ULTRASONIC TECHNIQUES IN OIL WELL LOGGING

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ABSTRACT

Oil well logging is used to provide the oil and gas industry with information essential to discovering and extracting hydrocarbons.

This paper addresses two ultrasonic measurements that are presently used in oil well logging. The most widely used is an ultrasonic technique that evaluates the integrity of the cement seal after a steel casing has been lowered and cemented in place. This instrument is also capable of monitoring the effects of corrosion both on the inner and outer surfaces of the casing. The measurement is based on a pulsed resonant technique.

Less widely used is the the Borehole Televiewer, an ultrasonic scanning device based on a pulse-echo technique. It provides an acoustic image of geologic features such as rock layers and fractures.

INTRODUCTION

When an oil well is drilled, little information is available at the surface as to whether the drill has penetrated an oil or gas reservoir. For over fifty years, measuring instruments called sondes have been lowered into these boreholes to depths of up to 30,000 feet on a wireline. The sondes are typically cylindrical tubes tens of feet long crammed with sensors and electronics. As the instruments are pulled back to the surface, continuous measurements of the physical parameters of the subsurface rocks are recorded using electromagnetic, acoustic, and nuclear measurements. The measurements, recorded as a function of depth, are called logs.

Logs, also called surveys, are first made in open-hole when the well has been freshly drilled and the rock surfaces are still exposed. Later measurements are made in cased-hole after a steel casing has been set and cemented into the borehole prior to production. A casing is used to keep the hole from collapsing and to seal oil-bearing formations from water-bearing formations.

In all cases the environment is hostile. A drilling fluid, called mud, is used that is caustic, abrasive, and contains particulate matter to increase its density and seal the rock formation. Temperatures can exceed 175°C and pressures can range up to 20,000 psi.

This environment had precluded the use of ultrasonics in boreholes until recently. The need for high resolution measurements leads naturally to ultrasonics. In open-holes, finely laminated or fractured rocks can be imaged. In cased-holes, casing corrosion and cement bonding conditions can be readily evaluated.

BOREHOLE IMAGING

An open-hole problem that has confounded geologists for years has been the evaluation of fractured reservoirs. Various approaches using optical techniques ranging from optical cameras to television cameras were tried in optically clear borehole fluids. Unfortunately almost all boreholes are filled with opaque drilling mud.

In 1969, Zemanek et al [1] at Mobil developed and patented an ultrasonic logging tool that produced images of the borehole wall. The device was called a Borehole Televiewer (BHTV) (Figure 1). It consisted of an 1/2-inch diameter 2 MHz piezoelectric transducer operated in the pulse-echo mode. This transducer was rotated within a sonde housing behind a protective acoustic window. The signal was envelope-detected and the low frequency envelope transmitted to the surface. A magnetometer system provided a means for orientation in open-hole logging. The BHTV provided adequate images of the geologic features such as fractures, rock layering and corrosion pits in casings as long as the sonde was well centered in the borehole. The images were adversely affected when the tool was eccentered in the borehole and had black vertical stripes which obscured the underlying geological features of interest. Consequently, the tool was difficult to operate and interest as a commercial service quickly waned. Georgi [2], in a recent paper, has given an excellent analysis of the geometric aspects of the BHTV.

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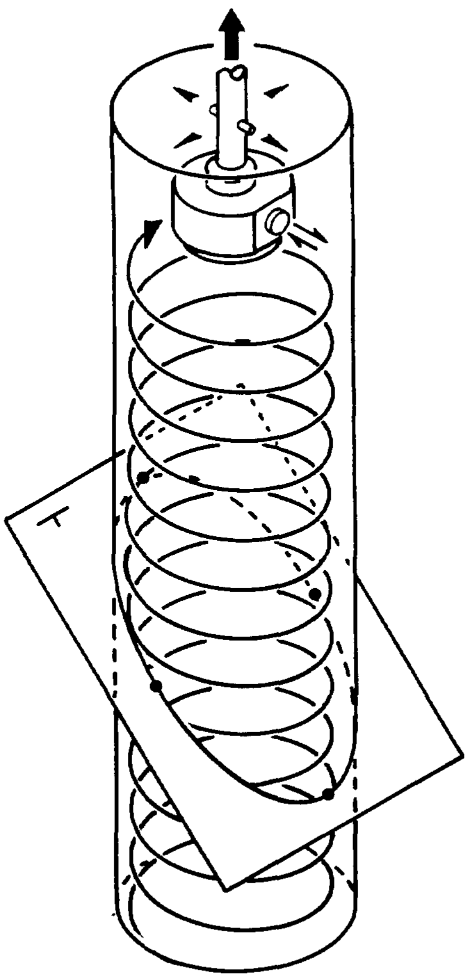


