across the faces of certain materials under the effect of mechanical vibrations (Kinsler et al. 1982, Bray and Stanley 1989).

In the three layered system used in the tests (Fig. 3.2), waves sent by the transducer travel through the coupling medium (rubber or water), the steel plate or casing, and the seal. When the incident wave encounters the boundaries between layers, its energy is distributed between the reflected and transmitted waves. The seal layer to be investigated is the third layer in this system; that is, the presence and type of layer is to be determined with the ultrasonic evaluation technique. Therefore, it is desired to transmit the maximum amount of energy into this layer through the plate or casing (layer 2) using an appropriate transducer to obtain the maximum amount of information.

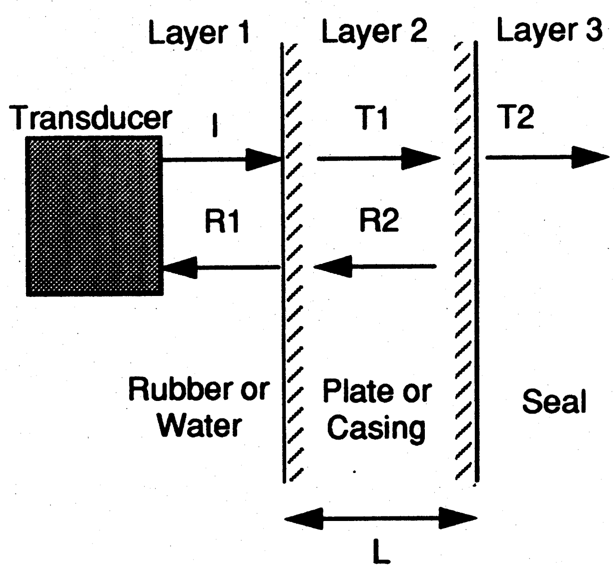
The intensity transmission coefficient, T_I, can be used as an index of the amount of energy transmitted into the layer of interest:

$$T_I = \frac{I_t}{I_i} \qquad (3.1)$$

In Eq. 3.1, I_t is the intensity of the transmitted wave and I_i is the intensity of the incident wave.

For normal incidence, T_I for transmission into layer 3 through layer 2 (Fig. 3.2) can be computed as:

$$T_I = \frac{4}{2 + \left(\frac{z_3}{z_1} + \frac{z_3}{z_1}\right)\cos^2 k_2L + \left(\frac{z_2^2}{z_1\, z_2} + \frac{z_1 \times z_3}{z_2^2}\right)\sin^2 k_2L} \qquad (3.2)$$



I = Incident wave
R1= Wave reflected from the boundary between 1 and 2
T1= Wave transmitted to layer 2
R2= Wave reflected from the boundary between 2 and 3
T2= Wave transmitted to layer 3

Fig. 3.2. Three Layered System Used in the Tests

where z_1, z_2, and z_3 are the impedances of layers 1, 2, and 3, k_2 is the wave number for layer 2 (equal to the angular velocity, ω, divided by the wave velocity c_2 in layer 2), and L is the thickness of layer 2. Derivation of the equation can be found in Kinsler et al. 1982. When the derivative of Eq. 3.2 with respect to k_2L is set equal to zero, the frequency (f) yielding the maximum intensity transmission coefficient is obtained:

$$f = \frac{c_2}{2l} \quad \text{.......................................}(3.3)$$

where f is the frequency of the sound wave, c_2 is the velocity of sound in the plate or casing, and l is the thickness of the plate or casing.

When 3.2-mm-thick steel plates are used, the frequency required for maximum transmission is 922 kHz (velocity of sound in steel is 5900 m/sec) according to Eq. 3.3. The steel casings used in the second phase of the research program were 3.9 mm thick. The lowest ideal frequency for testing these casings is 754 kHz. A broad-band transducer having a wide frequency range (0 to 5 MHz) with 2.25 MHz center frequency was chosen for the tests. This frequency range satisfies the maximum transmission criteria required. The first two harmonics of the lowest ideal frequencies for both the plate (1.8 and 2.8 MHz) and the casing (1.5 and 2.3 MHz) lie around the center frequency (2.25 MHz) of the transducer. A 1 MHz center frequency transducer was also tested with the planar setup. This frequency also satisfies the frequency requirements for the plate and casing tested. However, this transducer didn't produce reflections as sharp as those obtained with the 2.25 MHz transducer. Thus the 2.25 MHz transducer has been used.

The transducer is connected to the pulser-receiver unit with a RG-58 BNC cable. The cable is connected to the transducer through a BNC-tomicrodot adapter that is sealed against water leakage. The adapter is a 50-mm-long rigid connector with a diameter slightly larger than the diameter of the BNC cable.

3.4.2 Pulser-Receiver

A 10-MHz-bandwidth broad-band pulser-receiver is used for the tests. The pulser-receiver actuates the transducer and receives ultrasonic waves coming from the test object (Fig. 3.3). The pulser has an adjustable repetition rate in the range of 100 Hz to 2 kHz, with a 2V output for synchronous triggering of the waveform analyzer during data acquisition. The "pulser" section of the instrument generates electric pulses. Electrical pulses cause mechanical vibration of the piezoelectric crystal in the transducer. These vibrations are transmitted to the medium of interest for investigation. The maximum pulse voltage is -400 V with a rise time less than 10 nanoseconds.

The pulser-receiver can be operated in pulse-echo, through-transmission, or pitch-catch modes. A single transducer is connected to the pulser-receiver unit for transmitting and receiving in pulse-echo mode. In through-transmission and pitch-catch modes two transducers are used, one for transmitting the other for receiving ultrasonic energy. The controls on the pulser-receiver are:

(1) *Repetition Rate:* Used to regulate the frequency at which excitation pulses are applied to the transducer.

(2) *Energy:* Used to select the optimum pulse width and excitation amplitude for a given transducer.

(3) *Attenuation:* Provides stepwise attenuation of the signal to the receiver.

(4) *H.P. Filter:* Used to adjust the frequency content of the input signal.

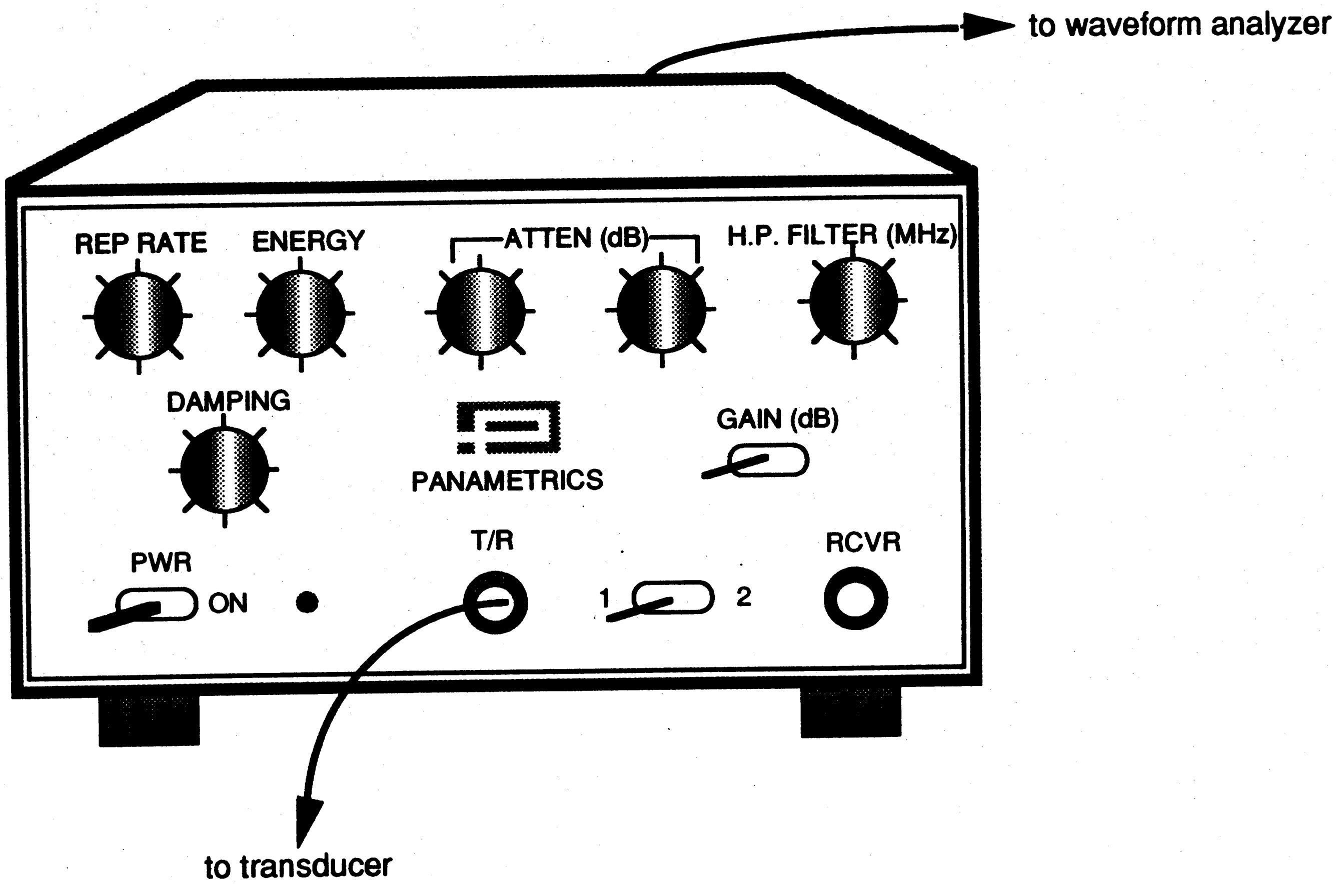


Fig.3.3. Pulser-Receiver

(5) *Damping:* Varies the resistance load presented to the transducer by the pulser-receiver.

(6) *Gain:* Controls the gain of the receiver.

(7) *Mode Switch:* Used to set mode of operation; pulse-echo or through-transmission.

3.4.3 Waveform Analyzer

The waveform analyzer digitizes and displays analog input signals that come from the pulser-receiver. It is possible to apply several functions to the data acquired. The data and/or the processed information can be displayed on its screen. Analysis functions can be performed individually or can be chained in a programmed sequence.

The waveform analyzer (Fig. 3.4) consists of three parts: mainframe, plug-in unit, and floppy disk drive. The waveforms are displayed on the screen in the mainframe. Signal processing and selection of display parameters is conducted by operating appropriate mainframe keys. Acquisition parameters are selected by operating appropriate plug-in keys. Plug-In Model 620-1 provides data acquisition with frequencies up to 100 MHz. The waveforms can be stored on disks in the disk drive. It is also possible to obtain a numerical record of the waveforms (i.e. the abscissa and the ordinate corresponding to every point in the waveform) with a computer program.

The waveform analyzer is connected to the pulser-receiver unit with RG-58 BNC cable.

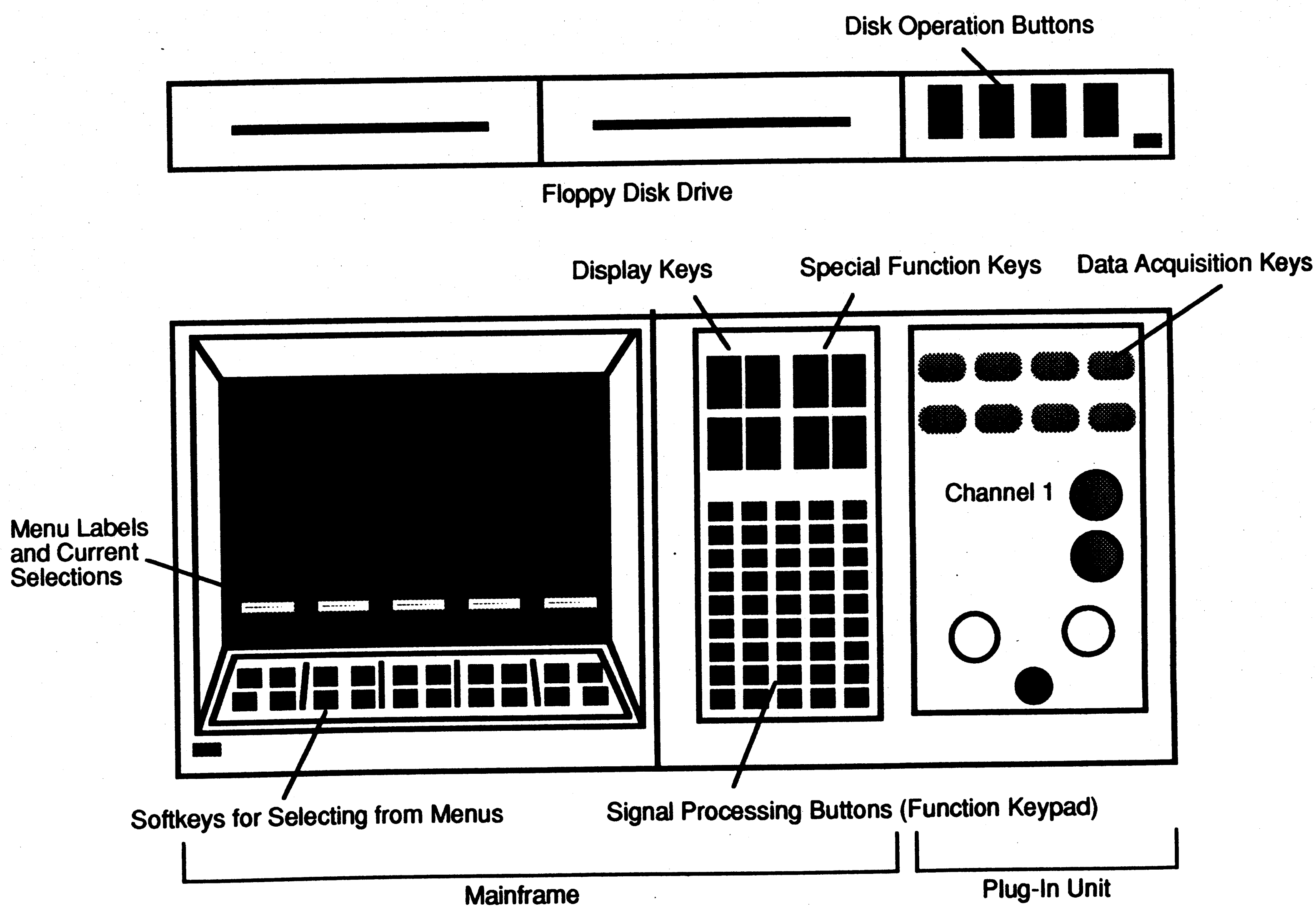


Fig.3.4. Waveform Analyzer

3.5 WAVEFORM ANALYSIS METHODOLOGY

The reflected wave sequences generated in planar tests are shown in Fig. 3.5. The incident sound impulse from the transducer travels through the coupling medium (rubber) and strikes the surface of the steel plate. Some energy is reflected back to the transducer, and some undergoes multiple reflections within the plate. The integrity of the seal is assessed by evaluating the amount of energy transmitted into the backing, i.e., intact seals receive and damp more energy. The transmission of energy is assessed by examining the amplitude of reflections from the interface between the steel plate and backing, which is affected by the contrast in acoustic impedance between the plate and backing.

