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Borehole Geophysical Logging Techniques Applied to Monitoring Well and Water Well Completions

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ABSTRACT

Monitoring and production water wells are required to be carefully completed to ensure protection of groundwater resources. Health of water users, and quality of data collected from monitoring wells are also well completion concerns. Because of poor completions, groundwater resources may be lost to other aquifers, discharged to the ground surface, or contaminated either by surface water leaking through the annulus or by leakage from a previously contaminated aquifer.

Water well completion forms are typically the only information available about the types of materials and depths of installation in wells. Once the well is finished, the only access is through the casing.

Standard borehole geophysical tools can be used to provide useful information about well completions. A reported completion can be verified or rejected based on geophysical tool responses. In order to apply borehole techniques to completed wells, the tools must be calibrated by logging known completions, preferably in a controlled setting such as a laboratory.

This project undertook the testing of caliper, natural gamma, omni-directional and focused gamma-gamma density logs, neutron logs, electric logs, and sonic full-waveform logs. Tool responses were measured in 312 laboratory tests representing different well completions. Tool responses were then measured in the field in nine monitoring wells in eastern Montana.

The suite of tools provided data that were used to successfully identify most completion types. Casing material was clearly distinguished by all of the nuclear tools. Steel casing attenuated the signals in contrast to PVC casing. Greater wall thickness of either PCV or steel also attenuated the signal. Grouts were identified using 4pi omni-directional gamma-gamma density tools. In some situations, focused gamma-gamma density and neutron logs were also very helpful in identifying grout materials. In general, cement grout attenuated the signal the most, sand was next, and bentonite grouts returned the highest signal. The thickness of the grout was very difficult to identify in the field settings. In the laboratory tests higher density grout, such as cement, reduced the return signal in relationship to greater radial thickness of grout, and less dense grouts such as bentonite showed higher signals for greater radial thicknesses of grout.

Successful investigation of well completions requires a suite of geophysical tools, not a single tool. Caliper, 4pi omni-directional gamma-gamma density, and full waveform sonic logs are probably the most valuable of the tools tested. Each individual tool should be calibrated in known settings prior to use in field investigations.

INTRODUCTION

Purpose of Research

The completion of monitoring wells and water wells (herein referred to generically as water wells or wells) are regulated to protect groundwater resources and groundwater users. Proper well completion includes selection and placement of the most appropriate casing material, perforation locations, gravel pack, and annular seal. Well construction can have a critical effect upon the sanitation of the well and its ability to provide safe domestic, public, stock, and other water supplies. Well completions are designed to protect the aquifers. In the case of monitoring wells, the completion affects the validity of data collected and resultant interpretations, and decisions based on those data. This problem is especially critical in the mineral development field, where large numbers of monitoring wells are used for baseline data and permit decisions.

Improper completions can result in contamination of well-water by surface water or undesirable groundwater, and cross-contamination of local, areal, or regional aquifers. The potential effects of this contamination may include subtle changes in quality (tapping a hard water source), diminishing use category (reducing a domestic well to livestock quality), or outright threats to human health or safety (coliform bacteria, nitrates, arsenic, or other contamination). Improper completions also may cause the diminution or depletion of specific water sources by the downward draining of shallow aquifers or by the improper control of artesian aquifers.

In Montana, proper completion techniques are specified in current state water well contractors regulations (Title 37, Chapter 43, MCA and Title 36, Chapter 21, ARM).

Actual well completions have seldom been documented because of the lack of techniques and equipment. Typically, the sole source of information after a well is completed is an engineering or driller's report. Secondary parameters are of some limited use, including water levels that appear inappropriate, exceptionally low (or high) yields from wells, or poor water quality where good quality is expected. Some impacts from poor completions may take years to be observed. It was noted that abandonment problems near a coal-mining area of Montana first appeared in the early 1980s. Borehole leakage however, went undocumented until the late 1980s when local water-level responses were interpreted as interaquifer mixing (Wheaton and Reiten 1996).

This report presents the results of research into the use of standard borehole geophysical tools for investigating well completions. When lowered into a borehole, geophysical tools are used to investigate the sidewall lithology and water- producing potential. They represent the only method of gathering data in a completed well that can be related to the completion materials. Geophysical tools were developed to investigate lithologic materials; however, new guidelines were needed to interpret well-completion data. The purpose of this project is to provide those guidelines.

For the purpose of this report, the term, geophysical tool, refers to any probe that is lowered into a well and returns an electrical signal to the surface which is recorded and interpreted. Such tools include downhole cameras; hole calipers; resistivity and other electric logs; gamma, density, and other nuclear logs; and sonic logs.

Well Completion Problems

Several examples of possible well completion problems are shown in figure 1. These and other problems have been found in actual well completions. In one highly studied, severely contaminated area, as many as 90 % of the monitoring wells were found to not be completed as reported, based mainly on downhole camera surveys (Crowder and Keys 1993).

In figure 1A, a properly completed well is reported with slots and sandpack in the aquifer zone, bentonite seal, and cement grout to surface. Figure 1B shows that the casing shifted to the side of the borehole and allowed voids to be left in the grout. Groundwater moves from the contaminated aquifer to the good quality aquifer. In figure 1C, cracked PVC casing and poorly installed cement grout allow water to flow through voids left in the grout by bridging and enter the casing through cracks, again contaminating the good aquifer. Improper planning in figure 1D puts the slotted interval in the wrong aquifer. Bentonite grout rather than cement is shown, and groundwater is allowed to flow through cracks or voids and enter the well. Water may be pumped and data collected from this well, but the data represent the wrong aquifer.

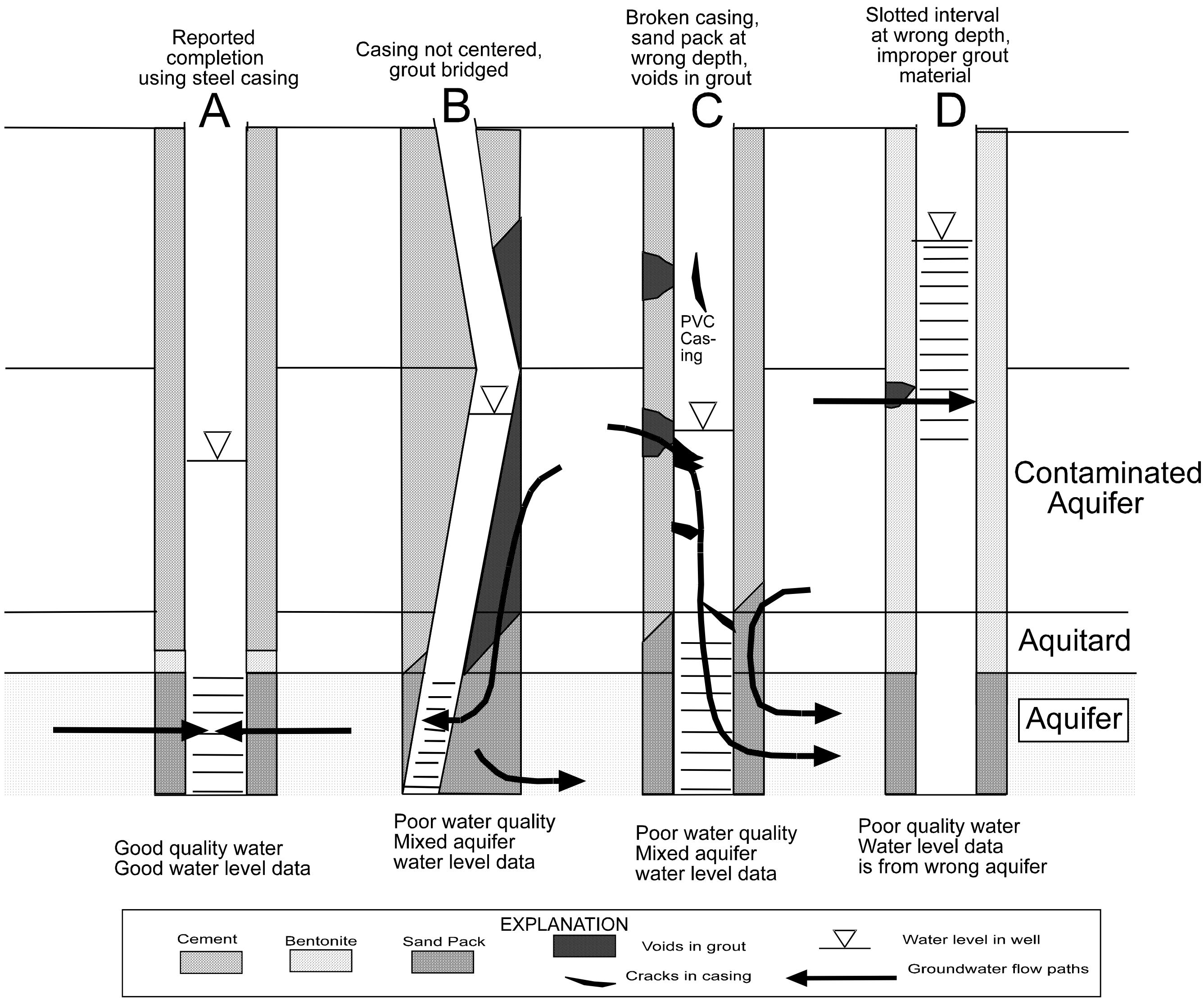


Figure 1. Examples of well completion problems.

Once a well has been completed, the grout and downhole casing conditions are covered and difficult to check. Various attempts have been made to investigate well completions, including the use of geophysical tools. Some successes have been achieved. Downhole cameras have been particularly useful in documenting the condition of casing and depth of slotted intervals. Caliper tools also are successful in certain settings at identifying slots and cracked casing. In the petroleum industry, well verification has received a great deal of attention. Oil- field equipment is generally too expensive for water wells or is unavailable. In some cases, such as cement-bond logs, the tools are not applicable to many water well completions and materials.

Techniques of calibrating geophysical tools that allow differentiating between steel and PVC casing, or among bentonite grout, neat cement, drill cuttings, or sandpack are not universally available. The results of this investigation indicate that a suite of logs can be used to identify most of the major concerns about completions that are listed above. Interpretation of log results must be based on qualified training and experience; no simple technique can be developed using these tools.

Geophysical Methods Investigated

Tools used during this investigation were omni-directional and focused, gamma-gamma density (4pi tool), focused tool, neutron, single-point resistivity, normal resistivity, spontaneous potential, caliper, and full waveform sonic. Natural gamma logs were run as a check of background conditions.

To be useful, a geophysical tool must meet several criteria. It must be available and economic to use in the given setting. Many highly sophisticated oil-field tools and techniques exist, and are used occasionally for aquifer investigation (Temples and Waddell 1996). For most water wells, however, mobilization and usage charges for these tools are prohibitive. Smaller units for mineral exploration, logging, and normal aquifer investigations are available in many areas and can be mobilized to other areas at reasonable costs.

One geophysical company, headquartered in Montana, offers electric logs, natural gamma, and some acoustic and nuclear logs. Other companies are located in areas surrounding Montana including those in Wyoming and Colorado. These companies travel to Montana and offer various services. Costs for geophysical services include mobilization, per diem, and some daily fees such as a minimum daily charge. Logging charges are based on logged footage. Some examples are non-radioactive probes, \$0.30/ft, \$150 minimum/day; radioactive sourced probes, \$0.60/ft, \$300 minimum/day; fullwave form acoustic, \$1.00/ft, \$500 minimum/day; downhole video camera, \$0.75/ft, \$375 minimum/day; water quality log, which includes temperature, \$0.60/ft, \$300 minimum/day.

BACKGROUND

Previous Work

A few references exist on the use of geophysical logs in determining water well completions. General responses of some tools in completed wells are described in the following discussion, which is based on Keys (1990), and Yearsley *et al*. (1991).

Electric logs will deflect in steel casing to show zero resistance as the current flows through the casing, however, the actual depth of change between steel and PVC is difficult to determine from electric logs. Gamma-gamma density also may deflect in steel, while a change in borehole diameter produces a similar log trace. Neutron logs show a drop in counts due to the hydrocarbons in PVC, but this effect is lost below the water level. Caliper logs use multiple-arm tools to show screens, joints, and casing conditions in certain settings. Acoustic televiewers show that casing conditions exist; however, they are expensive and not readily available. Downhole cameras are very good for viewing casing material and condition if the casing is dry or the water is clear. The exothermic reaction of cement grouts during curing can be verified by temperature logs. Cement bond logs work well in certain situations to determine if cement grout exists behind steel casing. However, this oil-field log relies on building high pressure in the casing to expand it against the grout to return a sonic signal and is useless with PVC casing and bentonite grouts.

In at least one instance, a downhole periscope was designed and used with success to 42 ft (Trainer and Eddy 1964). Many of the obvious shortcomings of this tool have been overcome by the introduction of the modern downhole camera.

