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FINAL REPORT

MECHANICAL INTEGRITY TESTING

OF

INJECTION WELLS

Contract No. 68-01-5971

Submitted to

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Prepared for

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OFFICE OF DRINKING WATER

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April 30, 1980

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ACKNOWLEDGMENTS

This report was prepared under the direction of Mr. Vincent P. Amy, Senior Scientist, Geraghty and Miller, Inc., for the Office of Drinking Water. The EPA Task Manager was Mr. Paul M. Beam. Mr. Amy was assisted by Mr. Oliver C. Lewis, Drilling Specialist, and Nola Gillies, Regulatory Analyst, of Geraghty and Miller, Inc.

EXECUTIVE SUMMARY

The various logging techniques used in determining mechanical integrity are widely employed and were developed for this purpose. They were designed to enable man to detect evidence rather than observe conditions which cannot be seen first hand. In effect, they are an indirect measurement and are indicators of a condition. They measure something electronically: temperature, sound velocity, noise levels, etc. Thus, the data interpretation is subjective and dependent on the skills and experience of the operator, in contrast to a pressure test which is a more direct, readily observable indicator of a condition.

Experience shows that the presence of a condition is often discovered by weight of evidence. In many cases, the results of a single survey produce unclear and somewhat confusing results, and additional, different surveys clarify and confirm the results of the first. In any case, a program for determining mechanical integrity should be kept flexible to provide the greatest benefit. Also, the logs described in this report are regarded as the best for the purpose. However, flexibility must be provided to permit the use of other surveys to permit collection of evidence offering the clearest indication that a problem exists. For example, a [illegible] the adequacy of the cement at the bottom of the casting by detecting fluid movement at that point. Abnormally high radioactivity would be detected above the casing shoe. This could only occur when the cement seal at the casing shoe is poor, permitting fluid to leak upward.

Similarly, surveys such as noise, temperature, and tracer logs could be substituted for pressure testing. Economics would play an important role. While the pressure tests yield more positive results, it may be more economical for the operator to substitute the appropriate log or logs. The evidence will be less direct, but the burden of proof should be on the operator to demonstrate conclusively that his well possesses the required integrity.

Cost of pressure tests and wire-line surveys range widely depending on various factors such as depth of well, distance from service center, presence or absence of tubing and packer, type of survey, time factors, and general site conditions. For example, under certain conditions, pressure tests could range from about $400 to more than $7,000. Likewise, some types of wire-line surveys for common injection well depths (2,000-6,000 feet) may range from $1,500 to $2,800.

Continuous monitoring of annulus pressure and regular checks of injection pressure are now the common means of monitoring well integrity during operations that are required by regulations in the 12 states surveyed. Of these states, California, Illinois, New York, Michigan, and Oklahoma require periodic well integrity testing. The majority of the 12 states require the submission of data on casing, cementing, tubing, and packers as part of the pre-permitting report to assure that integrity is designed into an injection well. There appears to be little distinction among classes of wells in the regulations of these states.

INTRODUCTION

Section 146.08 of the proposed State Underground Injection Control Program (40 CFR Part 146, Federal Register, Volume 44, No. 78, April 20, 1978) concerns the mechanical integrity of injection wells. According to the proposed rules, an injection well has mechanical integrity if: (1) there is no significant leak in the casing, tubing, or packer; and (2) there is no significant fluid movement into an underground source of drinking water through vertical channels adjacent to the injection well bore. The rule also states that some combination of a number of tests shall be used to evaluate the absence of significant leaks. A list of these tests is contained in Section 146.08. The section also describes means by which the absence of fluid movement may be demonstrated. These are: (1) well records demonstrating the presence of adequate cement to prevent such migration; or (2) the results of a cement bond log, sonic log, temperature log, density log, or dual neutron log.

On October 16, 1979, Geraghty & Miller, Inc., received approval from the U. S. Environmental Protection Agency to commence work on Contract 68-01-5971, Work Assignment #1, dealing with identifying and evaluating methods used by industry and regulatory agencies to determine the two aspects of mechanical integrity. In particular, the tests described in Section 146.08 were to be evaluated, along with others that could be employed.

The costs for performing the various surveys and tests referred to in this report are expressed in 1977 dollars. These were computed by converting the costs in 1979 dollars using the Consumer Price Index (CPI). These are based on a December 1979 CPI of 229.9 and a December 1977 CPI of 186.1. Thus, the conversion was accomplished by dividing 1979 costs by 1.235 (229.9÷186.1) to yield the estimated cost in 1977 dollars.

