

Cement Sheath Evaluation

API TECHNICAL REPORT 10TR1
SECOND EDITION, SEPTEMBER 2008



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Upstream Segment

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Cement Sheath Evaluation

1 Introduction

This document is an update of API Technical Report 10TR1, First Edition (June 1996). Great effort has been made to ensure that new technical developments are incorporated, and different views and perspectives are represented by contributions from both operators and service companies. Additionally, the document's relevance to field personnel has been improved by expanding the sections on tool capability, selection, running procedure and log QC. In addition, there is a discussion about how to best incorporate log-interpretation and cementing data into an overall determination of zonal isolation.

2 Framework—Put Cement Sheath Evaluation in Perspective

Cementing is one of the fundamental well-construction technologies for hydrocarbon extraction. The industry spends billions of dollars annually on cementing, and a significant portion is wasted as a result of inappropriate evaluation or incorrect recommendations based on misunderstanding. This document attempts to remedy this situation by gathering into a single treatise the information necessary for meaningful cement-sheath evaluation.

There are a large number of parameters at play throughout the many steps of engineering and effectively evaluating a cement job. Anyone who wants to competently evaluate the quality of a cement job must thoroughly understand all the variables, assemble and comprehend the relevant pieces of information, and reach the proper judgment. Practice, careful observation, and learning from experience will increase the chances for success.

One must understand and never lose sight of the purpose of cement-sheath evaluation. It is ultimately to assess the cement's integrity and ability to achieve its objectives throughout the lifetime of the well. It is not to interpret whether the logs indicate a “good” or “bad” cement bond. Such misguided practice tends to be more prone to error. It can cause financial loss and has, in part, given cement evaluation a bad name. Tools employed in logging operations have various physical limitations that will be described later; for this reason, one must never interpret logs in isolation, without the well and cementing data. Without a clear perspective and strategy for cement-sheath evaluation, one cannot defend against the age-old and often sensible assault.

If all we obtain from the logs is comfort when they look good, or discomfort when they look bad, but no confident remedial option, why do we waste time and money running the logs?

Therefore, performing a cementing job correctly in terms of design and execution is far more important. However, proper evaluation is indispensable, and the evaluation process is a powerful tool if used appropriately to improve future jobs.

This document focuses on logging and evaluation, presenting both the technology and the application from the end user's point of view. Although related key areas of cementing are highlighted wherever possible, the reader is strongly encouraged to gain the necessary knowledge or expertise in those areas elsewhere if needed.

3 A Brief Introduction to Cementing

3.1 Importance of Cement

The two principal functions of a primary cement job are to provide support for the casing and to provide hydraulic isolation between various zones. Cement-sheath evaluation is concerned with the question of whether zonal isolation exists. As emphasized earlier in this document, the evaluation of a cement sheath requires a complete and thorough assessment of the cement job, including job records and cement-evaluation logs. Cement-evaluation logs cannot be interpreted in a vacuum.

The two components of a successful primary cement job are slurry design and mud removal. The slurry must be designed to remain stable under downhole conditions. The pumping of the cement job must be optimized to promote mud removal and allow placement of a competent cement sheath without channels or voids. The following discussion highlights aspects of cement design and placement as they relate to the proper interpretation of cement-evaluation logs.

3.2 Slurry and Set Cement Properties

Density and Acoustic Impedance. Acoustic impedance of the cement sheath (Z , commonly expressed in $\text{MRayls}-10^6 \text{ Rayl}$ or Rayleigh) is defined as the product of the cement density and the acoustic velocity in the set cement. Generally speaking, higher density cement provides a greater acoustic contrast with the drilling fluid. This aids log interpretation. Lower-density or contaminated (low acoustic impedance) cement provides less contrast, making interpretation more difficult. Because of their low acoustic impedance, special interpretation techniques are required when assessing high-performance cement systems such as foamed cement or formulations containing glass microspheres or ceramic bubbles.

Density Variations. Varying the cement density changes the acoustic impedance. Therefore, it is important that the cement be mixed as uniformly and as close to the designed density as possible ($\pm 0.1 \text{ ppg}$ variation from designed density). Deviations from the planned values should be recorded. Ideally, a data-acquisition system should be used to record the slurry density throughout the job. Any density fluctuations should be noted when evaluating the cement log.

Free Fluid/Sedimentation. The slurry must be stable under downhole conditions. Solids settling, pockets of free fluid or lighter-than-designed cement will affect the acoustic impedance and the ability of the cement to provide proper zonal isolation. This is reflected in the log measurement.

Fluid Loss. Excessive fluid loss from the cement slurry during the primary cement job can adversely affect slurry rheology. The altered rheological profile can have a negative impact on mud displacement efficiency. Fluid-loss control is also a very important parameter governing fluid migration through the cemented annulus. Fluid loss can also cause localized microannulus.

Rheology. The rheological profiles and hierarchy of fluids pumped during the cement job determine the mud removal effectiveness. Mud removal effectiveness has a direct impact on cement sheath quality. Computer simulators can be used to optimize the mud-removal process.

Compressive Strength and Acoustic Impedance. Historically, many of the guidelines for cement evaluation log interpretation have been based on cement compressive strength. Acoustic impedance, as outlined earlier, is a better property to use. However, it is important to allow the cement to hydrate sufficiently before running an evaluation log. Generally, at least 48 hours should elapse after cement placement before running a cement evaluation log (see Figure 3.1).

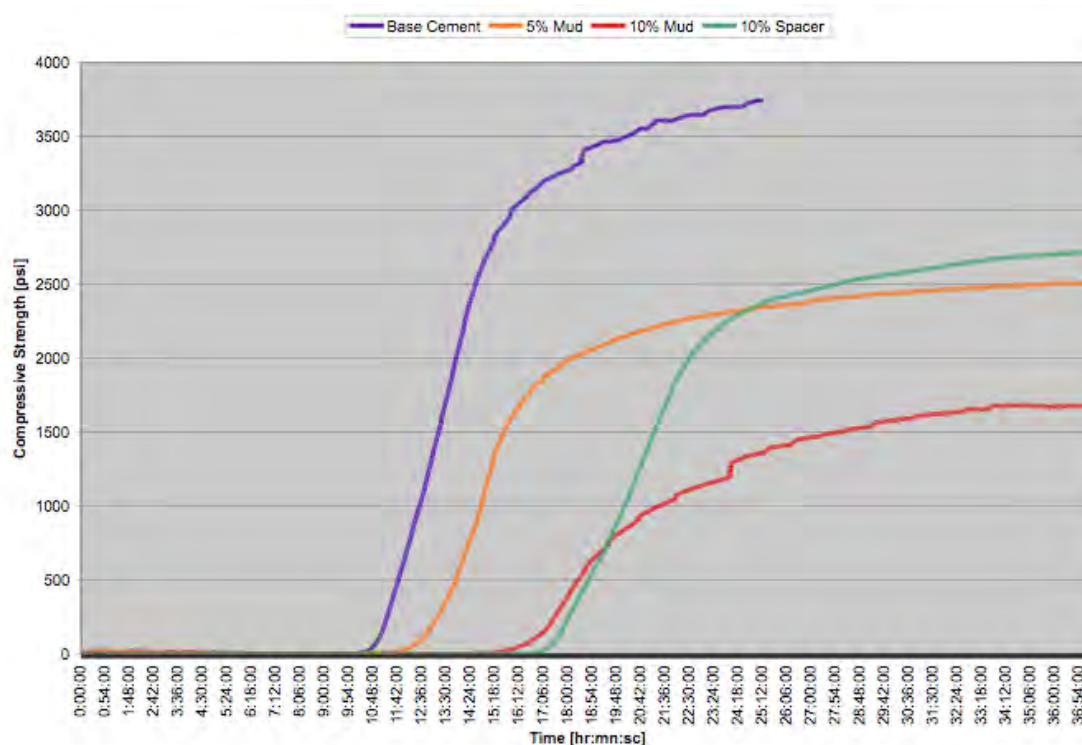


Figure 3.1—Time vs. Compressive Strength Plot (for Base Cement and Base Cement Contaminated Volumetrically with Mud or Spacer)

NOTE: This is used to determine the waiting time on cement hardening before the lower frequency cement evaluation logs should be run.

Cement acoustic impedance (Z) can be determined using lab ultrasonic cement analyzer (UCA) measurement which provides the cement slowness (inverse of acoustic velocity) during cement setting and hardening process (see Figure 3.2).

$$Z = \frac{\text{Density}}{\text{Slowness} \div 25.4} \quad (3-1)$$

where

Z is in MRayl;

Density is in kg/L;

Slowness is in microseconds per inch ($\mu\text{s/in.}$).

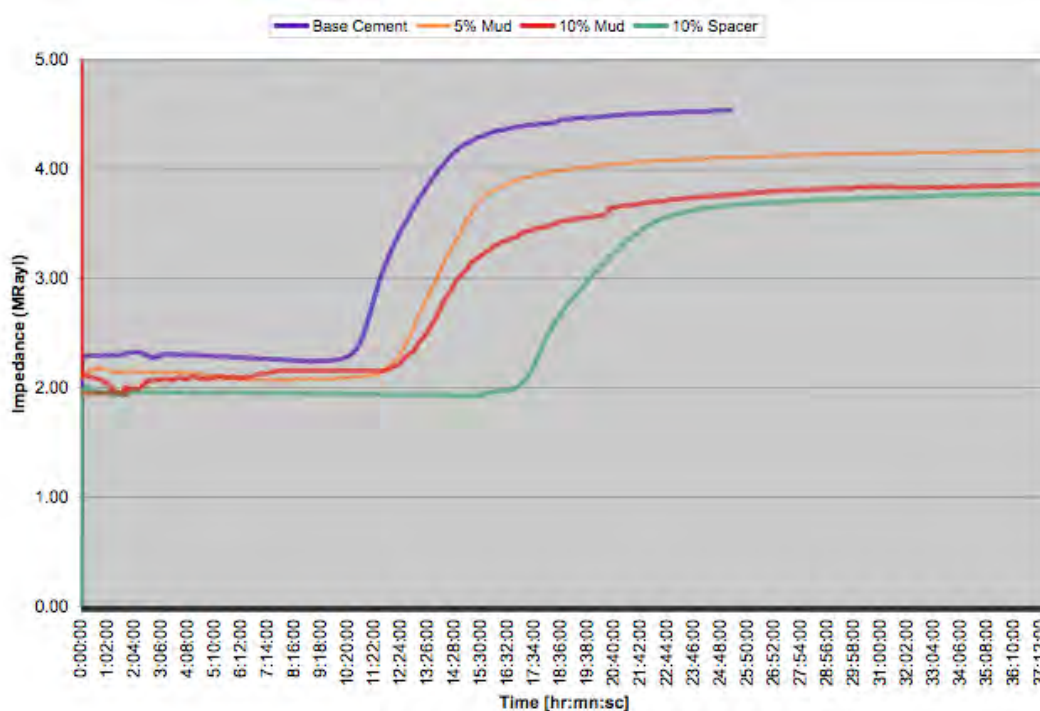


Figure 3.2—Time vs. Acoustic Impedance Plot (for Base Cement and Base Cement Contaminated Volumetrically with Mud or Spacer)

NOTE: This is used to determine the waiting period before a cement evaluation log should be run. This plot helps one to choose the logging parameters for ultrasonic cement evaluation logs.