An open-hole log and a corresponding cased-hole log have been used for completion investigations. Comparing two runs of the same tool can show differences related to the completion. Other factors, such as hole diameter and investigation depth affect the interpretation. Open-hole logs are rarely run on water well borings, and if logged, the standard geophysical tools used are natural gamma, electric log, and caliper. Comparison of these logs to gamma-gamma or neutron density provides little information.

Limiting Factors

Most geophysical tools investigate a volume of material that is spherical or semi-spherical in shape. In an open borehole, about 90% of the response comes from within six inches of the sidewall (Keys 1990). Spacing between nuclear source and detector, and density of the investigated material affect penetration depth. Yearsley *et al.* (1991) showed that focused tools were dominated by depths of about one inch, although the long-spaced sensor on the focused tool responded out to about four inches.

In an open borehole, a geophysical tool responds to hole diameter, fluid in the borehole, wall cake if present, intruded zones in the sidewall, formation material, and formation fluids. In a cased hole, geophysical tools respond to fluids in the casing if present, casing diameter, casing wall thickness, casing material, grout density, grout thickness, wall cake if present, borehole diameter, formation materials, and formation fluids. The range of possibilities is distinctly complicated. Fortunately, tools respond to a spherical shaped volume with the strongest influence being closest to the tool, and the weakest influence being the farthest from the tool.

Complications, such as those described, make an absolute calibration of geophysical tools in specific well completions impossible. Natural radioactivity in grout materials, different ages of tool sources for nuclear logs, and different calibration materials will influence the results. Each tool and logging unit should be calibrated to targeted well completions. Log interpretations must be performed by individuals trained specifically for that purpose.

Theory of Operation

Nuclear Logs

Theory of operation of geophysical tools is well documented in the literature, including Patten and Bennett (1963), Fetter (1980), Driscoll (1986), Sclumberger (1987), Keys (1990), and many hydrogeology text books such as Fetter (1980) and Driscoll (1986), and is briefly discussed herein to provide an understanding of the tests and the interpretations of the test data. The reader is referred to courses and detailed texts to develop a thorough understanding of individual logs. The following discussion draws heavily on Keys (1990) and technical papers written by COLOG, Inc. (Crowder and Keys 1993), (Crowder *et al.* 1991).

Logging tools are generally classified as nuclear, electrical, mechanical, or sonic. To help understand nuclear tools, a brief review of nuclear theory follows (Trainer and Eddy 1964) (Rosser 1969): protons have a mass of one and a positive charge, whereas neutrons also have a mass of one but have no charge. Electrons with a mass 1/1840 have a negative charge. Atomic numbers are the number of protons and in neutrally charged atoms, equal the number of electrons. Mass numbers are the sum of the protons and neutrons. Isotopes have the same atomic numbers as their related atoms, but have different mass numbers because of a differing neutron numbers.

Radioisotopes, which are of interest in nuclear logging, are unstable over time, decaying to become new, more stable isotopes. The decay process leaves excess energy in the nucleus that is emitted as alpha or beta particles (positive or negative charges, respectively) or as gamma photons (or rays). Gamma photons pass through a detector, such as a scintillation crystal, and cause ionization that can be counted and recorded. Also, compared to other radiation particles, gamma photons are difficult to stop. Because of this ability to pass through materials, only gamma photons are used in nuclear logging.

Gamma photons react with surrounding material in three manners: photoelectric absorption, pair production, and Compton scattering. Pair production and Compton scattering are applicable to geophysical logging. In pair production, the energy of a photon is lost to an electron (or negatron) and a positron (positively charged particle with the same mass as an electron). Eventually the electron-positron pair annihilate each other, and two or three gamma photons are emitted.

Passing through a medium, gamma photons collide with electrons, losing some energy, and continue at a slower rate. This process attenuates gamma signals in logging procedures and is referred to as Compton scattering .

Neutron sources emit high-energy neutrons that collide with the nuclei of atoms and lose energy. Eventually enough energy is released and captured by a nucleus that is then excited to emit a gamma photon. The gamma photons are detected by the sensor and recorded.

The distance a neutron travels before being captured is a function of the material it passes through. Because a neutron and a hydrogen nucleus are similar in size, hydrogen is the most effective atom for moderating and capturing neutrons. Neutron probes used in well logging are long spaced, so high gamma counts indicate more neutrons being captured near the detector. In other words, lower density material, or lower hydrogen (less water or less PVC), between the source and the detector allows more neutrons to reach the vicinity of the detector before capture. A lower gamma count correlates generally with a higher hydrogen content.

Several specific tools utilize the above theories. Of those, natural gamma is the most common logging tool. It consists of a detector that relies on natural gamma emissions from the surrounding material. The tool typically investigates about 6–12 in. of material radially. The detector unit records total gamma radiation, typically related to potassium (K-40), and daughter products of the uranium and thorium series. The tool will count all gamma photons, whether naturally occurring in the formation or from material added to the well, such as some sources of bentonite that are high in potassium. Gypsum, basalt, and coal usually show low counts; limestone and sandstone show higher counts; shale shows still higher counts; and gneiss, granite, and phosphate beds show the highest counts.

Gamma-gamma tools, or density tools, contain a source and a detector, and investigate 5–6 in. radially. The tools operate on the theory of Compton scattering, where a denser material has more electrons, so fewer gamma photons are emitted by the source escape capture and are counted by the detector.

Two types of gamma-gamma tools are common in the water well industry. Omni-directional, or 4pi tools, are centralized and emit radiation. They detect returning photons for 360˚ around the tool. Focused gamma-gamma tools are decentralized (source and detector windows are forced against the casing or well sidewall) and have two detectors: one nearer the source than the other. The signal recorded by the short-spaced detector is strongly influenced by material close to the tool. The long-spaced detector is strongly influenced by material deeper in the sidewall.

In a neutron logging tool, a neutron source is placed in the probe. The emitted neutrons are moderated and eventually captured, mainly by hydrogen, with the emission of a gamma photon as previously described. Logging tool detectors count either the slowed (moderated) neutrons or the slowed neutrons and gamma photons. The signal count is inversely proportional to hydrogen content in surrounding material if the detector is at least 12 in. from the source, as is the case in well logging tools.

Electric and Mechanical Logs

Formation resistivity between two electrodes is measured as a current by single-point resistivity tools or normal resistivity tools. Single-point resistivity tools measure current flow between a current electrode lowered in a well and a ground electrode at ground surface. As the amount of saturation and the salinity of the formation water increases, resistivity decreases. The radius of investigation for single-point resistivity is 5–10 times the radius of the probe.

Normal resistivity tools measure the current using four electrodes, two on the probe, one grounded about 50 ft above the probe on the cable, and one grounded at the surface. As with single-point resistivity, normal resistivity is a function of saturation, total dissolved solids in the water, and the geometry of formation pores.

Spontaneous potential tools measure differences in electrical potential between borehole walls and borehole fluids. No current is applied by the probe. Water salinity, temperature, porosity, and hydraulic conductivity affect the spontaneous potential of the formation. Of those, salinity of fluids in the borehole and of adjacent formations are the predominant factors. If the formation water is fresher than that in the borehole, an increasing reading is recorded. The reverse causes a decreasing reading. In situations where the water salinity is constant, a lithologic change from sandstone to shale will produce a positive deflection, while going from a shale to a sandstone unit causes a negative deflection.

Caliper logs are used to measure the diameter of the borehole or casing. One- or three-arm tools are used and may show competence of formations, washouts, and fractures if the increase in diameter lines up with an arm on the tool. In cased wells, caliper logs can show cracks in the casing and joints. Tools with small arms can show roughness associated with slotted intervals.

Temperature logs measure fluid temperature in the borehole by means of a thermistor. Because cement curing is exothermic, temperature logs can identify cement during this process. Fluid entering the borehole may be a different temperature than fluid in the borehole, and these entry points can be identified on temperature logs.

Flowmeter logs measure the direction and velocity of fluid movement in the borehole. Most probes are either simple impeller flowmeters, or heat-pulse flowmeters. Water moving between aquifers or entering the borehole can be identified with flowmeter logs.

Sonic and Acoustic Logs

Sonic logging tools transmit sonic energy (sonic waves) that travels through the borehole fluid along the casing or borehole wall; the return wave is recorded. Fractures and voids attenuate the signal of the tube wave traveling up the borehole or casing wall. Compression waves are slowed by voids and fractures. The transit time of the compression wave is recorded as the inverse of wave velocity. A representation of the compression wave is the variable density log, which is a gray-bar view of wave arrivals and provides a better graphic presentation of some conditions.

Acoustic cement bond logs were developed for oil-field applications to test continuity of cement grouts. From a simplified perspective, the acoustic signal travels from the source to the casing and is transferred to the cement if it is tight against the casing. The signal continues to the formation if a good seal exists between the cement and the formation. An attenuated signal recording by the sensor shows energy loss.

METHODS

Laboratory Calibration

During this project, laboratory and field investigations were undertaken. Laboratory tests were run to provide calibrations of the geophysical tools in different completions and to distinguish which tools showed the most favorable responses.

In the laboratory setting, miniature wells were constructed in 55-gallon and 85-gallon steel barrels. A well casing was fixed in the center of the barrel, and the barrel was filled with material to represent formations and grouts. Figure 2 shows a typical well completion in a barrel. The barrels were in most cases filled with sand to represent a reference geologic formation. The tests were repeated as follows: 1) dry sand and casing, 2) dry sand and a water-filled casing, 3) saturated sand and dry casing, and 4) saturated sand and water-filled casing. Tests also were performed with barrels filled with either neat cement or with bentonite surrounding the casing. Steel and PVC casing were used in several diameters and wall thicknesses. Several densities and radial thicknesses of bentonite and cement grouts were used. Grout densities were bentonite grouts of 9.0 and 9.3 pounds per gallon (lb/gal), cement and bentonite combined at 13.5 lb/gal, neat cement at 15.4 lb/gal. For reference, the sand density used was measured to be 11.7 lb/gal.

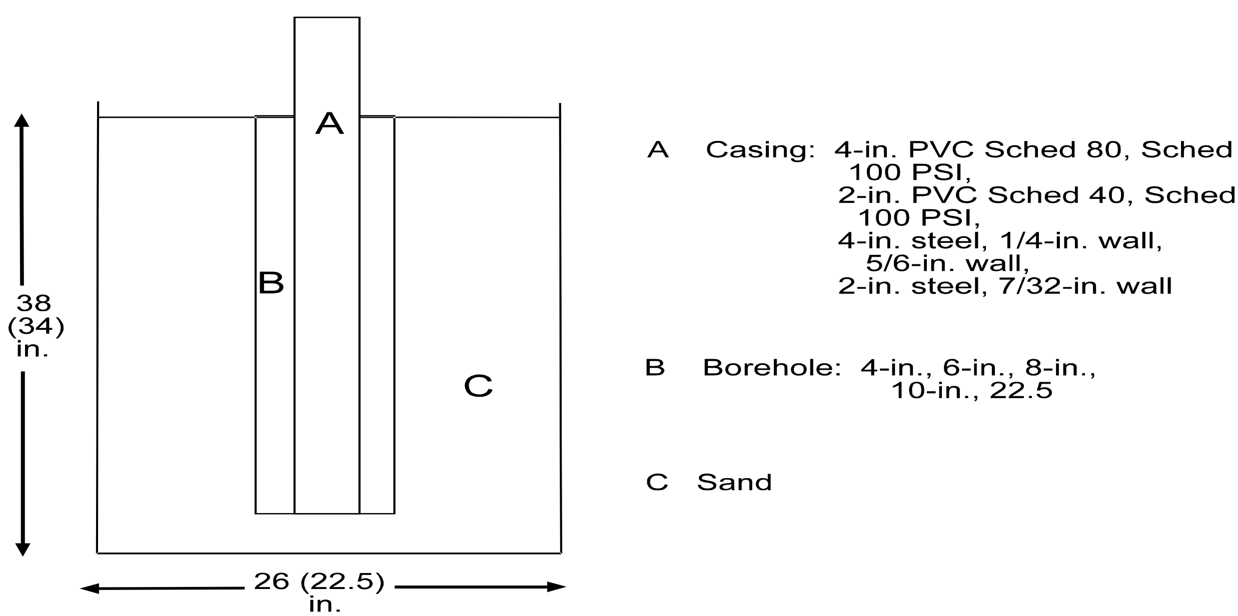


Figure 2. Schematic diagram of the laboratory calibration wells.

Geophysical tools used in the laboratory calibrations were an omni-directional or 4pi gamma-gamma, a focused gamma-gamma, and natural gamma. Two source strengths and two detector spacing arrangements were used in the 4pi tool. In the focused gamma-gamma tool, one source was used. Use of neutron, sonic, electric logs, and caliper were not feasible in the laboratory setting.