METHODOLOGY

To accomplish the objectives of Work Order #1, experienced Geraghty & Miller personnel contacted and interviewed representative of a number of service companies in the oil industry, drilling contractors, and regulatory agencies. Information was obtained on methods of costs for preparing and performing the various tests used to determine mechanical integrity. Senior personnel of companies recognized as experts in the field were contacted or interviewed as part of the data collection process. Technical manuals, service catalogs, and pricing schedules were obtained from the major companies who perform the various surveys used in determining mechnical integrity. Various state regulatory agencies also were contacted and pertinent information collected. In addition, the firm's library and files on the subject were researched and utilized.

COMPANIES AND ORGANIZATIONS CONTACTED

Information used in preparing Task Order #1 was obtained from the following companies and organizations:

Schlumberger Well Services
Welex
The Western Company
The East Texas Brine Disposal Company
Dowell Division of Dow Chemical Company
NL McCullough
Birdwell Division
Dresser Atlas
GO Wireline Services, Division of Gearhart Owens Industries
Progress Drilling and Marine
Kansas Department of Health, Division of Environment
California Division of Oil and Gas
Oklahoma Oil and Gas Division
Ohio EPA, Legal Services Department
Texas Department of Water Resources, Geological Services
Texas Department of Water Resources, Underground Injection Unit
Nuclear Regulatory Commission
Ohio River Valley Sanitation Commission
Illinois EPA
Pennsylvania Bureau of Water Quality Management
Pensylvania DER, Division of Oil and Gas
New York Department of Pure Waters, Industrial Programs Division
New York Department of Environmental Control
Louisiana Department of Conservation

LEAKS

Pressure Testing

According to Section 146.08, an injection well has mechanical integrity if there is no significant leak in the casing, tubing, or packer. "Significant" is not defined. Both industry and regulatory agencies utilize and/or require pressure testing of the various components such as casing, tubes, and packers as a means of determining the presence of leaks. One accepted means of defining a significant leak, which is used as a guideline by industry, deals with pressure testing. Typically, a test pressure equivalent to 125 percent of the design operating pressure is applied. The test is judged to be successful, and no significant leaks are deemed to be present, if any pressure loss or bleed off stabilizes at a point equal to or greater than the design operating pressure and does not fall below that value. Normally, pressure tests are performed for periods of time ranging in duration from five to thirty minutes. If the pressure falls below the design value, the test is judged to be a failure; a significant leak exists and remedial measures are taken to fix it. The State of California requires that a loss in pressure must not exceed ten percent of the test pressure (for casing tests) during thirty minutes and that corrective measures must be taken until a satisfactory test is obtained. A set of test specifications is set forth by the state. A set of test specifications is set forth by the state. California also requires that tubing, plugs, and packers hold pressure; otherwise a leak is presumed to exist.

Consideration of the various tests and procedures described in Section 146.08(b)(1) reveals that their principal purpose is the location of leaks rather than their detection. Aside from the various pressure tests (Items 2, [illegible], and [illegible]), the remaining surveys are primarily tools for locating leaks [illegible] known that they exist. Also, interpretation of the data from many of these tests is somewhat subjective, whereas pressure tests produce results that are simple and easy to interpret. Pressure testing is also economical (comparatively speaking) and relatively easy to perform in both old and new injection wells. For these reasons, pressure testing of the casing, tubing, and packer is considered the principal, most reliable means of determining mechanical integrity (leaks). The reliance on pressure testing by industry and its requirement by the various regulatory agencies attests to this fact.

Pressure testing is usually performed on casing, tubing, and packers. This would apply to Class I, II, and III wells. Many of these wells, regardless of classification, have similar construction characteristics. Performance of a pressure test is controlled by construction details rather than classification by use. The following descriptions of pressure testing are presented in this manner.

The inner casing, or long string, in a new well is usually pressure tested after it has been cemented and before the casing shoe is drilled out. At that time, cement is present at the bottom of the casing so that it is sealed. Usually the pipe is filled with fluid and pressure is applied using the rig mud pump, a positive displacement pump with suitable capacity, or pumping equipment operated by the cementing company. A seal at the top can be effected by using blow-out preventers. In the event a blow-out preventer is not on the well, it is a comparatively simple matter to seal the well head. Rig mud pumps usually can be utilized to supply pressures up to 1,000 psi; for greater pressures, cement pumping equipment is generally used.