Static Gel Strength (Transition Time) and “Gas Tight” Cement. Gas invasion into the cement sheath lowers its acoustic impedance and causes log-interpretation problems. For wells with a high gas-invasion potential, special cement designs and testing methods may be employed to minimize gas invasion. One method involves shortening the transition time of the cement slurry. As the cement slurry sets, it changes from a liquid that transmits hydrostatic pressure to a mass with sufficient gel strength to prevent gas influx. The transition time is the period between the beginning of gel-strength development and

the attainment of sufficient gel strength to prevent gas influx. Slurries should be tested for gas tightness when the potential for gas invasion or migration exists.

3.3 Mud Removal and the Cement Job

Methods and techniques employed to remove drilling fluid during cement-slurry placement affect the quality of the cement job and may have an impact on the log measurement. Post-cementing practices may also affect log quality.

Pipe Movement. Casing movement, either rotation or reciprocation, has been demonstrated to promote mud removal, reducing or eliminating channels of bypassed mud.

Centralization. Casing centralization promotes mud removal by minimizing the difference between the “wide side” and “narrow side” annular gaps, and reducing the energy required to overcome the mud gel strength. Channels of bypassed mud are reduced or eliminated.

Also, cement evaluation logs require a minimum $\frac{3}{4}$ -in. cement sheath to sufficiently attenuate the sonic signal and attain a good log response. The cement sheath around eccentric casing may not be thick enough to provide sufficient attenuation.

Density and Rheological Hierarchy. Generally, it is easier to displace a fluid with another fluid that is heavier and more viscous. So, in the succession of mud–spacer–lead slurry–tail slurry, each fluid should be more dense and exert more friction pressure than the one preceding it. This promotes good mud removal, a uniform cement sheath and better log response.

Casing Coatings. Thick mill varnish or anti-corrosion coatings can “break” the acoustic coupling between casing and the cement sheath, and cause a log response similar to a microannulus. Weathered or sandblasted casing provides better acoustic coupling.

Lost Circulation. Loss of circulation prior to and during the cementing treatment can negatively affect the attainment of zonal isolation. Loss of fluids to the formation can cause the top of cement (TOC) to be located far below the planned depth. The TOC is very important when determining the quality of the cement log. Monitoring returns during a cement job is critical to accurate log interpretation.

Post-cementing Practices. Pressure testing causes casing to expand. The casing contracts when the test is finished and pressure is released, potentially forming a microannulus that breaks the acoustic coupling between casing and cement sheath and harms log quality. In a similar manner, displacing heavier drilling fluid with lighter completion fluid causes casing to contract and damage the acoustic coupling. A localized loss of shear coupling could also come from radial cracks in the cement induced by the pressure test.

Temperature increases arising from hydrating cement can cause the casing to expand while the cement sets and to contract when the heat dissipates. Any of these scenarios can affect log response. Generally, logs must be run under sufficient pressure to expand the casing and reestablish the acoustic coupling. Both sonic and ultrasonic tools are affected by a microannulus, sonic tools showing the greater effect.

4 Cement Evaluation Tool Types "Categories"

For convenience, cement evaluation tools are often classified according to the frequency of the sound waves they employ: sonic (low frequency) and ultrasonic (high frequency).

4.1 Sonic (and Low-ultrasonic) Evaluation Tools

- CBL—cement bond log; A large-diameter tool with a frequency of 20 kHz; one transmitter and two receivers (3-ft CBL and 5-ft VDL), or a small-diameter tool with a frequency of 23 kHz to 30 kHz; one transmitter and one or two receivers. See Section 5.
- CBT—compensated cement bond log; a large-diameter tool that has two transmitters and three receivers. See Section 6.
- SBT—segmented bond tool; a six-arm tool with a transmitter and receiver on each arm. See Section 7.
- SBL—sector bond log; has one transmitter with three receivers (where one receiver is sliced into 8 to 10 sectors, or the transmitter and one receiver can be sliced into 8 to 10 sectors). See Section 8.

4.2 Ultrasonic Evaluation Tools

- Ultrasonic imaging tool (USIT). See Section 9.
- Circumferential acoustic scanning tool (CAST-V). See Section 9.
- Ultrasonic radial scanner (URS) See Section 9.
- Isolation scanner. See 9.8.

5 Cement Bond Log (CBL)

5.1 Amplitude and Attenuation Physics

The CBL tool emits an acoustic-energy pulse that travels in all directions through the borehole fluid as an expanding spherical wave of sound. When the sound pulse strikes the inner casing surface, some of it is refracted according to Snell's law:

$$\frac{V_1}{\sin \zeta_1} = \frac{V_2}{\sin \zeta_2} \quad (5-1)$$

where

zeta (ζ) is the angle of incidence and refraction;

V is the velocity of sound in the respective media.

Calculations show that the wave front striking the casing at an angle of approximately 17° will refract parallel to the casing wall (see Figure 5.1). The passage of the wave pulse through the casing wall acts as an intermittent pressure pulse, causing the steel of the casing wall to cycle through compression and tension. Cycling the steel through compression and tension causes the casing to “ring,” creating sonic waves that travel through the casing fluid and reach the logging-tool receiver. The pressure pulse loses energy as it travels inside the casing wall. This loss of strength, or decay, is commonly referred to as sound attenuation (see Figure 5.2).

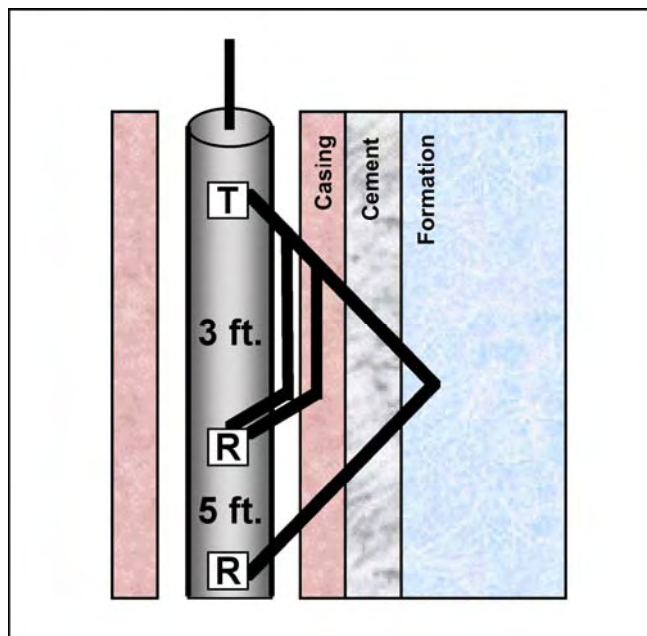


Figure 5.1—Tool Configuration in Which the Angle of the Sound Transmitted Follows Snell's Law

NOTE: The sound travels through the casing and borehole fluid to two receivers that are 3 ft apart (amplitude and travel time measurement) and 5 ft apart (full waveform measurement).

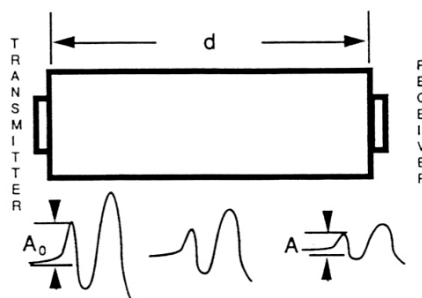


Figure 5.2—Sound Attenuation

NOTE: A_0 is the transmitter amplitude, A is the receiver amplitude and d is the distance between the transmitter and receiver. Attenuation = $\left(\frac{20}{d}\right) \log\left(\frac{A}{A_0}\right)$.

Some of the acoustic-energy pulse travels through the casing and then through the cement sheath into the formation, and is then reflected back to the tool receiver (see Figure 5.2). The signal paths from the transmitter to the receiver depend on the quality of the acoustic coupling between the cement to the casing (see Figure 5.2). Since the casing wave (see Figure 5.4 and Figure 5.5) typically arrives at the receivers first, its amplitude (energy level in millivolts) and the travel time (in microseconds) from the transmitter to the first receiver can be measured without interference.

At the 3-ft receiver, The first arrival amplitude (known as E_1 or E_2), or the attenuation rate of the received signal, is related to the cement's acoustic properties and the casing-wall thickness (see Figure 5.3), as long as the cement is set (capable of transmitting shear waves) and acoustically coupled to the casing.

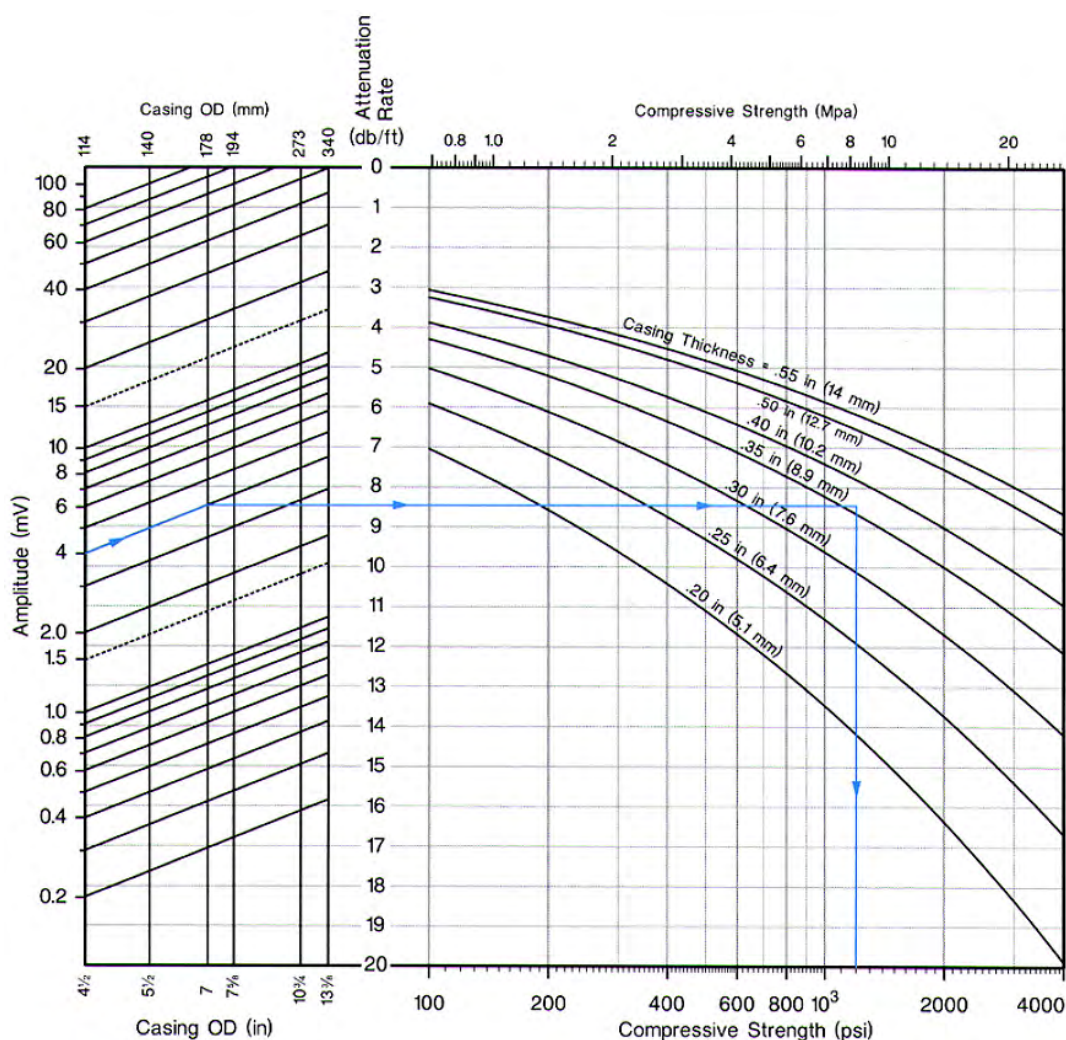


Figure 5.3—Typical CBL Interpretation Chart

NOTE: Cement compressive strength can be derived from casing-size, casing-thickness, amplitude or attenuation data. Inputs of casing size, casing thickness, and cement compressive strength will result in predicting the tool amplitude or downhole attenuation measurement. Each type of tool has similar but unique charts (consult each service company).