For each test, the geophysical tool was inserted in the well casing and supported overhead by a clamp. The center of the source to detector space was set at half of the well depth. Reading intervals were set at one second, with the tool depth remaining unmoved to collect data for 3–5 min. Several tests were run to verify the repeatability of the data.

Appendix 1 comprises variations on which tests were performed and from which acceptable results were obtained. Several tests failed because of mechanical problems such as water leakage from the casing. Results are listed from a total of 312 tests.

In actual applications, grout densities are normally discussed in terms of pounds per gallon. This terminology is used here but can be easily converted to grams per cubic centimeter by multiplying 0.1197 gm/c^3 per lb/gal by the mud density in lb/gal. For example, cement with a mud density of 15 lb/gal has a gram density of 1.80 gm/c^3, and a 9.3 lb/gal bentonite grout has a density of 1.11 gm/c^3.

Focused gamma-gamma data that are typically converted from counts per second (cps) to gm/c^3 are reported in terms of density. All data in this report are presented in cps units. The conversion formulas for short-spaced and long-spaced, focused gamma-gamma data are represented by the following straight-line formulas.

short-spaced conversion formula:

$$cps = [(gm/c^3 - 1.28\ gm/c^3) * (-1786.36)] + 4899$$

long-spaced conversion formula:

$$cps = [(gm/c^3 - 1.28\ gm/c^3) * (-938.64)] + 1338$$

Field Confirmation

Nine wells were logged to check the validity of the laboratory calibrations. These test wells were completed in aquifers of the Tongue River Member of the Tertiary Fort Union Formation in central and southeastern Montana and are active monitoring wells with good-to-fair completion information. Two of the wells showed data similar to other wells and are not presented in the results. Well completion details for these wells and for seven wells in adjacent lithologic units are shown in the plates. Lithologic units include coal, sandstone, shale, and coal mine spoils. Data are on file at the MBMG Billings office.

Completions and geophysical information are included for wells with steel and PVC casing. Grouts in these wells were bentonite, cement, a bentonite and cement mixture, and drill cuttings. Slotted intervals included saw-cut slots, torch-cut slots, factory slots, and one well with an open-ended completion.

Logs were run on selected intervals of each well rather than on entire depths.

RESULTS

Laboratory

Careful calibration is crucial to successful application of nuclear tools to well-completion materials investigations. Generally, all nuclear tools easily identified casing material in the laboratory settings. Grout material was identified by certain tool arrangements, but grout thickness was not reliably identified. Test results are listed in appendix 1.

Discussing all tool responses for all settings is impractical; therefore, the most common well completions, using 2-in. or 4-in. PVC and steel casing, are discussed. Appendix 1 consists of the test settings, tools, and average counts per second (cps). Because gamma photon activity is erratic, a steady return signal is not expected. The normal statistical variation in the return is as follows:

$\sqrt{cps}$ (an average count of 40,000 cps should have a regular variation of ± 200 cps) (Yearsley, et al. 1991).

Between 180 and 300 readings were collected in each setting during the 3–5-min tests. Statistical analyses of the data indicate normal distribution, with standard deviations that are less than or equal to the predicted statistical variation. Standard deviations and population averages for each test setting are provided in appendix 1. In the following discussion, average cps values are used to represent the population.

To verify the interference of background radiation, natural gamma was measured in two barrels: one filled with sand and the other with 9.3 lb/gal bentonite grout. Natural gamma was measured in both barrels at rates of between 19.6 and 22.6 cps. Most count rates for the gamma-gamma tools in these settings were between 2,000 and 50,000 cps. The lowest count rate was 347 cps for the long-spaced focused tool. The normal statistical variation for 347 cps is 18 cps, or about equal to the background radiation. For the other tools, variation is much higher. Therefore, the influence of background radiation is insignificant.

Three omni-directional, 4pi gamma-gamma tool arrangements were tested to determine which were most useful. The tool arrangements were 18-in. source to detector spacing using 5-millicurie(mCi) and 100-mCi sources, and 9-in. spacing with a 5-mCi source.

The highest counts for the 4pi tools were with a 100-mCi source spaced 18 in. from the detector (appendix 1). The full barrel of bentonite simulated an annular thickness of 9-in. and had the strongest average response at 56,400 cps (figure 3). Reducing the annular radial thickness increased the attenuating effects of the more dense formation material (sand). With a bentonite thickness of 0.75 in. the signal was attenuated 15% (48,000 cps). By eliminating the grout completely, a sand-filled barrel attenuated the signal 22% (56,200–43,650 cps). Using cement to increase grout density attenuated the signal over 40% compared to the bentonite grout. Cement grout showed an inverse relationship to cps when decreasing the radial thickness of grout to result in a higher cps return. When water was added to the formation and the casing, the signals were attenuated 41% in bentonite, 67% in sand, and 69% in cement. In comparison to PVC casing, steel casing attenuated the signal between 50 and 60%.

The 5-mCi source spaced 9 in. from the detector had the next strongest signal (appendix 1). With a 9-in. radial thickness of bentonite grout, the counts averaged 19,900 cps (figure 4). When the bentonite grout was eliminated completely, the sand-filled barrel attenuated the signal 11% to 17,650 cps. Grout density was

4pi gamma-gamma

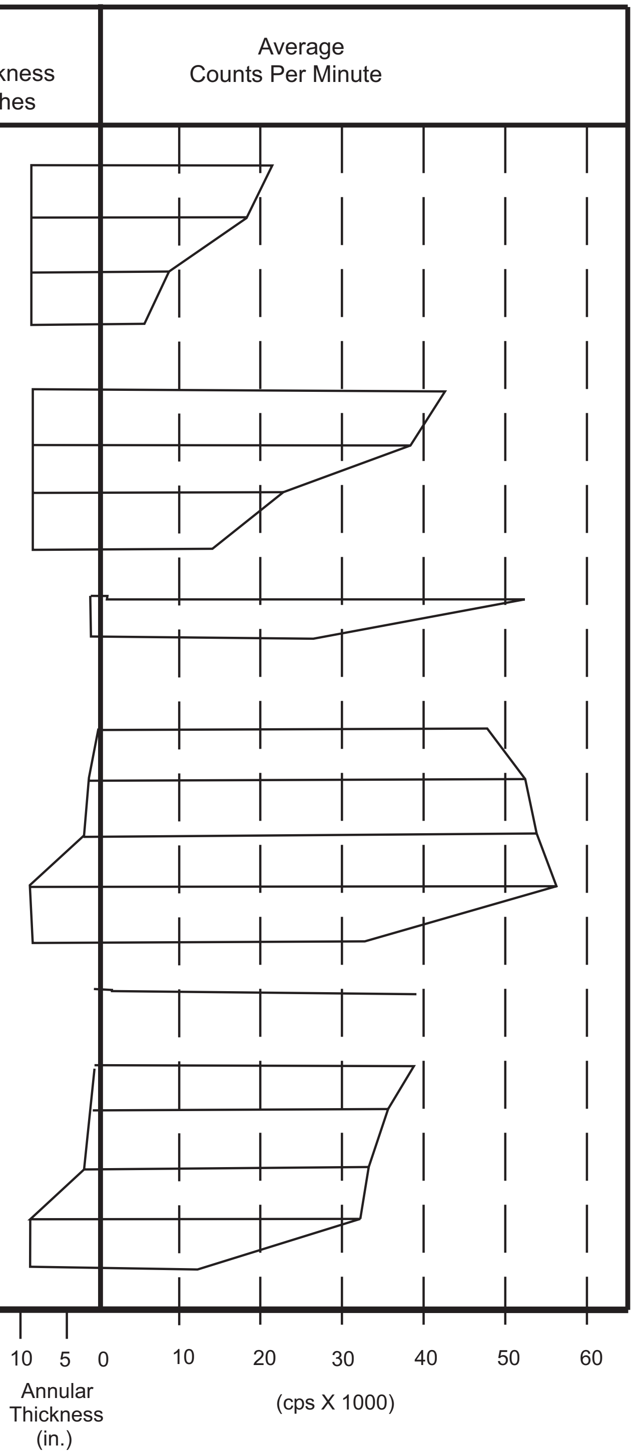
Source to Detector Spacing: 18 in.

Source: 100 mCi

Casing Diameter: 4 in.

Casing Wall Thickness: 0.25 in.

Casing Material	Water		Annular	
	Casing	Barrel	Material lb/gal	Thickness inches
Steel	NO	NO	Sand	9.00
Steel	NO	YES	Sand	9.00
Steel	YES	NO	Sand	9.00
Steel	YES	YES	Sand	9.00
PVC	NO	NO	Sand	9.00
PVC	NO	YES	Sand	9.00
PVC	YES	NO	Sand	9.00
PVC	YES	YES	Sand	9.00
PVC	NO	NO	9.0	2.00
PVC	YES	YES	9.0	2.00
PVC	NO	NO	9.3	0.75
PVC	NO	NO	9.3	1.75
PVC	NO	NO	9.3	2.75
PVC	NO	NO	9.3	9.00
PVC	YES	YES	9.3	9.00
PVC	NO	NO	13.5	1.75
PVC	NO	NO	15.4	0.75
PVC	NO	NO	15.4	1.75
PVC	NO	NO	15.4	2.75
PVC	NO	NO	15.4	9.00
PVC	YES	N/A	15.4	9.00



EXPLANATION

9.0: Bentonite Slurry

9.3: Bentonite Slurry

13.5: Cement with 8% bentonite

15.4: Neat cement

*Figure 3. Tool response, laboratory test: Gamma-gamma, 4pi, 18-in. Spacing, 100-mCi source, 4-in. casing.*1

4pi gamma-gamma

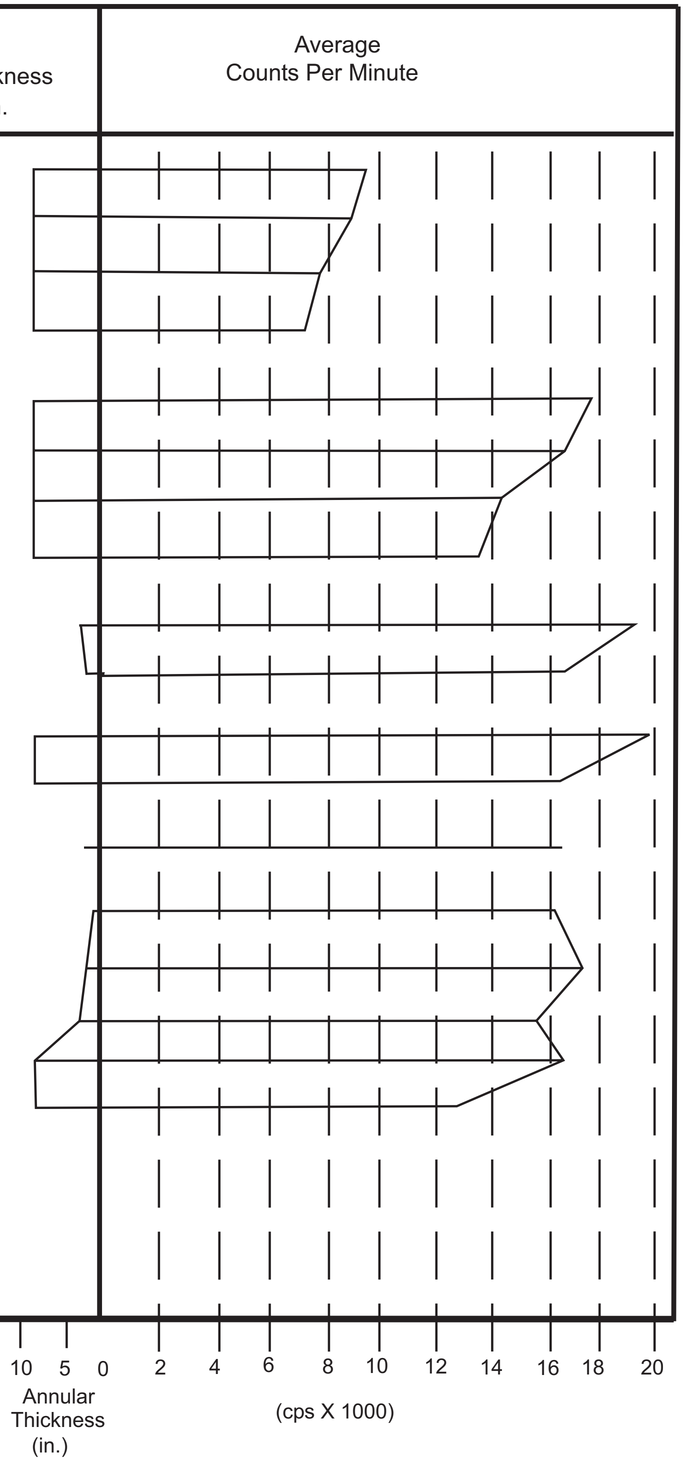
Source to Detector Spacing: 9 in.