When the inner casing of an old well without tubing or packer is tested, the bottom must be sealed with a retrievable plug (bridge plugs or packers are used) prior to testing. The same sources for pressure noted above can be utilized. For old wells with tubing but no packer, the outside casing is tested after the tubing has been pulled and a retrievable plug set. If successful, the tubing is reinstalled; otherwise, remedial measures are taken. Tubing is normally tested after reinstallation. Usually, the tubing is installed with a seating nipple at the bottom. A ball made of rubber-covered aluminum, steel, or plastic is dropped into the seating nipple to seal the bottom. It also is sealed at the top and a pressure test is performed. The ball is then "reversed out" and the well is ready for service.

New and old wells with tubing and packer are tested by pressurizing. The fluid-filled annulus is pressure-tested to determine the integrity of the casing; the tubing is tested in the well using a ball and seating nipple. A satisfactory test on the annulus also indicates the integrity of the packer.

A reverse type of test is used in some instances, especially in mining applications, to determine casing integrity of a new or used well. In this test, fluid is removed from the casing. Sometimes, if the well is not too deep, the inside of the casing is completely evacuated to the bottom. This must be done with care in order to prevent casing collapse. For deep wells, the evacuation is staged, using a bridge plug and packer. The space between the plug and packer is evacuated and then observed to determine whether or not fluid enters. This test is called a dry test and will work only in those portions of the casing opposite formations that are saturated with fluids and are somewhat permeable.

When the pressure that the outside casing will be subjected to is low and a low hydrostatic head exists on the outside of the casing, it can be tested by filling it with fluid. If there is a lowering of the fluid level, a leak exists. This test can be performed on both new and old wells.

Other Surveys

Television:

The down-the-hole television camera is classified as one of those tools which can be used as an aid in determining the location of a leak. However, the equipment is not readily available and few companies provide this service.

Monitoring of Annulus Pressure:

Annulus pressure can be monitored in wells with tubing and tubing and packers, along with injection pressures and rates. If a pressure change occurs, a leak is indicated. Continuous or frequent monitoring of annulus pressure is probably the best tool for determining mechanical integrity, providing a well's construction permits it to be done.

Radioactive Tracers, and Temperature Logs:

Surveys of this type normally are not undertaken to test well integrity. Their most usual application is for locating a leak after it has been discovered. In certain situations they may be used to estimate well integrity. For example, integrity may be estimated this way if the well has a casing but no tubing, and cannot, therefore, be pressure tested.

ADEQUACY OF WELL RECORDS

Existing well records have limited use in determining the adequacy of the cement sheath outside of a well casing. These records usually contain information on the types, sizes, weights, and lengths of casing, and the types, quantities, and weights of cement pumped, along with additives used. By themselves, they do not indicate if the cement was successfully emplaced and an effective seal was obtained. Only some means of determining whether or not leakage is occurring can establish this. If excellent data on annular volumes are available (caliper and temperature logs and accurate volumetric cement measurements), a rough estimate of whether or not an adequate cement seal exists may be possible. This determination can be made as follows. A temperature log is used to pick the cement top. The amount (footage) of actual cement fill-up is calculated based on this information. If this footage exceeds the theoretical fill-up which should have occurred, the possibility of channelling of the cement exists and there would be a potential for fluid movement through the channel. In this case, other surveys would be called for such as a cement bond log, or temperature and noise logs. In effect, well records offer clues to, but not necessarily definitive indications of, the adequacy of cementing.

COSTS FOR PRESSURE TESTS

Costs for pressure testing are directly related to a well's construction details. For a new well or an existing one equipped with tubing and packer, the test is simple and the cost is not expensive. In a new well, the pressure test is performed on the inner or long string of casing after it has been completely cemented in place, the cement has set up, and before the cement at the bottom of the casing has been drilled out. The well head can be sealed in with the blow-out preventer. Depending on the pressure required, the rig mud pumps can be used or the pump on the cementing equipment can be used. For pressure testing the casing with the rig, the estimated cost is approximately $400.00. If a cement pumper is required, the cost is estimated to be $800.00 to $1,200.00, depending on the amount of time the equipment is on location.

A similar cost would be incurred in performing a pressure test on an existing well equipped with a tubing and packer. Usually this could be done by operating personnel, using their own or rental pumping equipment. As an example, a positive displacement pump with a suitable capacity could be used. This would account for the lower cost of $400.00. If a pumper is needed, the cost could be in the range of $800.00 to $1,200.00.