Because the acoustic impedance of the rubber and steel plate are essentially constant, the signal inside the casing decays at a rate that depends on the acoustic impedance of the material behind the plate. In a typical waveform, a high amplitude initial reflection from the rubber-plate interface is followed by multiple reflections inside the plate that exponentially decay. The amplitude of reflections from the rubber-plate and plate-backing interfaces are proportional to the length of the arrows in Fig. 3.5.

Two typical waveforms obtained from the tests are shown in Fig. 3.6.. The initial high amplitude reflection from the rubber-plate interface is followed by sharp multiple reflections when there is no-backing (air). The low acoustic impedance of air, compared to the acoustic impedance of steel plate (Table 3.1), results in very low transmission of energy into the air. Consequently, most of the energy in the incident pulse that strikes the plate-air interface is contained in the plate. This generates the sharp reflections shown in Fig. 3.6a.

The initial high amplitude reflection from the rubber-plate interface is followed by low-amplitude reflections that decay quickly when neat-cement is

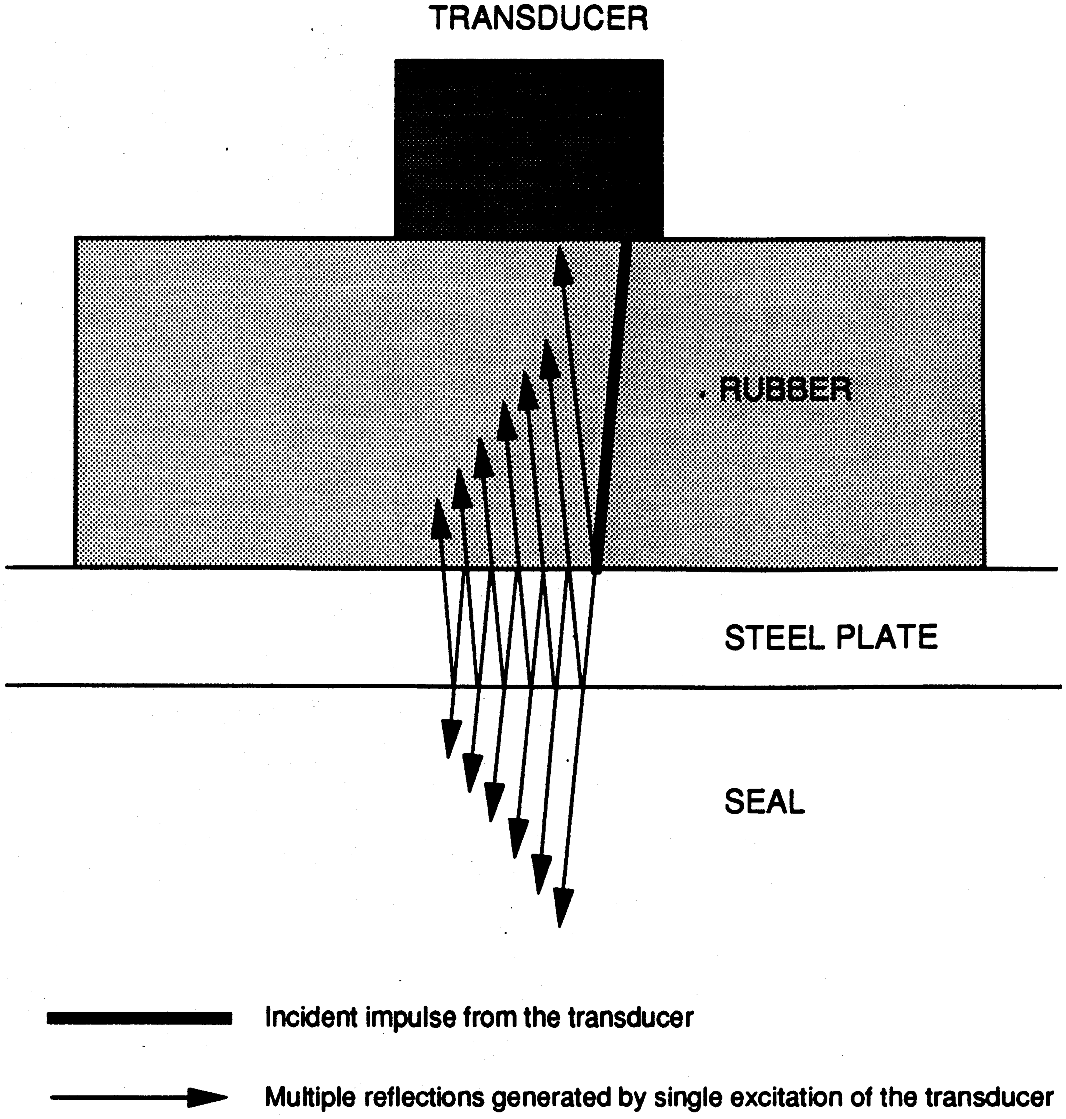


Fig. 3.5. Wave Sequences Generated in Planar Tests (Waves are normal to the interfaces, however, they are distorted for demonstration purposes)

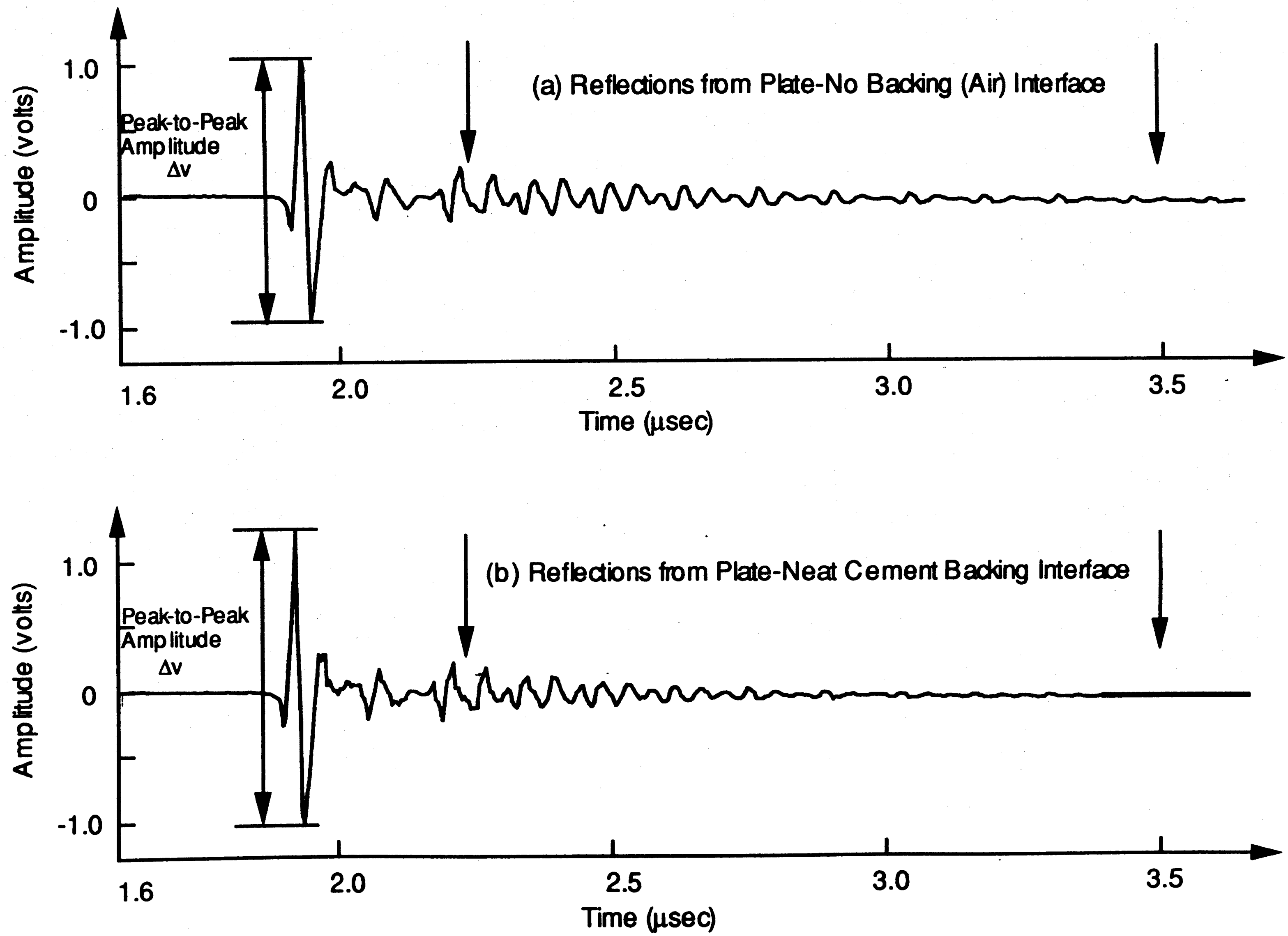


Fig. 3.6. Two Typical Waveforms Obtained in the Tests: No Backing and Neat Cement Backing

present behind the steel plate. The acoustic impedance of neat-cement is significantly higher than that of air (Table 3.1). This results in a smaller contrast in acoustic impedance between the plate and cement compared to the contrast between the plate and air. Hence, transmission into cement is considerably higher than transmission into air. As a result, a smaller amount of energy is contained in the plate. This generates the low amplitude reflections shown in Fig. 3.6b.

Reflections from the interface between the plate and the backing material are analyzed to evaluate the bond between the plate and the seal. The initial high amplitude reflection from the rubber-plate interface (Fig. 3.6) is not affected by changing the backing. However, the shape and amplitude of the reflections from the plate-backing interface (shown between arrows in Fig. 3.6) change when different materials are present behind the plate. Changes in these reflections from the plate-backing interface are quantified using an algorithm developed to predict the presence of different materials behind the steel plate.

3.5.1 Algorithm

The waveforms obtained during a test are represented by a specified number of points (256 or 512). The reflections are displayed on the coordinate axes with time shown on abscissa and amplitude shown on ordinate (Fig. 3.6). A "fill" function is used to connect the individual points in the waveform to create a continuous representation. Each individual point in the waveform has time as the abscissa and amplitude measured by means of the changes in voltage as the ordinate.

Two different statistical measures are used to evaluate the waveforms: Root Mean Square (RMS) and Energy (ENG). Root Mean Square is the square root of the average value of the squares of the amplitudes (voltage) with respect to a designated reference value. RMS gives an average for the amplitudes of consecutive points in the waveform over a specified time interval. ENG is the area under the amplitude-time plot over a specified time interval. ENG is calculated as the sum of the squares of the amplitudes (voltage) with respect to a designated reference value multiplied with the corresponding time.

The presence of different materials behind the steel plate causes changes in the amplitudes of reflections from the plate-backing interface. Therefore, RMS and ENG are used to evaluate the parts of the waveforms lying between arrows in Fig. 3.6. When RMS is calculated only the amplitudes of the waveforms are used in the analysis, whereas ENG is an integral measure of both amplitude and time.

The equation for RMS is:

$$RMS = \left[\frac{1}{N} \sum_{i=1}^{N} (v_i - v_{ref})^2 \right]^{1/2} \quad (3.4)$$

where N is the total number of points in the waveform, v_i is the amplitude of point "i" in volts, and v_{ref} is a designated reference amplitude value in volts.

The equation for ENG is:

$$ENG = \sum_{i=1}^{N} \left[(v_i - v_{ref})^2 \Delta t \right] \quad (3.5)$$

where Δt is time difference between consecutive points in the waveform in µsec.

3.5.2 Program

The waveform analyzer was programmed to take 16 RMS and 16 ENG measurements at each sampling point of the grid on the steel plates. The mean and standard deviation of these 16 measurements were recorded and analyzed. Procedures for using the different components of the electronic equipment are given in Appendix A1.

The waveform is normalized to reduce the effects of amplitude changes on RMS and ENG and then the normalized waveform is analyzed. Normalization is conducted in two steps:

(1) The mean amplitude for a given waveform [$\Sigma v_i / N$] is subtracted from the amplitudes of each point (v_i) in the waveform:

$v_{i1} = v_i - (\Sigma v_i / N)$ for i from 1 to N..(3.6)

where N is the total number of points in the waveform. Amplitudes have units of volts

(2) The amplitude of each point (v_{i1}, volts) in the resulting waveform is divided by the peak-to-peak amplitude "Δv" (Fig. 3.6) of the resulting waveform:

$v_{in} = v_{i1} / \Delta v$ for i from 1 to N...(3.7)

where N is the total number of points in the waveform.

The peak-to-peak amplitude [Δv] corresponds to the highest amplitude (in volts) obtained in the waveform, which is always the amplitude of the first reflection from the rubber-plate interface in planar arrangement tests. The normalized waveform (v_{in}) is unitless.

After normalization, RMS and ENG for "v_{in}" are calculated using Eqs. 3.4 and 3.5 for the 13.5 μsec interval shown between arrows in Fig. 3.6. Because "v_{in}" is unitless, RMS is also unitless, whereas ENG has units of time. The program used to make these calculations is given in Appendix A2.

3.5.3 Data Analysis

Measurements conducted with a single medium behind the steel plates are analyzed using box plots. The ENG from all of the 16 cells on the grid are represented with a single box in a box graph. In a box plot, each box encloses 50% of the data, with the median displayed as a centrally located line (Fig. 3.7). The top and bottom of the box correspond to the 25^{th} and 75^{th} percentiles (the whiskers). The lines extending from the top and bottom of each box correspond to the 10^{th} and 90^{th} percentiles. Outliers are the data points that do not fall between the 10^{th} and 90^{th} percentiles; they are shown with symbols.

Box graphs provide an effective representation for comparison of tests conducted on different materials. Variation in data obtained from a single material behind a casing can be readily observed. The difference in ENG between different materials can be analyzed by comparing the median ENGs shown on the plot.

The measurements conducted on planar specimens having defects are analyzed using two-dimensional contour maps ENG corresponding to each point of the 121-cell grid is entered in the computer and a contour map is drawn. The resulting map is compared with the actual defect placed in the specimen.

3.6 RESULTS AND DISCUSSION: PLANAR TESTS

Planar arrangement tests were conducted as the first phase of the testing program. An analysis method to evaluate the seals was developed and the effectiveness of the method was tested. Perfect seals, seals with defects, and formation materials were tested.