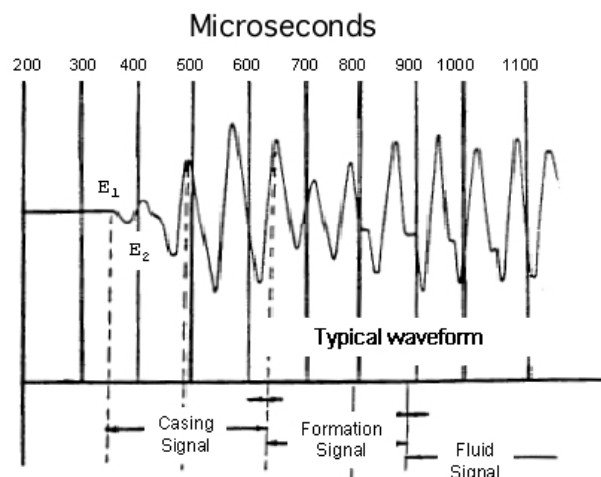


Figure 5.4—Composite Waveform

NOTE: Where E_1 and E_2 are the first arrivals. Above display assumes a formation velocity greater than 90 $\mu\text{s}/\text{ft}$.

5.2 Waveform/Variable Density Physics

The acoustic-waveform signal is recorded at a second receiver that is typically 5 ft from the transmitter. The composite waveform, illustrated in Figure 5.4, is a combination of the casing waveform, the cement-sheath waveform, the formation waveform and the logging-fluid waveform. The waveform reflected from the cement and the formation is indistinguishable. Standard waveform nomenclature lists the first positive peak as the E_1 peak, with subsequent positive peaks denoted as E_3 , E_5 , E_7 , etc. The first negative peak is referred to as E_2 , with subsequent negative peaks denoted as E_4 , E_6 , etc. Figure 5.4 illustrates the typical arrival times for casing, formation, and casing fluid. The composite waveform is affected by the quality of the cement's acoustic coupling to the formation and casing, the shear strength of the cement, the thickness of the cement sheath, and the thickness of the casing wall.

Figure 5.5 illustrates a typical waveform for uncemented casing. The amplitude is highest in free casing because the signal creates a ringing effect that is unattenuated by solid material (cement) coupled to it. When the casing is not acoustically coupled to a high-shear-strength solid in the annulus, the only signal detected by the receiver will be from the casing. This effect can be observed on a bond log when the annulus is filled with unset cement or very weak cement (< 250 psi compressive strength) with thick-wall casing in the hole, a microannulus at the casing-cement interface, gas-cut or foamed cement, mud, water, gas or sloughed formation particles. Good acoustic coupling of the cement to the casing and the formation is required for signal transmission through all of the conductors. The E_1 curve of the free casing waveform should appear on the display between 300 microseconds (μs) to 400 microseconds (μs) when the signal is received at the 5-ft receiver (the travel time of sound through steel is 57 $\mu\text{s}/\text{ft}$).

Figure 5.6 illustrates a waveform when high-shear-strength cement completely occupies the annular space and is acoustically coupled to the casing. The strongest portion of the

waveform is the formation signal. The casing signal is very weak. With good casing and formation coupling provided by high-shear-strength, uncontaminated cement, the waveform should reflect formation-bed changes corresponding to, and at the same depth as, the gamma ray (GR) curve. The high shear strength of the cement dampens the pressure-pulse effect during passage of the sonic signal through the length and thickness of the casing wall. This dampening decreases the amplitude of the sound traveling through the pipe and increases the attenuation rate.

The presentation of the composite waveform on the log may be in the form of a “total energy wave” (signature plot, X-Y plot, etc.) or a linear form commonly called a VDL (variable density log) or microseismogram. The presentation is scaled from 200 to 1200 μ s. The method of recording the linear presentation from the acoustic waveform is illustrated in Figure 5.7. The linear presentation is shown every 6 in., and the waveforms are presented every 4 ft. A waveform presented every 6 in. would be very messy, and no details could be observed.

Linear presentation makes it much easier to separate casing signals from formation signals. Casing signals will always be straight unless the logging tool is eccentric, and casing collars will be evident. Formation signals usually vary and are rarely straight. The presentation will mimic an openhole sonic DT.[†]

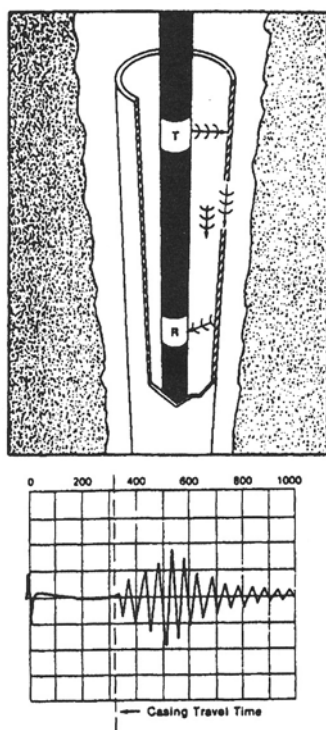


Figure 5.5—Uncemented Casing at Which the Amplitude is at its Maximum Value

[†] Sonic DT is the duration of time sound travels through a given distance in the formation, typically measured in μ s/ft.

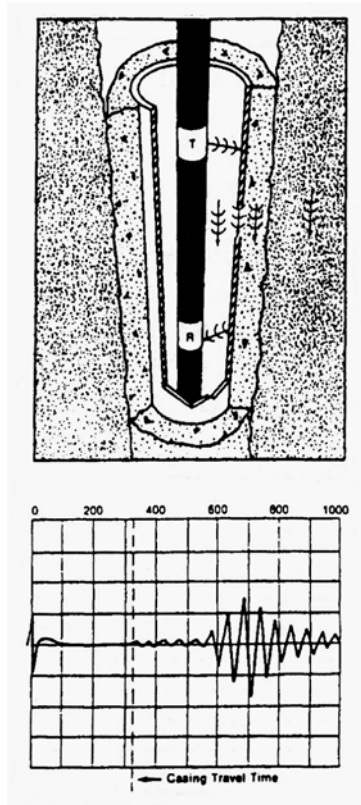


Figure 5.6—High-shear-strength Cement

NOTE: This completely occupies the annular space, and is acoustically coupled to the casing. Casing arrivals are weak and formation arrivals are strong.

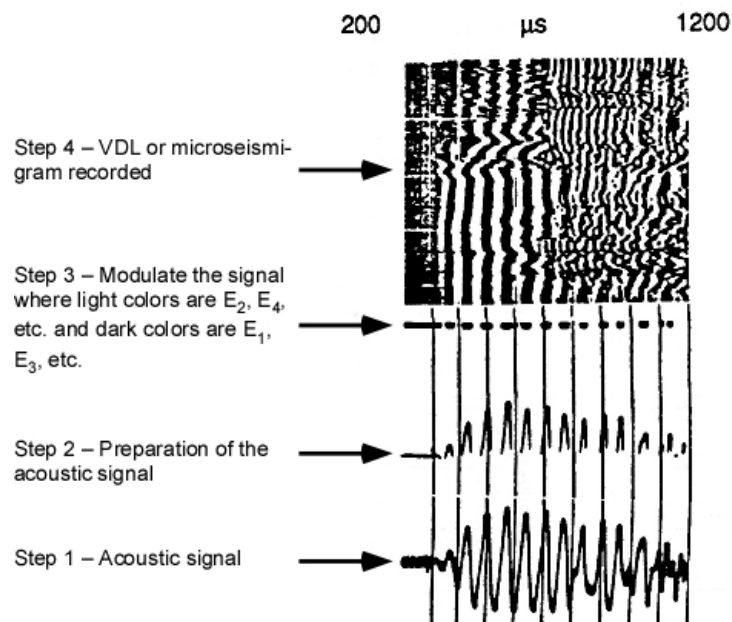


Figure 5.7—Full Waveform Signal Recorded at the 5-ft Receiver

NOTE: This figure shows the process to obtain a VDL or microseismogram.

5.3 Key Requirements

The following are required to produce a valid CBL.

1. A fluid-filled borehole. Gas or air bubbles will induce inaccurate readings.
2. Centralized CBL tool during the run.
3. A bit and scraper run is recommended to remove cement and/or scale from the casing wall.
4. Wellbore schematic.
5. Plot of the cement strength vs. time to determine the time after which logging can produce a valid log (see Figure 3.1).
6. Predicted cement tops for the lead and tail cements.
7. Casing and centralizer report to determine where casing eccentricity may occur.
8. Openhole logs with a caliper and lithology.
9. An understanding of fluid type or gas in the formation pore space.

5.4 CBL Presentation

The presentation of CBL logs varies from company to company. An example of a CBL presentation is shown in Figure 5.8. The first track (Track 1) from the left, called the correlation track, shows the GR recording and the travel time (TT) (the TT is the elapsed time from the firing of the transmitter until the first sound is sensed at the receiver). The GR signal is used for correlation between the openhole and cased-hole logs. As shown in the log, the TT (sometimes called the transit time) in the upper portion of the log is consistent and straight at 250 μ s, indicating that the tool was well centralized in this portion of the log. This will be discussed later in the quality-control section.

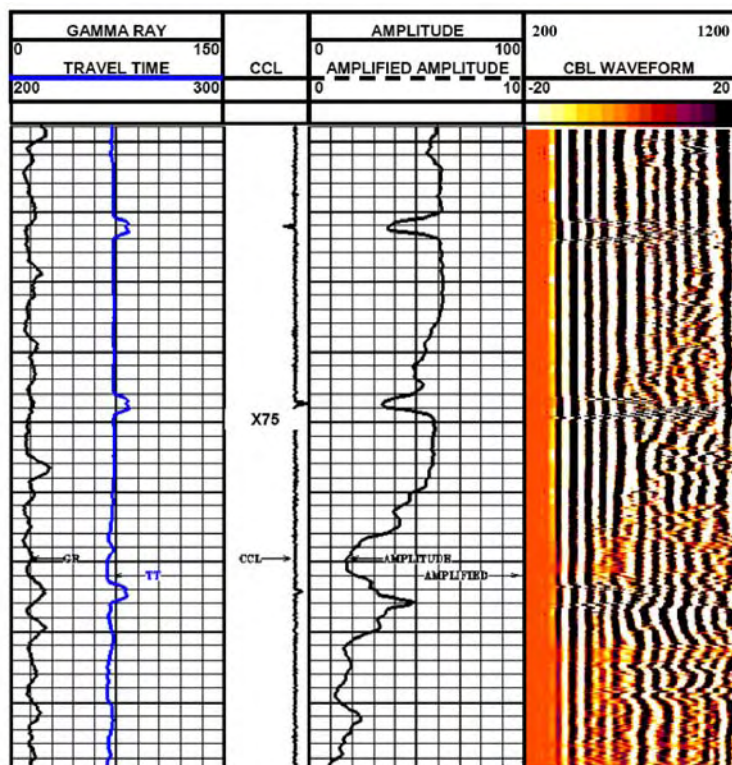


Figure 5.8—Example of a CBL Log

The depth track consists of both the depth and a collar locator or CCL (CCL is sometimes located in Track 1). The CCL is used to find the casing collars and, like the GR, is used for correlation purposes.