Source: 5 mCi

Casing Diameter: 4 in.

Casing Wall Thickness: 0.25 in.

Casing Material	Water Casing	Water Barrel	Annular Material lb/gal	Annular Thickness in.
Steel	NO	NO	Sand	9.00
Steel	NO	YES	Sand	9.00
Steel	YES	NO	Sand	9.00
Steel	YES	YES	Sand	9.00
PVC	NO	NO	Sand	9.00
PVC	NO	YES	Sand	9.00
PVC	YES	NO	Sand	9.00
PVC	YES	YES	Sand	9.00
PVC	NO	NO	9.0	2.00
PVC	YES	YES	9.0	2.00
PVC	NO	NO	9.3	9.00
PVC	YES	YES	9.3	9.00
PVC	NO	NO	13.5	1.75
PVC	NO	NO	15.4	0.75
PVC	NO	NO	15.4	1.75
PVC	NO	NO	15.4	2.75
PVC	NO	N/A	15.4	9.00
PVC	YES	N/A	15.4	9.00



EXPLANATION

9.0: Bentonite Slurry	13.5: Cement with 8% bentonite
9.3: Bentonite Slurry	15.4: Neat cement

12 *Figure 4. Tool response, laboratory test: Gamma-gamma, 4pi, 9-in. spacing, 5-mCi source, 4-in. casing.*

increased by using cement, which decreased the signal about 18% to an average 16,350 cps. The relationship between signal strength and radial thickness was erratic in the cement grout. By adding water to the casing the signals were attenuated 18% in bentonite, 23% in sand, and 26% in cement.

The 5-mCi source spaced 18 in. from the detector had the lowest average return signal (appendix 1). With a 9-in. radial thickness of bentonite grout, the counts averaged 2,450 cps (figure 5). By eliminating the bentonite, the sand-filled barrel attenuated the signal by 26% to 1,800 cps. Increasing the density of the grout by using cement decreased the signal about 50% to an average 1,250 cps and showed an inverse relationship with radial thickness to increase counts relating to decreasing grout thickness. Adding water to the casing attenuated the signals 50% in bentonite, 72% in sand, and 68% in cement.

The 4pi gamma-gamma tool was tested in a limited number of 2-in. cased settings (appendix 1). Data from several tests are shown in figures 6 and 7. Signal strength in 2-in. cased wells ranged from 12 to 52 percent of that in similar settings for 4-in. wells. Generally responses were comparable but with a stronger influence on the signal by grout and formation materials.

One focused gamma-gamma tool was employed in the laboratory tests (appendix 1). A 100-mCi source was used in the focused tool tests. With a single tool, three sets of data were generated: short source-to-detector spacing (3.9 in.), long spacing (13.8 in.), and the calculated difference between the two readings (delta). Representative results in 4-in. well completions are shown in figures 8, 9, and 10.

As shown in figures 8–10, the focused tool was not generally sensitive to changes in grout and formation parameters. Of the focused tool arrangements, the short spaced was the least sensitive to completion parameters (figure 8), and the long spaced was the most sensitive (figure 9) in terms of percent signal attenuated by changes in casing, and grout and formation materials. The differences between long- and short-spaced detectors, or the delta values, show sensitivity midway between the individual detector responses (figure 10).

The highest signal count for the long-spaced focused tool was 1,400 cps in a full barrel of bentonite, representing a 9-in. radial thickness (figure 9). Decreasing the grout thickness attenuated the signal to 1,160 cps (17%) for a grout thickness of 0.75-in. Eliminating the grout, the sand-filled barrel attenuated the signal farther to 950 cps or 32% less than the 9-in. bentonite grout thickness. Increasing the grout density attenuated the signal as much as 72% (390 cps) for a full barrel of cement. In settings using the high-density cement grout, decreasing the radial thickness of the grout increased the return signal. Adding water to the casing and formation attenuated the signals 5% in bentonite, 53% in sand, and 8% in cement.

Discussion of Lab Results

Comparison of laboratory results for each tool in different settings shows how well the tools can identify casing material, grout material, and grout radial thickness. Overall, casing material is fairly easy to identify, grout material can be readily identified by certain tool arrangements, and grout thickness is very difficult to identify.

4pi gamma-gamma

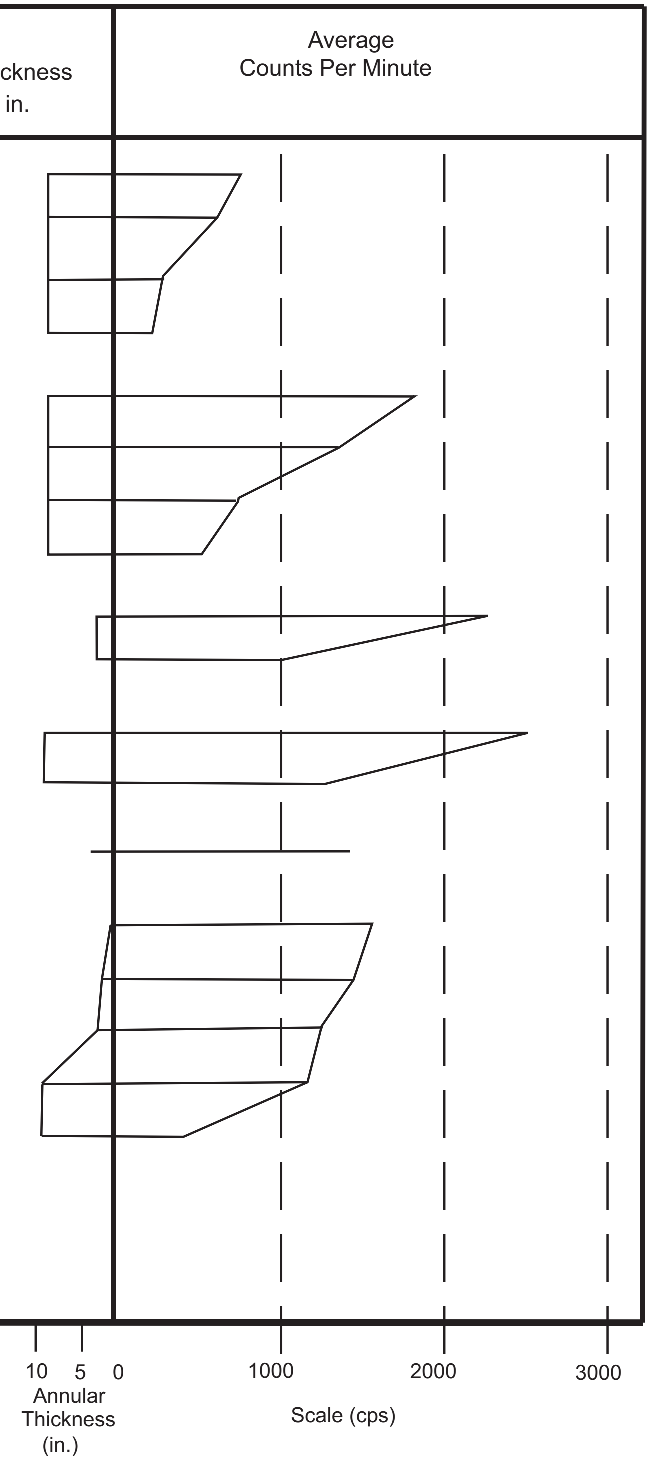
Source to Detector Spacing: 18 in.

Source: 5 mCi

Casing Diameter: 4 in.

Casing Wall Thickness: 0.25 in.

Casing Material	Water Casing	Water Barrel	Annular Material lb/gal	Annular Thickness in.
Steel	NO	NO	Sand	9.00
Steel	NO	YES	Sand	9.00
Steel	YES	NO	Sand	9.00
Steel	YES	YES	Sand	9.00
PVC	NO	NO	Sand	9.00
PVC	NO	YES	Sand	9.00
PVC	YES	NO	Sand	9.00
PVC	YES	YES	Sand	9.00
PVC	NO	NO	9.0	2.00
PVC	YES	YES	9.0	2.00
PVC	NO	NO	9.3	9.00
PVC	YES	YES	9.3	9.00
PVC	NO	NO	13.5	1.75
PVC	NO	NO	15.4	0.75
PVC	NO	NO	15.4	1.75
PVC	NO	NO	15.4	2.75
PVC	NO	NO	15.4	9.00
PVC	YES	N/A	15.4	9.00



EXPLANATION

9.0: Bentonite Slurry

9.3: Bentonite Slurry

13.5: Cement with 8% bentonite

15.4: Neat cement

Figure 5. Tool response, laboratory test: Gamma-gamma, 4pi, 18-in. Spacing, 100-mCi source, 2-in. casing.

4pi gamma-gamma

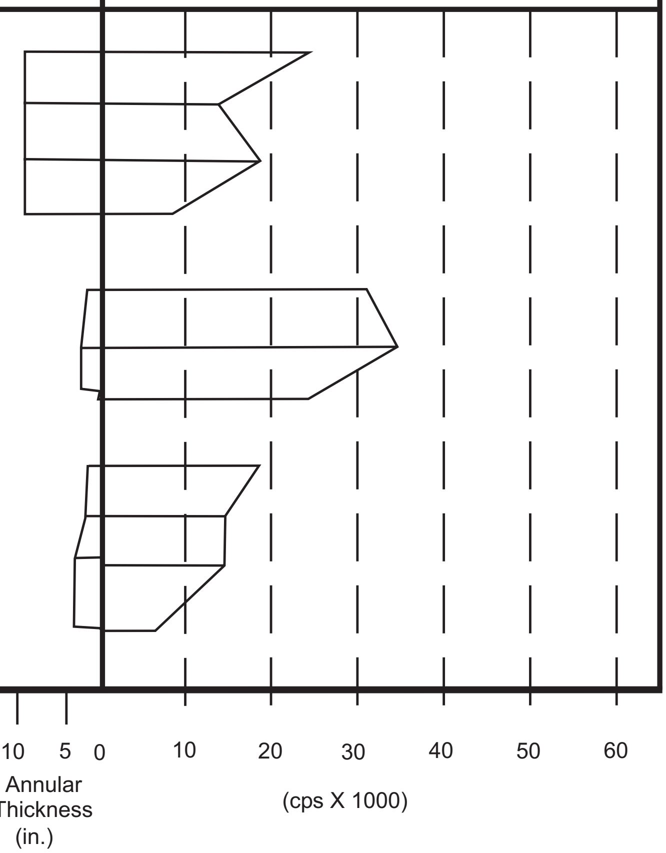
Source to Detector Spacing: 18 in.

Source: 100 mCi

Casing Diameter: 2 in.

Casing Wall Thickness: 0.156 in.

Casing Material	Water Casing	Water Barrel	Annular Material lb/gal	Annular Thickness in.	Average Counts Per Minute
PVC	NO	NO	sand	9.00	
PVC	NO	YES	sand	9.00	
PVC	YES	NO	sand	9.00	
PVC	YES	YES	sand	9.00	
PVC	NO	NO	9.3	1.81	
PVC	NO	NO	9.3	2.81	
PVC	YES	YES	9.3	2.81	
PVC	NO	NO	15.4	0.84	
PVC	NO	NO	15.4	1.81	
PVC	NO	NO	15.4	2.84	
PVC	YES	YES	15.4	2.84	



EXPLANATION	
9.0: Bentonite Slurry	13.5: Cement with 8% bentonite
9.3: Bentonite Slurry	15.4: Neat cement

Figure 6. Tool response, laboratory test: Gamma-gamma, 4pi, 18-in. spacing, 100-mCi source, 2-in. casing.

4pi gamma-gamma

Source to Detector Spacing: 9 in.

