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CORE LABORATORIES

PHYSICAL AND DYNAMIC MECHANICAL PROPERTIES
OF REDBED SANDS AND ANHYDRITE
BRIDGES STATE NO. 507

Performed for:
Mobil Exploration and Producing U.S.
Box 633
Midland, Texas 79702

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Performed by:
Core Laboratories
Dallas Special Core Analysis Lab
1300 East Rochelle
Irving, Texas 75062-3963
(214) 570-5055

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PROGRAM PARTICIPANTS

Basic Properties Measurements	Tommy Wallace
Acoustic Measurements	Marilyn Price
Report Preparation	Greg Salter
	Carol Admire
	Geraldine Luke
	Frances McGlinn
Report Review	Marilyn Price
Final Review	Dr. Joel Walls

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SECTION 1

SUMMARY

In a telephone conversation, Mr. Bill Hermance of Mobil Exploration and Producing U.S. requested that representatives of Core Laboratories obtain selected core pieces from the Mobil warehouse facility located in Dallas, Texas. Air permeability and porosity measurements were requested on samples obtained from the Redbed Sandstone Formation while rock mechanics determinations were requested on samples obtained from the anhydrite section of the core. Preliminary results of the air permeability and porosity data for all samples were given on December 4, 1987. The final results of the above analyses are presented herein. The one conglomerate and four sand samples are lithologically described and are identified as to sample number and depth interval in Section 3.

SECTION 2

EXPERIMENTAL PROCEDURES

Sample Preparation

Eight core boxes containing selected whole core segments, four each from the aforementioned lithological zones, were obtained for use in this study. For the Redbed Sandstone Formation, four horizontal, 1.5-inch diameter cylindrical core plugs were obtained using a diamond core bit with water as the coolant and lubricant. Four vertical 1-inch diameter cylindrical anhydrite plugs were obtained using a diamond core bit with a brine containing 100,000 ppm sodium chloride saturated with calcium sulfate as the bit coolant and lubricant.

All samples were extracted of hydrocarbons using toluene in a soxhlet reflux apparatus and leached of salt using methanol. The samples were dried in a vacuum oven at a temperature of 220 degrees fahrenheit.

Physical Properties

Length and diameter were measured with precision calipers, and then bulk volume was determined by Hg immersion. Air permeability at 400 psi net stress and Boyle's Law porosities (using Helium as the gaseous medium) were measured on the clean and dried core plugs. Grain density was calculated using the following equation:

$$G.D. = \frac{\text{dry wt.}}{V_b - V_p}$$

where: dry wt. = weight after vacuum drying

V_b = bulk volume from Hg immersion

V_p = He pore volume

The four anhydrite samples were then pressure saturated at 2000 psi with 100K ppm NaCl and 8 g/L $CaSo_4$ brine. Bulk density, used in the calculation of dynamic elastic moduli, was calculated by dividing the saturated weight by the Hg bulk volume.

Velocity Measurements

The anhydrite samples were loaded into the mechanical properties vessel while confining pressure was applied incrementally with pore pressure, so as not to exceed a net stress of 1000 psi. During velocity measurements, pore pressure and confining pressure were held at 1000 and 2000 psi respectively.

Compressional and shear velocity, along with dynamic elastic moduli, are presented in the following section.

SECTION 3

TEST RESULTS

Basic Properties

Rock Descriptions

Ultrasonic Velocity and Dynamic Moduli at Increased Stress

BASIC PROPERTIES

SAMPLE I.D.	DEPTH (feet)	PERMEABILITY TO AIR (md)	POROSITY (%)	GRAIN DENSITY (g/cm^3)
1	1264	88	12.8	2.74
2	1311	103	22.5	2.66
3	1340	247	24.0	2.66
4	1396	34	18.6	2.66
5V	1543	0.004	0.3	2.95
6V	1562	0.006	0.4	2.94
7V	1602	0.007	0.5	2.95
8V	1610	0.007	0.7	2.95