Track 2 is to the right of the depth track and typically consists of two curves showing the same E_1 first positive peak-amplitude reading on two different scales. The solid black line is the amplitude presented on a scale of 0 to 100. This curve will normally have a lower scale value of 0 with a variable upper limit. The upper limit should be the free-pipe amplitude, with lower values indicating better quality cement. The amplified or expanded scale curve is the amplitude plotted on a scale from 0 to 10 (or sometimes 0 to 20). This dashed curve only appears when the amplitude curve is lower than the upper scale, and provides more detail about bonded pipe than can be seen on the amplitude curve. In this example the amplitude does not drop below 10 mV, so the amplified presentation is never active.

Track 3 is the CBL waveform or VDL, shaded from white to black. The lighter colors depict the negative peaks of the CBL waveform, and darker colors represent the positive peaks. The color code depends upon the waveform amplitude. In this example, the free-pipe section is indicated by high (black) and very low (white) waveform amplitude. The first three or so black bands on the left represent the sound received from the casing.

5.5 CBL Interpretation

NOTE

This practice is not recommended as a best practice for cement evaluation. It is presented to provide an understanding of the history of CBL interpretation and its flaws.

The CBL-interpretation process is based on the following assumptions:

- cement sheath thickness ≥ 0.75 in. and
- Constant cement compressive strength and density is around the casing circumference and throughout the height of the cement column. (**This is a major flaw in CBL analysis.**)

Warning: A thin, low-density, low-compressive-strength cement sheath placed against thick-walled casing (even in well cemented casings) may each yield a relatively high waveform amplitude (low attenuation), seeming to indicate less than desired casing bonding. If any of the above conditions are present, special care should be used when determining zonal isolation.

Bond Index (Method #1): The amplitude or the attenuation rate of the received signal is proportional to the casing circumference that is in contact with cement, the casing-wall thickness, and the density, thickness, and shear strength of the cement. The Bond Index is percentage of casing circumference that is bonded to cement (see Figure 5.9).

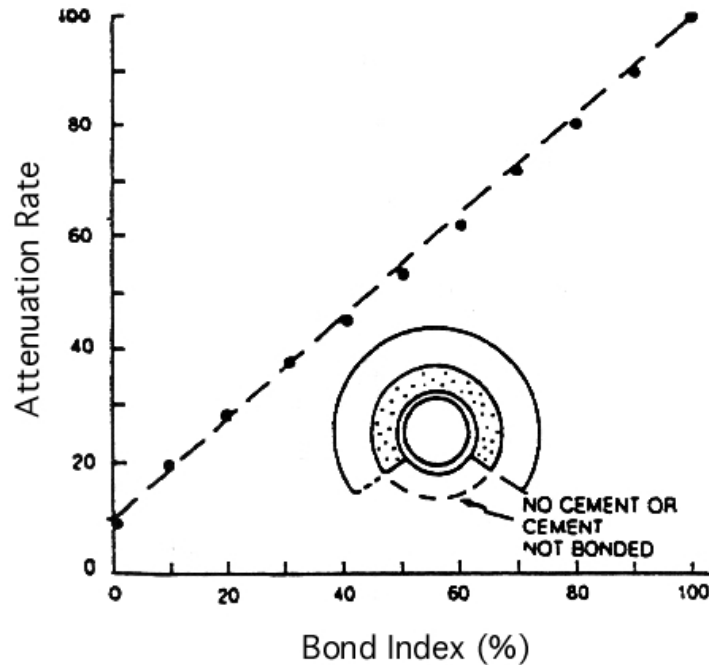


Figure 5.9—Attenuation Rate

NOTE: Attenuation rate is proportional to the casing circumference in contact with the cement (% Bond Index). Bond Index = (Attenuation at zone of interest / Attenuation for 100% cement bond). A major flaw in this analysis is the assumption that lack of cement is in the form of a channel.

The amplitude or attenuation is often used as a “bonding indicator” to infer that the cement is “poorly bonded” or “well bonded” to the casing. These “bonding indices”, or “bonding percentages”, can be totally misleading. There is very little agreement in the industry as to the definition of good bonding vs. poor bonding. The Bond Index is commonly derived from a general ratio:

Attenuation:

$$BI = \frac{A_{fp} - A_{ls}}{A_{fp} - A_{100}}$$

Amplitude:

$$BI = \frac{\log A_{fp} - \log A_{ls}}{\log A_{fp} - \log A_{100}} \quad (5-2)$$

where

BI is the Bond Index;

A_{fp} is the free-pipe attenuation or amplitude from the log or from service company charts;

A_{ls} is the attenuation or amplitude in any logged section;

A_{100} is the attenuation or amplitude from a 100% cemented section or a service-company chart (e.g. Figure 5.3).

100% Cemented Section

Figure 5.3 is an interpretation chart that may be used to estimate expected amplitude and/or attenuation values for known casing sizes and thicknesses, and cement compressive strength. Each service company publishes an interpretation chart. It is prudent to use charts corresponding to a specific company's tool. Figure 5.3 shows that changes in cement compressive strength, casing size or casing weight will change the amplitude or attenuation value. The change in amplitude or attenuation is interpreted as a change in Bond Index and not compressive strength. A Bond Index of 40% may be incorrect if the amplitude increase arises from low-strength cement rather than channeling. BI can be misleading when A_{100} is not adjusted for cement compressive-strength changes. Major changes include:

- cement density difference between the lead and tail slurries,
- slower strength-development rates resulting from low curing temperatures in the shallow portion of the wellbore,
- cement contamination by mud, spacer or influx of gas, oil or water into the cement column,
- lithology effects on the signal amplitude and
- change in cement-sheath thickness.

Figure 5.10 illustrates an excellent cement bond (where BI is assumed to be 100%). The amplified amplitude curve shows more detail because of the low amplitude resulting from high cement compressive strength and excellent bonding. The VDL shows good formation signals with no casing arrivals, and has a pattern that correlates to the GR changes.

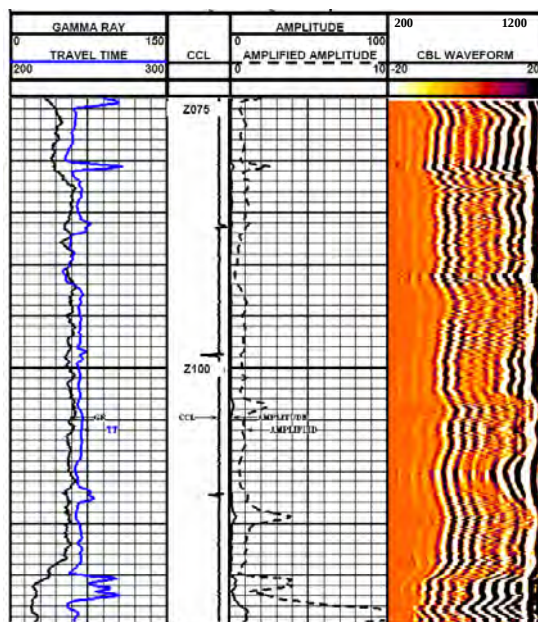


Figure 5.10—CBL Presentation of an Excellent Cement-bond Case

NOTE: Low amplitude is shown, with no casing arrivals and strong formation arrivals on the VDL.

Free-pipe Section

Figure 5.11 is a log section recorded in free pipe (casing with a liquid filled annulus). The amplitudes are very high and constant. The TT is straight. The only anomalies are caused by the collars. The VDL consists solely of straight, parallel bands called “casing arrivals.” These arrivals correlate to the waveform illustrated in Figure 5.5. The casing collars on the VDL exhibit a distinctive diffraction pattern known as chevron patterns.

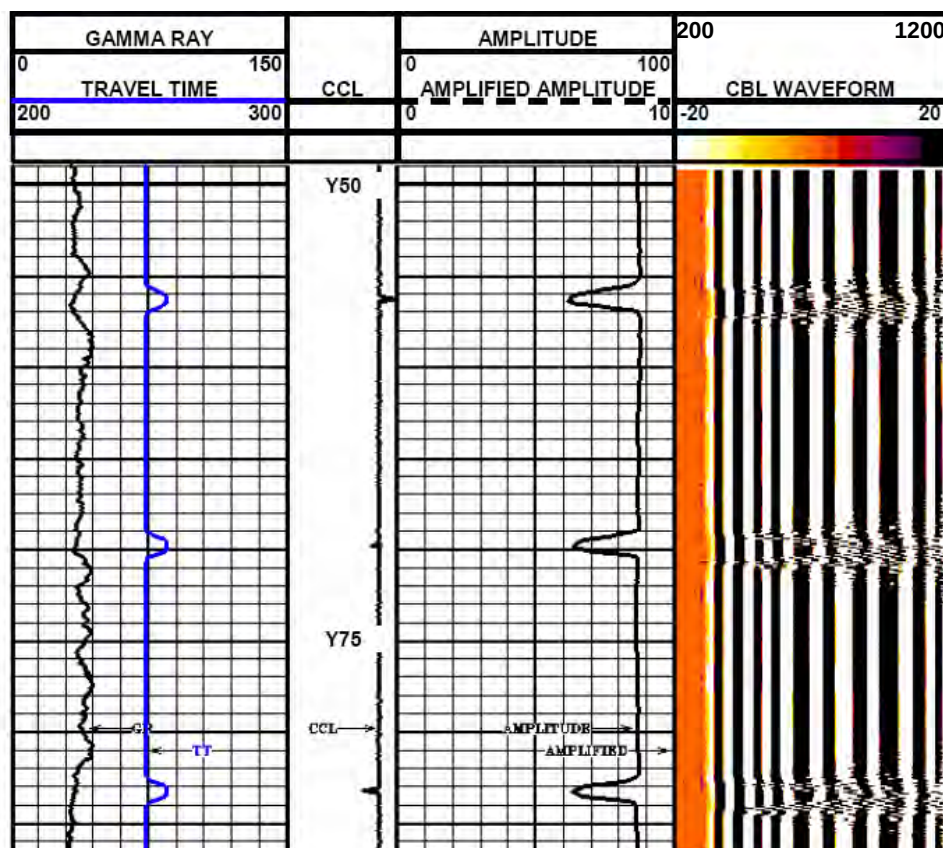


Figure 5.11—CBL Presentation in a Non-cemented Interval (Free Pipe)

NOTE: The observed log character is a high amplitude value, constant VDL signature, and strong collar signals on the amplitude and VDL recordings.