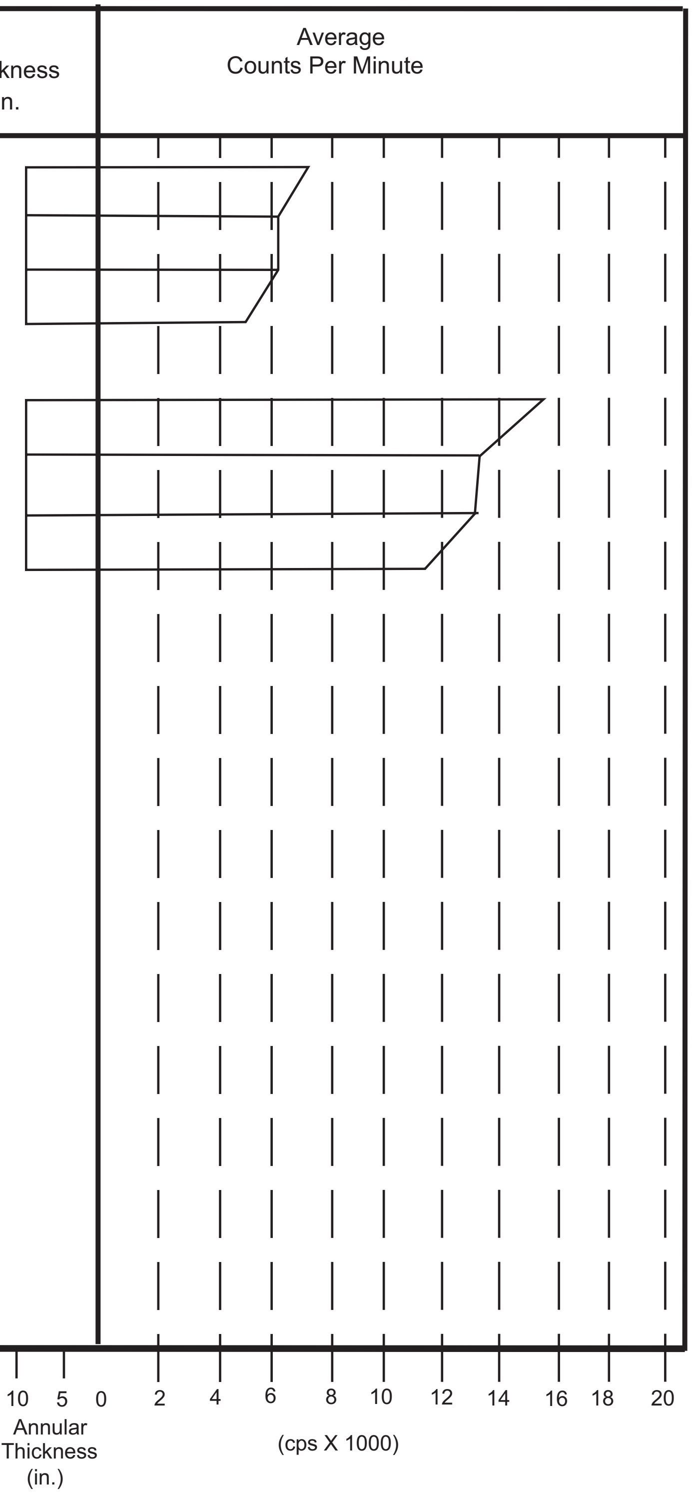
Source: 5 mCi

Casing Diameter: 2 in.

Casing Wall Thickness: Steel - 0.219 in.

Casing Wall Thickness: PVC - 0.156 in.

Casing Material	Water		Annular	
	Casing	Barrel	Material lb/gal	Thickness in.
Steel	NO	NO	Sand	9.00
Steel	NO	YES	Sand	9.00
Steel	YES	NO	Sand	9.00
Steel	YES	YES	Sand	9.00
PVC	NO	NO	Sand	9.00
PVC	NO	YES	Sand	9.00
PVC	YES	NO	Sand	9.00
PVC	YES	YES	Sand	9.00



EXPLANATION

9.0: Bentonite Slurry	13.5: Cement with 8% bentonite
9.3: Bentonite Slurry	15.4: Neat cement

Figure 7. Tool response, laboratory test: Gamma-gamma, 4pi, 9-in. spacing, 5-mCi source, 2-in casing.

Casing Material

To distinguish between PVC and steel casing, all tools work very well. The 4pi tool, using a 5-mCi source spaced 18 in. from the detector, worked the best with a 58% signal attenuation difference (table 1). Using 18-in. spacing and a 100-mCi source showed an attenuation of 52%, the 5-mCi source with 9-in. spacing showed a 47% attenuation. The focused tool, short spacing and long spacing, showed attenuations of 55% and 53%, respectively.

Table 1. Casing material versus cps for each tool in sand-filled barrels, with no water in either the formation or the casing.

Tool Attenuation (percent)	Spacing (in.)	Source (mCi)	Casing	cps (average)	
4 pi	18	100	4-in. PVC	43,650	0
4 pi	18	100	4-in. steel	20,993	52
4 pi	9	5	4-in. PVC	17,625	0
4 pi	9	5	4-in. steel	9,371	47
4 pi	18	5	4-in. PVC	1,794	0
4 pi	18	5	4-in. steel	755	58
focused	short	100	4-in. PVC	4,457	0
focused	short	100	4-in. steel	2,023	55
focused	long	100	4-in. PVC	951	0
focused	long	100	4-in. steel	449	53

Annular Material

Cement, bentonite, and sand can be successfully identified as annular materials. Best results were achieved using the 4pi tool with a 100-mCi source spaced 18 in. from the detector (table 2). The difference in signal return between 9.0-lb/gal and 9.3-lb/gal bentonite is so small that it is unusable. The 4pi tool with a 5-mCi source and 18-in. spacing produced acceptable results, as did the long-spaced focused tool with a 100-mCi source. The 4pi tool with 5-mCi source and 9-in. spacing was unacceptable in distinguishing annular materials.

Annular Material Thickness

None of the tested tools provided data that easily quantified annular radial thickness for bentonite grouts (table 3). The focused long-spaced tools and 4pi with 100-mCi source and 18-in. spacing provided the best results. In bentonite grouts signal increase with increasing grout thickness was 17% and 20% over the range of radial thicknesses tested. In cement, the focused, long-spaced data do an acceptable job of separating annular thicknesses, with an attenuation of 46% between 0.75 and 9 in. 4pi tools utilizing 18-in. spacing showed attenuations of 19% and 17%. The other tools, at best, provided only mediocre data.

Focused gamma-gamma

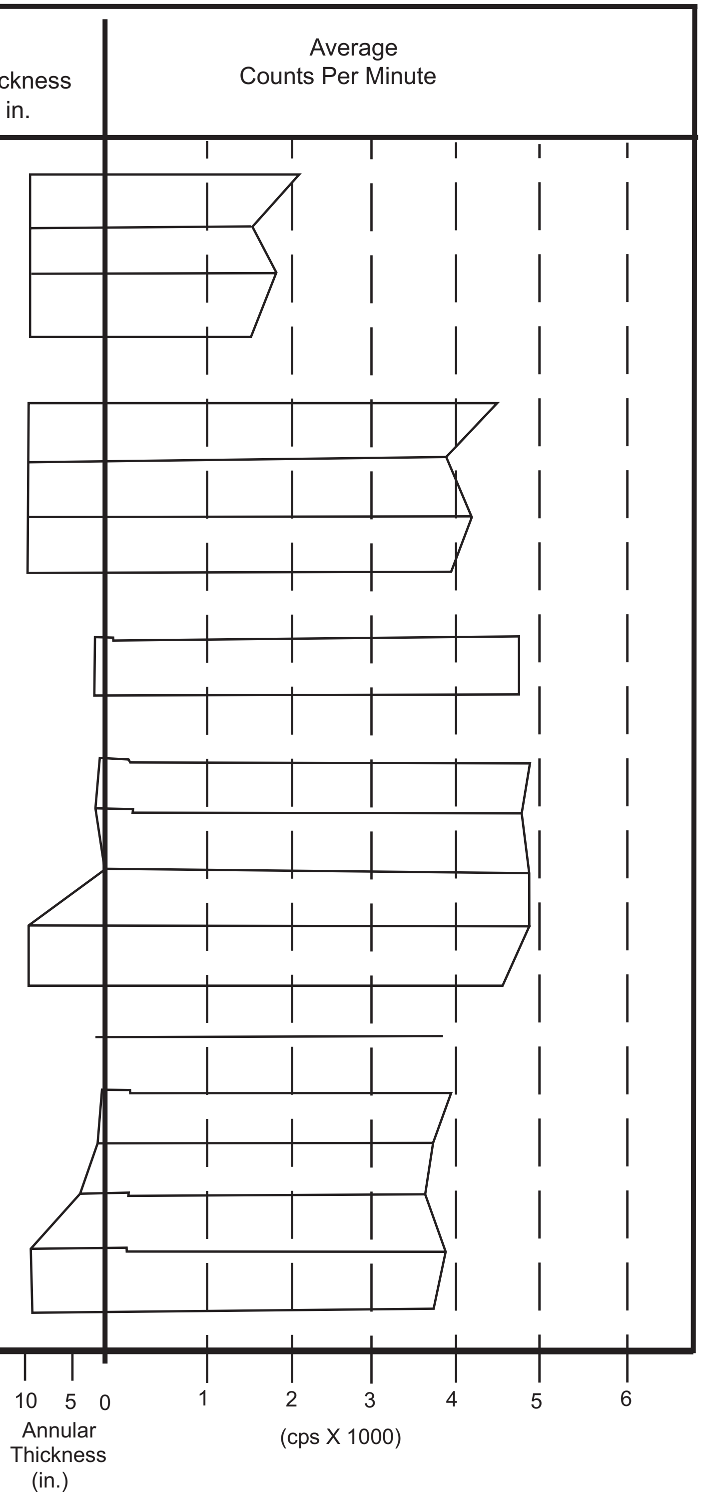
Source to Detector Spacing: Short Spacing (3.9 in.)

Source: 100 mCi

Casing Diameter: 4 in.

Casing Wall Thickness: 0.25 in.

Casing Material	Water Casing	Water Barrel	Annular Material lb/gal	Annular Thickness in.
Steel	NO	NO	Sand	9.00
Steel	NO	YES	Sand	9.00
Steel	YES	NO	Sand	9.00
Steel	YES	YES	Sand	9.00
PVC	NO	NO	Sand	9.00
PVC	NO	YES	Sand	9.00
PVC	YES	NO	Sand	9.00
PVC	YES	YES	Sand	9.00
PVC	NO	NO	9.0	2.00
PVC	YES	YES	9.0	2.00
PVC	NO	NO	9.3	0.75
PVC	NO	NO	9.3	1.75
PVC	NO	NO	9.3	2.75
PVC	NO	NO	9.3	9.00
PVC	NO	NO	9.3	9.00
PVC	NO	NO	13.5	1.75
PVC	NO	N/A	15.4	0.75
PVC	YES	N/A	15.4	1.75
PVC	NO	NO	15.4	2.75
PVC	NO	N/A	15.4	9.00
PVC	YES	N/A	15.4	9.00



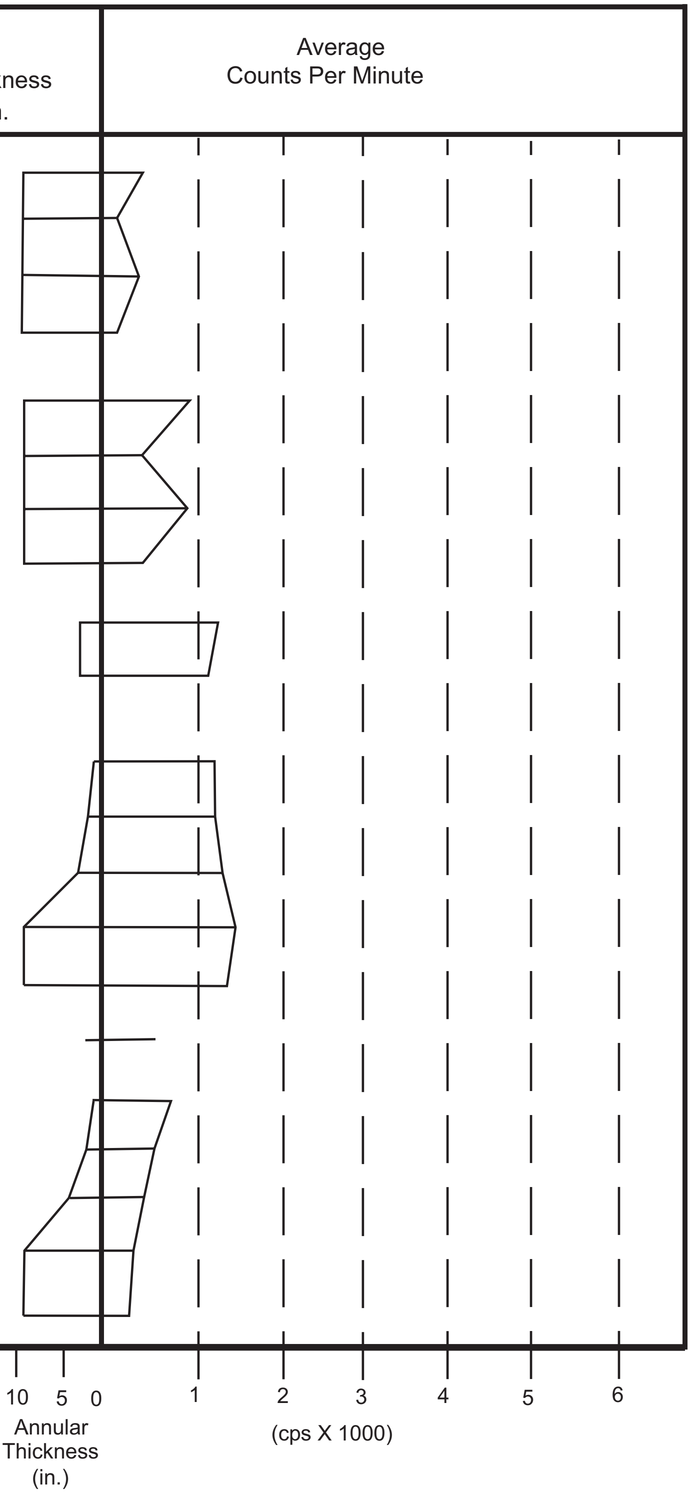
EXPLANATION

9.0: Bentonite Slurry
9.3: Bentonite Slurry
13.5: Cement with 8% bentonite
15.4: Neat cement

Figure 8. Tool response. Laboratory test: Gamma-gamma, focused, 100-mCi source, short spacing.