Greater costs will be required to perform pressure tests on the casing in wells with no tubing or packer or only tubing. In the case of a well with tubing, a rig will have to be used to pull the tubing and reset it. For a well with no tubing or packer, it is assumed a rig will be used to set and pull a retrievable plug. In most cases, a workover rig rather than a standard rig is employed. This equipment is designed specifically for work of this type; it is lighter, more mobile, and less expensive than a conventional drilling rig.

Determination of the cost of performing pressure tests in the above situations is complicated by the fact that there is no such thing as a typical well. Casing depths and diameters vary, as do the depths of the tubing settings. The condition of the well is a controlling factor in how long it takes to do a particular task. Companies doing this kind of work charge strictly on a time and material basis for the use of rig and crew. Similarly, companies who furnish the plugging devices and related equipment charge according to complicated schedules. Time, distance to the well, standby charges, working depths, and the size of the tools to be used are components of the total charge. In the event the equipment must be used in a "hostile environment" (abnormal pressure, high temperatures, and a corrosive fluid) additional charges are billed. Consequently, because of the numerous variables that would have to be considered, it is impossible to arrive at the precise cost for pressure testing.

Some idea may be obtained by setting up some arbitrary examples using assumptions based on a range of well depths, distance to the well, and time required to pull tubing, set and remove a retrievable plug, and reset the tubing. For these examples, it is assumed it is a 300-mile round trip to the well, the well depth ranges from 2,000 to 6,000 feet (80 percent of injection wells are included in this depth range), rig time is figured at $125 per hour, and mileage charges are $1.50 per mile. Also, it is assumed that there are minimal delays; in this case, 8 hours of rig time due to unanticipated conditions (site work to make the well more accessible, problems in removing well-head equipment prior to entry, etc.). Costs due to lost production time, use of alternative waste disposal facilities, in-house administration and engineering associated with any testing are not included. The same set of conditions was used to develop costs for performing a test on a well with no tubing, but for which a rig was required. In this case, no rig time is needed for pulling and resetting tubing.

Costs for performing pressure tests for wells with tubing and packer and without, based on the above assumptions, are listed in the following table., (Estimates are rounded to the nearest $100.) converted to 1977 dollars.

Working Depth (feet)	Estimated Costs	
	Tubing & Packer	Without
2,000	$ 4,600	$ 4,000
3,000	$ 5,300	$ 4,300
4,000	$ 6,000	$ 4,600
5,000	$ 6,600	$ 5,000
6,000	$ 7,300	$ 5,300

It should be noted that these costs are based on no unusual or unanticipated conditions which would cause delay and add to the cost.

RESULTS OF LOGGING

Section 146.08(c)(2) lists five wire-line geophysical logs which could be used to demonstrate the absence of significant fluid movement into an underground source of drinking water through vertical channels adjacent to the injection well bore. (It is understood that the vertical channels referred to are those which may exist in the cementing annulus outside of a casing as a result of an inadequate cement job.) These logs are cement bond, sonic, temperature, density, and neutron logs. Some of them may not be effective or useful for determining the absence of fluid movement, while others not on the list can be used for this purpose. Each log on the list, as well as others which can be used, is discussed below. The reasons for a particular log's unsuitability for detecting fluid movement are given, as well as a discussion of those logs which are used for that purpose.

Sonic, density, and neutron logs are not suited for detecting fluid movement; the cement bond log indicates the potential for fluid movement; and the temperature log and a survey known as a noise log can be used to detect fluid movement. Radioactive tracers could be used, but this presumes that a leak exists in or around the casing so that the tracer can be introduced and its movement tracked.

The typical record of each one of these tests is a log or graph of the parameter being measured versus depth. The record is a continuous one (except for most noise logs) and is either made directly on a paper strip chart or recorded on film. In both cases, the log is easily duplicated. Blueprints (ozalids) are the most common form of reproduction. Two depth scales are usually used: 5 inches equal 100 feet, and 2 inches equal 100 feet. Pertinent information on the well (depth log, casings, dates, etc.) is contained in a heading form which is filled out for each log.

Apparatus used in logging consists of the logging tool itself, multi-conductor armored cable, and the electronic equipment for measuring and recording the various parameters. The equipment is usually mounted in a vehicle designed specifically for the purpose.