Bond Index (Method #2)

Instead of using equations to calculate Bond Index from the amplitude, the semi-log plot below can be used in its place (see Figure 5.12). The free-pipe amplitude value is entered at 0% Bond Index. The 100% cemented amplitude is entered at 100% Bond Index. In this example, the free-pipe amplitude is 70 mV and the 100% cemented amplitude is 0.2 mV (read from an area of the log with the lowest amplitude). Therefore, an 80% Bond Index would have an amplitude of about 0.6 mV. Percent Bond Index is determined by drawing a line across from an amplitude found on the log to the diagonal line and reading down to the “Bond Index.”

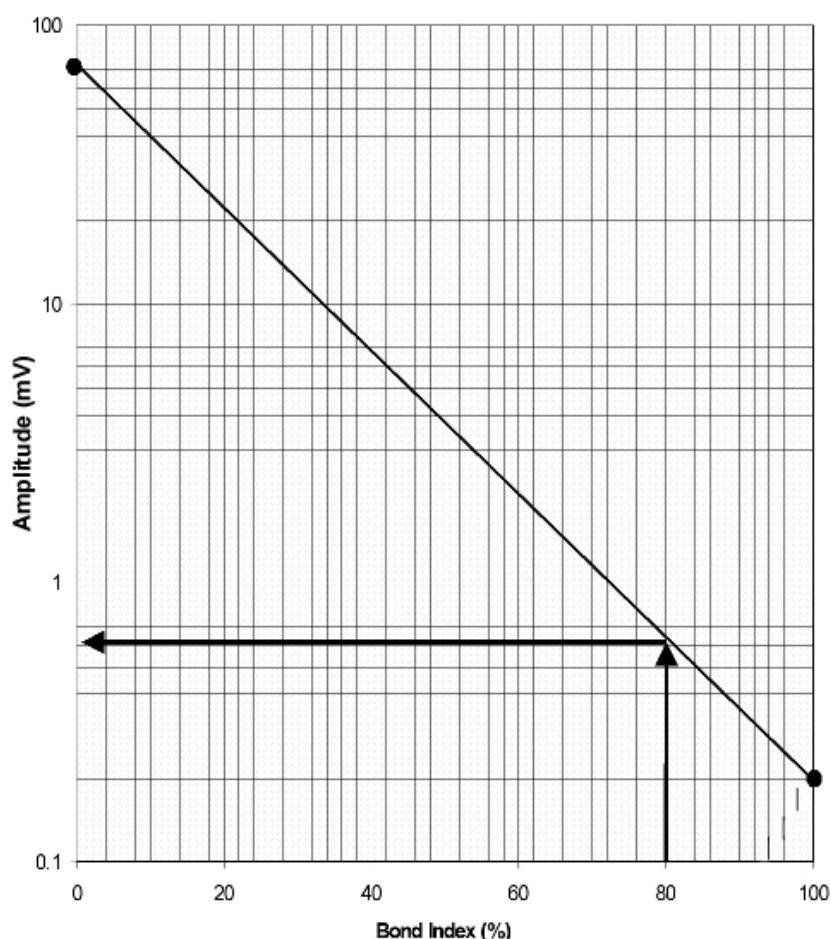


Figure 5.12—Semi-log Plot for Calculating the Bond Index

5.6 CBL Quality Control

Tool Eccentering: The signal TT, normally shown in Track 1 of the log, may be used to detect tool eccentricity. When the tool is eccentric in the casing, the bond log quality is highly questionable. “Critical travel time” is defined as the elapsed time (μs) for the signal to travel from the transmitter to the 3-ft receiver via the casing when the tool is centered in the casing. The TT curve should be straight in free pipe, except for consistently spaced, minor increases (shifting to the left) as the tool crosses the casing collars. Tool eccentricity in the casing will induce shorter TTs and lower amplitudes (see Figure 5.13). Tool eccentricity is easier to see if the TT measurement range is adjusted from the conventional 200 μs to 100 μs . If the tool TT decreases by 4 μs or more, the tool should be pulled from the hole and fitted with additional centralizers or replacement centralizers. TT decreases may also be caused by early signal arrivals from “fast formations,” so it is necessary to recognize lithology effects. TT increases do not pose a problem, and are caused by casing collars, very soft formations, and extremely high strength cement in contact with medium-to-thin walled casing.

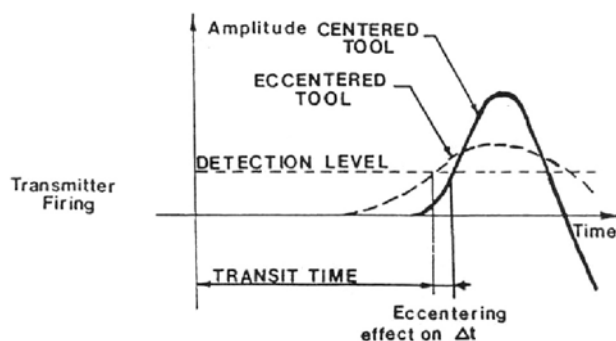


Figure 5.13—Waveform Variations Induced by Tool Eccentering

Cycle Stretch and Cycle Skip: Figure 5.14 illustrates the causes of phenomena known as “cycle stretch” and “cycle skip.” Casing signal-detection (threshold) levels are generally set by a “gate” that is fixed at some level below 50% of the free-pipe amplitude, and the arrival time at the leading edge of the E_1 curve. As the E_1 amplitude decreases because of increasing cement strength, the distance to the leading edge of E_1 increases, which also increases the TT. This increase in TT is called “cycle stretch.” When the E_1 amplitude falls below the gate detection level, the measurement detects the next available curve—the leading edge of the E_3 curve. This causes the TT curve to “skip” to a much greater value. Cycle stretch and cycle skip infer very high-shear-strength cement in contact with medium- to thin-wall casing. Cycle stretch and cycle skip are generally an indicator of good log quality over that section of the log.

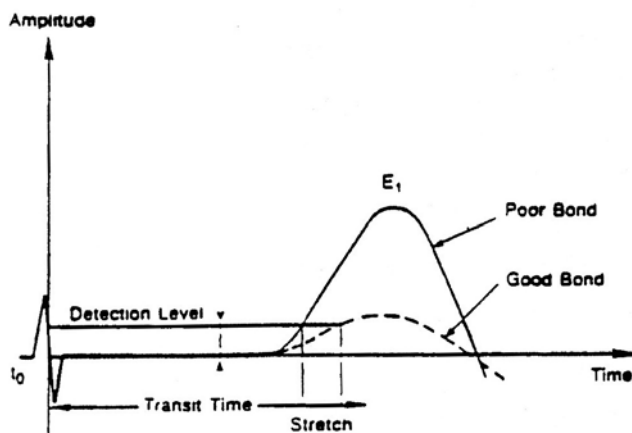


Figure 5.14—Cause of Cycle Skip and Cycle Stretch

Additional Quality Control Indicators

1. Amplitude or attenuation should never read zero.
2. 200 ft of a free pipe section should be run.
3. Free-pipe amplitude should be $\pm 10\%$ of the service-company specifications (may be lower in fluid weights > 11 ppg).
4. TT should be within ± 10 μ s of the service-company specifications (may be different for fast fluid-travel times).
5. 200 ft of repeat log should be run to ensure consistency.

5.7 Limitations (Environmental Effects)

Microannulus/Cement Channels: Figure 5.15 illustrates a typical waveform display when there are cement channels or if a microannulus exists at the casing-cement interface. The casing signal is reflected from a portion of uncemented casing, while the formation reflection is detected through a cemented portion of the casing. Channeling may result from several causes:

- poorly centralized casing,
- poor mud removal,
- inadequate removal of formation cuttings,
- settled barite at the low side of the hole and
- cement slurries exhibiting excessive free water separation and sedimentation after placement.

Microannuli are generally created by pressure changes after the cement has set. Common causes include:

- displacing the casing wiper plug with heavier mud then logging in lighter brine,
- pressure testing casing after the cement is set but before it has a chance to develop sufficient compressive strength,
- casing expansion caused by heat generated during cement setting,
- pressure inside the casing is less at the time of logging than when the cement is cured,
- cool fluids are circulated before running the CBL,
- performing a cement squeeze, and
- drilling ahead while the cement is curing.

One method to discriminate between a channel and a microannulus is to run a pressurized pass and a non-pressurized pass. The recommended amount of pressure in the casing is that required to compensate for previous pressure changes, plus 500 psi for casing expansion caused by the heat generated by cement setting. Typically, 2500 psi is the maximum pressure that can be applied with standard pressure equipment (**check with the service company for the safety limit**).

A second method to discriminate between a channel and a microannulus involves beginning with a zero-pressure pass, followed by pressuring up to 1000 psi and observing any changes in the amplitude or attenuation and VDL. If no changes occur, increase the pressure in 500-psi increments until amplitude or attenuation and VDL changes are observed. **Typically, 2500 psi is the maximum pressure that can be applied to standard pressure equipment (check with the service company for the safety limit).** If changes are observed, one may assume a microannulus is present. At this point one option would be to increase the pressure by 500 psi and determine if further improvements occur. A second option is to accept the fact that a microannulus exists and avoid further pressure increases.

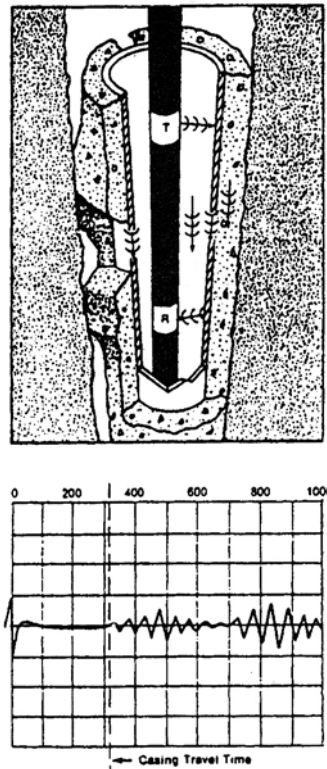


Figure 5.15—Waveform for a Cement Channel or Microannulus

If a microannulus is present, the casing signals will become lighter and may disappear from the waveform when pressure is applied to the casing. If a channel is present, the casing signals will remain. The following equation may be used to calculate the maximum size of the microannulus.

$$\Delta r = \frac{\Delta P \times r^2 \times 2}{t_w \times E} \quad (5-3)$$

where

r is the casing radius, in.;

P is the pressure, psi;

E is Young's Modulus of Elasticity for Steel ($30E_6$ psi);

t_w is the casing wall thickness, in.

Fast Formations:

The sound velocity in casing steel is generally higher than in most other borehole materials; therefore, early arrivals of the composite waveform are usually the casing signal. However, there are exceptions. Table 5.1 illustrates typical sound velocities through various downhole materials.

Table 5.1—Sonic Velocities Through Various Downhole Materials

Material	Transit Time ($\mu\text{s}/\text{ft}$)	Velocity (ft/s)
Anhydrite (Pure)	50	20,000
Dolomite/Calcite	43 – 70	9,740 – 15,856
Quartz (Pure)	52.9	18,900
Water	208	4,800
Air (1 atm)	919	1,088
Steel	57	17,544

Note that the sound velocity through certain rocks is higher than that through steel. This can cause sound traveling through the formation to arrive at the receiver at approximately the same time (or earlier) than the casing signal, and cause confusion when the formation signals are misinterpreted as casing signals. Normally, dolomite or limestone are considered to be fast formations that create this early signal dilemma. Occasionally, anhydrites or near-zero-porosity quartz could have the same effect.