A comparison of results was made to determine which measure (RMS or ENG) was superior. The percent difference in RMS and ENG resulting from the

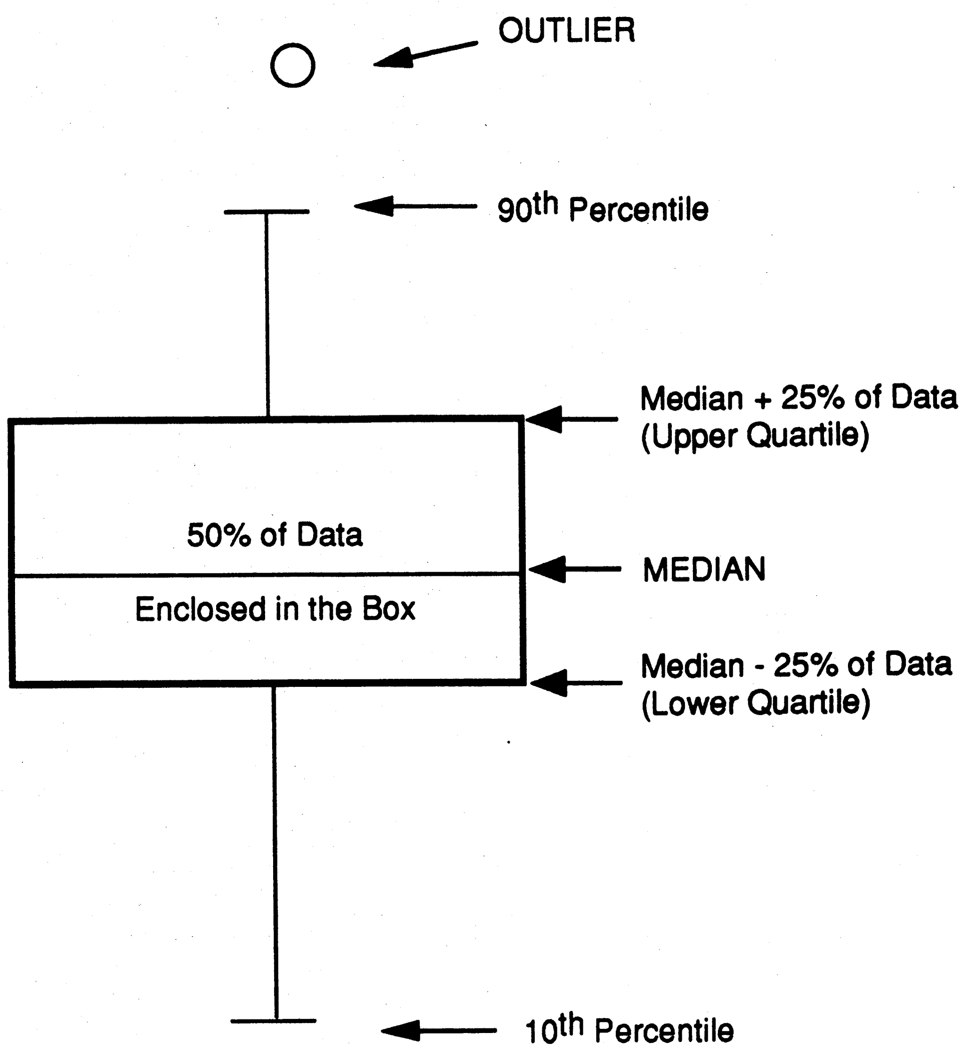


Fig. 3.7. Typical Box Plot

presence of different materials behind the steel plate was analyzed (Table 3.2). Three waveforms from tests with three different materials were investigated. "Air" is a waveform obtained from tests with no backing (i.e., air is backing), "Water" is a waveform from tests using water as the backing, and "Cement" is a waveform obtained from the tests with neat-cement behind the steel plate. The percent difference is always smaller for RMS than ENG for the same materials. Therefore, ENG has superior discriminating power and is being used for data analysis.

3.6.1 Single Material Tests

Measurements conducted with a single material behind the steel plates are analyzed using box plots. Results from the planar tests conducted with a single medium behind the steel plate tests are shown in Fig. 3.8 to demonstrate ENG resulting when different materials are placed behind the steel plate. Seals made with bentonite and neat-cement have low ENG. Most of the energy of the incident ultrasonic waves are transmitted into these media. Reflections from bentonite and neat-cement have low amplitudes and thus low ENG. However, for air and water, most of the energy of the incident waves is reflected from the back-wall of the steel plate. Less transmission occurs into air and water relative to that occurring into bentonite or cement. Consequently, reflections from air and water have high amplitudes and high ENG. The box-plot delineates the distinction among several materials. Medians for ENG from these tests are listed in Table 3.3. The ultrasonic method was shown to be effective for detecting the presence of different materials behind a steel plate.

Another neat-cement specimen was prepared in order to study the effects of curing on seal integrity. Results from the tests performed on a steel plate alone and the same plate placed on the neat-cement specimen are shown in

Table 3.2. Percent Difference in RMS and ENG Measured for Various Materials.

Materials Compared	% Difference RMS	% Difference ENG
Air - Cement	57	82
Water - Cement	44	69
Air - Water	23	41

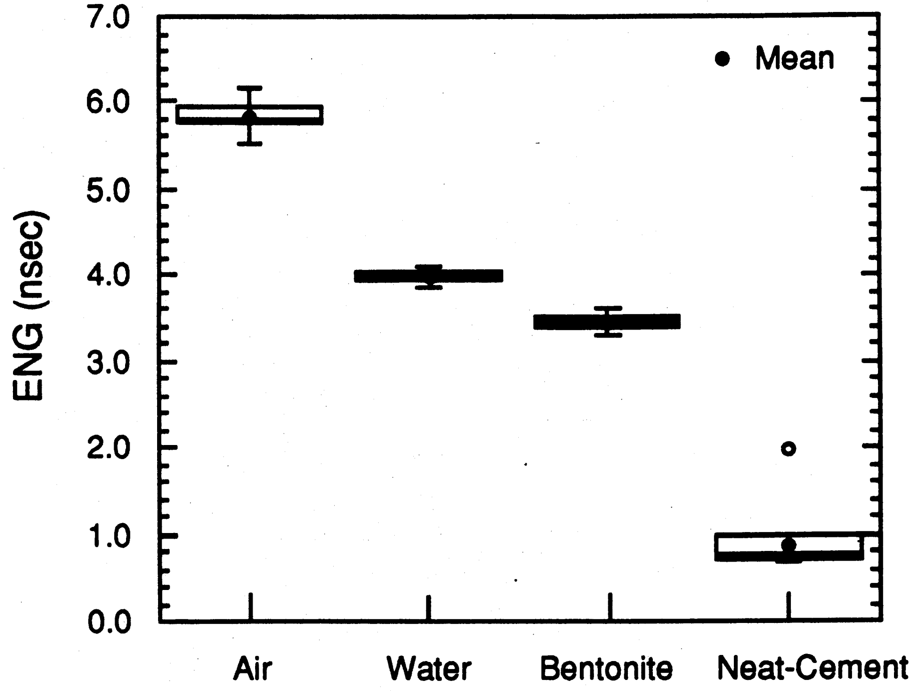


Fig. 3.8. Box Plot of ENG for Different Materials Tested in Planar Arrangement

Table 3.3. Comparison of ENG Obtained in Planar Tests for Different Materials

Backing	Median ENG	% Lower Than with Air
Air	5.8	0
Water	4.0	31
Bentonite	3.4	41
Neat-Cement	0.8	86

Fig. 3.9. Measurements of ENG were initially made on the steel plate before it was placed on fresh neat cement. Afterwards, measurements were made at 2.5 hours, 1 day, 3 days, 4 days, and 7 days after the onset of curing.

ENG changed as the cement cured (Fig. 3.9). A decrease in ENG occurred as the neat cement solidified, which is expected because the solid seal absorbs more energy compared to the grout initially placed under the steel plate. However, between 7 and 14 days, ENG increased sharply to a value that was essentially the same as the ENG obtained from steel alone (designated as "air" in Fig. 3.9). This occurred because the steel and cement separated, resulting in a poor contact. The specimen was then flooded with water to determine if a seal with poor contact would still be detected if water coupled the steel and neat cement. As shown in Fig. 3.9, the poor contact condition was still evident even under flooded conditions since the ENG obtained corresponds nearly to that of water.

Sand, a formation material, was also tested in the planar arrangement. Wet or dry sand can be encountered around a casing at an improperly sealed location. The presence of sand behind a steel plate is investigated with the ultrasonic method. The results obtained were compared with the ENG obtained from previous tests with other materials.

Results from the sand tests (dry and wet) are shown in Fig. 3.10 with previous results for the tests where air and water were behind the steel plate. The first set of tests were performed on dry sand. The sand was poured into the test pan in a loose condition and then the steel plate was placed on it. The ENG obtained for this arrangement was similar to ENG obtained from the plate tests with no backing (i.e. steel plate with air behind it). This occurs because the granular nature and the high porosity of the loose sand prevents transmission of ultrasonic waves.

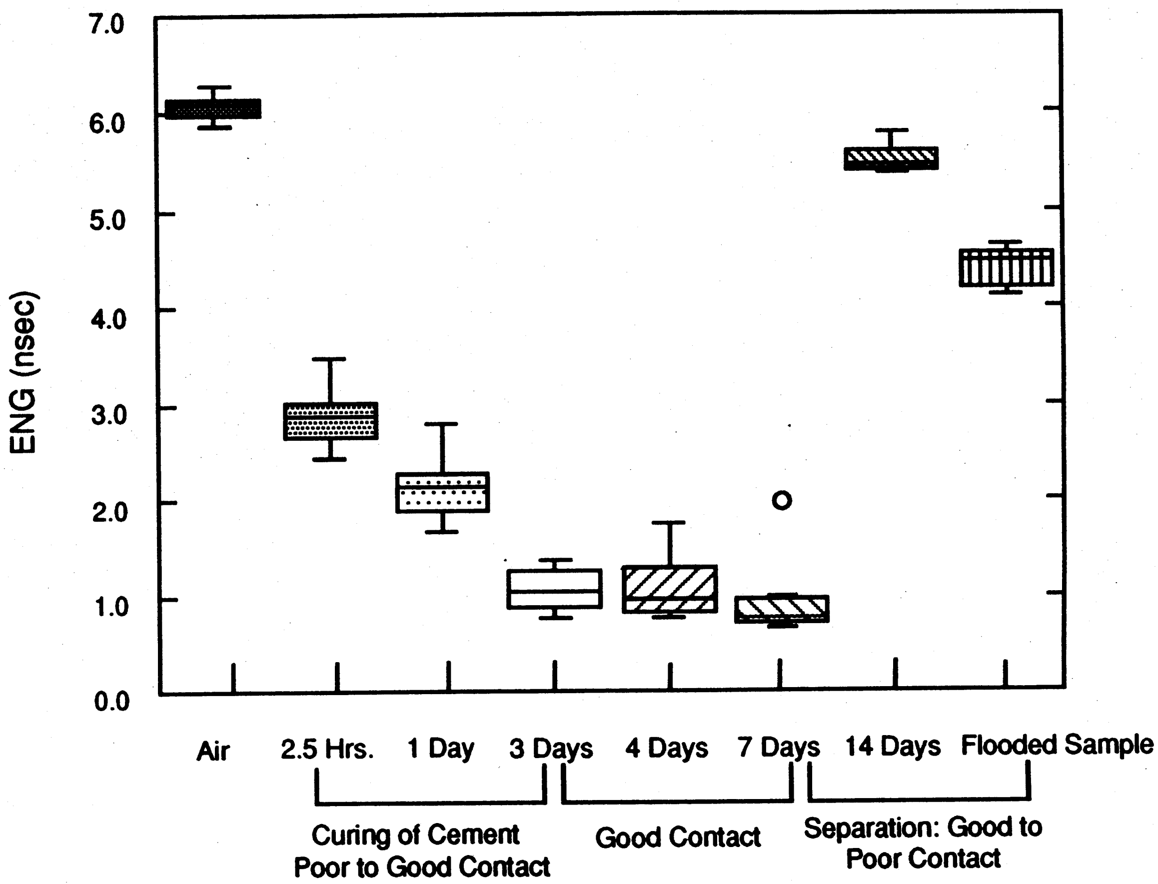


Fig. 3.9. ENG from Neat-Cement Specimen vs. Testing Time or Condition

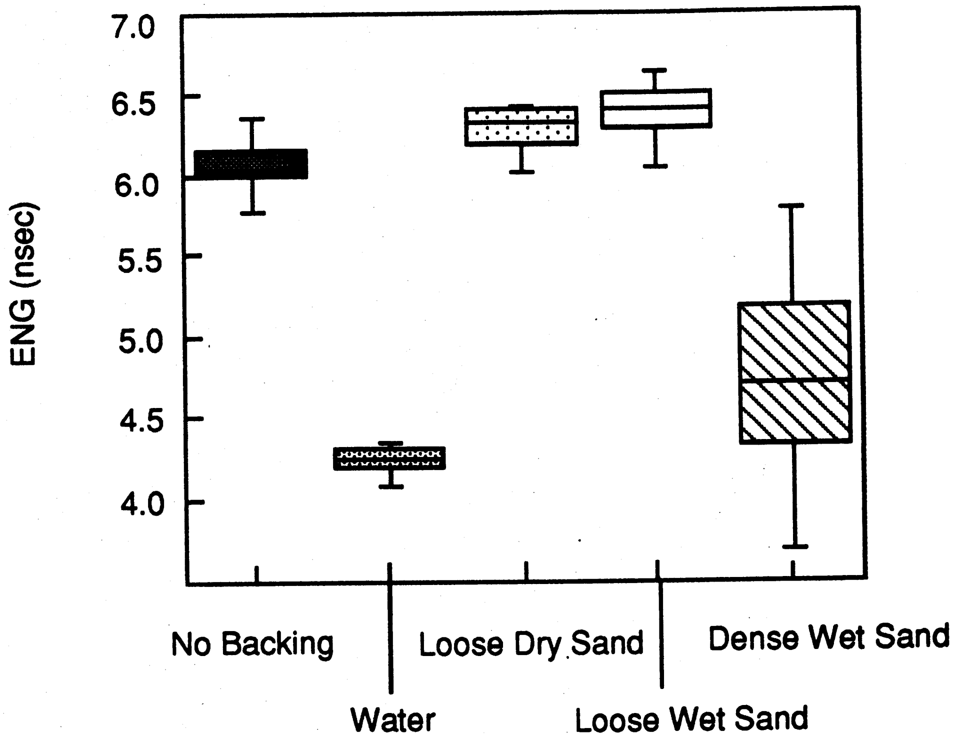


Fig. 3.10. Box Plot of ENG for Dry and Wet Sand Tested in Planar Arrangement

The second set of tests were performed on wet sand. These tests involved both loose and dense sand. For tests conducted with wet loose sand, the ENG obtained was similar to the ENG for the tests conducted with a steel plate having no backing (i.e. steel plate in air). For the wet dense sand, greater variation in ENG was observed.

A line graph was made (Fig. 3.11) because of the high variation in ENG for wet dense sand. ENG at the points where good contact existed between the plate and the sand were close to those obtained for water. At other locations where poor contact existed, the ENG were closer to those obtained from a steel plate with no backing. The non-continuous granular nature of sand prevents the detection of solid particles with the ultrasonic method. Only the presence of water can be detected behind the plate when the plate is placed firmly on the sand.

3.6.2 Seals Containing Defects

After the tests with single materials were completed, a testing program was initiated involving testing of neat-cement seals containing purposely induced defects filled with air. Tests were conducted on seals containing single and multiple defects.

Results from the first specimen are shown in Fig. 3.12. The area occupied by the single defect is shown with white, which corresponds to the ENG for steel plate having no cement backing. The areas shown with the darkest gray represent good contact and lighter shades of gray are for a transition. These measurements were made 5 days after the specimen was poured. After the data were collected, the plate was removed from the grout and the actual shape of the defect was inspected. The shape of the defect agreed well with the shape depicted in Fig. 3.12.