A number of companies can perform these surveys as well as a wide variety of other geophysical logging techniques. The principal companies are Schlumberger Well Services, Welex, GO Wireline Services, Birdwell, NL McCullough, and Dresser Atlas. These organizations maintain offices throughout the United States and overseas so that services can be offered with little or no difficulty. The principal locations are in or close to the major oil-producing areas. A number of other, smaller companies scattered throughout the United States specialize in providing logging or performing the surveys as part of the services they offer.

Sonic Log

The conventional sonic log measures the time required for an acoustic signal to travel from a transmitter to a receiver spaced a known distance apart. Other, special applications of acoustic signals are used in cement bond logging. These are treated separately and are not included in this discussion.

The logging tool, or sonde, contains both transmitters and receivers (more than one of each is used to compensate for bore-hole effects). The sonde is usually centered within the bore hole by centralizing straps on the tool. While the tool is being raised or lowered in the hole, a signal is generated, is transmitted through the bore-hole fluid and the formation, and is refracted back through the fluid and detected by the receiver. The first arrival of the signal is detected, amplified, and presented on the strip chart or film. The time of travel for the signal, expressed in microseconds per foot (µsecs/ft), is the conventional method of presentation.

The conventional sonic log is a tool used to determine porosity. The time required for the signal to travel through a rock formation is a function of density and porosity; dense, non-porous rock will transmit sound much more rapidly than less dense, porous rocks. Given the same lithology or rock type, the rock with the greater porosity will have the slowest travel or transit time.

If the rock type is known, it is possible to compute its porosity from a sonic log. Information on the transit time for various rock types is readily available from the various texts and literature describing sonic logging, and it is a comparatively easy task to compute the porosity based on the following relationship.

$$\varnothing = \frac{\Delta t_{log} - \Delta t_{ma}}{\Delta t_{f} - \Delta t_{ma}}$$

where $\varnothing$ = porosity

Δt_{log} = transit time from log, in µsec/ft

Δt_{ma} = transit time of matrix material, in usec/ft

Δt_{f} = fluid travel time, in µsec/ft

The sonic log reacts to primary or intergranular porosity, but does not usually respond to secondary porosity, such as that occurring from vugs and fractures in the rock. The former is usually more evenly distributed throughout the rock and will influence travel time. The latter is erratically distributed, usually constitutes a small percentage [illegible] therefore, permits sound energy to pass around it so that it is not detected and does not show on the log. This characteristic is utilized to determine a secondary porosity index by comparing logs which measure total porosity with porosities calculated from the sonic log.

The sonic log cannot be used to determine whether there is fluid movement behind casing, nor can it be used to locate zones where voids or channeling in the cement may be present. The steel casing is much more dense than the cement and the formation. Therefore, the sonic log will record only the transit time of the steel, which is 57 μsecs/ft and significantly faster than that of rock and cement. The presence of the steel will mask out the arrivals of sound energy from rock and/or cement, thus making it impossible to investigate the nature of the cement.

Neutron Log

The neutron log is another tool used for the measurement of porosity. It employs a radioactive source in the logging tool as well as detectors, counters, and the circuitry to convert the signals and display them as porosity values on the log. Because it employs a source which emits neutrons, it is used in cased holes where information on porosity is desired, as well as in open bore-holes.

During the logging process, the radioactive source in the tool emits neutrons. Some of these are captured by the nuclei of hydrogen atoms. The capturing nuclei become excited and emit high-energy gamma rays. These are detected and counted by the logging tool. Pore space, either primary or secondary, saturated with water contains hydrogen atoms. The higher the porosity, the greater the number of hydrogen atoms available to capture neutrons emitted by the logging tool. Thus, measurement of the emitted high-energy gamma rays associated with the capture of the neutrons becomes an indirect measurement of porosity.

The neutron log is a widely-used tool employed by industry to evaluate porosity in both cased and uncased holes. When used in conjunction with other geophysical logs, it is possible to identify selected minerals, determine limestone-dolomite content, identify hydrocarbons, and assess secondary porosity.

Because of the principle on which the neutron log is based, it cannot be used to determine the presence or absence of significant leaks in injection wells. The logging tool cannot discriminate between hydrogen atoms contained in free water associated with porosity and those associated with or bound in the molecular structure of minerals, cement, or compounds used in cementing. When cement hardens or [illegible], water becomes bound up in the structure of the various compounds that are formed. Also, additives used in cementing contain water in their molecular structure. For example, bentonite (gel), which is widely used as a filler, is a hydrous montmorillonite (a type of clay); and gypsum, which is used for a variety of purposes, is a hydrous calcium sulfate. A neutron log made in a cased cemented hole would show a high porosity because of the presence of the "bound" water in the cement and additives, yet the cement could have completely filled the annulus and bonded both to pipe and formation, achieving an adequate seal.