IDENTIFICATION AND LITHOLOGICAL DESCRIPTION OF SAMPLES

SAMPLE I.D.	DEPTH (feet)	LITHOLOGICAL DESCRIPTION
1	1264	Cg, pk, lge slty sd pbls in f-med g mtrx, wl ind
2	1311	Ss, pk, f g, wl srt, wl ind
3	1340	Ss, pk, f g, wl srt, wl ind
4	1396	Ss, pk, f g, wl srt, wl ind

ULTRASONIC VELOCITY AND DYNAMIC MODULI AS A FUNCTION OF PRESSURE

SAMPLE I.D.	PNET (psi)	COMP.VEL. (ft./s)	SHEAR VEL. (ft./s)	POISSON'S RATIO	SHEAR MOD. (1E6 psi)	BULK MOD. (1E6 psi)	YOUNG'S MOD. (1E6 psi)
5V	1000	20320	10672	0.30954	4.38810	10.0570	11.4928
6V	1000	20780	10604	0.32396	4.30150	10.7839	11.3901
7V	1000	20014	10180	0.32551	4.00630	10.1448	10.6208
8V	1000	19795	10052	0.32626	3.93338	10.0096	10.4344

SECTION 4

DISCUSSION

Eight plug samples from Bridges State No. 507 have been tested for physical properties. The one conglomerate and three sandstone plugs (samples 1 - 4) range in porosity and permeability from 12.8 to 24% and 34 to 247 md respectively. Grain densities vary from 2.66 to 2.74 grams per cubic centimeter. The anhydrite plugs (samples 5V - 8V) are extremely tight, ranging in porosity from 0.3 to 0.7% and in permeability from 0.004 to 0.007 md. Grain densities of the anhydrites are 2.94 - 2.95 grams per cubic centimeter.

The anhydrite samples were also tested for compressional and shear velocity. Their low porosities result in high compressional and shear velocities and correspondingly high elastic moduli.

SECTION 5

APPENDIX

EXPERIMENTAL METHODS AND MEASUREMENT APPARATUS

FOR ULTTRASONIC VELOCITY

Ultrasonic Velocity Apparatus and Methods

Measurement Basics

In laboratory rock measurements, ultrasonic waves are generated by ceramic transducers which are specially made to exhibit "piezoelectric" properties. When voltage is applied to a piezoelectric material it expands, contracts or changes shape depending on the type of material and the polarity of the applied voltage. Conversely when the material is stressed mechanically it generates an electrical voltage. Because of this property, piezoelectric transducers are ideal for sending and receiving sound waves.

There are two types of transducers used to measure ultrasonic velocity in rock samples: compressional and shear. The compressional transducer is usually a thin round disk which, when driven by a voltage across its faces, will become slightly thicker or thinner. This expansion or contraction is less than 1 microinch but is sufficient to create a pulse which will travel through the rock sample and be detected by an identical transducer on the other side. The shear transducer responds somewhat differently to an applied voltage. In this transducer, one face moves left or right with respect to the other face. Again the displacement is very small but is sufficient to generate a "shear wave" which will travel through a solid material and be detected by another shear transducer. A diagram of compressional and shear wave transducer response to an applied voltage is shown in Figure 1.

Historical Note: The compressional wave is often called the "P" wave and the shear wave called the "S" wave. These abbreviations originated with early seismologists who noted that earthquakes generate two types of energy which arrive at distant detectors at different times. The faster moving wave was called the Primary wave and the slower one, the Secondary wave.

The frequency of sound energy generated by these two types of transducers is controlled by the thickness of the piezoelectric material. When pulsed with a high voltage square wave or spike, the transducers oscillate at their principle resonant frequency which increases as the transducer is made thinner. For a compressional disc 0.1 inch thick, the resonant frequency is about 750 kHz. For a shear plate 0.1 inch thick the resonant frequency is about 550 kHz. Both the P and S transducers in our system are of the proper thickness to generate 1 MHz sound energy. This frequency was chosen because its corresponding wavelength is usually much less than the length of our samples but greater than their grain size. Typical wavelengths (1 MHz) in rock range from 2 mm to 5 mm. The relationship between frequency (F) and wavelength (λ) is simply $\lambda = V/F$ where V is velocity.