Figure 1. Borehole Televiewer

Since the need for evaluating fractured reservoirs remained important, technological advances were incorporated to improve its images [6,7,8,9,10,11]. The operating frequency was lowered and is switchable between approximately 1 MHz and 0.5 MHz. Variable gain amplifiers increased the dynamic range. Travel time, indicating the distance between the transducer and borehole wall, was added as a new measurement. As digital telemetry became commonplace for logging tools, the signals were digitized to allow image processing techniques to be applied to the data. Figure 2 and Figure 3 show images that benefit from all of these improvements. However, even with these advances, the BHTV is used only in special cases.

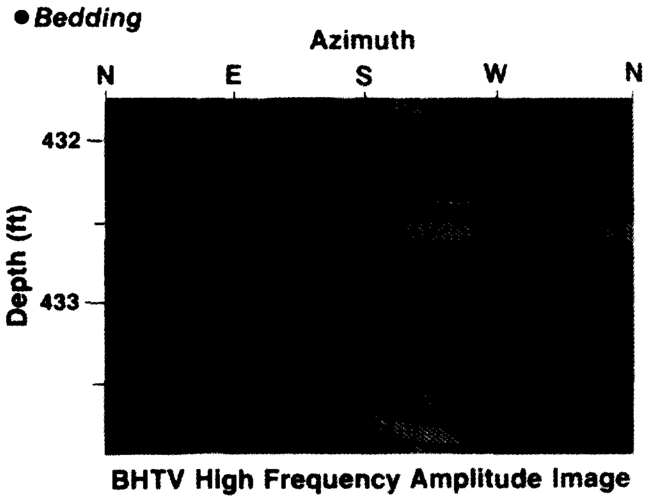


Figure 2. BHTV Image

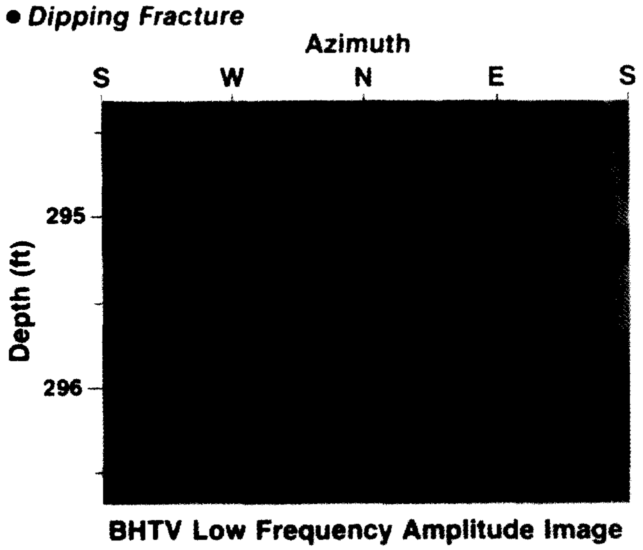


Figure 3. BHTV Image

CEMENT EVALUATION

The most widely used ultrasonic measurement, developed and patented by Havira [3,4,5] at Schlumberger, evaluates the hydraulic seal formed by the cement which is pumped between the casing and the borehole wall. The cement hydraulically seals the hydrocarbon bearing zones from water bearing zones and mechanically supports the casing.

In the process of cementing problems occur. Channels in the cement allow hydraulic communication between zones. A small gap (microannulus) between the casing and cement due to thermal or pressure effects may exist. This gap is generally less than (0.004") and does not allow hydraulic communication. Low frequency sonic techniques exist for evaluation of the cement by measuring the attenuation of an extensional mode in the casing which is generated by an omnidirectional source. However, this technique is sensitive to the physical bond to the casing and as such indicates a poor hydraulic seal when a microannulus exists. Also, the lack of azimuthal resolution makes the location of channels difficult.

To overcome these limitations, ultrasonic techniques were investigated. The objective was to find a method that would provide information about hydraulic sealing in the presence of microannuli; achieve sufficient circumferential resolution so that channels could be detected, and to evaluate the cement to formation (borehole wall) seal. The major challenges in achieving these objectives come from the environmental conditions shown in Table I.