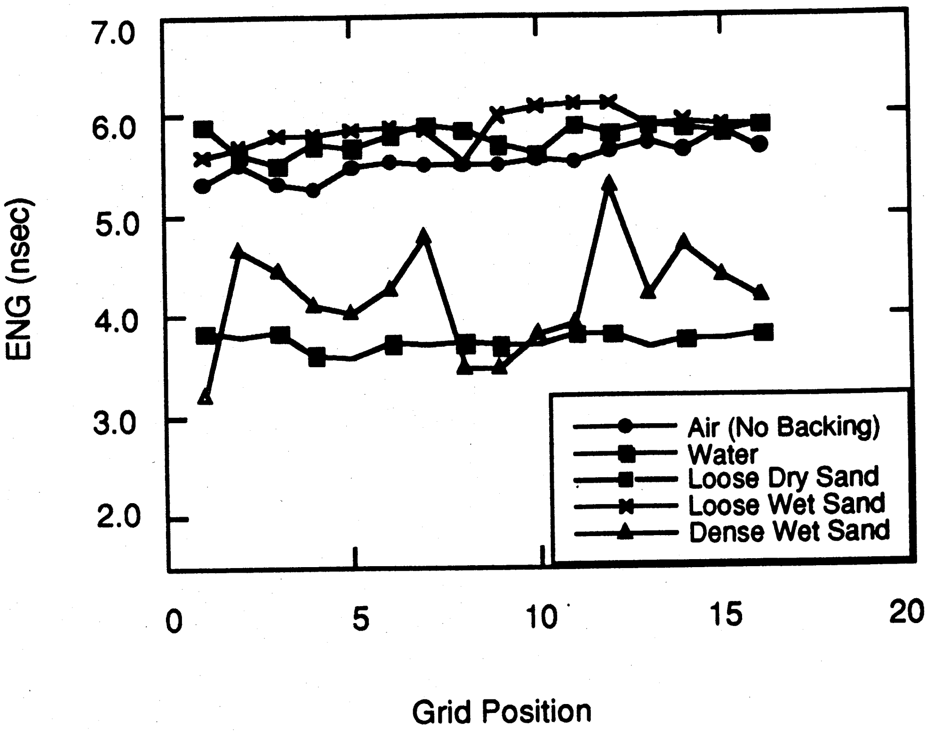


Fig. 3.11. Comparison of Planar Tests Conducted with Air (no backing), Water, Loose Dry Sand, Loose Wet Sand, and Dense Wet Sand

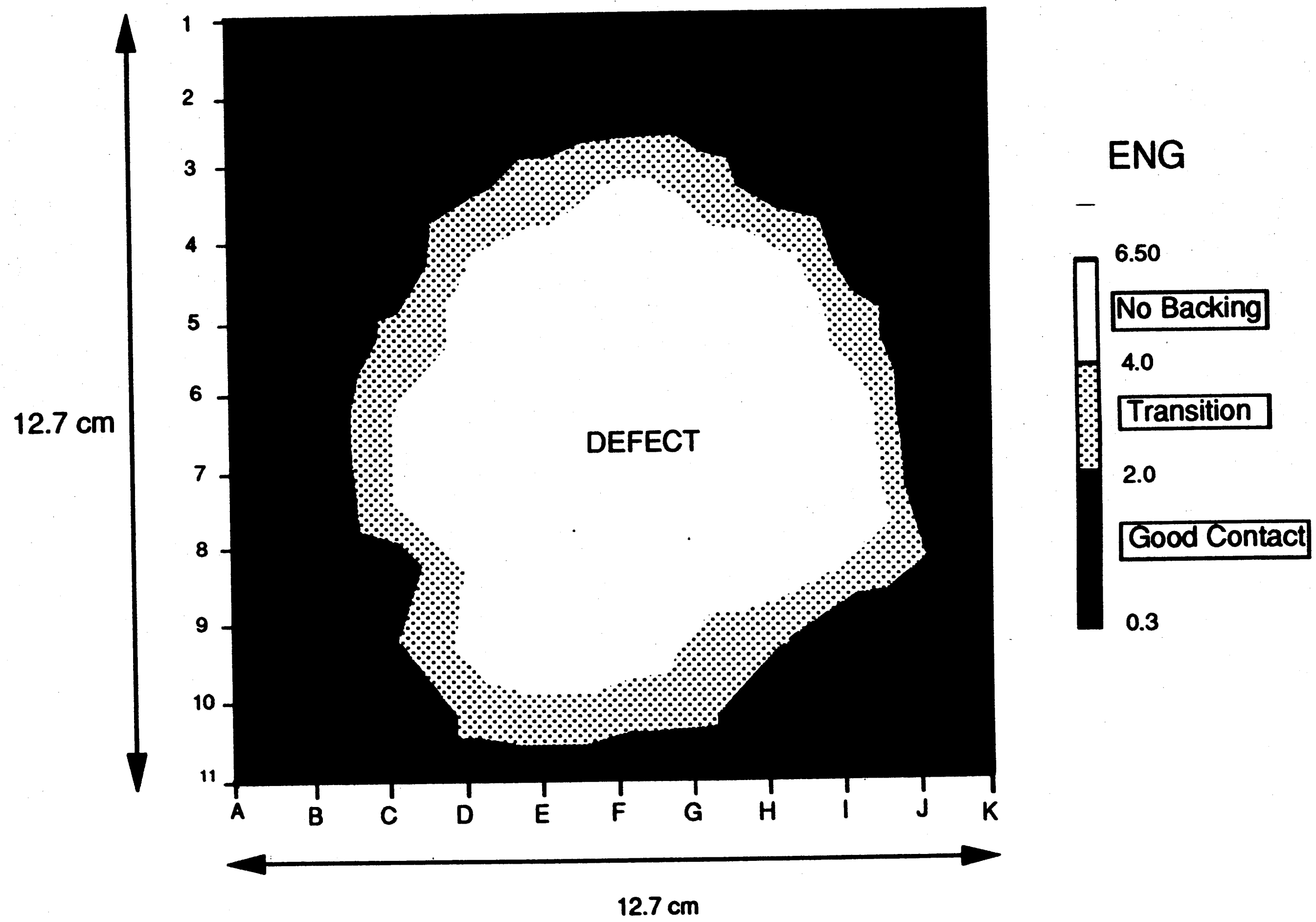


Fig. 3.12. Neat-Cement Specimen with a Single Defect

Multiple defects were placed in the second neat-cement specimen. These defects were smaller than the defect placed in the first specimen, such that the capability of the ultrasonic method to detect small defects would be evaluated. Results of the tests are shown in Fig. 3.13 and were verified by visual inspection. Molds of the defects were taken with a soft putty and matched with the map given by the ultrasonic measurements (Fig. 3.13). The agreement was found to be exact.

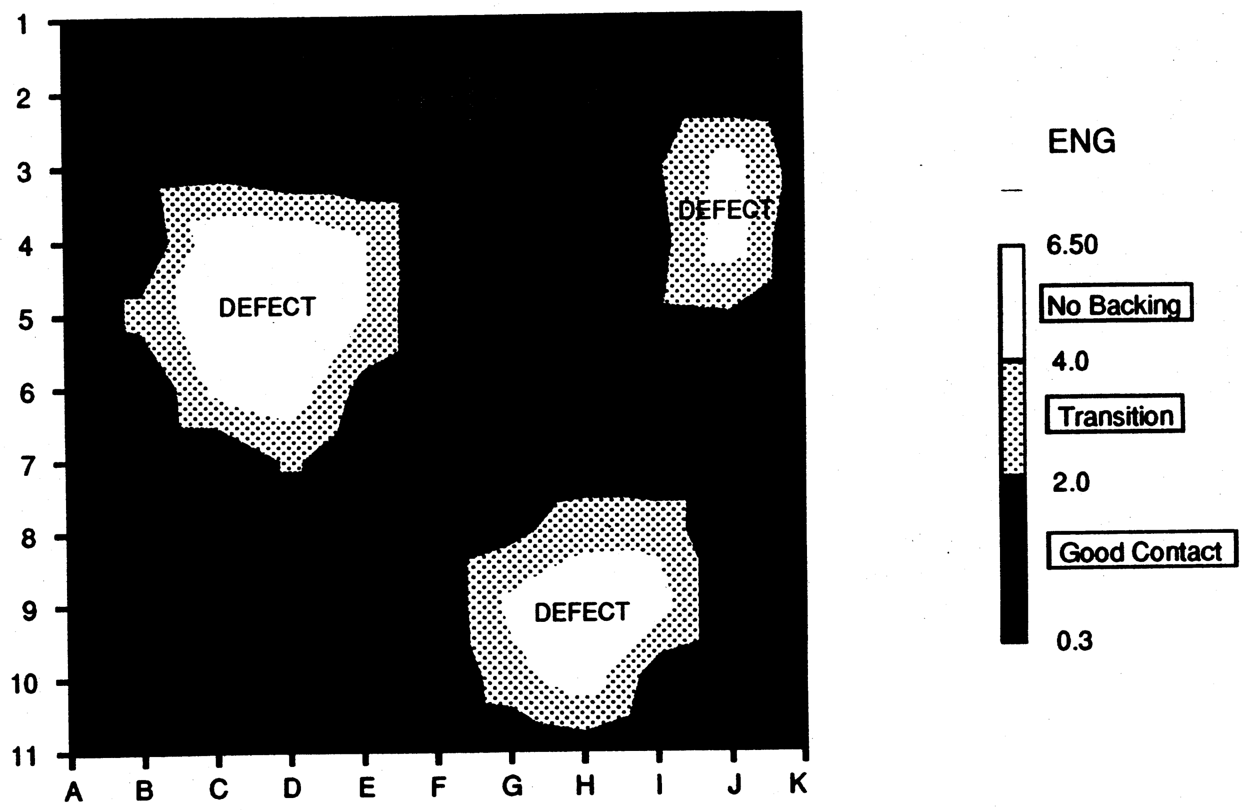


Fig. 3.13. Neat-Cement Specimen with Multiple Defects

SECTION FOUR
MODEL BOREHOLE TESTS

4.1 PROBE DESIGN

A probe was designed for down-hole testing. The probe was designed to be placed in a casing to test the integrity of the casing-seal bond. The probe was constructed from cylindrical stock of Delran® (a plastic). Its height is 82 mm and diameter is 49 mm. A thin circular brass disk was attached to the bottom of the probe as a counterweight (Fig. 4.1). The probe is lowered into a casing using a rigid rod.

Three pistons are placed inside the probe. Two pistons are on one side (Front-Piston 1 on top and Front-Piston 2 on the bottom) and the other piston (back-piston) is on the opposite side (Fig. 4.1). The transducer is placed in Front-Piston 1 and rests against the back-wall of the piston. The probe is designed to fit into casings having diameters ranging from 50 mm to 100 mm. A number of back-pistons with varying lengths can be placed in the probe for use in different diameter casings.

Dry contact was desired to be used in casings to avoid the need for filling casings above groundwater table with water. Front-Piston 2 was included in the probe design for testing with dry contact. The transducer was placed in the upper piston (Front-Piston 1) and a soft rubber plug (same type of rubber used in planar tests) is placed in front of it to act as a couplant. Another rubber plug was placed in Front-Piston 2. When the probe was lowered into the measurement depth in a casing, both pistons were pushed out against casing wall. A pressure of 275 kPa was required to maintain good contact between the transducer and casing wall. The rubber plug deformed under this pressure and

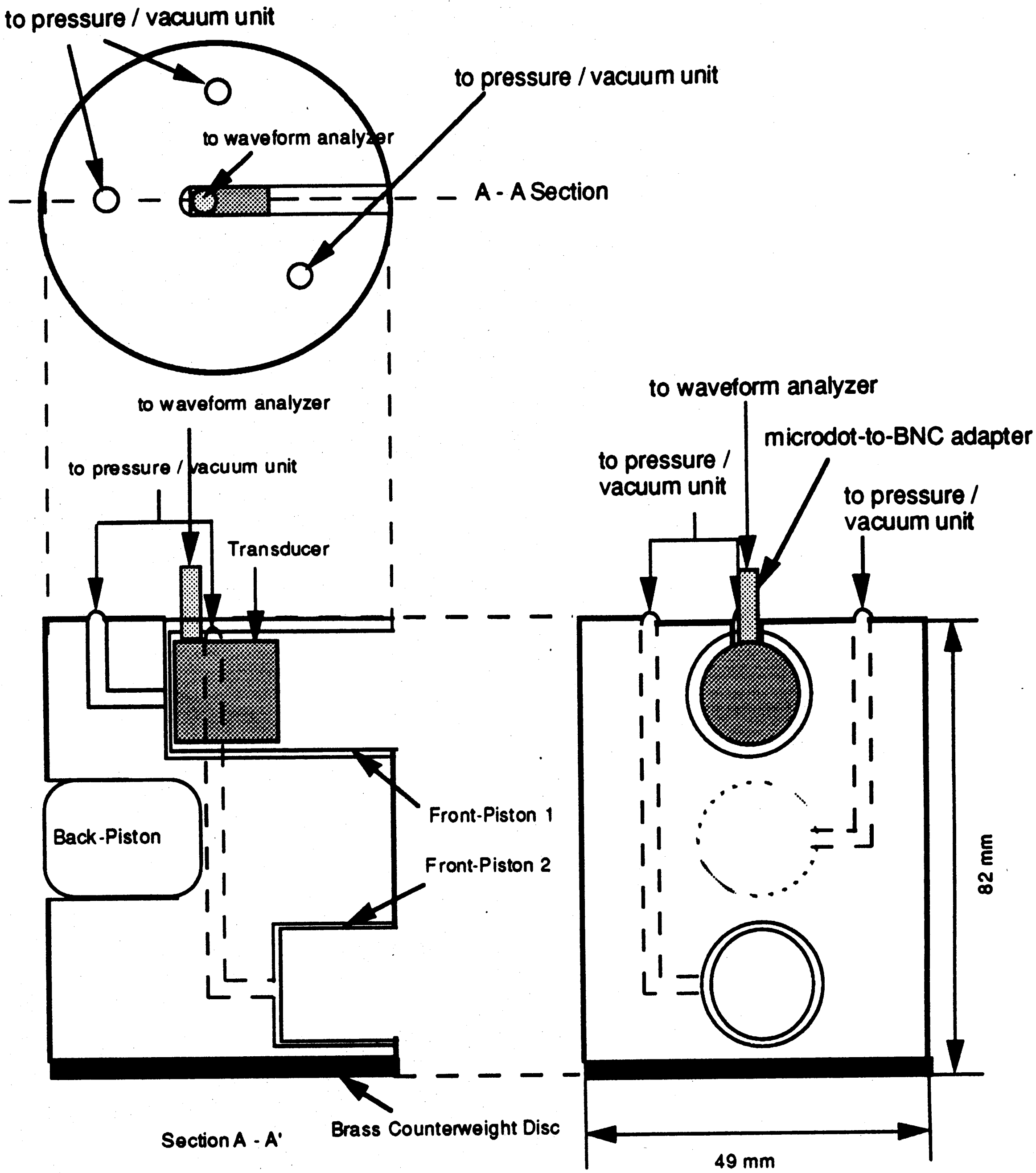


Fig. 4.1. Probe Design

filled the space between the transducer and casing without leaving any air gaps.

Problems were encountered in the dry contact tests. The rubber plug slowly deformed under pressure, resulting in data that changed with time. The probe also could not be properly centralized in the casing with this configuration. The variability resulting from the time dependent behavior of the rubber and centralization problems made acquisition of repeatable data impossible. Therefore, dry contact was abandoned.