Because shear transducers are not perfect they always produce some compressional energy which travels faster than the shear wave and causes unwanted "precursor" signal ahead of the desired shear signal. Another peculiar feature of the shear plate transducer is that the azimuthal orientation of the sender and receiver must be the same or the energy generated by one will not be detected by the other (see Figure 2A). Both of these problems can be avoided by using a circular pattern of shear plates all facing in the same rotational direction, but with opposite compressional polarizations. This configuration is called a torsional transducer and is used in all of our experiments. Because these shear plates only need to contact the outer perimeter of the plug sample, the inner space can be used for a compressional disc. The combination of a P disc and torsional S transducer is called a coaxial transducer (Figure 2B).

The displacements generated by piezoelectric transducer are very small. This means that the transducer and the rock must be in very "intimate" contact. One way to accomplish this would be to glue the transducers directly to the rock. Of course this is impractical for several reasons so the transducers are bonded to metal end plugs instead. The end plugs in our system are made of titanium which is noncorrosive and has a low density. The acoustic waves are efficiently transmitted from end plug to sample when the rock face is very flat and some pressure is applied by the confining fluid.

The determination of acoustic velocity with the system is accomplished by careful timing measurements on the digital oscilloscope. The scope is triggered by the high voltage pulser which drives the transmitting transducer. The waveform displayed is that of the corresponding receiving transducer. The travel time between trigger and the "first break" is read directly from the oscilloscope screen. An example of shear (torsional) and compressional waveforms is shown in Figure 3. This travel time also includes the end plugs so this end plug travel time must be subtracted from what is shown on the screen to obtain a rock travel time. The acoustic velocity is simply the length of the sample divided by the rock travel time. Velocity is usually reported in km/sec or mm/μsec which are numerically equivalent. Other possible units are m/sec, ft/sec, or inverse velocity (slowness) in μsec/ft.

As mentioned previously, the shear transducer also produces a small amount of compressional energy. Since the P wave always travels faster than the S wave, this P energy can show up on the shear waveform as precursor noise. In severe cases this noise can make it difficult to find the shear wave first break. Such problems usually occur in very long samples or at very low effective pressure. In such cases the waveforms are recorded on floppy discs for more intense scrutiny and comparison to subsequent waveforms recorded under higher effective stress conditions.

In addition to simply calculating and reporting P and S velocity, we can also calculate certain elastic moduli from the velocity data. An elastic material is one that strains (or deforms) in an amount directly proportional to the pressure applied to it. Most materials behave elastically when the stresses and corresponding strains are small. An elastic modulus is the number that describes how much a given material strains in response to a given stress. The theory of elasticity states that if a material is isotropic, or the same in all directions, that its elastic behavior can be completely described by only two elastic moduli. These two moduli are the shear modulus, μ, and the bulk modulus, K. Both of these can be calculated from V_p, V_s, and bulk density ρ, with the following relations:

$$\mu = \rho V_s^2$$

$$K = \rho(V_p^2 - 4/3\ V_s^2).$$

Two other elastic moduli which are often used are Poisson's ratio, ν, and Young's modulus, E, which are given by:

$$\nu = \frac{\left(\frac{V_p}{V_s}\right)^2 - 2}{2\left(\left(\frac{V_p}{V_s}\right)^2 - 1\right)}$$

$$E = \frac{9\rho V_s^2\left(\frac{K}{\rho V_s^2}\right)^2}{3\left(\frac{K}{\rho V_s^2}\right)^2 + 1}$$

Measurement Apparatus

The system used by Core Lab to measure ultrasonic velocity is a four sample device with automated pore pressure and confining pressure control. Figure 4 is a schematic diagram of the system. Equal hydrostatic confining pressure is applied to four jacketed samples by a hydraulic pump. A pressure transducer, the pump, and a bleed valve are connected to the Data Acquisition and

Control (DAC) unit which communicates over an IEEE 488 bus to the computer. In this way, confining pressure can be automatically continuously adjusted. Confining pressure can range from 200 psi to 15,000 psi.