ENVIRONMENT

Temperature	-	to 175°C
Pressures	-	to 20,000 psi
Borehole fluid	-	drilling mud
	-	attenuation - 0-9 db/cm at 0.5 MHz
	-	density - 1-2.5 gm/cc
Cement	-	impedance - 3-7 MRayls
Space limitation	-	sonde diameter less than 4 inches

Table I

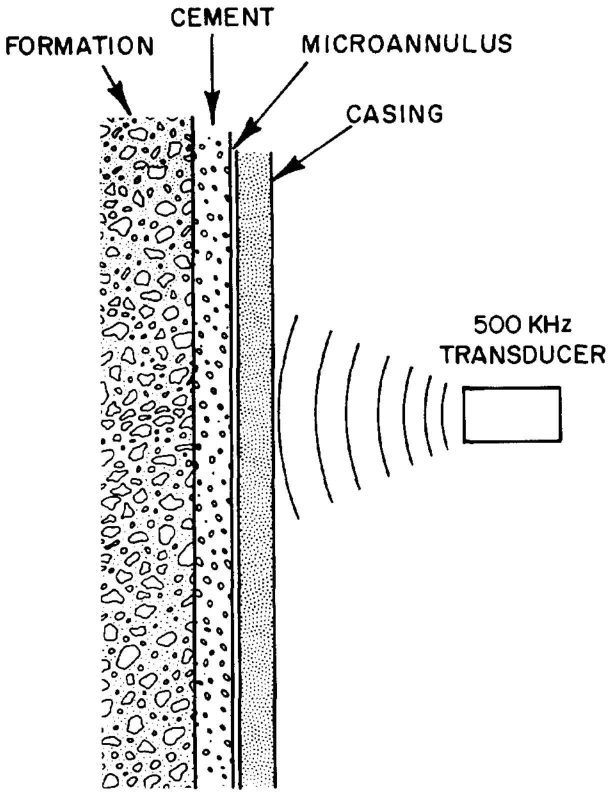


Figure 4. Casing-cement Model

MEASUREMENT TECHNIQUE

Complete waveform analysis has been extensively employed in non-destructive testing, sonar, and medical applications. In oil logging, only the peak amplitude of the reflected signal has been employed in the Borehole Televiewer. In order to obtain information about the media behind the casing, further analysis of the observed echos is required.

A simplified but reasonable model for the casing-cement system is a planar layered media. The layers are the mud, casing, a microannulus, cement and the formation as shown in Figure 4. Further simplification results by neglecting diffraction from the finite transducer size and assuming the direction of propagation is exactly normal to the layers. These simplifications allow a transmission line model to be applied to the problems with a delta-function excitation.

Analysis of casing bounded on either side by semi-infinite layers as shown in Figure 5 and excited by an impulse gives much physical insight. The reflected sequence is:

$$r(t) = r_0\delta(t) + (1+r_0)(r_1)(1-r_0)\delta(t-T) + \ldots$$

where

Z_0, Z_1, Z_2 = acoustic impedance of each layer with $Z_1 > Z_2 \geq Z_0$.

r_0 = reflection coefficient $\dfrac{Z_1 - Z_0}{Z_1 + Z_0}$.

r_1 = reflection coefficient $\dfrac{Z_2 - Z_1}{Z_1 + Z_2}$.

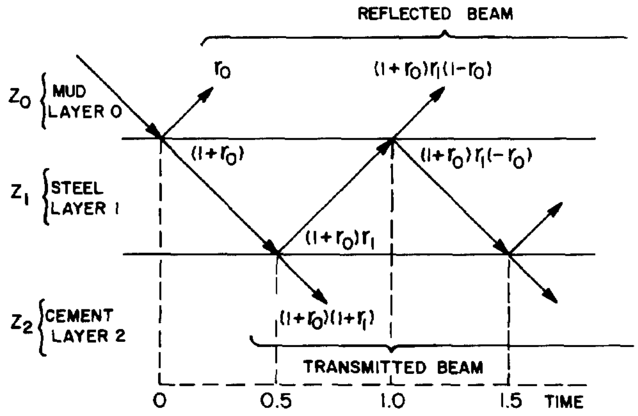
L = thickness of the layer.