The alternative was to conduct downhole measurements using a casing filled with water. The water acts as a coupling medium between the transducer and the casing wall. The probe is lowered in the casing to the measurement depth and then is pressurized against the casing wall using the back-piston. A pressure of 240 KPa is applied to place the probe firmly against the casing. In this configuration, the face of the transducer is orthogonal to the casing wall, which permits the maximum ultrasonic energy to be transmitted into the casing. Also, a fixed thickness of water (12.7 mm) is maintained in front of the transducer to act as a couplant. Pressurizing the probe against the casing wall and maintaining a fixed thickness of water in front of the transducer eliminates the need for centralizing the probe, which is a major concern in commercially available cement evaluation tools (Schlumberger 1981, Bigelow 1985). A vertical cross-section showing the pressurized probe in the casing is shown in Fig. 4.2.

A test is conducted at the measurement location after the probe has been pressurized against the casing wall. After the test data have been collected, the probe is released by applying vacuum to retract the back-piston. The probe is then lowered to the next measurement location.

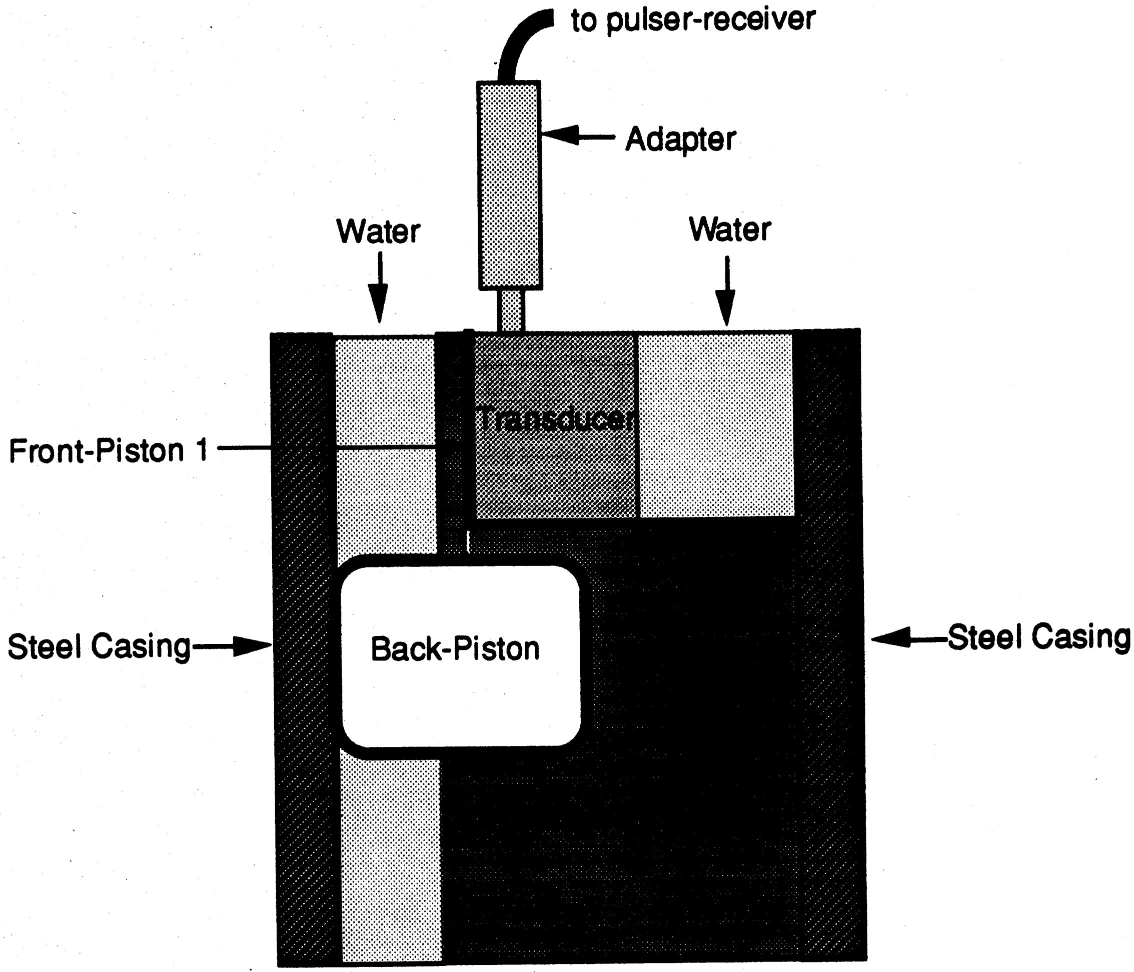


Fig. 4.2. Pressurized Probe in the Casing

4.2 BOREHOLE MODEL SETUP

A borehole model constructed in the laboratory was used to simulate a casing and the annular space (Fig. 4.3). The annular space is filled with different sealants and formation materials. Different size borehole models are constructed using 100 mm, 300 mm, and 380 mm diameter PVC pipes mounted on 50 mm thick PVC base plates. Sch. 40 stainless steel pipe (50 mm nominal diameter) simulating a casing is placed in the middle of the PVC pipe. An acrylic plate is placed on top of the PVC pipe and secured to the base plate using four rods. A cap is mounted on the top plate.

The probe is lowered into the casing at the end of a rigid rod. The rod fits tightly into the hollow space in the middle of the cap. The cap ensures vertical movement of the probe in the pipe without tilting or rotation.

4.3 MATERIALS EVALUATED IN MODEL BOREHOLE TESTS

The backing materials used in the tests are air, water, bentonite, and neat-cement. Air and water represent defect materials. Bentonite and neat-cement are most common types of sealants used in sealing applications.

The bentonite seals were prepared with bentonite, a retarding agent, and water using recipe and procedures given by Baroid Drilling Fluids Inc. (1994). The recipe resulted in a slurry composed of 22.6% bentonite (Benseal®), 2% retarding agent (Aqua-Grout™), and 75.4% water by weight. Benseal® is a granular Wyoming bentonite manufactured by Baroid Drilling Fluids Inc. Aqua-Grout™ is an additive composed of fine particles. It delays the swelling of the bentonite in the slurry and increases the workability. The Benseal®/Aqua-Grout™ system is manufactured to be used in sealing wells and other casings (Baroid Drilling Fluids Inc. 1994). The neat-cement grout was

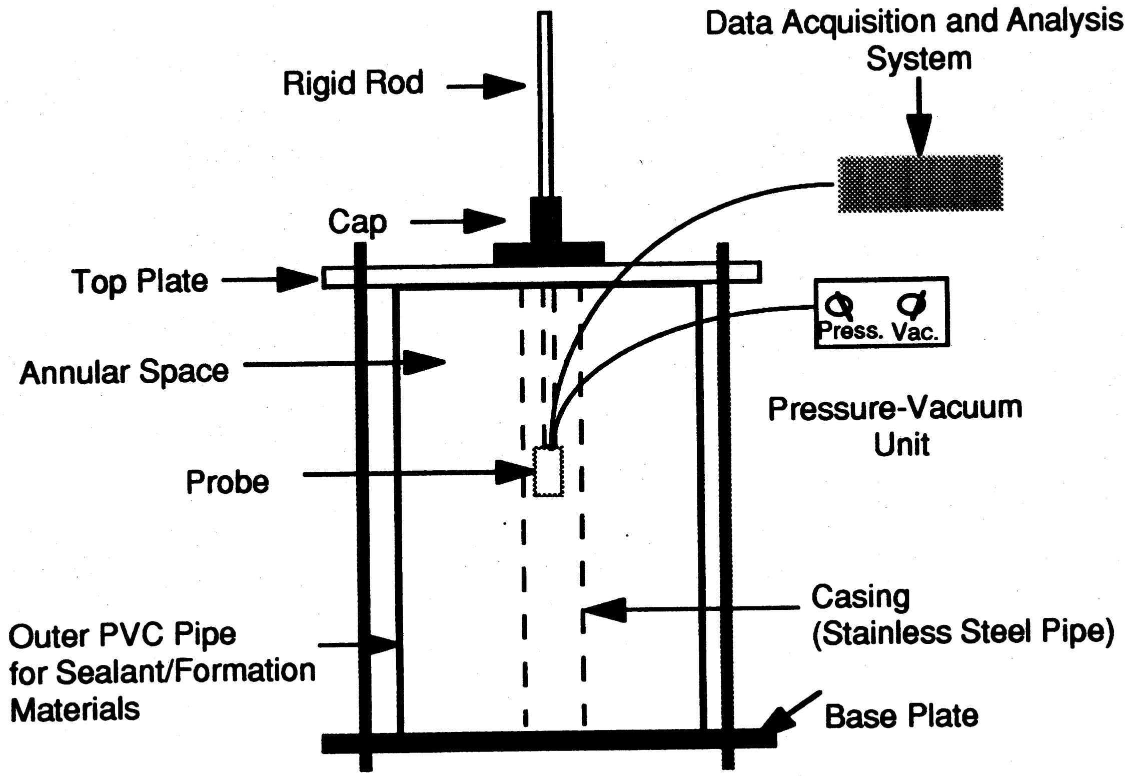


Fig. 4.3. Laboratory Borehole Model with Probe

cement grout was prepared using a ratio 2 kg Type-I Portland cement to 1 L of water (same ratio used in planar tests).

4.4 WAVEFORM ANALYSIS METHODOLOGY

4.4.1 Algorithm and Program

The wave sequences generated in the model borehole tests is shown in Fig. 4.4. The wave sequences in this figure is similar to the wave sequences generated in the planar tests (Fig. 3.5), except for being vertically aligned instead of horizontally aligned. Another difference is that the couplant used for the model borehole tests is water instead of rubber. The typical waveforms obtained from model borehole tests and used in the analysis are similar to the waveforms obtained and used in planar tests (Fig. 3.6).

The measurement algorithm developed for the planar tests is also used for the cylindrical tests. The only difference is the use of a different time interval for measurement. The computer is programmed to take measurements for an interval of 13.5 μsec for the planar tests and 10.5 μsec is used for the cylindrical tests. Less data points are collected in the 10.5 μsec interval compared to 13.5 μsec interval. Thus, the ENG obtained for a material tested in cylindrical arrangement is less than the ENG obtained for the same material tested in planar arrangement.

4.4.2 Data Analysis

In the borehole model tests, measurements are conducted at 2.0 cm intervals. Results of the tests are analyzed to assess the integrity of seals by graphing ENG vs. location along the casing. Differences in quality of the seal are reflected as changes in ENG with depth.

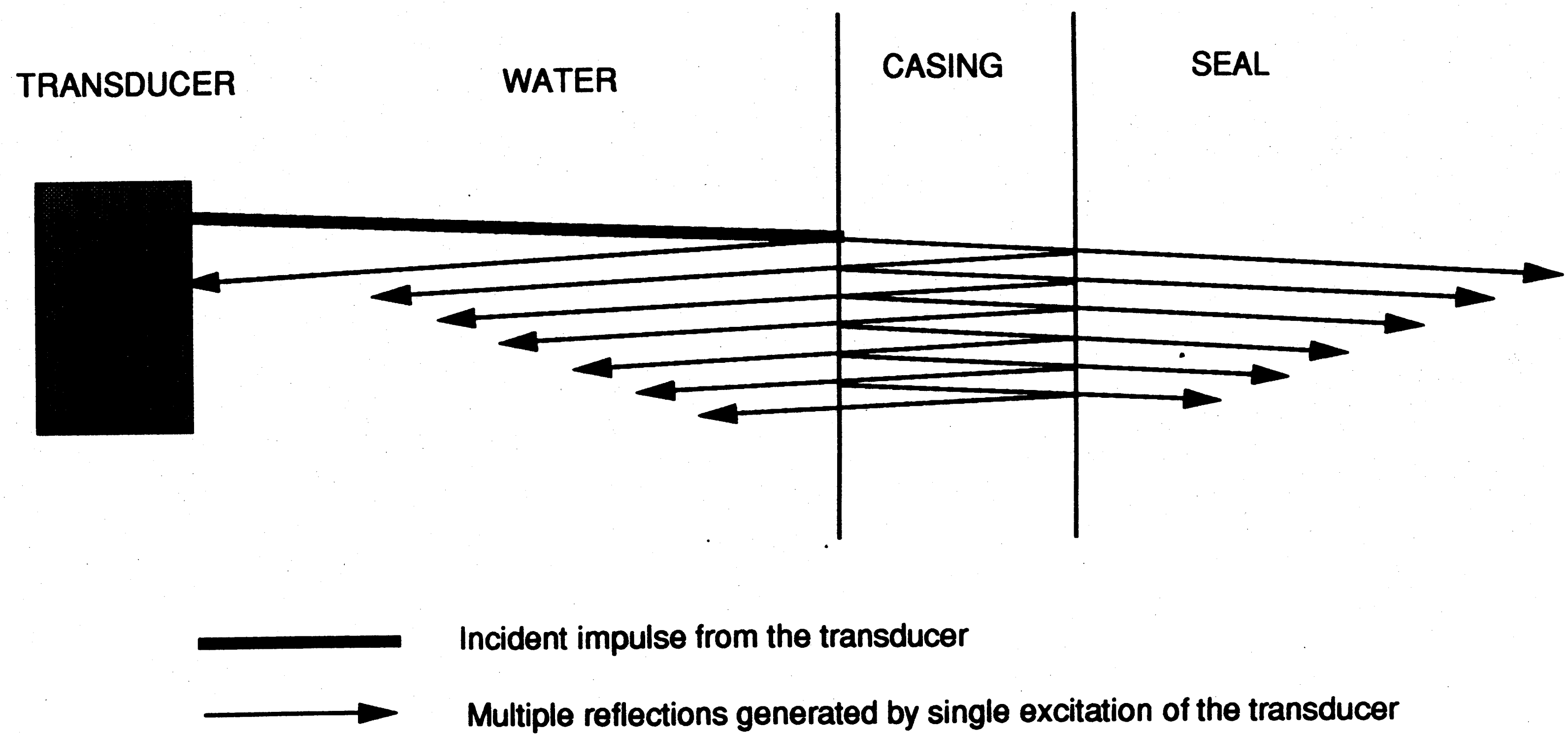


Fig. 4.4. Wave Sequences Generated in Model Borehole Tests
(Waves are normal to the interfaces, however, they are distorted for demonstration purposes)

4.4.2.1 Measurement Noise

The variability in ENG resulting from vertical movement of the probe in the casing and from rotation of the probe along a horizontal plane at a certain depth was determined such that the "noise" in the measurement could be assessed. The range of "noise" that is expected in ENG due to variations in diameter, wall thickness, and eccentricity of the casing in the presence of a single material behind the casing is given in Table 4.1. This assessment shows that casing-specific noise is low compared to the difference between typical ENG for air and water. The assessment is shown graphically in Figs. 4.5 and 4.6. The variation in ENG resulting from physical properties of the casing or the rotation of the probe in the casing is small enough such that misinterpretation of the quality of a seal as a result of noise is unlikely. It is shown that significant variation occurs in ENG in the presence of different materials around a casing, but not because of changes in the physical properties of the casing. This makes ENG suitable for seal evaluation.