The pore pressure in each sample is controlled by a separate positive displacement pump with a stepping motor drive. These four pumps are connected via the DAC to the computer. Four individual transducers monitor the pore pressure of the samples. This combination allows the computer to both control pore pressure and measure pore volume change on each sample individually. Pore pressure can range from 0 to 5000 psi.

Temperature of the system can be adjusted from ambient (about 25°C) to 100°C by a proportional controller. A thermocouple inside the oil-filled pressure vessel measures the sample temperature to 1 degree C.

There are eight compressional and eight torsional shear transducers in the system. They are switched electronically to the pulse generator or input amplifier depending on whether they are transmitters or receivers. The driving pulse is a high voltage square wave of 1 to 10 microseconds in duration. The received signal on the other side of the rock sample is amplified by 20 or 40 db and displayed on the digital scope. A reference marker is moved to the location of the first break and the time to the reference marker is digitally displayed on the scope screen. The signal can be recorded onto a floppy disc for future analysis.

A summary of the system measurement accuracy and resolution is given below:

Parameter	Accuracy	Resolution
Pressure	0.01%	0.1 bar
Temperature	1%	1.0°C
Travel Time	0.1%	0.05 usec
Calculated Velocity*	1%	0.5%
Elastic Moduli	5%	2%
Pore Volume Change	0.1%	0.0001 cc

*Velocity accuracy and resolution are usually better than stated.