Additional Environmental Effects:

1. Cement curing (see 3.2 on slurry design/compressive strength).
2. Gas contaminated cement (see 3.2 on slurry design/static gel strength).
3. Thin cement sheath (see 5.5 on CBL interpretation).
4. Eccentered casing (see 3.3 on mud removal/casing centralization).
5. Coated casing (see 3.3 on mud removal/coated casing).
6. Identifying cement channels.

6 Compensated Bond Logging Tool (CBT)

6.1 Attenuation Physics

Innovations in bond logging technology led to the development of compensated logging tools for cement evaluation. The basic configuration of the tool is illustrated in Figure 6.1. The primary advantages of the tool include the following:

- measurement of the signal attenuation rate (dB/ft) is independent of casing fluids and transmitted signal strength;
- calibration is improved significantly;
- the TT curve is separated, allowing observation of tool eccentricity;
- attenuation rate can be measured within a 1-ft interval instead of signal averaging within a 3-ft to 5-ft interval.

Generally the compensated logging device measures casing signal attenuation between the 2.4-ft to 3.4-ft receivers (see Figure 6.1) and the formation signals at the 5-ft receiver. Signal attenuation from Transmitter No. 1 is measured at a “set” of receivers, then averaged with the signal attenuation from Transmitter No. 2 at the same receivers (signal direction is reversed). Log interpretation is similar to common “bond logs.” The microseismogram or VDL signature interpretations remain the same; however, the attenuation rate, dB/ft , is measured instead of calculated and presented on Track 2 of the

log (sometimes in tandem with the amplitude curve). Interpretation may be based on a chart similar to that shown in Figure 5.3. Another major advantage of this type of log is that it allows comparison of results from various logging company tools. The attenuation rate is specifically measured, and the effects of transmitter strength, borehole fluids, and tool variances are negated. The results of a cement-evaluation run should yield the same results, regardless of the tool manufacturer.

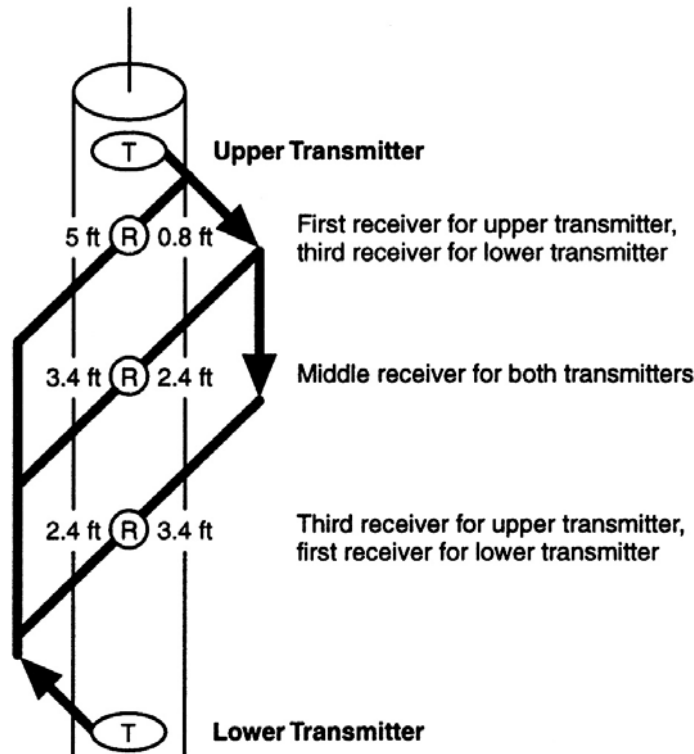


Figure 6.1—Compensated Bond Tool

6.2 Waveform/Variable Density Physics

(See 5.2.)

6.3 Key Requirements

(See 5.3.)

6.4 Compensated Logging Tool Presentation

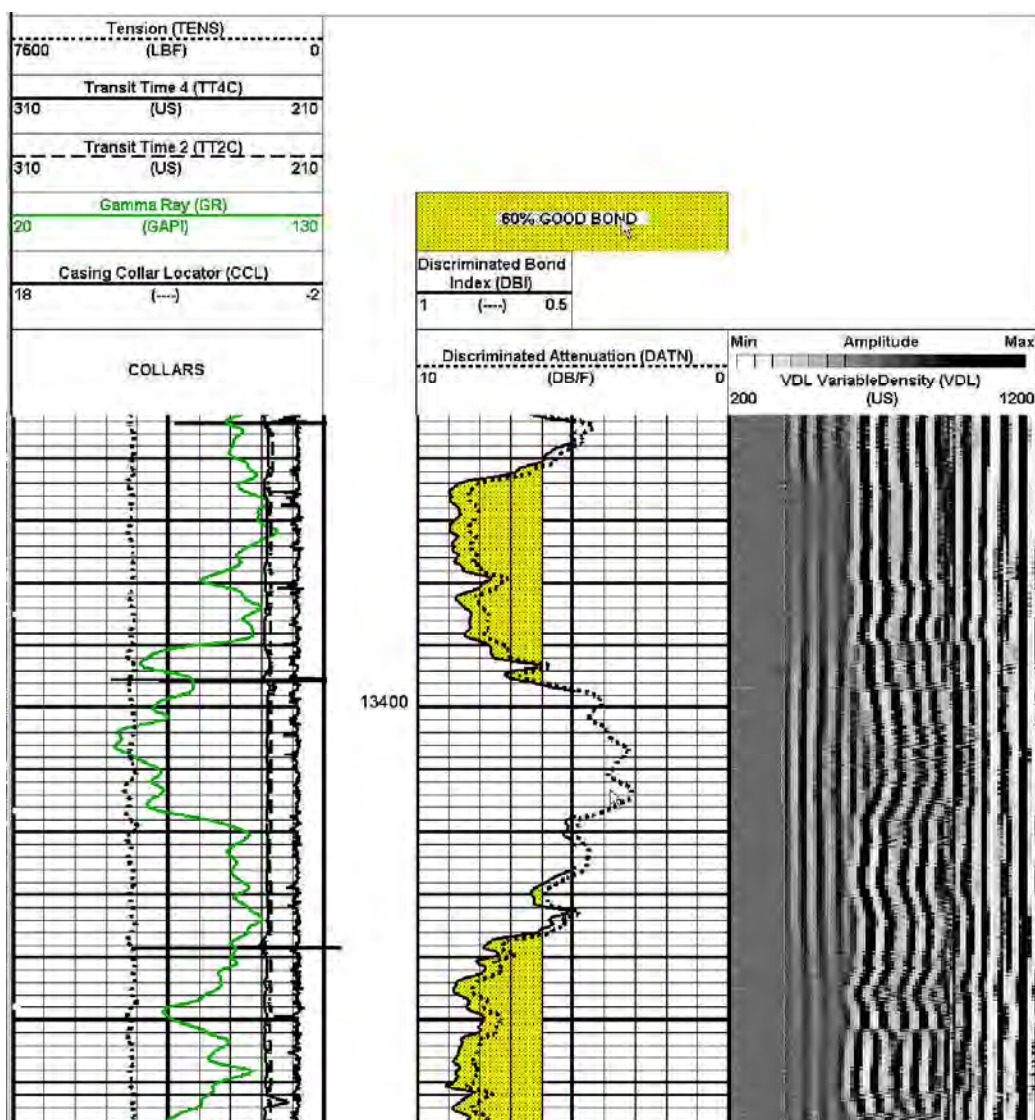


Figure 6.2—Compensated Bond Tool Presentation

6.5 Compensated Logging Tool Interpretation

(See 5.5—Method #1 using Bond Index Attenuation Equation.)

6.6 CBL Quality Control

1. Amplitude or attenuation should never read zero.
2. 200 ft of a free pipe section should be run.
3. Free-pipe amplitude should be $\pm 10\%$ of the service-company specifications (may be lower in fluid weights > 11 ppg).
4. 200 ft of repeat log should be run to ensure consistency.

6.7 Limitations (Environmental Effects)

(See 5.7.)

1. Microannulus.
2. Fast formations (to a lesser extent than traditional CBL due to 1-ft receiver spacing).
3. Cement curing (see 3.2 on slurry design/compressive strength).
4. Gas contaminated cement (see 3.2 on slurry design/static gel strength).
5. Thin cement sheath (see 5.5 on CBL interpretation).
6. Eccentered casing (see 3.3 on mud removal/casing centralization).
7. Coated casing (see 3.3 on mud removal/coated casing).
8. Identifying cement channels.

7 Segmented Bond Log

7.1 Introduction

The SBT is a high-frequency acoustic device that uses compensated logging technology. This unique tool features six pads that are placed against the inner casing surface to measure the casing signal attenuation rate (dB/ft) in each of six, discrete 60° arcs of the casing-cement interface. A standard-frequency VDL tool is part of the service, and it is used to produce full-waveforms for microseismogram presentations. A picture of the complete instrument is displayed in Figure 7.1.

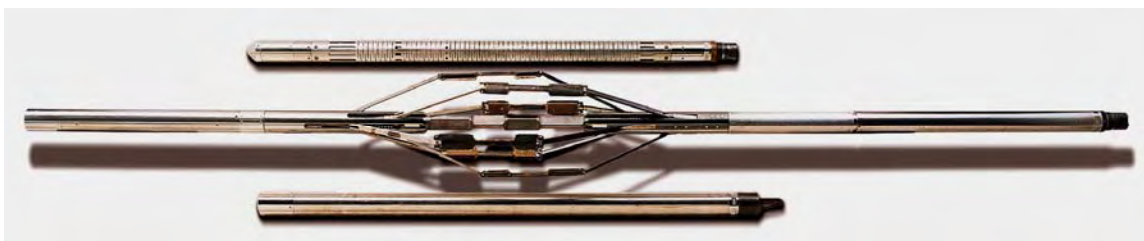


Figure 7.1—Segmented Bond Tool (SBT)

To better appreciate the operation of the instrument's pad section, it is easier to view the pads unfolded in a two-dimensional drawing (see Figure 7.2).

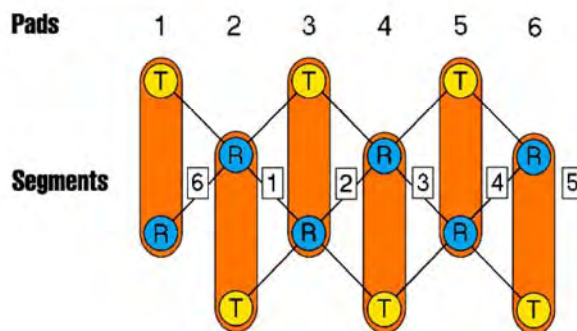


Figure 7.2—Segmented Bond Tool Pad Arrangement

7.2 SBT Physics

The SBT tool employs high-frequency focused transducers mounted on six pads. Motorized arms position each pad with a transmitter and receiver against the casing wall. The tool can be used in casing sizes from 4.5 in. to 16 in., with any type or density of fluid in the casing. A full waveform is produced from the 5-ft, omnidirectional transmitter-receiver module that is run in conjunction with the pad section.