4.3.2.2 Evaluating Seal Quality

To discriminate between a "good" seal and "no" seal, a measured profile of ENG is compared to the profile expected for a defective seal. An intact seal (full contact with the casing) is a "good" seal, whereas defects consisting of air or water around the casing correspond to "no" seal. Error bars corresponding to 1.65 standard deviations of ENG are shown on the profile to delineate variations expected due to noise. These error bars comprise 90% of the expected scatter. Defects are located by finding areas where error bars from the sealed casing overlap with error bars for profiles corresponding to air or water backings. The probability of misinterpretation of the quality of a seal is

Table 4.1 - Variability Assesment in the Tests

	Mean ENG Air	Std. Dev.[4] ENG Air	Std. Err.[5] ENG Air	Mean ENG Water	Std. Dev. ENG Water	Std. Err. ENG Water
Vertical Variation[1]	2.22	0.22	0.04	1.07	0.08	0.01
Horizontal Variation[2]	2.35	0.27	0.04	1.19	0.13	0.02
Variation at Same Location[3]	2.26	0.04	0.01	1.19	0.03	0.01

1 - Change in ENG due to variation in the wall thickness of the casing as the probe moves down (or up) in the casing along a vertical line.

2 - Change in ENG due to variations in the diameter and eccentricity of the casing as the probe rotates along a horizontal plane at a certain depth.

3 - Change in ENG due to pressurizing and retracting the probe at a certain point on the casing.

4 - Standard Deviation

5 - Standard Error

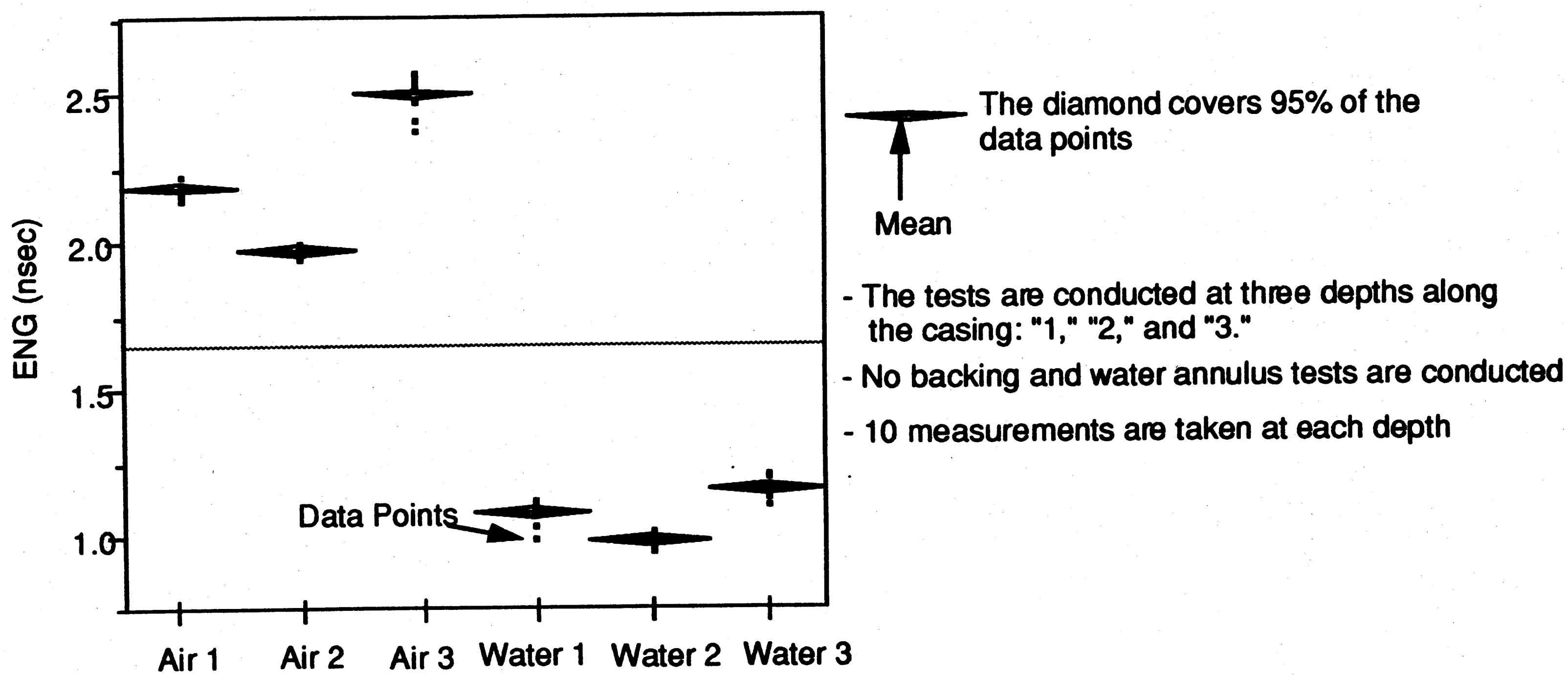
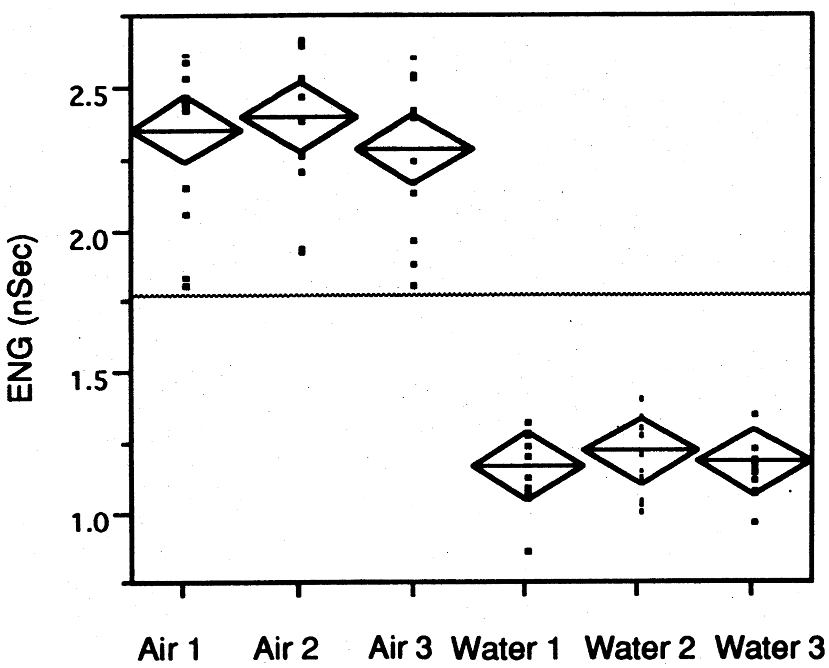
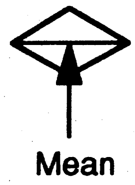


Fig. 4.5. Results of Vertical Variability Tests





- The tests are conducted at three depths along the casing: "1," "2," and "3."
- No backing and water annulus tests are conducted
- 12 measurements with 30° separation along the horizontal plane are taken at each depth.

Fig. 4.6. Results of Horizontal Variability Tests

10%, because the confidence intervals used for both seals and defect materials (air and water) comprise 90% of the data. A step-by-step procedure for data analysis is:

(1) Make a plot of ENG vs. depth along the casing. Show the profiles for the sealed casing, water backing, and no backing (air) on the same plot. Show ENG on the abscissa and depth on the ordinate.

(2) Show error bars corresponding to 1.65 standard deviations on the data.

(3) Compare profiles for the sealed casing to profiles for water backing and no backing (air). Locations where error bars overlap correspond to locations where the seal is defective.

(4) If the ENG profile for air and water backing are not known for the sealed casing tested, average values from tests with similar casings for water and air backing can be used for comparison. The results from the sealed casing are plotted on the same graph with average values for air or water and a similar evaluation of the data is conducted. An example of such a plot is given in Fig. 4.7.

4.5 RESULTS AND DISCUSSION OF MODEL BOREHOLE TESTS

Cylindrical tests were conducted as the second phase of the testing program. Perfect seals and seals with defects are being tested in the model borehole. The effectiveness of the analysis methodology developed during the planar arrangement tests applied to cased boreholes is verified.

4.5.1 Single Material Tests

Tests with single material around the casings were initially conducted using the borehole model. The materials tested separately were air, water,

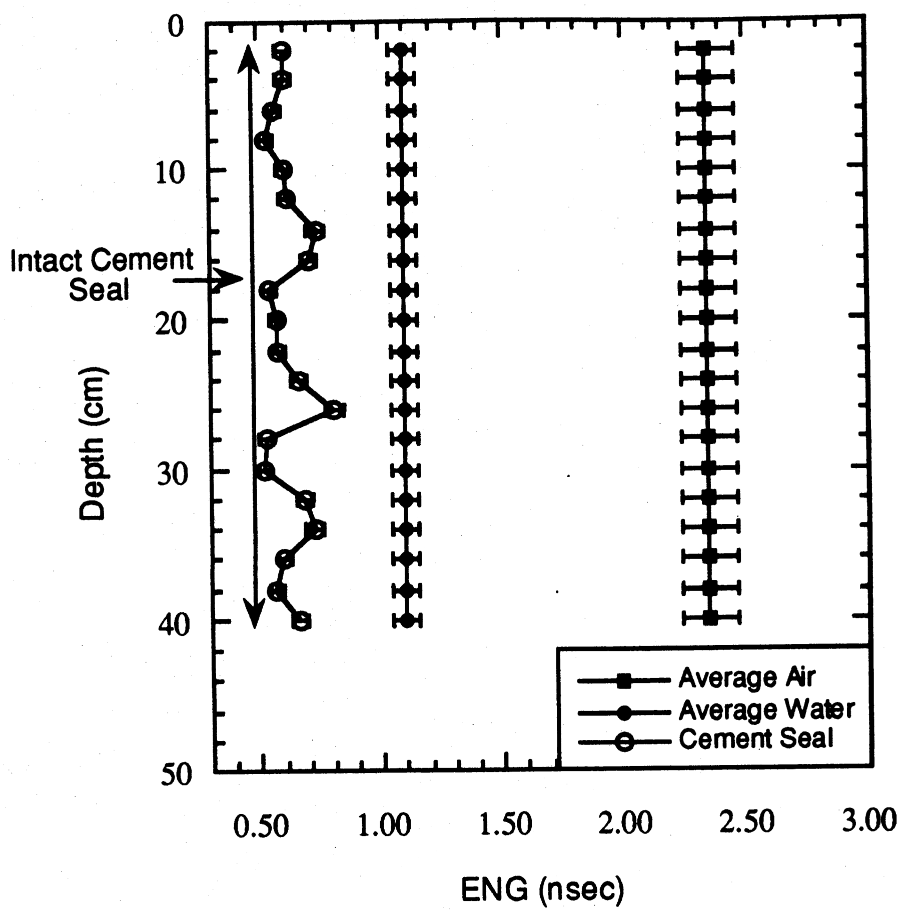


Fig. 4.7. ENG Profiles for a Sealed Casing, Average Water Backing, and Average Air Backing

bentonite, and neat-cement. The purpose of the single material tests is to define ENG for various materials behind a casing. The tests conducted on air and water provide a means of reference for comparison to other materials. Both air and water behind a casing indicate the presence of a defect, and thus a poor quality seal.

A bentonite specimen was prepared in a 300-mm-diameter borehole model and tests were conducted over time. The test results indicate that the ultrasonic properties of bentonite are very close to those of water (Fig. 4.8). The ENG of bentonite and water cannot be differentiated from each other soon after the seal has been placed (Fig. 4.8a). Error bars from water and bentonite overlap at most locations along the casing. However, as time passed, the ultrasonic behavior of the bentonite changed. For example, desiccation cracking occurred in the bentonite near the top of the specimen where it was exposed to air. This increased the ENG to values corresponding to that of air. The depth of separation was measured by inserting a ruler around the casing. The agreement between the depth of separation predicted with the ultrasonic method and the measurement separation was found to be good. Another change that occurred is ENG for the bentonite seal decreased near the bottom of the specimen (Fig. 4.8 b,c). After 24 days the ENG was different from that of water (Fig. 4.8d). Thus, at least at the bottom of the specimen, the bentonite could be differentiated from water.

One explanation for the decrease in ENG that occurred toward the bottom of the specimen is consolidation of the lower bentonite under the weight of the upper bentonite. The bentonite has very high water content (400 - 500%), which makes the ultrasonic response of bentonite close to that of water. However, when specimens are consolidated, the solids content of the bentonite mix is expected to increase as water is expelled, which produces lower ENG

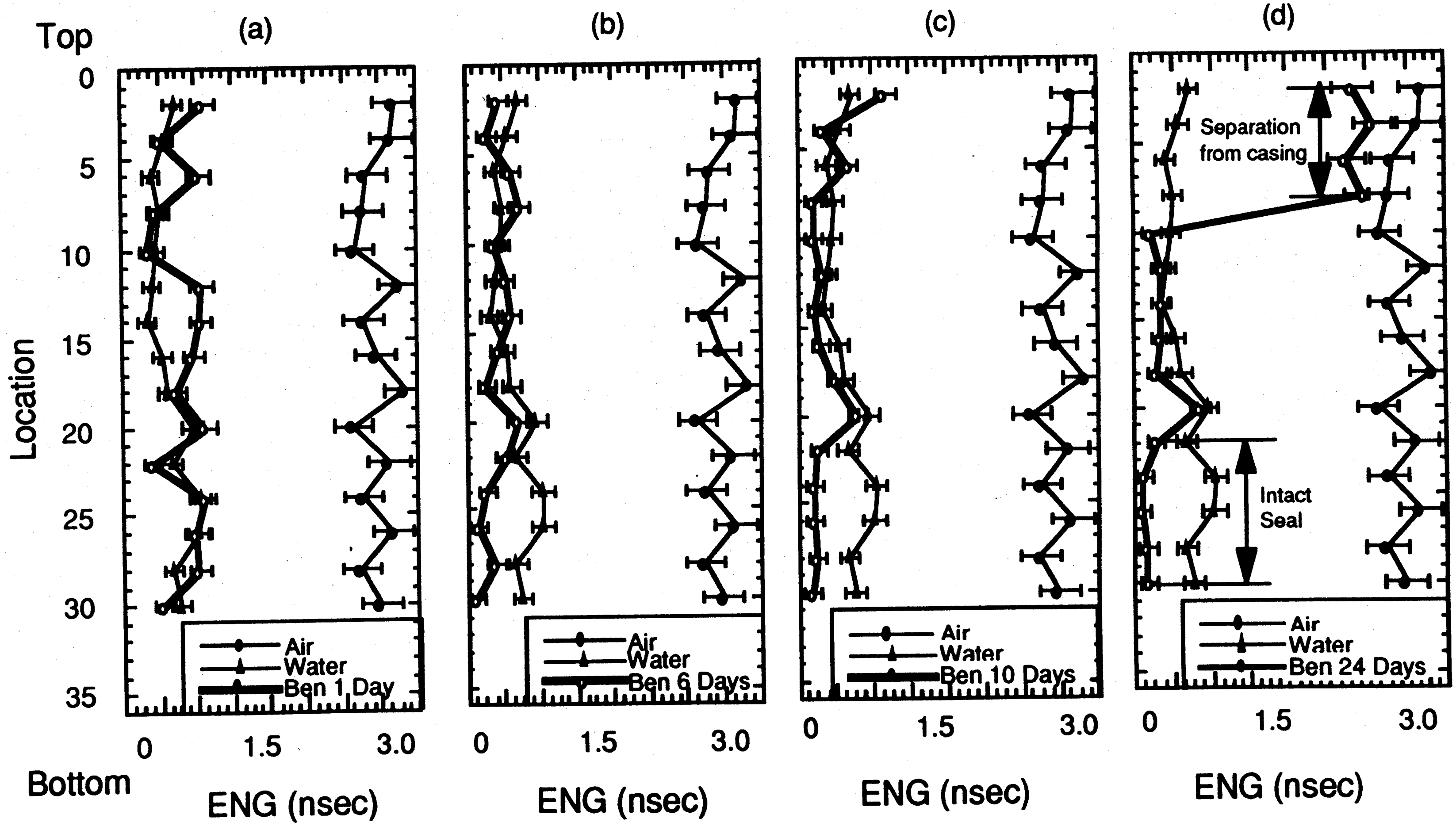


Fig. 4.8. Tests with Bentonite in the Annular Space

(more ultrasonic energy is transmitted to solid particles). To test this hypothesis, a bentonite specimen was consolidated in the laboratory under elevated effective stress. Results from these tests are shown in Fig. 4.9. Initially, water was tested in the annular space of a 100 mm diameter borehole model. Then a bentonite sample was prepared in the model. This sample was tested 2 days after its placement in the annular space. After this test, the bentonite sample was subjected to a load of 55 kPa. Pressure was applied to the bentonite sample for 2 months. The bentonite sample was tested again at the end of the 2 month consolidation. The water and unconsolidated bentonite (2 days) tests produced similar results (Fig. 4.9). Error bars from water and unconsolidated bentonite overlap at most locations along the casing. On the other hand, measurements conducted on the consolidated bentonite sample (2 months) are distinctly different from measurements conducted on the water at most locations. Consolidation increased the solids content of the bentonite mix. Consequently, the ultrasonic behavior of the bentonite sample became distinguishable from that of water.