C = compressional sound velocity of the layer

T = two-way travel time given by 2L/C.

The reflection coefficient sequence as a function of time can be written as

$$r(t) = \frac{1}{r_0}\delta(t) - \left[\frac{1-r_0^2}{r_0}\right]\delta(t-nT)\, e^{-anT}, \; n = 0, ,1, 2, \cdots$$



Sound Reflection and Transmission by Casing
Figure 5.

where

$$a = -\frac{C}{2L}\ln|r_0 r_1|$$

and is shown in Figure 6. If a light mud (water) is assumed to be filling the borehole, the corresponding reflection coefficients are:

$r_0 = 0.937$ - light mud
$r_{1B} = -0.937$ - bad bond
$r_{1G} = -0.731$ - good cement bond

The reflection coefficient at the first interface is the same for both the good and bad bond case and is independent of the media behind the casing. All subsequent reflections are a function of the media on each side of the casing because the wave reverberates in the casing and only loses energy at each interface. Both the rate of decay and the amplitude of these reflections can be used as a measure of the bonding conditions. Both can be contained in one measurement by integrating the envelope of the decaying tail and normalizing to the first reflection. For example, if the integration is started after travel time T, the ratio of these areas can be expressed as

$$\frac{A_{bad}}{A_{good}} = \frac{r_{1B}}{r_{1G}}\,\frac{\ln|r_0 r_{1G}|}{\ln|r_0 r_{1B}|} = 3.8$$

This is an extremely large contrast, but will be significantly reduced when the drilling mud density increases or the cement density decreases. Experimental and later theoretical modeling have shown that the above processing, while very simple, is robust since in actual field operation, with real casings and transducer effects, the waveform is not exactly a simple decaying exponential.

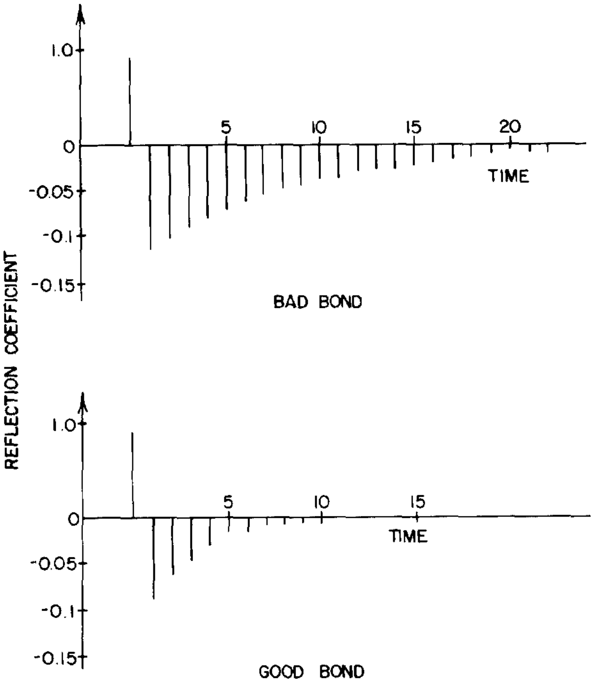


Figure 6. Response to a Unit Impulse

It can be concluded that a pulse-echo technique provides a means of clearly differentiating between the presence or absence of cement. It might also be concluded that a high frequency pulse can be used. Practical considerations such as casing roughness and attenuation in the mud requires that the lowest possible frequency be used. Furthermore, the microannulus thickness need only be a small fraction of a wavelength to adversely affect the transmission of energy across it.

The lowest possible frequency is determined by the fundamental thickness resonant frequency f_0 of the casing, that is

$$f_0 = \frac{C}{2L}$$

To cover the entire range of casing thicknesses presently employed, a frequency range of 200-600 kHz is required. By using both the fundamental and harmonic frequencies, a single broad-band transducer of 300-600 kHz covers the entire range of casing sizes. Measurement of the resonant frequency f_0 provides a measure of the casing thickness since the speed of sound in steel is almost a constant. (This simple analysis belies the great complexity of estimating the fundamental resonant frequency of a plate,' let alone a cylindrical tube when excited by real sources [10,11,12].) Should more sensitivity to microannulus conditions be desired, high frequencies can be used. This is a fortuitous result in that the predicted microannulus has a dimension on the order of 0.002" which is a very small portion of a wavelength thus making the microannulus appear as a good hydraulic seal.