Focused gamma-gamma
Source to Detector Spacing: Long Spacing (13.8 in.)
Source: 100 mCi
Casing Diameter: 4 in.
Casing Wall Thickness: 0.25 in.

Casing Material	Water Casing	Water Barrel	Annular Material lb/gal	Annular Thickness in.
Steel	NO	NO	Sand	9.00
Steel	NO	YES	Sand	9.00
Steel	YES	NO	Sand	9.00
Steel	YES	YES	Sand	9.00
PVC	NO	NO	Sand	9.00
PVC	NO	YES	Sand	9.00
PVC	YES	NO	Sand	9.00
PVC	YES	YES	Sand	9.00
PVC	NO	NO	9.0	2.00
PVC	YES	YES	9.0	2.00
PVC	NO	NO	9.3	0.75
PVC	NO	NO	9.3	1.75
PVC	NO	NO	9.3	2.75
PVC	NO	NO	9.3	9.00
PVC	YES	YES	9.3	9.00
PVC	NO	NO	13.5	1.75
PVC	NO	NO	15.4	0.75
PVC	NO	NO	15.4	1.75
PVC	NO	NO	15.4	2.75
PVC	NO	N/A	15.4	9.00
PVC	YES	N/A	15.4	9.00



EXPLANATION

9.0: Bentonite Slurry

9.3: Bentonite Slurry

13.5: Cement with 8% bentonite

15.4: Neat cement

Figure 9. Tool response. Laboratory test: Gamma-gamma, focused, 100-mCi source, long spacing.

Focused gamma-gamma

Source to Detector Spacing: Delta Spacing

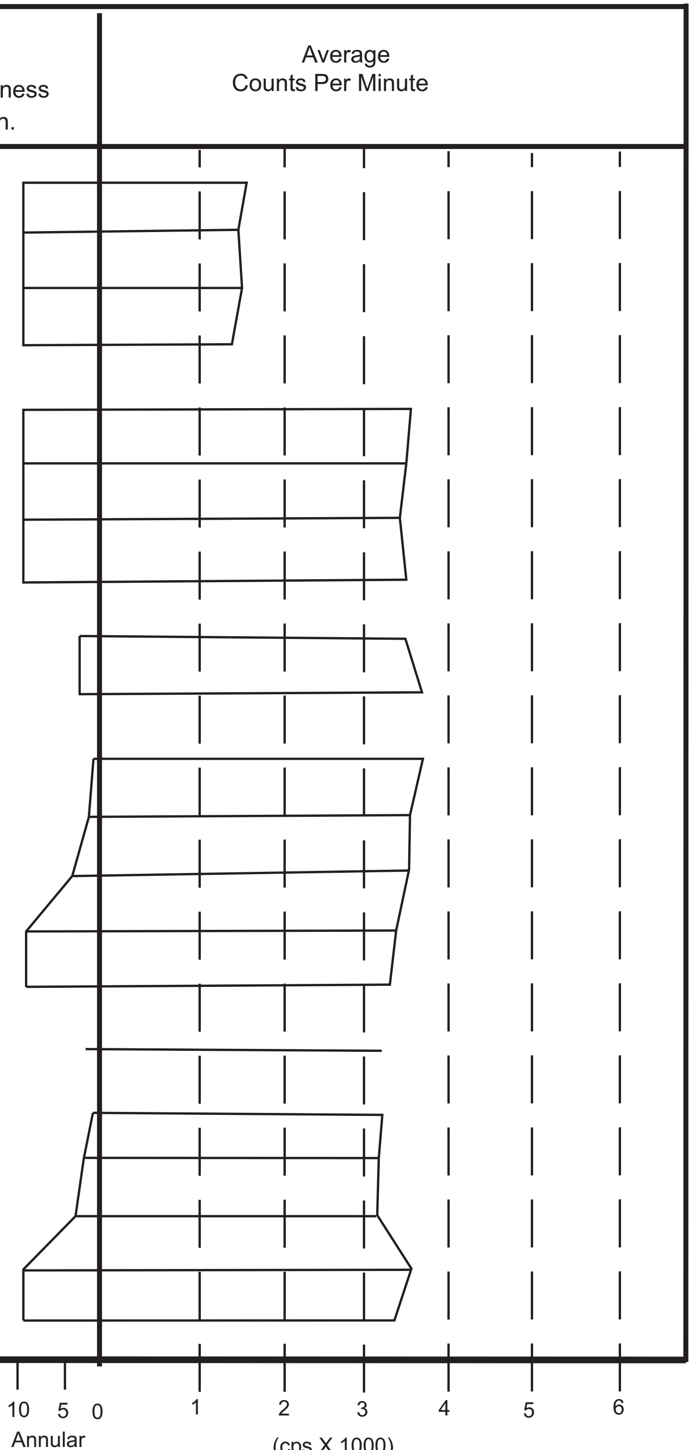
(short-spaced response minus long-spaced response)

Source: 100 mCi

Casing Diameter: 4 in.

Casing Wall Thickness: 0.25 in.

Casing Material	Water Casing	Water Barrel	Annular Material lb/gal	Annular Thickness in.
Steel	NO	NO	Sand	9.00
Steel	NO	YES	Sand	9.00
Steel	YES	NO	Sand	9.00
Steel	YES	YES	Sand	9.00
PVC	NO	NO	Sand	9.00
PVC	NO	YES	Sand	9.00
PVC	YES	NO	Sand	9.00
PVC	YES	YES	Sand	9.00
PVC	NO	NO	9.0	2.00
PVC	YES	YES	9.0	2.00
PVC	NO	NO	9.3	0.75
PVC	NO	NO	9.3	1.75
PVC	NO	NO	9.3	2.75
PVC	NO	NO	9.3	9.00
PVC	YES	YES	9.3	9.00
PVC	NO	NO	13.5	1.75
PVC	NO	NO	15.4	0.75
PVC	NO	NO	15.4	1.75
PVC	NO	NO	15.4	2.75
PVC	NO	N/A	15.4	9.00
PVC	YES	N/A	15.4	9.00



EXPLANATION

9.0: Bentonite Slurry

9.3: Bentonite Slurry

13.5: Cement with 8% bentonite

15.4: Neat cement

Figure 10. Tool response. Laboratory test: Gamma-gamma, focused, 100-mCi source, delta or the difference between short and long spacing.

Table 2. Annular material versus cps for each tool in sand-filled barrels, with no water in either the formation or the casing. Radial thickness of grout is between 1.75 and 2 in. except for sand, which is a full barrel with 9-in. radial thickness. All data are from 4-in. schedule 40 PVC casing.

Tool	Spacing (in.)	Source (mCi)	Densities[1] (lb/gal)	cps (average)	Attenuation (percent)
4 pi	18	100	9.0	52,864	0
4 pi	18	100	9.3	51,294	3
4 pi	18	100	13.5	38,961	26
4 pi	18	100	15.4	36,054	32
4 pi	18	100	sand	20,993	60
4 pi	9	5	9.0	19,047	0
4 pi	9	5	13.5	16,556	13
4 pi	9	5	15.4	16,727	12
4 pi	9	5	sand	17,625	7
4 pi	18	5	9.0	2,261	0
4 pi	18	5	13.5	1,512	33
4 pi	18	5	15.4	1,393	38
4 pi	18	5	sand	1,793	21
focused	short	100	9.0	4,723	0
focused	short	100	9.3	4,723	0
focused	short	100	13.5	3,972	16
focused	short	100	15.4	3,747	21
focused	long	100	9.0	1,258	0
focused	long	100	9.3	1,205	4
focused	long	100	13.5	633	50
focused	long	100	15.4	578	54
focused	long	100	sand	951	24

[1] 1 9.0 lb/gal bentonite slurry, 6% solids by volume
9.3 lb/gal bentonite slurry, 8% solids by volume
13.5 lb/gal cement with 12% bentonite
15.4 lb/gal neat cement
Sand lb/gal washed sand

Table 3. Radial thickness of bentonite and cement grout material versus cps for each tool in sand-filled barrels, with no water in either the formation or the casing. All data are from 4-in., schedule 40 PVC casing.

Tool	Spacing (in.)	Source (mCi)	Grout Thickness (in.)	cps (average)	Attenuation (percent)
Bentonite Grout (9.3 lb/gal)					
4 pi	18	100	0.75	47,955	0
4 pi	18	100	1.75	51,294	7 (+)
4 pi	18	100	2.75	52,798	10 (+)
4 pi	18	100	9.00	56,189	17 (+)
4 pi	9	5	no data		
4 pi	18	5	no data		
focused	long	100	0.75	1,157	0
focused	long	100	1.75	1,205	4 (+)
focused	long	100	2.75	1,279	11 (+)
focused	long	100	9.00	1,395	21 (+)
Cement Grout					
4 pi	18	100	0.75	39,487	0
4 pi	18	100	1.75	36,054	9
4 pi	18	100	2.75	33,503	15
4 pi	18	100	9.00	32,862	17
4 pi	9	5	0.75	16,187	0
4 pi	9	5	1.75	16,727	3 (+)
4 pi	9	5	2.75	15,809	2
4 pi	9	5	9.00	16,359	1 (+)
4 pi	18	5	0.75	1,544	0
4 pi	18	5	1.75	1,393	10
4 pi	18	5	2.75	1,272	18
4 pi	18	5	9.00	1,258	19
focused	short	100	0.75	3,933	0
focused	short	100	1.75	3747	5
focused	short	100	2.75	3,635	8
focused	short	100	9.00	3,941	0
focused	long	100	0.75	744	0
focused	long	100	1.75	578	22
focused	long	100	2.75	475	36
focused	long	100	9.00	402	46

Overall, the 4pi tool with 18-in. spacing, with either the 5-mCi or 100-mCi source, appears to provide the best data for interpretation of well completions. Focused, long-spaced data are also useful in some settings. Differences in completions cause enough attenuation with these tools to identify major components of water wells. If the completion has been documented and only grout thickness is in question, focused, long-spaced tools may provide the best data.

The anticipated signatures for a standard monitoring well can be predicted, based on the calibrations from the laboratory tests. The following example is based on a well completed with 4-in. schedule 40 PVC casing, with 9.3-lb/gal bentonite grout (6– 8% bentonite solids by volume). The signal above the saturated zone of the casing and the formation, for 4pi tools using 5-mCi and 100-mCi sources, should be about 2,300 cps and 51,000 cps, respectively. Below the water table, the signals should be 900 cps and 26,000 cps respectively.

The same well, but completed with neat cement grout, should have signals of 1,300 cps and 35,000 cps above the saturated zone, and 500 cps and 12,500 cps below saturation.

In the sand-packed portion of the well, signals of 1,800 cps and 44,000 cps should be received above saturation, and 500 cps and 14,000 cps below saturation.

Based on the preceding figures and table, approximate tool response for other completion arrangements can be predicted.

Field Verification

Monitoring wells in eastern Montana were logged using the logging unit that was calibrated in the laboratory tests. The wells are completed in sandstone, coal, or coal mine spoils of the Tongue River Member of the Tertiary Fort Union Formation. A variety of completions were chosen, including PVC casing, steel casing, bentonite grout, cement grout, drill cuttings in the annulus, sand-packed slotted interval, and one open-ended well. Several geophysical tools were used in the field tests that were impractical in the laboratory. Not all tools were used on all wells because of lack of water in the casings and tool failures. The full suite of tools tested on monitoring wells was: caliper, natural gamma, 4pi gamma-gamma using a 100-mCi source spaced 18 in. from the detector, focused gamma-gamma, neutron density, normal resistivity, single-point resistivity, and full-waveform sonic.