As the transmitters are fired sequentially, amplitude measurements are made on two consecutive and adjacent receivers. A transmitter on the fourth adjacent pad is fired, and amplitudes at the same two receivers (in the opposite direction) are measured (somewhat analogous to the CBT). Energy (amplitude) losses across the receivers are averaged, producing a direct attenuation measurement over a short distance.

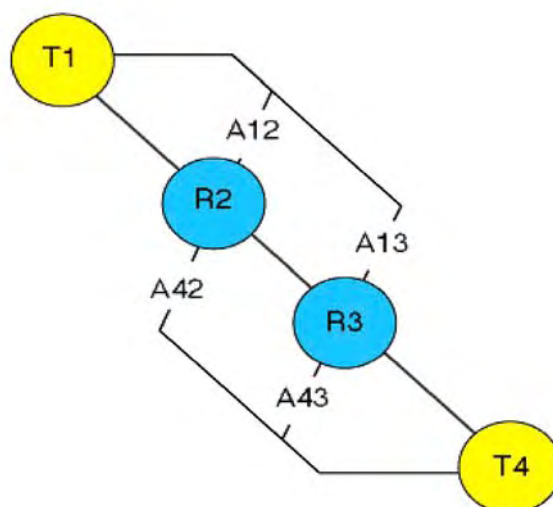


Figure 7.3—Attenuation in Segment 1 from SBT Tool

Attenuation is calculated as follows.

$$\text{Atten} = \frac{10 \log_{10} (A_{13} \times A_{42})}{(R_2 - R_3)(A_{12} \times A_{43})} \quad (7-1)$$

where

A_{xx} is the amplitude at respective receiver;

$R_2 - R_3$ is the physical distance between receivers.

Thus, the measurements are compensated for transducer variations. Calibrations of matching transmitter/receiver pairs are not required. Following acquisition of Segment 1, the remaining Segments 2 to 6 are acquired, and the tool cycle begins again.

7.3 Waveform/Variable Density Physics

(Same as 5.2.)

7.4 Key Requirements

(Same as 5.3.)

7.5 SBT Presentation

(See Figure 7.4.)

Track 1 contains the GR, collar locator, DTMN (DT minimum) and DTMX (DT maximum) curves.

Track 2 is the depth track.

Track 3 displays the six individual attenuation measurements in six “sub-tracks”, labeled ATC1, ATC2,...ATC6, with the relative bearing curve (RB) indicating the tool face relative low side of the hole.

Track 4 contains the average and minimum attenuations (ATAV and ATMN).

Track 5 is a cement map that is a graphic form of interpretation of the cement quality.

Track 6 is a VDL display from the 5-ft receiver.

7.6 SBT Interpretation

The GR and collar log are used for correlation and depth control.

The six individual attenuation measurements are labeled ATC1, ATC2,...ATC6. The higher the attenuation, the greater the likelihood of cement presence. The relative bearing (RB) indicates the tool face relative low side of the hole. This feature is used to depict cement anomalies radially around the casing (see cement map discussion below). It is only useful in deviated wells.

The average and minimum attenuations (ATAV and ATMN) are exactly as described. The average is the sum of the six individual attenuations divided by six. The minimum is the lowest of the six individual attenuations. These two curves will normally display some separation. They will nearly stack when certain conditions are satisfied—completely free pipe (no cement) and pipe uniformly cemented around the casing.

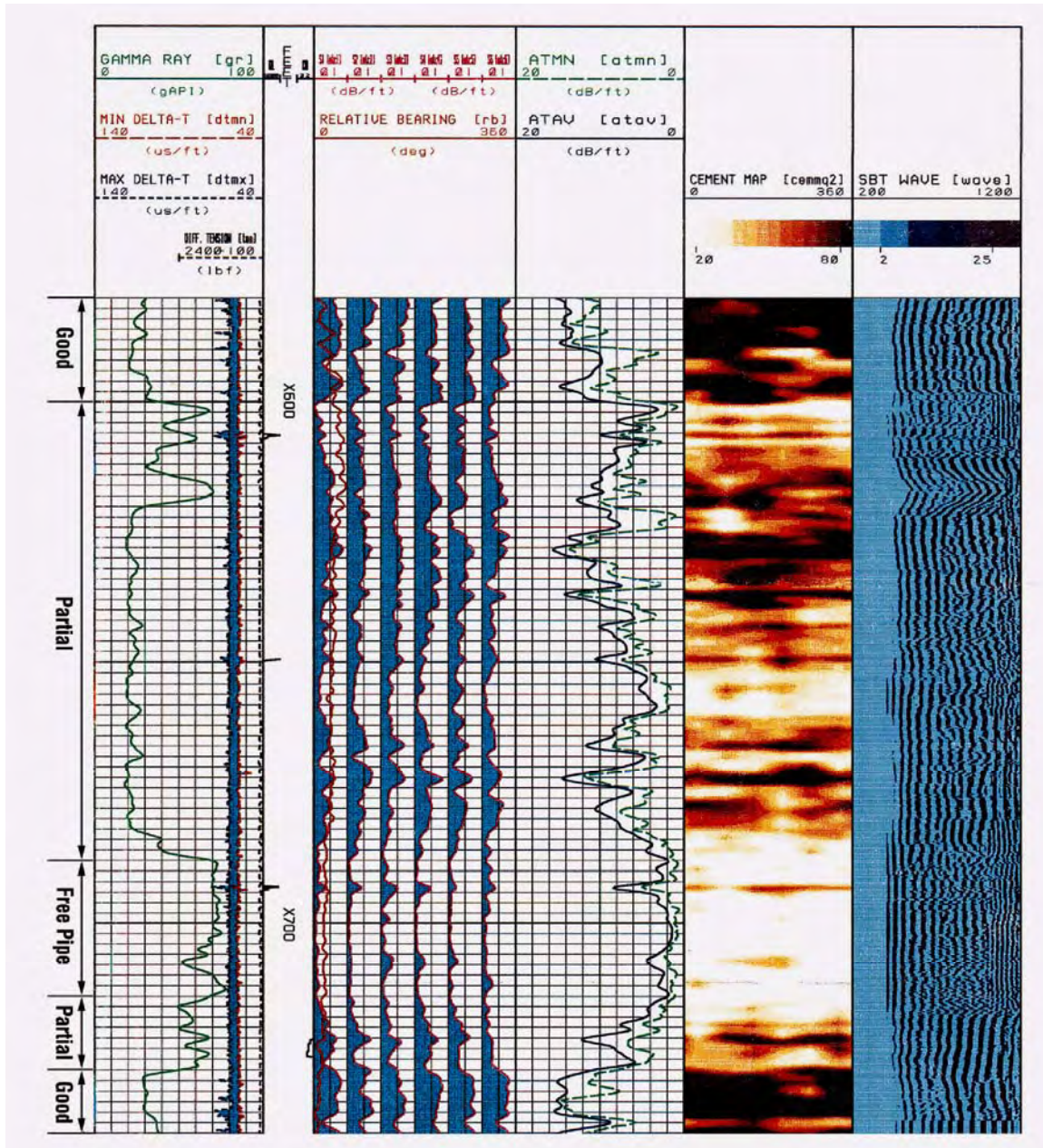


Figure 7.4—SBT Presentation

A cement map is a graphic interpretation that is subject to certain user inputs. The interpreter must understand how the cement map was constructed and know whether reasonable inputs were used in its construction. In the case of the SBT cement map, six regions across the map left to right correspond to the values in each of the six individual attenuation measurements. Higher attenuation rates (better cement) will appear as darker regions on the cement map. Normal user input is automated, and based on inputs of casing size and weight as well as cement compressive strength. The parameters are stated in the log header. For deviated wells, the RB curve mentioned earlier can be used as an input to orient the low or high side of the hole to the middle of the cement map. The

purpose of this high-side/low-side option is to detect whether cement anomalies correlate with the high or low side of the casing. The most useful feature of a cement map is the detection of uncemented channels over significant intervals as opposed to isolated voids.

The SBT Interpretation Chart (see Figure 7.5) depicts the relationship between casing-wall thickness and cement compressive strength. The chart should be used as a guideline when evaluating conventional cements (Class H, Class G, etc.) that are not mixed with volume extending additives. When evaluating foamed cements or other cement systems containing low-density additives (e.g. microspheres) or volume extending additives, the relationship between cement compressive strength and cement acoustic impedance tends to be less reliable.

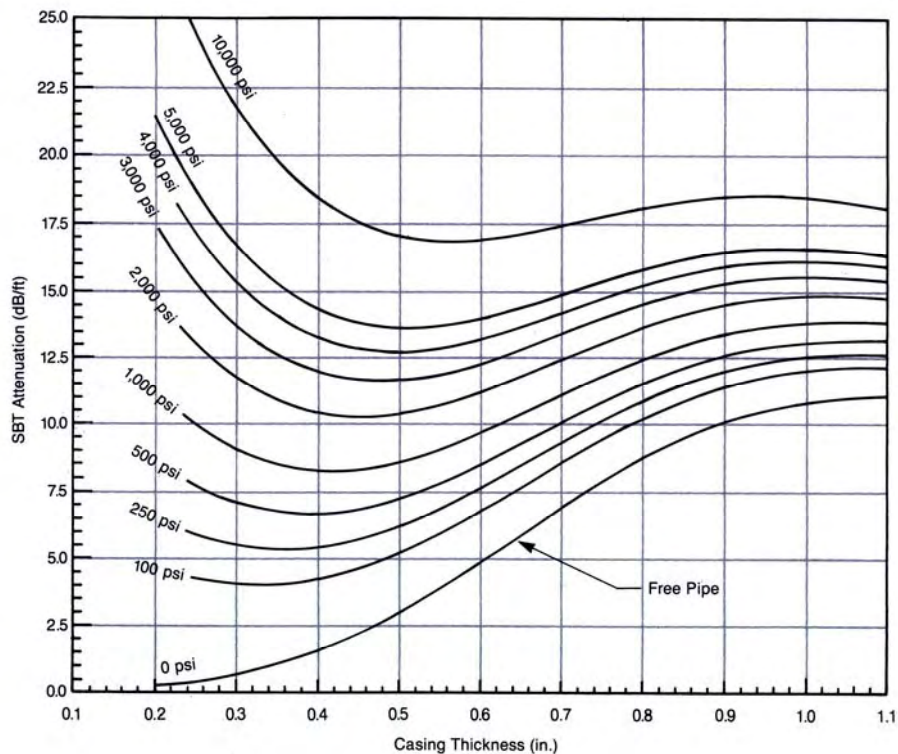


Figure 7.5—SBT Chart to Convert Attenuation to Compressive Strength for Classes G and H Cement

NOTE: Draw a horizontal line from the attenuation measurement on the y-axis, and a vertical line from the casing-thickness on the x-axis. The point at which both lines intersect is the apparent cement compressive strength.

7.7 SBT Quality Control and Recommendations

1. Attenuation should never read zero.
2. Run 200 ft of repeat section.
3. Run 200 ft of a free-pipe section.
4. DTMN and DTMX curves are the primary log-quality indicators. They indicate the degree of casing centralization, and are a direct acoustic couple of the

instrument pads with the casing wall. Excessive internal scale or residual cement may not permit effective acoustic coupling. The two curves should be scaled 140 $\mu\text{s}/\text{ft}$ to 40 $\mu\text{s}/\text{ft}$, and should track each other within 4 $\mu\text{s}/\text{ft}$ to 5 $\mu\text{s}/\text{ft}$, except across casing collars where greater separation will be present. The two curves should center over the 57- $\mu\text{s}/\text{ft}$ value, which is the TT of steel casing. Finally, the DTMN and DTMX curves are excellent indicators of instrument integrity. Should one of the transducers or related circuitry fail, its DTMN and DTMX curves will depart significantly from the standard behavior of the other transducers.