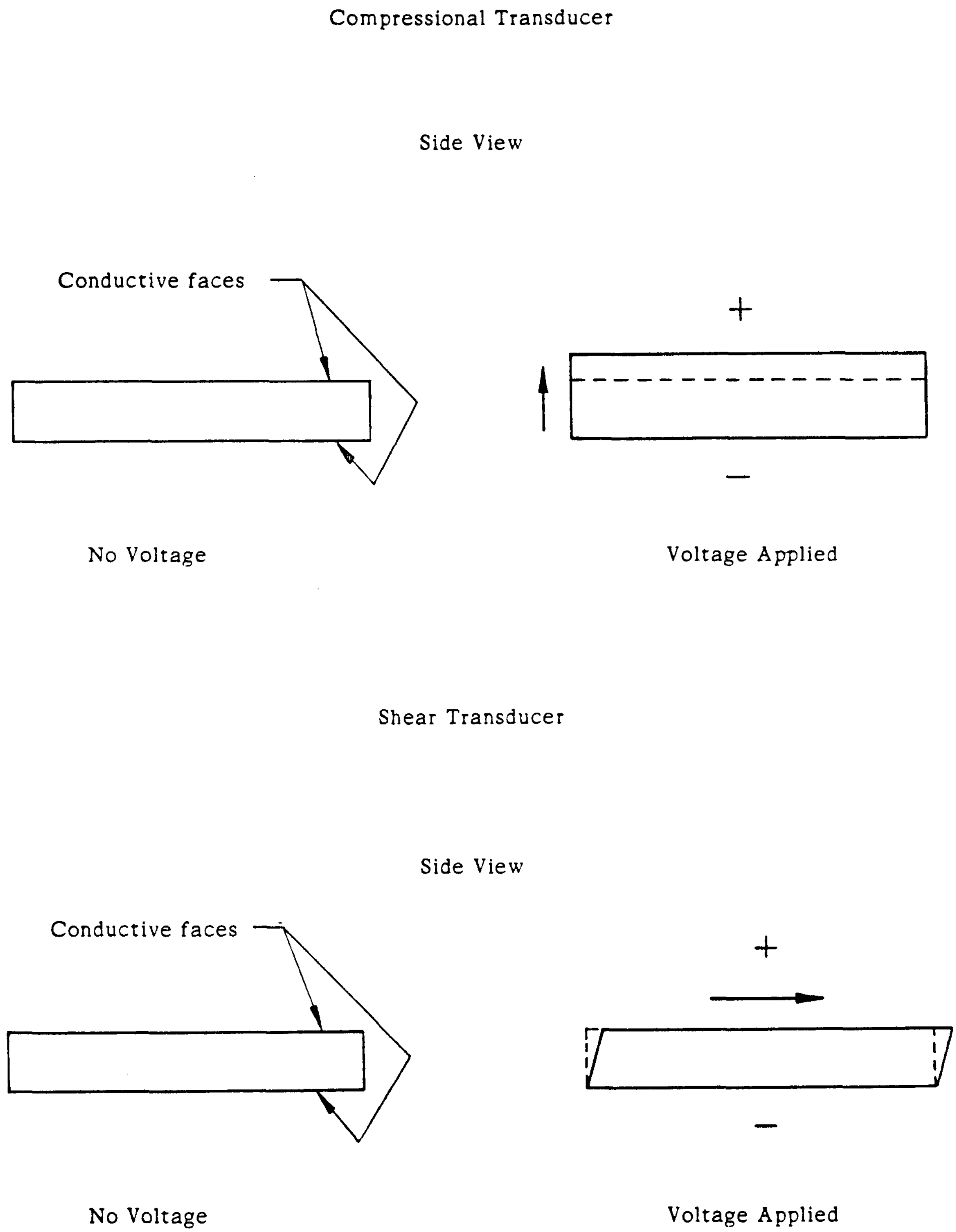


Figure 1. Shear and compressional transducer response to applied voltage.