Thus far the measurement method (i.e., integration of the envelope of the reverberations) and frequency range have been determined. Cement-to-formation bonding and microannulus effect on the response must yet be discussed. Figure 7 shows the response of the casing, including the formation, using a broad-band pulse as discussed above. The return signal from the formation will in general be lower in amplitude than shown due to a lower contrast in impedance between the cement and formation, borehole wall roughness and eccentering of the casing in the borehole. For these reasons, only the reverberations in the casing are considered at present.

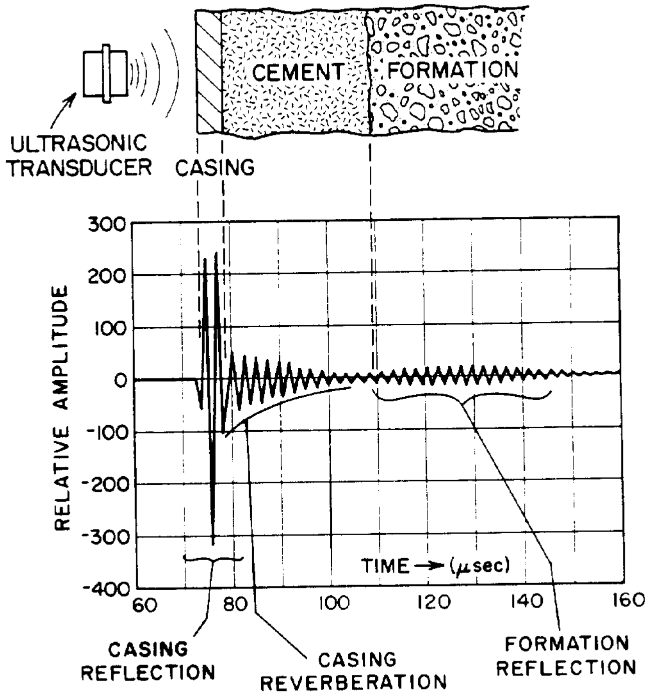


Figure 7. Typical Waveform

Figure 8 shows the waveforms and spectra for the emitted pulse, reflected from an infinite half space, and received waveforms for both good and bad bonding. Observe that the depth of the notch at the casing's resonant frequency is deep for a bad bond and shallow for a good bond. For a microannulus, the depth of this notch and the rate of decay of the reverberations is a function of the microannulus thickness.