Data were recorded digitally, and traces were then generated from the computer files. Plates 1–7 are traces of the geophysical data collected at seven of the tested wells. Well completion diagrams on the left side of the plates indicate reported completion information on the left half, and completions as interpreted from geophysical log data (with consideration of reported data) are shown on the right half. Table 4 lists average values for specific completions from the monitoring wells.

PVC Casing Sealed with Drill Cuttings

Plate 1 shows data from a monitoring well drilled with a 6 1/4-in. bit, and completed with 4-in. 160-psi PVC casing. A neoprene shale packer was installed above saw slots, and the annular seal material was not described on the driller's completion report. The caliper log shows a consistent inside diameter except for roughness in the slotted interval and a very large diameter near the neoprene packer. Natural gamma is around 100 cps through the shales and shaley sandstones of the Tongue River Member, dropping to near zero in the coal. Through the shale and sandstone in the dry casing, 4pi gamma-gamma recorded 43,000 cps, and dropped to 12,000–20,000 cps below the water level in the casing (table 4). The focused gamma-gamma tool response above water level is 1,040 cps and 570 cps below water level (table 4). Neutron tool response is 1,400 cps above water and 360 cps below

Table 4. Average geophysical tool responses from the field tests.

Casing		(Slotted Blank)	Water in Casing (wet/dry)	Grout Material	4pi[1] 18/100 (cps)	Focused[2] Long spaced (cps)	Neutron (cps)	Resistivity Normal (ohms/m)	Resistivity Single Point (ohms/m)	Sonic Transit time (μ sec/ft)
PVC, 4",	160-psi	blank	dry	cuttings?	43,000	1,040	1,400			
	blank	wet	cuttings?		12,000–20, 000	570	360	off high scale	off high scale	160
	slotted	wet	open		33,000	1,320	240	0–90	500	160
PVC, 4",	Sched 40	blank	dry	bentonite	42,000	1,370–1,320	1,110			
	slotted	dry	sand		41,000	1,280	1,500			
	slotted	wet	sand		12,000	1,090	700			
PVC, 5"	Sched 40	slotted	wet	sand	20,000	940–850	420	0–200		150–200
	blank	dry	bentonite		48,000	940–470	750			
	blank	wet	bentonite		16,000–25,000	1,130–380	340			
PVC, 4"	Sched 80	blank	dry	cement	36,000	1,040	550			
	blank	wet	cement		10,500	1,040–570	300			
	slotted	wet	sand		15,000	760	340			
PVC, 4"	Sched 80	blank	dry	cement	30,000	570–470	600			
	blank	wet	cement		10,500	570–470	320			
	slotted	wet	sand		11,000	380–290	420	20		
Steel, 5"	1/4" wall	blank	dry		28,000	850–100	1,500			
	blank	wet			9,000	1,320–5	300			70
Open hole	none	wet	none		30,000	1,220–570	400			75–150
Steel, 5",	1/4" wall	blank	dry	bentonite	24,000	760–190	1,400			
	blank	wet	bentonite		9,000–14,000	1,130–190	400–800			60
	slotted	wet	sand		7,000	100	500			85

[1] 4pi gamma-gamma density tool with 8-in. Spacing using 100 mCi source.
[2] Focused gamma-gamma density tool, long spaced (13.8 in. Between source and detector) using 100 mCi source.

water. Both resistivity logs indicate slotted intervals by dropping from off-scale high to scaled readings. The sonic log was run below water level and showed travel times of 160 micro-seconds per foot (μ-sec/ft) increasing to 180 (μ-sec/ft in two intervals.

The geophysical data are interpreted to indicate PVC casing with drill cuttings in the annular space. The 4pi data agree with calibration data for PVC casing with no bentonite grout (figure 3). Data from the focused tool are lower than expected for bentonite grout, especially below water (figure 9). High counts in the 4pi and neutron data just above water level indicate a dry void or washout behind the casing. A broken section of casing is shown by the caliper log in the slotted interval. Neutron data are probably impacted by natural gamma below the water level, where the natural gamma log counts represent about 25% of the count rate of the neutron log. This rate has little or no effect on the completion interpretation. The positive kicks on the 4pi and the focused gamma-gamma logs below the packer indicate no sandpack around the slotted interval. All three nuclear logs indicate material in the annulus above the packer. The sonic log indicates broken casing at 125 ft. A second problem at 134 ft is not identifiable but also causes kicks on the nuclear logs.

PVC Casing Sealed with Bentonite Grout

First Case

Plate 2 shows geophysical logs from a well that was completed with 4-in. schedule 40 PVC casing and centralized in an 8.5-in. borehole with bentonite chips as grout. The surrounding formation is composed of spoils material from a surface coal mine in Tongue River Member sandstone and shale. A sandpack had been installed around factory slots. The caliper log shows a smooth inside diameter. Natural gamma is about 50 cps, and drops to about 30 cps in the sandpack. 4pi gamma-gamma averages 42,000 cps above the water level, with a small drop to 41,000 in the unsaturated sandpack, and dropping farther, to 12,000 cps, below the water level. Focused gamma-gamma is around 1,370 cps, with decreases to 1,320 cps in the sandpack, and 1,130 cps below the water level. Neutron counts, approximately 1,100 cps in the grout, are increasing to 1,500 in the sandpack, and are dropping to 700 cps below the water level. Because of the small saturated zone at this well, no electric logs or sonic logs were run.

At this well, natural gamma is probably an insignificant addition to the counts on other logs; however, it does show the contact between bentonite and sandpack at 53 ft. The 4pi log shows a lower cps rate than expected for bentonite grout. Calibration data indicate readings of 51,000 in dry casing adjacent to bentonite, 44,000 cps in dry sandpack, and approximately 14,000 cps in saturated sandpack, as opposed to 42,000 cps, 41,000 cps, and 12,000 cps, respectively (actually measured in the field). The focused, gamma-gamma trace is much higher than expected and does not clearly show the sandpack to bentonite contact. The neutron log clearly shows the sandpack to bentonite interface, and a slight break at 58 ft may indicate the top of the slotted interval.

Second Case

Plate 3 shows well details and geophysical logs for a well completed with 5-in. Schedule 40 PVC, and sealed with a bentonite slurry grout in an 8 3/4-in. borehole. The grout was a pumpable mixture, with a density near 9 lb/gal. The well was completed in Tongue River Member shale, sandstone, and coal beds. The caliper log indicates a generally smooth inside casing wall, with bumps at 20-ft intervals indicating joints. The bottom 40-ft is 0.25-in. larger than the rest of the casing. Natural gamma ranges from near 0 to ~150 cps, and indicates shale, sandstone, and coal beds. The 4pi gamma-gamma response is about 48,000 cps above the water level and between 16,000 and 25,000 cps below the water level. Focused gamma-gamma varies widely between 940 and 470 cps above water level and 1,130 to 380 cps below water level. Neutron data averages 750 cps above water level and 340 cps below water level. Resistivity is off scale, dropping to between 0 and 200 umhos/cm just below the water level and again in the slotted interval. The sonic log shows travel times between 150 and 200 μsec/ft.

The 4pi data indicate bentonite grout behind PVC casing. Based on the calibration tests, 51,000 cps is expected and 48,000 cps was measured, which appears to confirm laboratory tests. Below water level a reading around 26,000 cps was expected and the drop from 48,000 cps to 16,000 cps is much greater than expected. Overall, the focused gamma-gamma log shows very little, with no clear response for water level, sandpack or slotted interval. Data from the neutron log agrees with other completions of PVC casing in bentonite grout. Normal resistivity data are interpreted to show a slotted interval at 295 ft. The upper disturbance in resistance (175–195 ft) is not understood. The sonic log is very erratic, but does show slots starting at about 296 ft. The full-waveform sonic shows casing joints on 20-ft intervals, and slots at 296 ft. All logs agree that the slots are about 8 ft higher in the well than reported.

One interesting kick at 270 ft shows on several logs. A fast arrival at 270 ft, where nuclear logs indicate a high density zone, may be in part because of a ledge in the borehole against which the casing is resting. The drill bit may have deviated sideways because of a resistant layer, such as a hard siltstone, and left an uneven borehole.

PVC Casing with Cement Annular Seal

First Case

Plate 4 shows construction details and geophysical data for a well completed with 4-in, Schedule 80 PVC in cement grout. The borehole diameter is 8 3/4 in. The lithology is sandstone, shale, and coal of the Tongue River Member. The caliper log indicates a smooth inside casing wall. Natural gamma is around 70 cps, decreasing through the coal. 4pi gamma-gamma above water level in cement grout reads 36,000 cps, and 10,500 cps below water level. The 4pi data are erratic but average about 15,000 cps through the sandpack and slotted interval. Focused gamma-gamma shows about 1,040 cps above water level and between 1,040 and 570 cps below water level. A slow instrument drift appears to occur from about 360 to 305 ft. Neutron reading averages 550 cps above water and drops to 300 cps below water, with no indication of sandpack or slots. Resistivity data are too erratic to interpret and may indicate a ground problem or other mechanical fault.

Based on calibration data, the 4pi results indicate PVC casing with cement grout. The readings averaging 36,000 cps agree with anticipated readings of 35,000 cps. Below-water readings of 12,000 cps were expected and values between 10,000 and 11,000 were measured. The readings in the sandpack also were very good, 15,000 cps compared to an expected 14,000 cps. Two voids are recognized on the 4pi log: one at 283 ft and the other from 345 to 336 ft. The focused gamma-gamma data are high and provided little information except to confirm the voids. The neutron data indicate the void at 283 ft is dry.

Second Case

Plate 5 shows details and geophysical data for a well completed with 4-in. Schedule 80 PVC, surrounded by cement grout in an 8 3/4-in. borehole. The monitored zone is sandpacked around factory slots, with a bentonite seal separating the cement from the sandpack. The caliper log shows a smooth inside wall of the casing. Natural gamma ranges from about 20 cps to about 120 cps, following the shale, sandstone, and coal beds. The 4pi data average about 30,000 cps above water, 10,500 cps below water, and about 11,000 cps through the saturated sandpack and slots. The focused gamma-gamma data are very even, showing a response of about 470 cps through the cement with no break for water. The response decreases to below 380 cps in the sandpack. The neutron data are 600 cps above the water, 320 cps below the water and 420 cps in the saturated sandpack. Normal resistivity breaks several times from off-scale to zero. Sonic logs were not run on this well.

The response from 4pi gamma-gamma is low for cement at 30,000 cps compared to an expected 35,000 cps for dry, 10,500 cps versus expected 12,000 cps below water, and 11,000 cps compared to an expected 14,000 cps in the sandpack. However, the data are consistent with PVC casing in cement grout. Several voids are shown by the 4pi and the focused data between 80 and 120 ft, and above the sandpack. The focused data agree fairly well with calibrated values for this completion but are slightly low at 470–570 cps compared to the predicted 580 cps. Breaks in 4pi and focused gamma-gamma responses at 372 ft may indicate the top of the bentonite seal, with the bottom of the bentonite at 379 ft. Resistivity data indicate the top of the slots at 380 ft. The bentonite and the slots are lower than reported by several feet.

Steel Casing with Possible Drill Cutting Annular Seal

Plate 6 shows details and geophysical data for a well completed with 5-in. steel casing in an 8-in. borehole. The hole diameter reduces to five inches. below the open-ended casing. No slotted interval or sandpack were used in the completion. The caliper log shows a smooth inside casing wall, and an erratic borehole with washouts below the casing. Natural gamma, buffered by steel casing, shows coal beds but does not distinguish shale from sandstone. The 4pi gamma-gamma readings average 28,000 cps in the dry casing, 9,000 cps below water level, and increase to 30,000 cps below the steel casing. The focused gamma-gamma data are generally erratic through the steel casing, ranging from 1,320 cps to about 5 cps, and increasing to between 1,220 cps and 570 cps below the casing. Above water level, neutron readings are about 1,500 cps, dropping to 300 cps below water level and increasing to 400 cps below the steel casing. Sonic travel times are generally constant at 70 μ-sec/cm below the water level in the casing, and increase to between 75 and 150 μ-sec/cm below the casing.

The 4pi calibration data indicate readings in excess of 20,000 cps for steel casing in sand. The higher values in this well indicate lower density than sand, possibly loosely packed drill cuttings or bentonite. The 5-in. casing diameter would also allow a higher return signal. Data below water level (9,000 cps) are higher than expected for sand around steel casing (5,600 cps). The focused gamma-gamma data do not provide insight into the well completion. The sonic data and full-waveform log clearly show casing joints and the open hole below the casing. Calibration data are insufficient to verify the grout material used in this well completion.