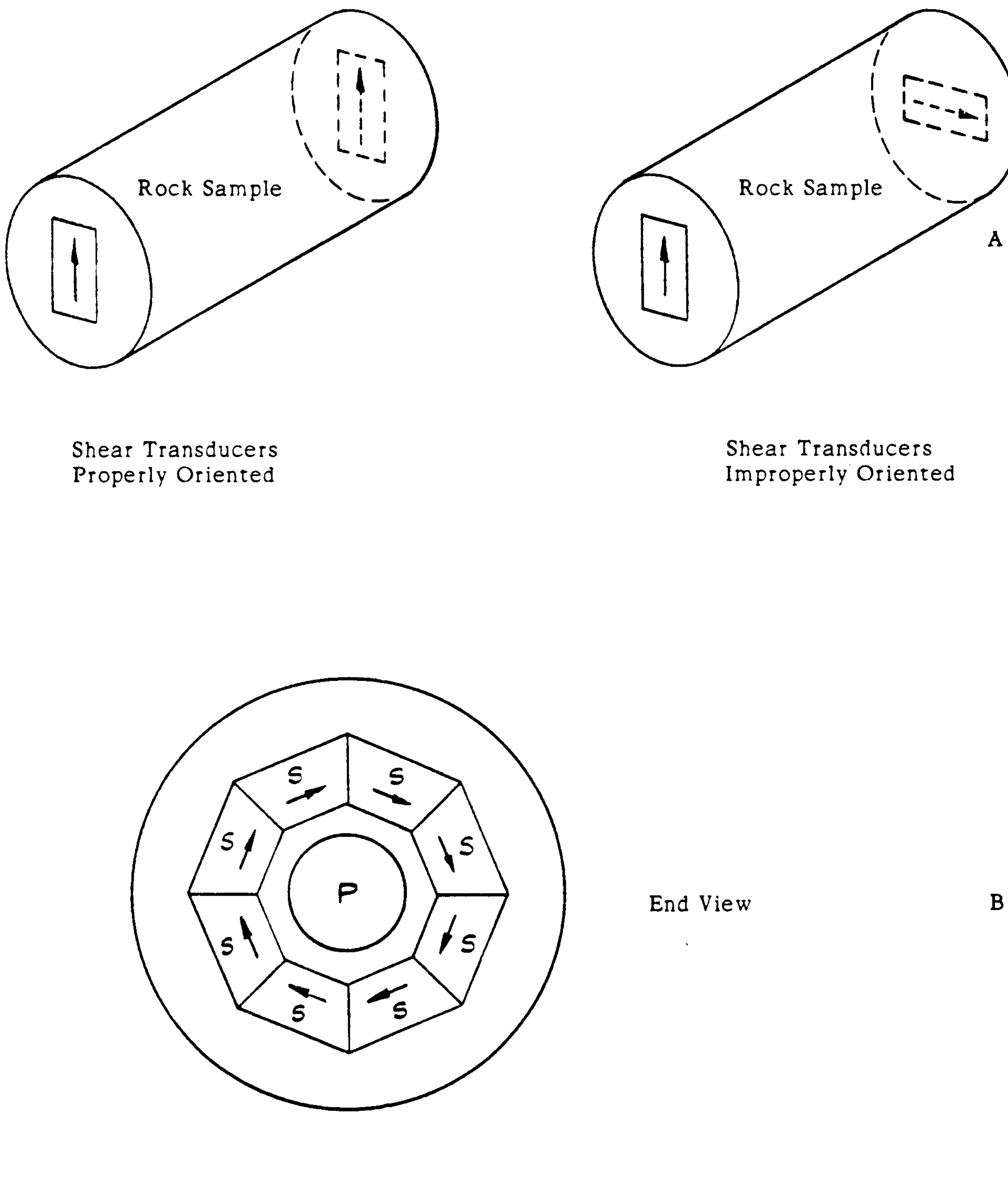
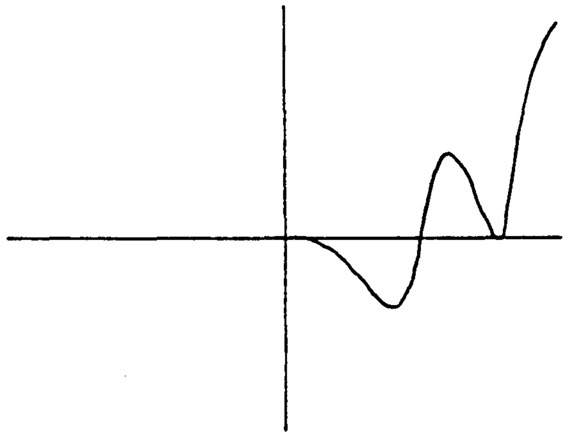
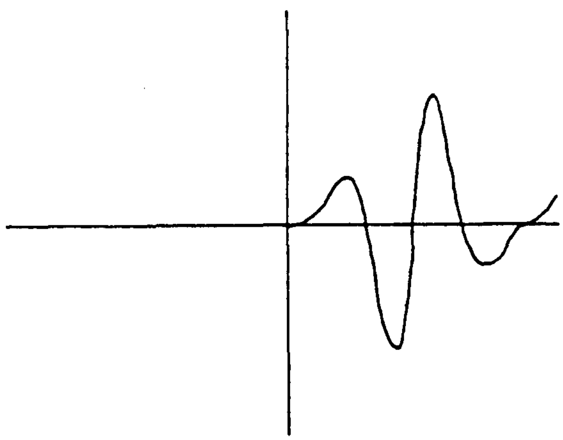


Figure 2. Coaxial P and S transducer.



TORSIONAL S WAVE SIGNAL



P WAVE SIGNAL

Figure 3. Shear and compressional waveforms.