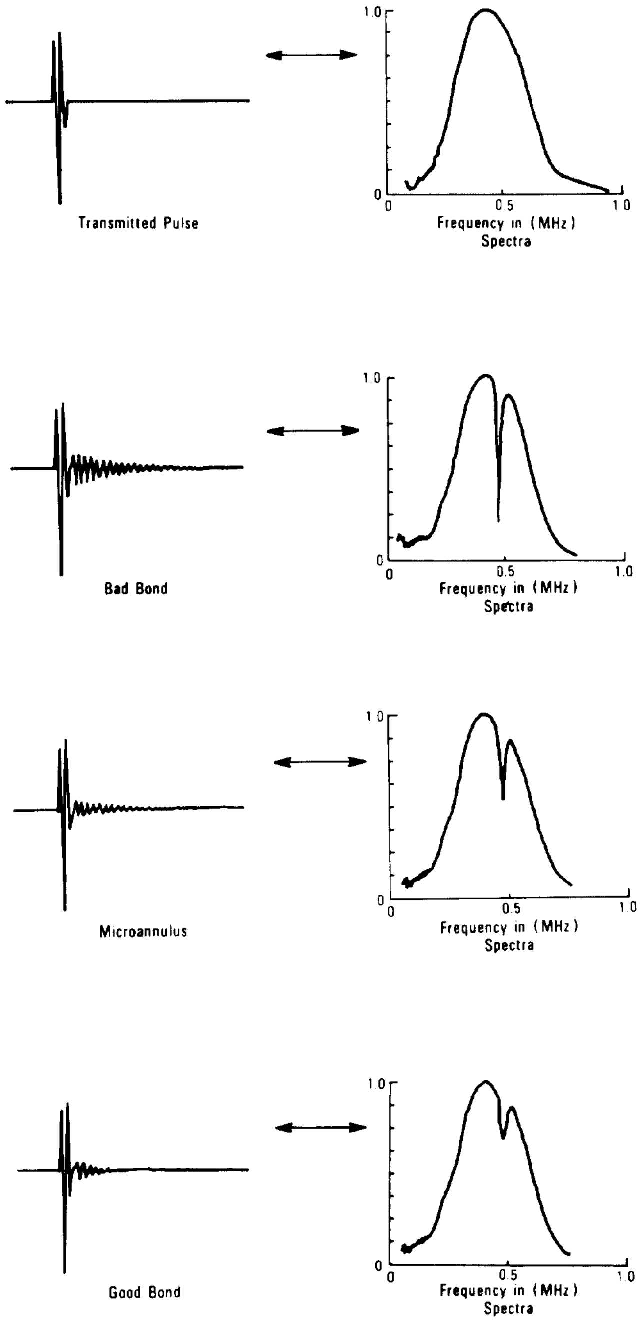


Figure 8. Temporal and Frequency Response

To demonstrate the effect of different microannulus thicknesses on tool response, a series of calculations was performed. The results are shown in Figure 9 for a 0.281" thick 9 5/8" diameter casing. These waveforms were processed by full-wave rectification as shown in Figure 10, and then integrated over the window from 6 to 40 μsecs after the beginning of the waveform. The "bad bond" reading corresponds to a water layer behind the casing that is infinite in extent. It is interesting that annuli large enough to provide hydraulic communication produce readings larger than the bad bond reading shown, due to constructive interference. Small microannuli (<0.003") will be seen as a good hydraulic seal.

Therefore, this ultrasonic method easily differentiates between good and bad hydraulic seals between the casing and cement, provides enough circumferential resolution to detect channels, is relatively insensitive to microannuli, and potentially can determine the cement-to-formation bond quality.

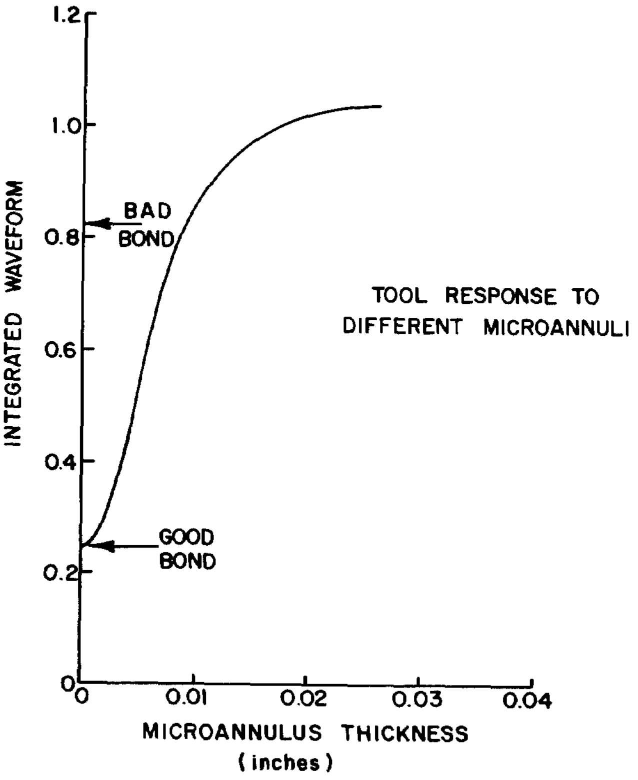


Figure 9. Tool Response to Different Microannuli

TOOL DESIGN

The Cement Evaluation Tool was originally envisioned to:

1. determine the hydraulic seal
2. detect channels behind the casing
3. measure the casing thickness
4. provide an internal casing caliper
5. provide digital waveforms for detailed analysis