Steel Casing with Bentonite Annular Seal

Plate 7 shows details and geophysical data for a well completed with 5-in. steel casing in an 8 3/4-in. borehole sealed with bentonite. Torch-cut slots are surrounded by sandpack. The caliper log indicates a smooth inside wall of the casing. Natural gamma is buffered by the steel casing, but identifies coal and some contacts between shale and sandstone units of the Tongue River Member. The 4pi gamma-gamma data average 24,000 cps in dry casing, range from 9,000 to 14,000 cps below water level and average 7,000 cps in the completion zone. The focused gamma-gamma data vary from 1,130 to 190 cps above the completion zone and are about 100 cps in the completion zone, allowing for the low-density section of surrounding coal. Neutron data average 1,400 cps above water, range from 400 to 800 cps below water and average 500 cps in the sandpack. The sonic data indicate travel times of 60 μ-sec/cm below the water level and fluctuate in the slotted interval.

No laboratory calibration data were generated for steel casing in bentonite grout. The nuclear logs indicate a dry void or washout just above water level. Overall, the data from this well are slightly lower counts than for previously discussed steel cased well. This well may provide a beginning calibration for steel in bentonite grout. A break on the 4pi and neutron logs at 370 ft is probably the top of the sandpack, about six feet higher than reported.

Sonic and full-wave-form sonic logs clearly show casing joints and slots that are about two feet lower than reported.

APPLICATIONS

The geophysical tools tested as part of this project can successfully be used to investigate water well completions. Individual tools, however, should be calibrated to provide signatures for the anticipated completions. Calibration using barrel tests, as run in the laboratory setting, works well. Choosing barrel tests that bracket the targeted completion is the best approach. The actual cps values measured during this project cannot be directly applied to other similar tools without further verification. Calibration curves for one tool will only give an idea of sensitivity, not of the actual response for another tool.

Investigating well completions requires a suite of tools. As demonstrated by the field trials, no single tool provided a complete understanding of all wells. One of the best tools is probably a downhole camera. This was not tested because no calibration is needed. The caliper tool is simple and readily available so should always be included, given its ability to identify changes in casing conditions. In well-completion investigations electrical logs have very limited value, only showing slotted intervals and only in PVC casing.

Omni-directional gamma-gamma tools such as the 4pi unit tested are very good and should be utilized for casing material and annular material identification.

Focused gamma-gamma and neutron tools are less valuable. In PVC casing, focused, long-spaced data are generally useful in interpreting the well completion. In some PVC-cased wells, however, no useable pattern can be developed from the focused-tool data.

Neutron tools have some value for investigating well completions. Table 4 provides data that can be used for calibrations, but more calibration work is needed.

Sonic logs are not readily available but do provide valuable data. Full-waveform presentation of the data are especially easy to interpret. When warranted for casing integrity, these logs should be used. Resistivity can be used to indicate slotted intervals and are available on most logging units.

CONCLUSIONS

Geophysical techniques provide the best currently available techniques for verification of water well completions. Additional work with different techniques is needed, as are calibration of existing techniques in different settings. The actual interpretation of well completions from geophysical data depends on a suite of logs and on the theoretical understanding of the equipment.

It may be possible to apply calibration data and trends measured during this project to other tools. Conversion factors would need to be developed through a calibration process. Any tool used for well investigations must be fully calibrated. Calibration is best performed by running tests in known completions. The barrel tests used in this research were an excellent and economically efficient method of calibration data for various completions.

Interpretation of geophysical data from well completions is probably best done by comparing changes in tool response. Percent change, as shown by calibration tests for a specific tool, is probably the most important indicator of changes in downhole completion materials.

All nuclear logs, however, required very specific training and understanding of the theory of operation. This report provides a discussion of how theoretical knowledge gained elsewhere can be applied to well completion investigations.

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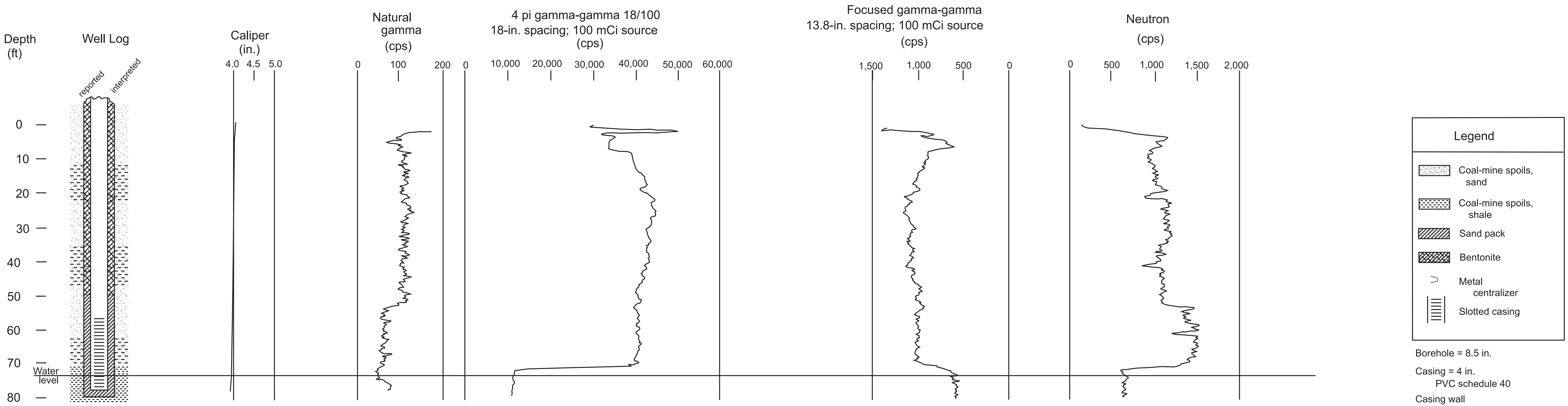
APPENDIX I

Plates

Plate 1. Well completion schematic and geophysical logs for well completed with PVC casing and unknown grout.

MBMG 355
PLATE 1

Plate 2. Well completion schematic and geophysical logs for well completed with PVC casing and bentonite grout.



Borehole = 8.5 in.

Casing = 4 in.
PVC schedule 40

Casing wall thickness = .25 in.

Plate 3. Well Completion schematic and geophysical logs for well completed with PVC casing and Bentonite grout.

Plate 4. Well completion schematic and geophysical logs for well completed with PVC casing and cement grout.

MBMG 355
PLATE 4

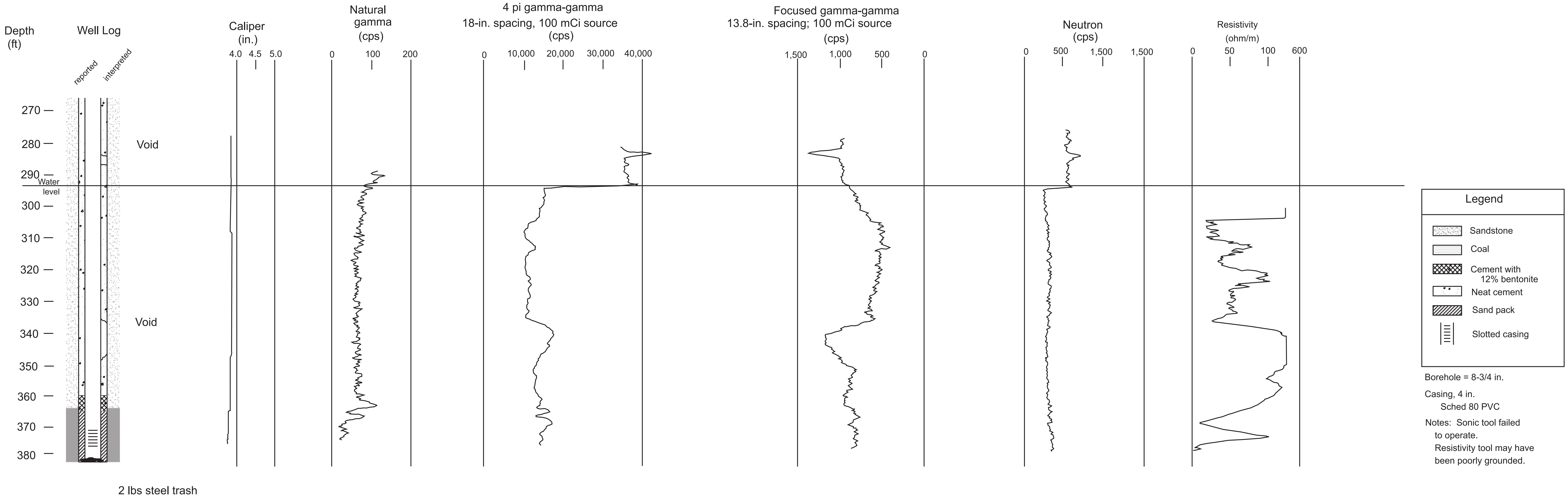


Plate 5. Well completion schematic and geophysical logs for well completed with PVC casing and bentonite grout.

MBMG 355
PLATE 5

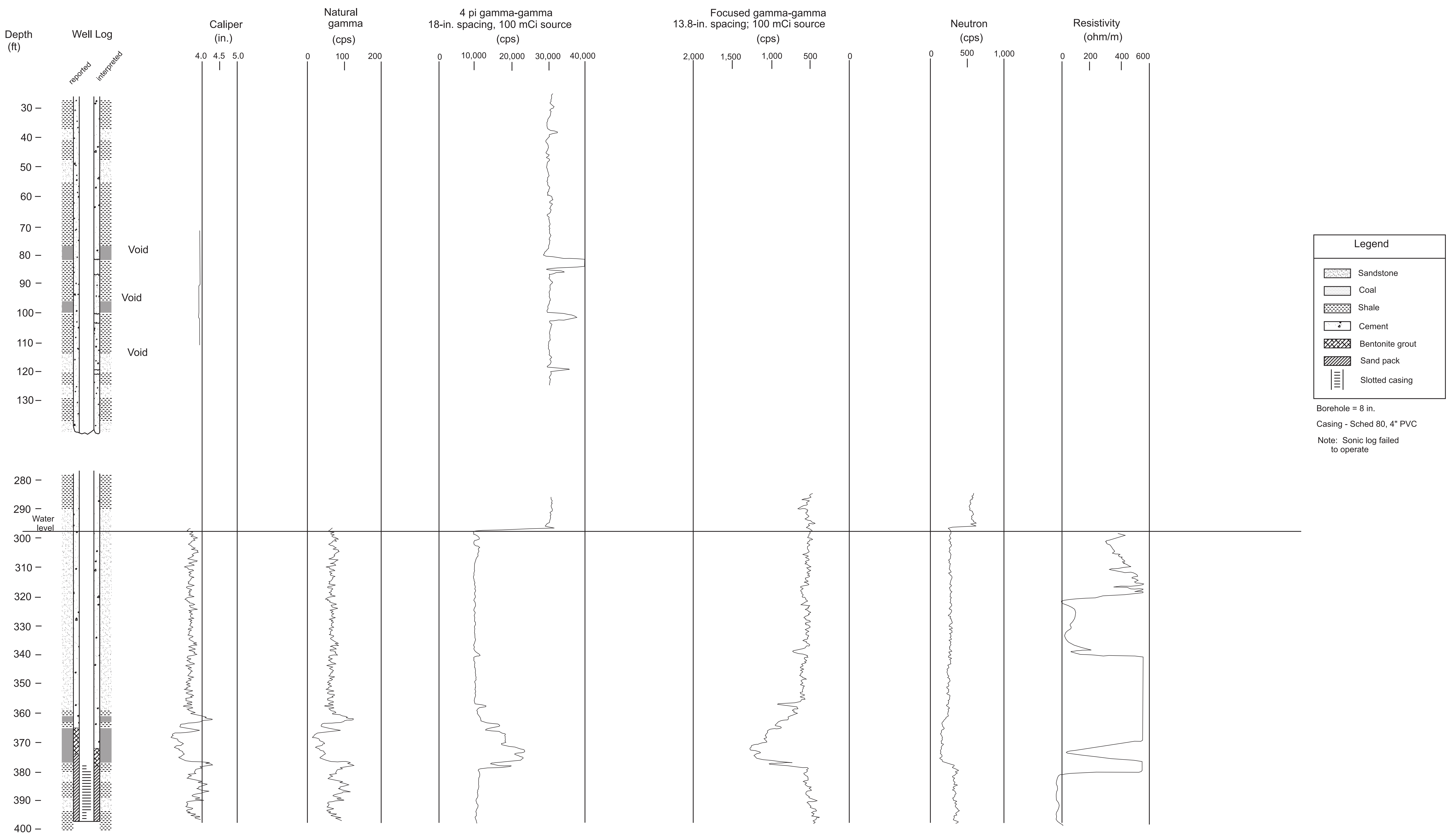


Plate 6. Well completion and geophysical logs for well completed with steel casing and unknown grout.

MBMG 355
PLATE 6

Plate 7. Well completion and geophysical logs for well completed with steel casing and bentonite grout.