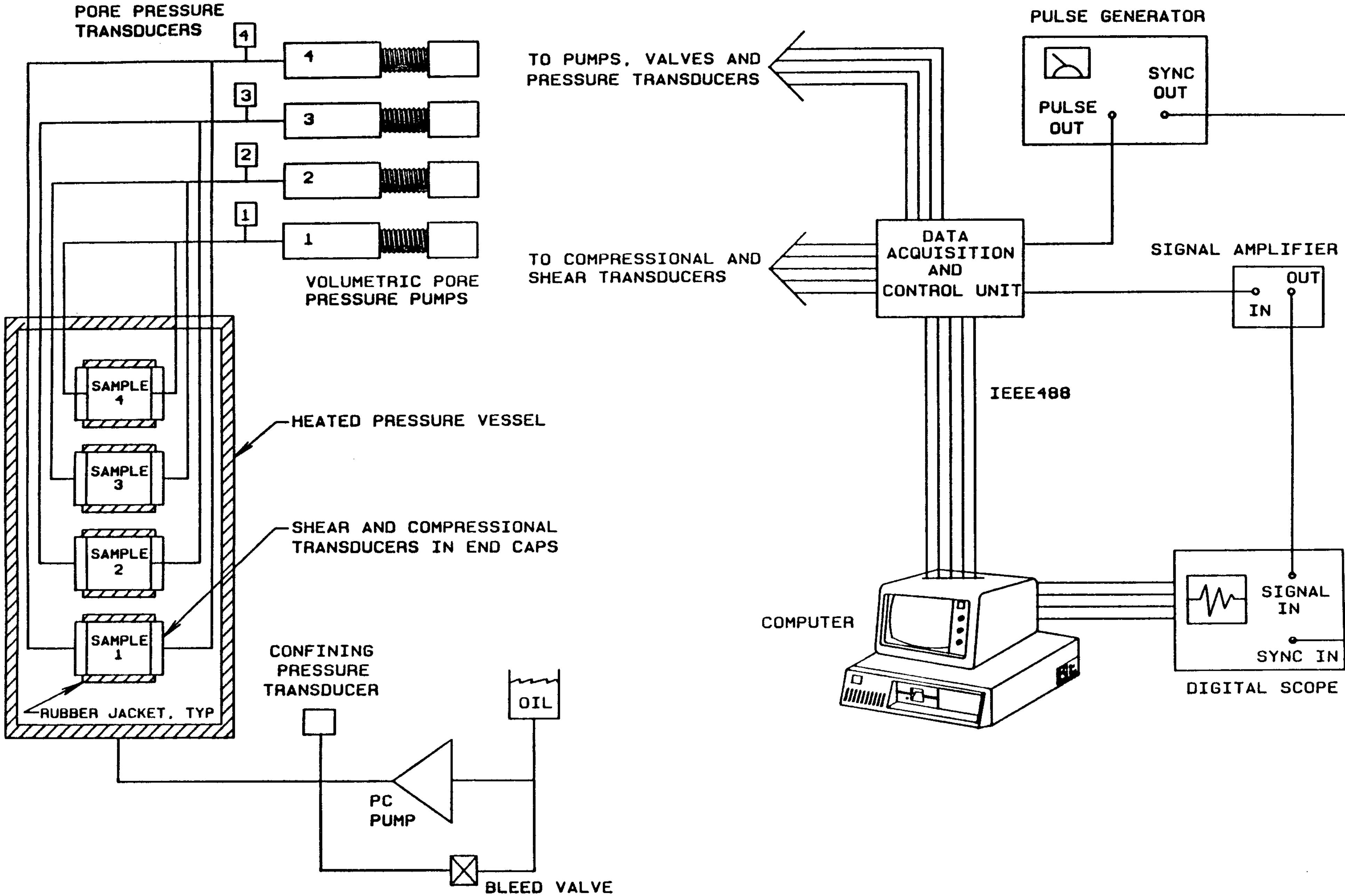


FIGURE 4: SCHEMATIC, ULTRASONIC VELOCITY SYSTEM