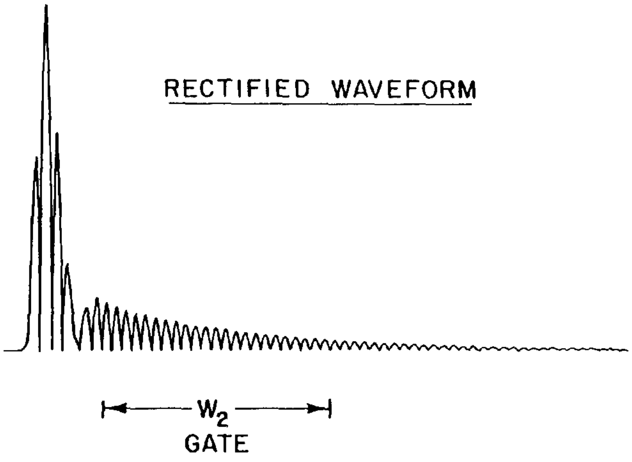


Figure 10. Rectified Waveform

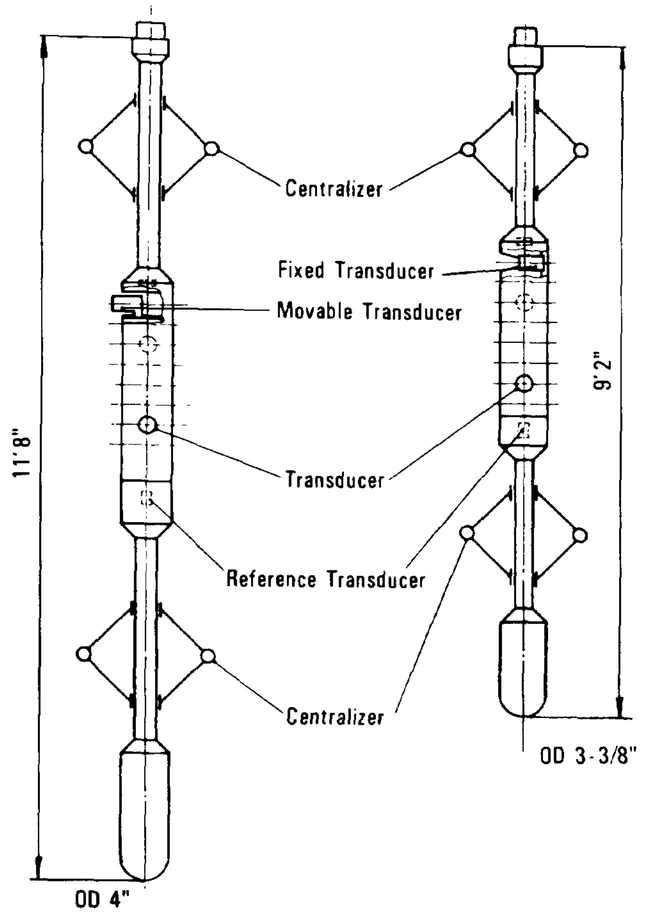


Figure 11. Cement Evaluation Tool

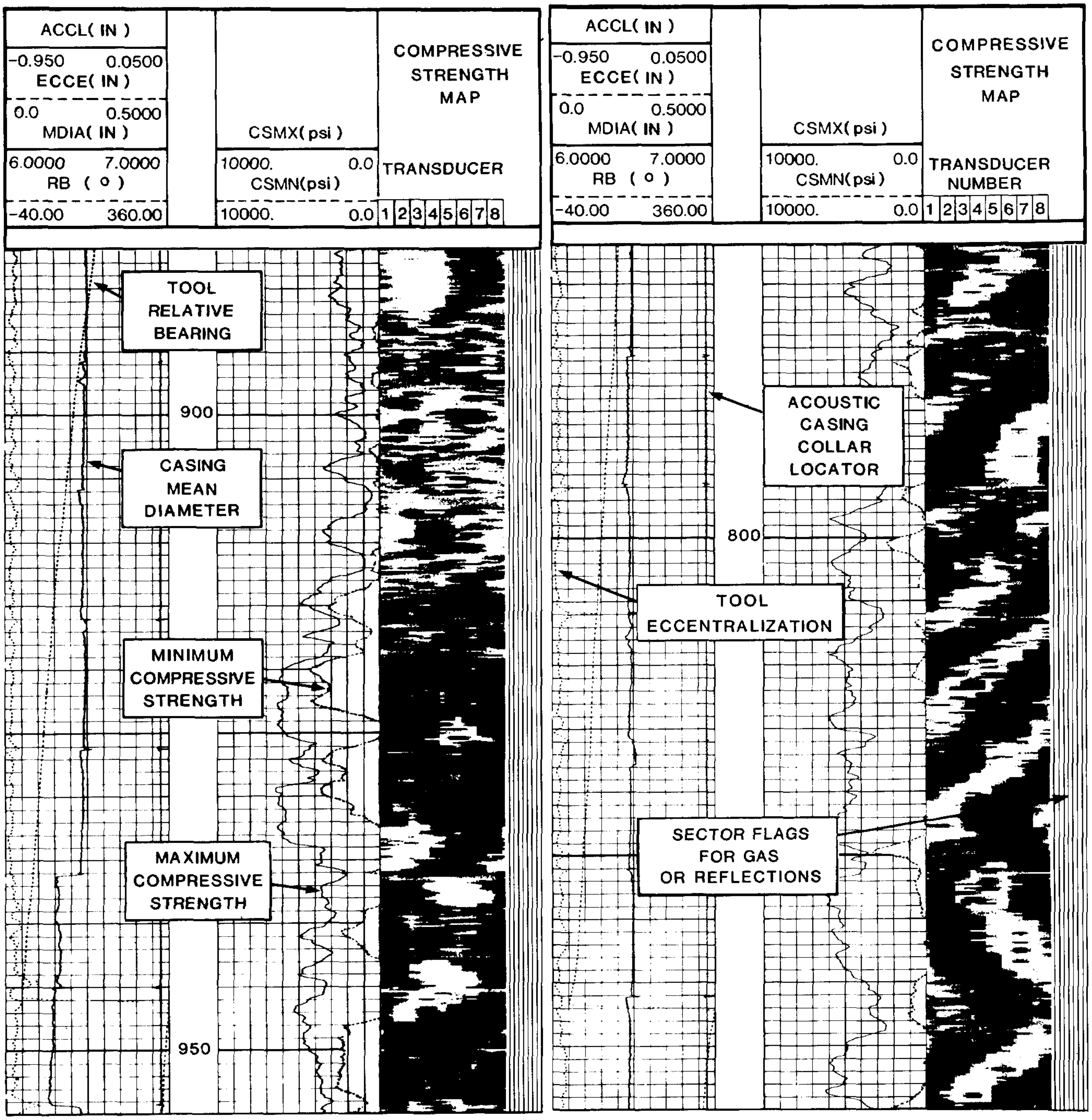


Figure 12. Typical Log

In order to accomplish these objectives the sonde was designed with eight ultrasonic transducers arranged in a helix to give azimuthal information every 45°. A ninth transducer is used in the tool to measure the acoustic properties of the mud. A broad band transducer with a center frequency of 500 kHz is used in the pulse-echo mode (Figure 11). This transducer proved to be a technological challenge since its spectral shape must remain relatively constant and the self noise level must be low relative to the decaying resonant tail up to 175°C and 20,000 psi. Requirements become more severe in attenuative muds.

The transducers can be adjusted before logging to maintain a nominal 2" standoff from the casing, to minimize attenuation in the mud while avoiding interference between successive echos. Each transducer is excited, and when the signal is detected the integration of the reverberations begins after a suitable delay. Since the casing reflection is a constant, it is used for adjusting a digitally controlled variable-gain amplifier to keep the peak of this signal within a narrow amplitude window. The gain control compensates for attenuation due to mud and eccentering effects. Normalization of the signal corrects for eccentering up to about 0.3".

For each waveform received by the transducer, the following measurements are made:

- Peak Amplitude
  This is the reflection from the inside of the casing. It is used to adjust the variable gain amplifier and to normalize the decay measurement.
- Integrated Resonant Decay
  Separate windows are used for cement evaluation and to identify reflections from the formation.
- Delay-Time
  This is the interval of time that separates the firing of the transducer from the reception of the first echo. It is used, after correction for mud velocity, as a caliper measurement.
- Resonant Frequencies
  The entire waveform is digitized and telemetered to the surface where a frequency analysis is performed. Algorithms have been developed that achieve a thickness resolution of (0.004") even in well-cemented zones where the Q is low.

A data acquisition system collects the data downhole and telemeters it to a surface computer. The data is recorded as a function of depth on magnetic tape, and after processing, on photographic film. Casing thickness measurements are generally obtained by post-processing the data.

Figure 12 [20] is an example of a cement evaluation log. The two curves represent the maximum and minimum estimated compressive strength of the cement behind the casing. An image is also presented with cement appearing as black and fluid as white. A rotating channel in the cement is clearly visible in this example.

Additional display outputs provide mean internal casing diameter and casing ovality, the difference between the largest and smallest diameter.

SUMMARY

Significant progress has been made in applying ultrasonic techniques to oil well logging. The harsh borehole environment, however, has severely limited rapid progress since only the most robust techniques along with sound system design can be employed.

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