An example from tests conducted in a 380 mm diameter borehole model with air, water, and neat-cement in the annular space is shown in Fig. 4.10. Changes in ENG were monitored as the cement cured. Fresh cement (2 hour test) produced low ENG indicating full contact with the casing. However, as the cement cured, the ENG increased at the base and top, indicating a defect was developing. At the end of three days, all of the measurements of ENG overlapped those for air, indicating the entire casing lost contact with the cement. Apparently, a gap filled with air formed between the casing and the cement sealant. Gaps of this type have been reported in the oil and gas industry and are attributed to the formation of a "microannulus," which is defined as a small gap between a casing and cement seal that does not permit fluid flow

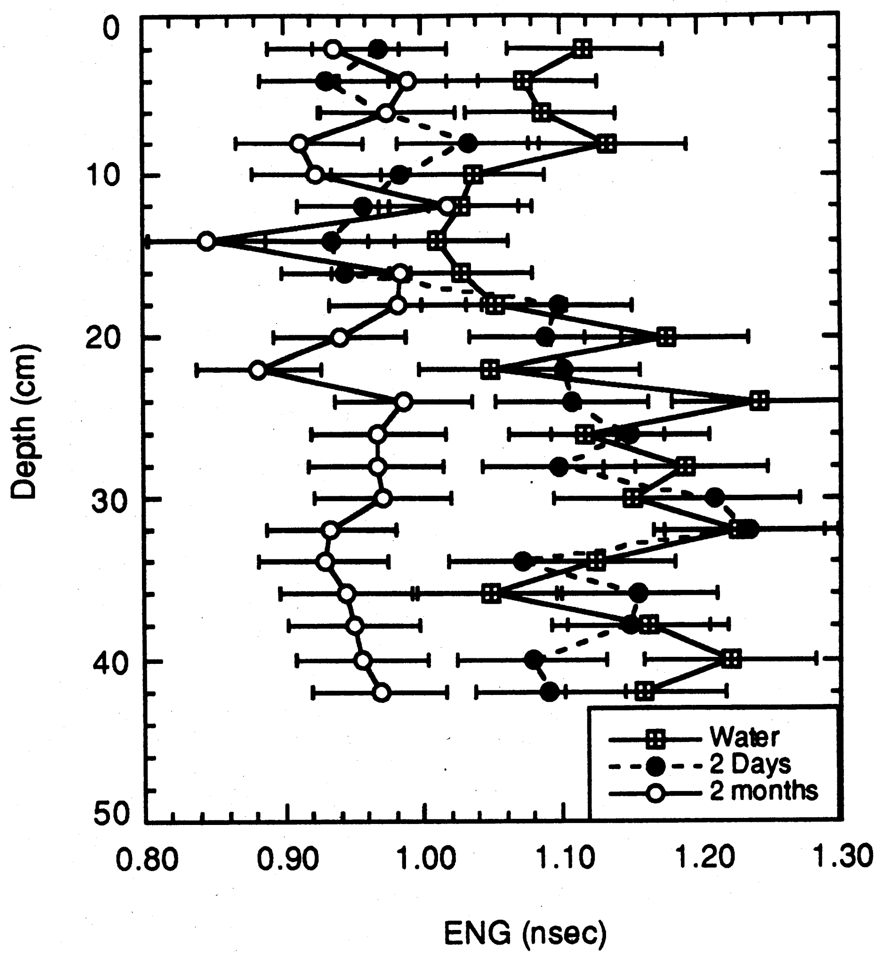


Fig. 4.9 Tests with Water and Unconsolidated and Consolidated Bentonite in the Annular Space

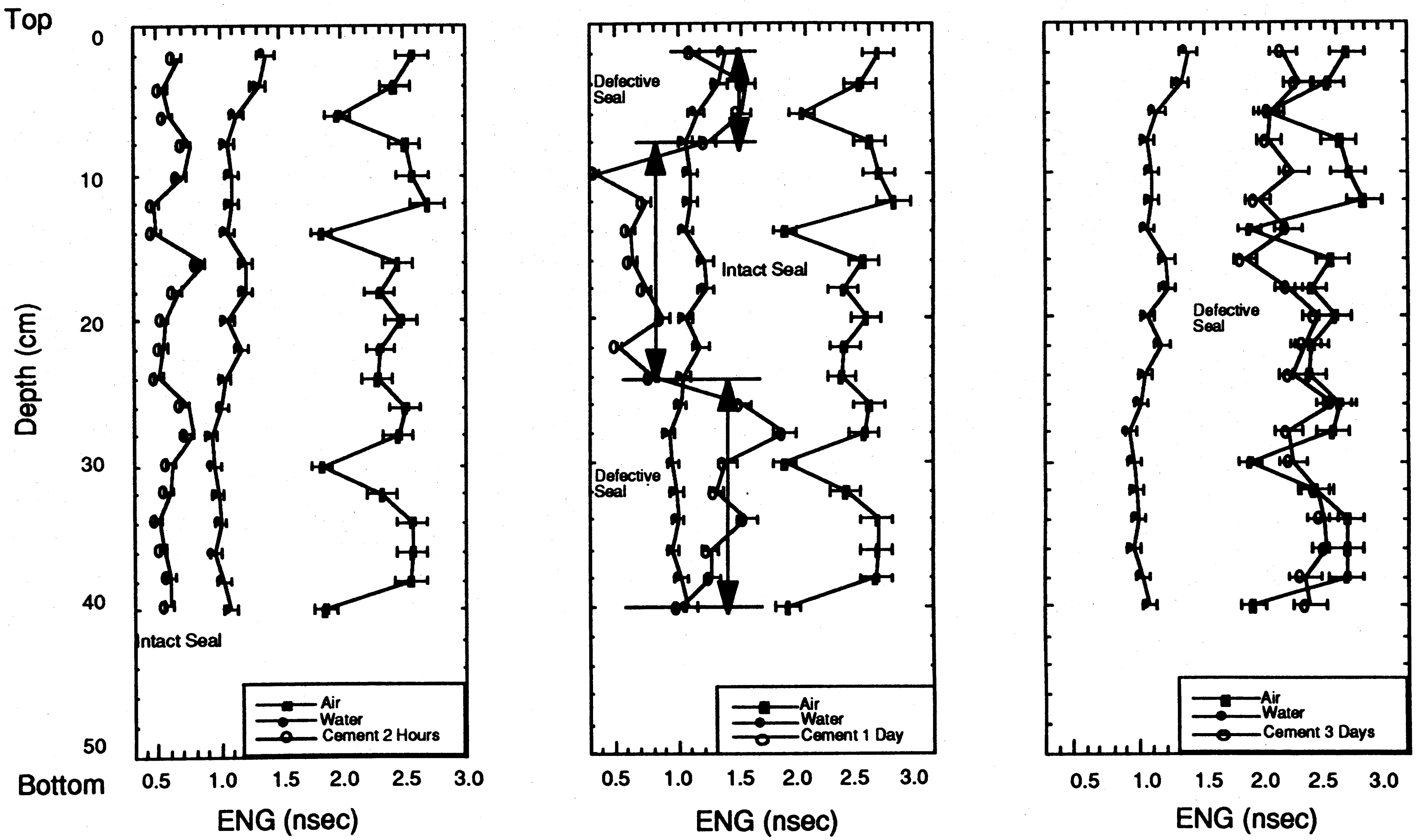


Fig. 4.10. Tests with Air, Water and Neat-Cement in the Annular Space

(Fertl et al. 1974, Schlumberger 1981, Bigelow 1985). Hydraulic tests are currently being conducted on the cement specimens to determine if such an annulus exists and if it is hydraulically active.

4.5.2 Seals Containing Defects

After the tests with single materials were completed, a testing program was initiated involving testing of bentonite seals containing purposely induced defects filled with air or water. Tests were conducted on seals containing single and multiple defects.

A bentonite specimen with a single large defect (Fig. 4.11a) was prepared by first filling the bottom 25 cm of the borehole model with bentonite. A 15-cm-thick layer of filter sand was then placed over the bentonite layer to simulate a defect. An additional 20 cm of bentonite was placed on top of the sand. Results of ultrasonic tests on this specimen are shown in Fig. 4.11b. Low ENG are obtained at locations where the casing is surrounded by bentonite. The ENG increased sharply to values similar to that of air at locations where the casing is surrounded by sand.

A 2 cm diameter PVC pipe extending to the top of the specimen was inserted into the sand when the specimen was prepared. The sand layer was later filled with water through the PVC pipe. The presence of water in the defect was readily detected by the ultrasonic method (Fig. 4.11c). If the defect had been filled with water before any testing, the location of the defect could not have been detected. The ENG of bentonite and water could not have been differentiated from each other.

A second specimen sealed with bentonite was prepared in a 100 mm diameter borehole model with multiple defects. These defects were smaller than the defect placed in the first specimen, such that the capability of the

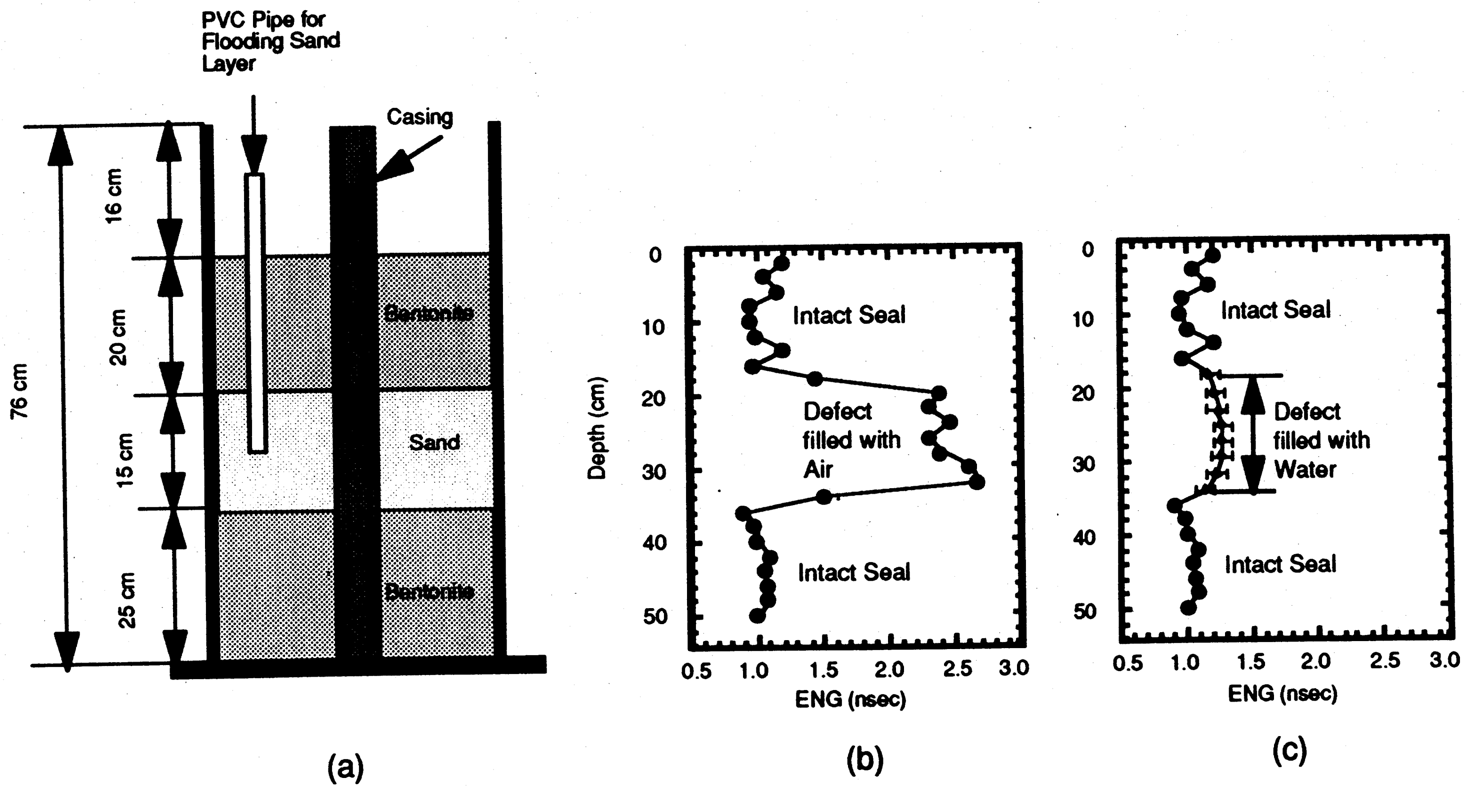


Fig. 4.11. Bentonite Specimen with a Single Defect

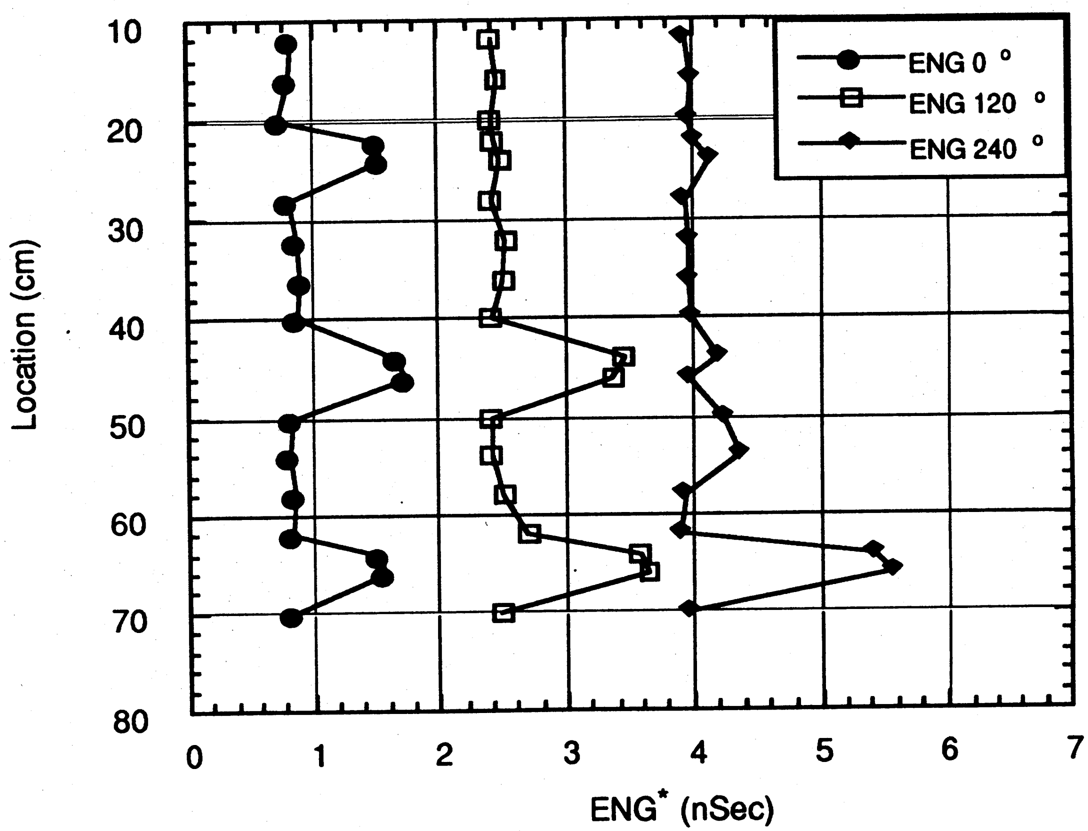
ultrasonic method to detect small defects would be evaluated. Results of the tests are shown in Fig. 4.12.