5. Scale the ATC1, ATC2, ...ATC6 attenuation rates to 20–0 dB/ft.
6. On the SBT, scale the Attenuation Rate to 0–9 dB/ft and the Cement Map using the SBT interpretation chart. The minimum coloration value should be equal to that of free pipe on the chart (based on casing wall thickness) (see Figure 7.5).
7. The SBT can be run in any casing-fluid density, and in casing sizes up to and including 16 in. Larger sizes have been logged with special arm extenders; however, the log quality is lower.
8. Generate a receiver-calibration and verification summary.

7.8 Limitations (Environmental Effects)

(See 5.7.)

1. Microannulus.
2. Fast formations (to a lesser extent than traditional CBL—reduced transmitter-receiver spacing).
3. Cement curing (see 3.2 on slurry design/compressive strength).
4. Gas contaminated cement (see 3.2 on slurry design/static gel strength).
5. Thin cement sheath (see 5.5 on CBL interpretation).
6. Eccentered casing (see 3.3 on mud removal/casing centralization).
7. Coated casing (see 3.3 on mud removal/coated casing).
8. Identifying small cement channels.

8 Sector Bond Log (SBL)

8.1 Introduction

SBL tools are mandrel-type devices that combine the traditional 3-ft CBL and 5-ft VDL feet measurements (provided by 1 monopole, omnidirectional transmitter and 2 omnidirectional receivers) with an array of eight or six sector transmitters, located next to the monopole transmitter (1.66 ft to 2 ft spacing and circumferentially located at angles from 45° to 60°). The array of directional receivers provides an azimuthal segmented map or image of cement bond quality. This tool has different nomenclatures depending on the service company (e.g. RAL: radial attenuation log; CMT: cement mapping tool; SCMT: slim cement mapping tool; SSBT: slim sector bond tool; SBL: sector bond log).

Slim (1 ¹¹/₁₆ in.) tools are available for through-tubing operations. High-temperature and high-pressure tools, rated up to 400°F to 420°F and 15,000 psig to 20,000 psig, can be provided.

One type of SBL employs a different tool configuration. This 2 ³/₄-in. tool combines the traditional 3-ft CBL and 5-ft VDL measurements, with an array of eight directional transmitters working in combination with an array of eight directional receivers. The transmitter array is linearly spaced 2 ft from the receiver array, and each sector transmitter-receiver pair is radially spaced 45° apart to scan the cement around the casing circumference. The sector-transmitter resonance frequency is in the low-ultrasonic region between 80 kHz to 120 kHz.

8.2 SBL Physics

There are two types of SBLs; the radial bond tool (RBT) and the sector bond tool (SBT).

The radial bond tool (RBT) uses a method similar to the traditional 3-5 ft CBL-VDL. The six or eight directional receivers analyze the waveforms transmitted along the casing in 45° or 60° sectors of the casing circumference (see Figure 8.1a). The two omnidirectional receivers work in combination to provide the traditional CBL-VDL.

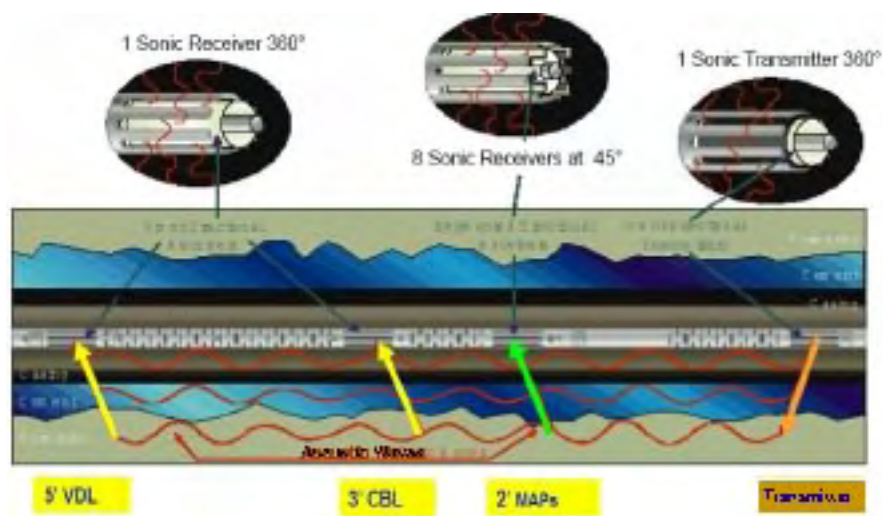


Figure 8.1a—Illustration of the Measurement Principle Used by the Radial Bond Log (Eight Directional Receivers for Cement Mapping)

The sector bond tool (SBT) works in a similar fashion. The eight pairs of directional transmitter-receivers emit an acoustic signal down the casing with each 45° sector transmitter-receiver simultaneously (see Figure 8.1b).

For RBT and SBT, the directional receivers or transmitter-receiver pairs used for radial channel identification.

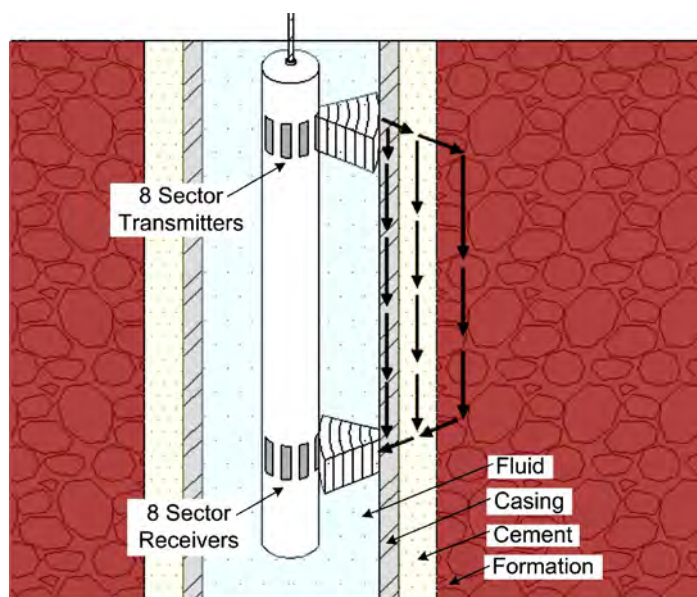


Figure 8.1b—Illustration of the Measurement Principle Used by the SBT

8.3 SBL Waveform/Variable Density Physics

(Same as 5.2.)

8.4 Key Requirements

(Same as 5.3.) A few important key requirements should be emphasized.

1. Tool centralization for slim RBT.
2. Calibration of each directional receiver (RBL) or transmitter-receiver pair (SBT)
3. Tool setup: Casing-size and thickness data, especially for the SCMT (signal processing).

8.5 SBL Presentation

The following are two examples of available SBL presentations. (See Figure 8.2 and Figure 8.3.)

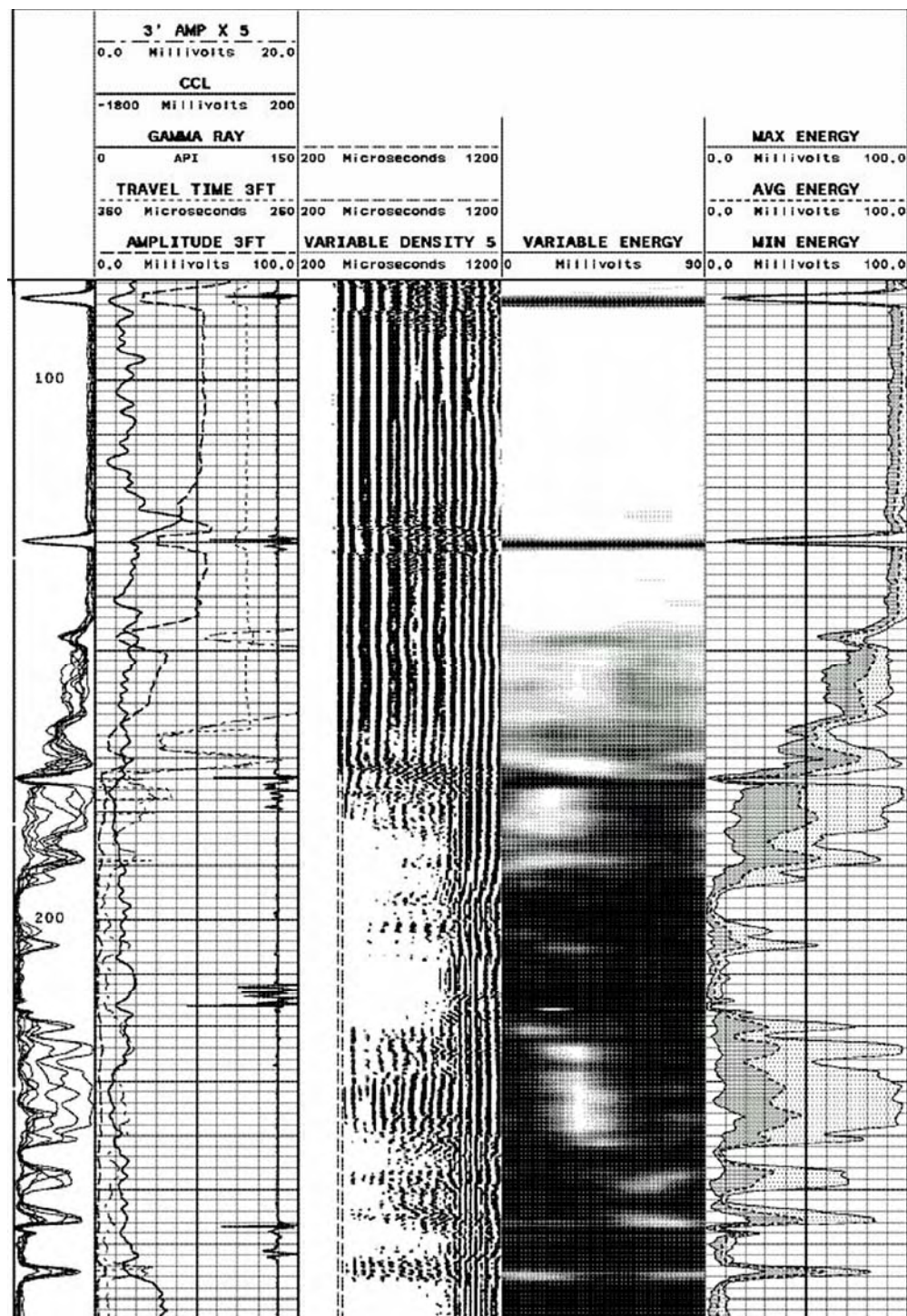


Figure 8.2—Sector Bond Log (SBL) Presentation #1

NOTE: The first track shows the amplitude curves from the 2-ft receiver. The second track contains the 3-ft amplitude, 3-ft TT, GR and collar locator. The third track is variable density log or waveform presentation. Track four is the cement map for cement evaluation, based on the parameter picks for the sectors. The last track has the minimum, maximum and average amplitude from the 2-ft spacing sectors.