Defects constructed from geotextile strips were placed around the casing at 3 different depths. The geotextile strips are 4 cm wide and cut to various lengths. The top defect was constructed by placing the geotextile strip around one fourth (90°) of the perimeter of the casing. The middle defect was constructed by placing the strip around half (180°) the perimeter of the casing. The bottom defect was constructed by wrapping the geotextile strip around the entire (360°) perimeter of the casing. The defects were placed at equal distances from each other. The strips are taped into position.

Measurements were conducted at three different orientations within the casing by rotating the probe (Fig. 4.12). All of the defects were detected in the first test (0° orientation). When the probe was rotated 120° horizontally, the top defect could no longer be detected. Finally, when the probe was rotated 240°, only the bottom defect could be detected. These results agree precisely with the placement of the strips, suggesting that the ultrasonic methods is effective in detecting small defects in model borehole tests.

4.5.3 Probe Design for Field Tests

Presence of water is required in front of the transducer to act as a couplant for the transmission of ultrasonic waves into a casing. Therefore, a system to supply water in front of the transducer was designed for use in field tests. The system consists of lowering a soft rubber ball inside the casing and pressurizing the ball at a desired depth. The inflated ball plugs the casing, allowing for the part of the casing above the rubber ball to be filled with water (Fig. 4.13) After data acquisition is complete the rubber ball can be retracted by applying vacuum and then removed from the casing. Rubber balls of various



* ENG is similar in all of the tests conducted in different directions. 1.5 nSec is added to the ENG obtained from 120° tests, 3.0 nSec is added to the ENG obtained from 240° tests to provide a clear represantation of the results from all three tests on the same graph.

Fig. 4.12 - Bentonite Sample with Multiple Defects

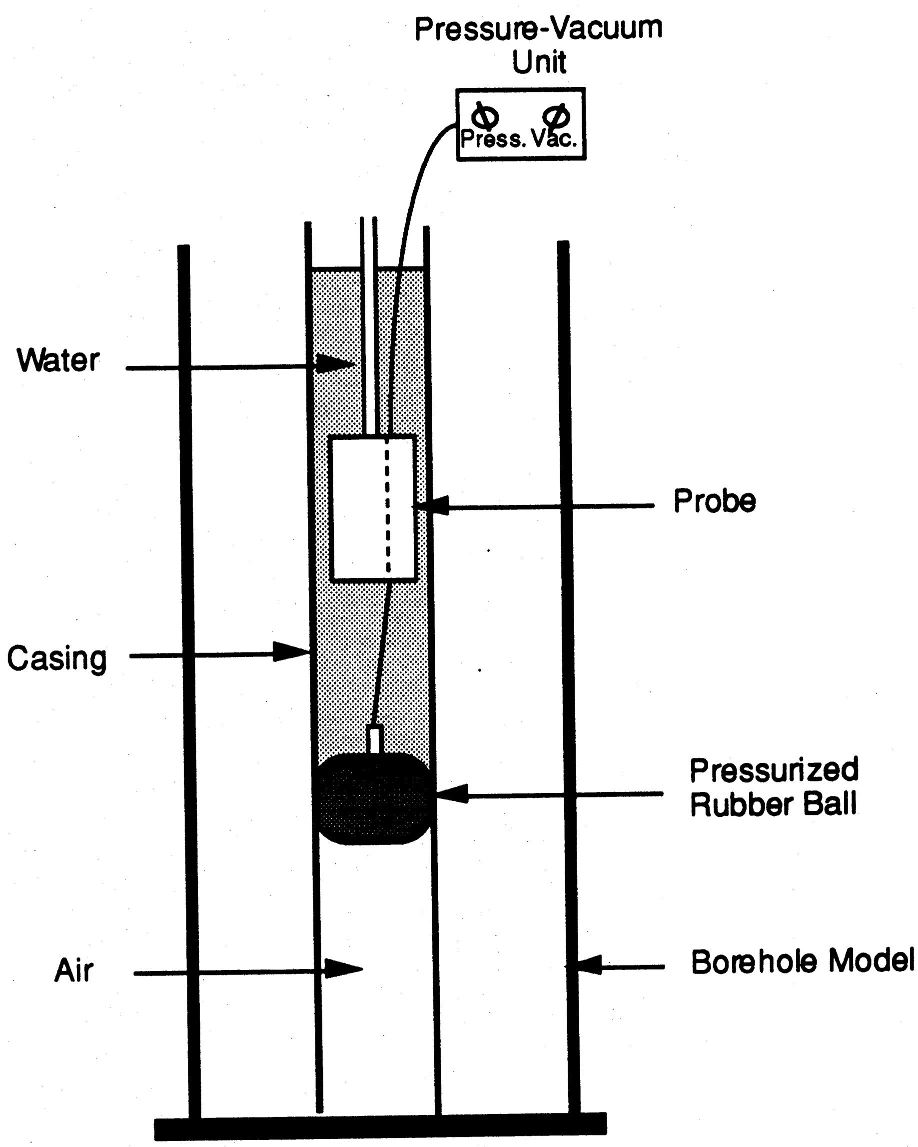


Fig. 4.13. Water Supply System for Field Tests

diameters are available for use in different diameter casings. The effectiveness of the system is currently being evaluated in the borehole models constructed in the laboratory.

SECTION FIVE
SUMMARY AND CONCLUSIONS

An ultrasonic nondestructive testing technique employing the pulse-echo inspection method was developed to evaluate the quality of the bond between a casing and a seal. The advantages of ultrasonic inspection are: the condition of a seal can be evaluated without disturbing the seal or formation, a single transducer along with commercially available hardware can be used for data acquisition and analysis, and data acquisition and analysis are simple and very sensitive.

The study was conducted in two phases. An initial phase of study was conducted using a planar arrangement of casing materials and seals to develop a measurement algorithm. A second phase of study consisted of the design, construction, and evaluation of a probe for downhole testing in well casings. Intact seals and seals containing defects were tested around a casing in both phases of the project. The conclusions drawn from the results of the tests are: the presence of seals consisting of bentonite and neat-cement and the presence of defects filled with air or water can be detected using the method developed, separations in the order of micrometers between the seal and the casing can be detected, and defects having an area as small as 2.50 cm^2 can be located with an accuracy of few millimeters.

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APPENDICES

APPENDIX A1

Settings on Pulser-Receiver

(1) - **Rep Rate:** 1

(2) - **Energy** : 1

(3) - **Atten** : 0 (both coarse and fine attenuator switches)

(4) - **H.P. Filter** : 0.3

(5) - **Damping** : 6

(6) - **Gain** : 40

(7) - **Mode Switch** : 1 (towards "T/R" BNC connector, pulse-echo mode)

The settings for these controls are selected once and used for all tests. Turning the instrument on or off does not affect these settings.

Operation of Waveform Analyzer

To initialize the waveform analyzer, the floppy disk drive is turned on and then the main body is initialized. The "ARM" key (upper right corner of the "Data Acquisition Keys") starts blinking shortly after the unit is turned on. The blinking (which shows waveforms are being received) is stopped by pressing the "DARM" key located in the same area. This allows for initial setup of the system for data acquisition under the desired settings. The other light that is on at this time comes from the "DISP" key located in the "Display Keys" area. The "DSPL MODE" is changed from "2 SEPR" to "SINGLE" by pressing the upper left softkey under the "DSPL MODE" menu.

The "TMB" button in the "Data Acquisition Keys" area is pressed to set up the timebase parameters: number of points, period, and delay. The default values in this area are "512" for "# POINTS", "20.0000nS" for "PERIOD" and "0.00000S" for "DELAY." The "# POINTS" is maintained at "512." The

"PERIOD" is set to "40.0000nS" by pressing the upper right softkey located in this area. The "TMB" setup is completed by pressing the upper right softkey under "DELAY" to increase it to "16uS" (the Greek letter "μ" is shown with a "u" by Data 6000).

The "INP" key in the "Data Acquisition Keys" area is used to set the coupling of the system. The default value "DC" under the "COUPLING" menu is changed to "AC" by pressing the upper right softkey under the menu. The brightness of the screen can be increased by pressing the "DISP" and "MARK" keys simultaneously that are located in the "Display Keys" area. The intensity can be increased up to "15" by pressing the upper right softkey located in this area.

Data Acquisition

The computer program is loaded into the main body every time the waveform analyzer is turned on. There is no way of saving and storing a program in the main body of the Data 6000. A step-by-step procedure to load the program is:

(1) Press the "XFER" button on the "Floppy Disk Drive." Change the "FILE" setting from "BUF.A1" to "BUF.X0" by pressing the upper right softkey under the "FILE" menu. The error message that appears on the screen is just a warning, not a real error message, and should be ignored. Press the upper right softkey located under the "ENTER" menu. The message "BUF.X0 = BUF.A1" appears on the upper left corner of the screen.

(2) Put the floppy disk that contains the computer program in the left drive, which is drive "A".

(3) Press the "DIR" button located next to the "XFER" key on the "Floppy Disk Drive." Change the "VOLUME" from "SYSTEM" to "A:" by pressing the upper

right softkey located in this area. Move the ">" mark down next to the desired program by pressing the lower softkey under "↓." When the ">" mark is next to the program of interest, press the upper right softkey under the "LOAD" menu.

(4) Press the "PROG" key located in the "Special Function Keys" area. Verify the program with a written copy by scrolling up and down using the upper softkeys located under the arrow menu. After verification is complete, change the "MODE" from "EDIT" to "RUN" by pressing the upper right softkey located in this area.

(5) Press "DISP" key located in the "Display Keys Area". Press the "CLR," "α" (the only green button), "DIFF," "COPY," "MEAN," and "R/S" keys located on the "Function Keypad," specifically in this sequence. All of these labels are printed in black above the keys except for the green "α" key. The message "N=0" will appear on the screen and the "SOURCE" will be moved from "BUF.X0" to "N" automatically. Press the "PROG" and "DISP" keys (in sequence) to see the counter "N=0.00000" on the upper left corner of the screen. The Data 6000 is now ready for data acquisition.

(6) Press the "ARM" key to initiate data acquisition. When "N" reaches 16.000, stop acquisition by pressing the "DARM" key located directly below the "ARM" key.

(7) Press upper right softkey under the "SOURCE" menu to move to the "TR.RMS" screen that contains the record of RMS measurements obtained from this set of measurements. Press the "MEAN" key located on the "Function Keypad" to view the mean of the 16 consecutive RMS measurements. Record this number. Press the "SDEV" key located next to the "MEAN" key to view the standard deviation of the measurements. Record this number, also.

(8) Press the upper right softkey under "SOURCE" menu again to move to the "TRENGY" screen that contains a record of ENG values obtained from this set of measurements. Repeat the procedure described in the pervious step to obtain the mean and standard deviations of the ENG values. This completes the data acquisition for the first location.

(9) To start the next set of measurements, press the "DIR" key located in the "Display Keys" area. Change the "VOLUME" from "A:" to "SYSTEM" by pressing the upper left softkey under the "VOLUME" menus. Move the ">" mark down by pressing the upper softkey under the arrow ("↓"). Stop at the line showing "TR.RMS..." Press the softkeys under the "DELETE" menus diagonally to change the number of points given in this line to zero. Repeat the same procedure to the following line ("TRENGY...").

(10) Press the "DISP" key. The "SOURCE" will appear as "NONE" on the screen. Press "CLR," "α," "DIFF," "COPY," "MEAN," and "R/S" keys located on the "Function Keypad" in this sequence. The message "N=0" will appear on the screen and the source will be moved to "N" automatically. Press the "PROG" and "DISP" keys in sequence so that the message "N = 16.00000" appears on the upper left corner of the screen. Press the upper right softkey under "SOURCE" to move to the "TR.RMS" screen. The Data 6000 is now ready for the next data acquisition exercise.

(11) Press the "ARM" key to start data acquisition. The number in the counter "N = 16.00000" will move to "N = 1.00000" automatically when acquisition starts. The rest of the data acquisition procedure is the same as above (Steps 6 to 8) and it can be repeated (Steps 9 to 10) as many times as desired.

(12) If a "bad" data point (a data point significantly lower or higher than the rest of the data points) is acquired, it can be detected in the "TR.RMS" screen.

Data acquisition can be stopped immediately by pressing the "DARM" key. Data acquisition can be reinitiated following the procedures described in Steps 9 to 11. However, the data points acquired before the "bad" point are lost in the analysis. It is not possible to eliminate only the "bad" data point from the record of the 16 consecutive measurements and use the rest of the points. The data acquisition at that particular location must be repeated.

APPENDIX A2

TREND* PROGRAM

```
N = N + 1

DSPL(N)

BUF.X0 = BUF.A1

BUF.X0(16.00011uS, 17.5uS) = 0

BUF.X0 = BUF.X0 - MEAN(BUF.X0)

BUF.X0 = BUF.X0 / PKPK(BUF.X0)

CURSOR = 2

XSTART = XMIN(BUF.X0)

XSTART = XSTART + 5.5uS

XEND = XSTART + 10.5uS

TR.RMS = TRND(CR:RMS(BUF.X0),,16,16,1))

TRENGY = TRND(CR:ENGY(BUF.X0),,16,16,1))
```

* Trend is the name of the function used to store consecutive data points in the waveform analyzer.