The neutron log is a contact tool; that is, the sonde or instrument is in physical contact with the formation or well casing when the survey is being made. This is done to minimize or eliminate the influence of drilling mud or other fluids in the bore hole. Consequently, the tool investigates only a portion of the circumference of the well casing.

Density Log

The density log, a tool employing a radioactive source, can be used in both cased and open holes. It is primarily a tool for measuring porosity. It operates by measuring the electron density of a material, which is related to its actual density.

Density log data are presented as the bulk density of the material in gm/cc (grams per cubic centimeter). If the type of rock is known, its true density can be determined quite easily. The difference between the bulk and true densities serves as the basis for determination of the porosity according to the following formula, which also requires a knowledge of the density of the interstitial fluids:

$$\phi = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f}$$

Where

ϕ = porosity

ρ_{ma} = matrix density

ρ_b = formation bulk density

ρ_f = formation fluid density

A density log is performed with the tool offcentered in the hole and in contact with the formation or well casing. This is done because the bore-hole fluids will interfere with the log and their influence must be either compensated for or eliminated. The tool investigates to a relatively shallow depth and has been used to locate cement tops, or identify the presence of cement behind casing due to the difference in density between cement and fluid. However, the results of the log are at best only indicative of the presence of cement and are by no means capable of providing detailed information on the adequacy of the cement. The tool only investigates a small portion of the circumference of the pipe which is in contact with the tool. Therefore, the density log cannot be relied upon to provide the information necessary to determine the presence or absence of fluid movement.

Temperature Log

The temperature log is one of the tools used by industry for locating casing leaks and up- or down-hole fluid movement behind pipe. This wire-line tool can be used in holes or casing and tubing with diameters as small as two inches. All of the geophysical logging companies offer temperature logs as part of their service. Temperature logs are made with electrical resistance thermometers (a device where resistance changes with changes in temperature). Resistance variations in the thermometer are transmitted electrically to the surface and are displayed on the strip log in the same manner as other geophysical logs.

Temperatures are usually recorded in degrees Fahrenheit. The equipment is reportedly capable of detecting changes of $0.5^{o}F$ in a range between $0^{o}F$ and $350^{o}F$. Two types of temperature logs are available. The first is simply the measurement and display of the temperature with respect to depth, utilizing a single temperature measuring device. The second measures the differential temperature between two units spaced a measured distance apart, and is used to determine changes in the temperature gradient. Temperature logs can be performed in both operating and shut-in wells whether they are under pressure or not. If they are under pressure, the tool and wire-line are installed in the well and the log run through a device known as a stripper head or lubricator.

The temperature of the earth increases with respect to depth, except for the first hundred feet or so which are influenced by partial fluid saturation and seasonal variations in temperature. Below this depth, the temperature gradually increases; the rate of increase is approximately linear and is known as the geothermal gradient. Variations in the gradient occur from place to place, but average about 1°F per 100 feet of depth.

In the event of a casing leak or fluid movement behind the casing, the normal geothermal gradient will be disturbed. This will be reflected as a change in the temperature which distorts the normal, characteristically smooth, curve of the temperature shown on the log. The degree of change is related to the quantities of fluid flow and the temperature difference. All gradations of this can exist and it is difficult to determine limits below which fluid movement cannot be detected.

Temperature logs will display characteristic signatures for fluid leaks and movement. Idealized curves are shown on Figure 1. Of particular importance is the signature for the upward movement of fluid. The leak or point where movement begins is at the base or lower portion of the curve where it joins the normal curve of the geothermal gradient. It should be noted that in the case of fluid upflow, the curve is distorted in the direction of increasing temperature, whereas the opposite is true where fluid is moving in a downward direction.

Temperature logging is widely used by industry to locate leaks and fluid movement behind casing. It is relatively accurate and is a readily available service offered by all of the logging companies.

Cement Bond Log

Cement bond logs were developed specifically to determine the condition of cement behind casing. By themselves, they do not indicate if fluid movement is occurring; they do indicate if the potential for fluid movement exists (i.e. the absence of cement or the presence of channeled cement). The bond log is a form of sonic log that utilizes sound energy in a slightly different manner. The conventional sonic or acoustic log mentioned previously is based on the measurement of the transit time for sound energy and its relationship to the density and

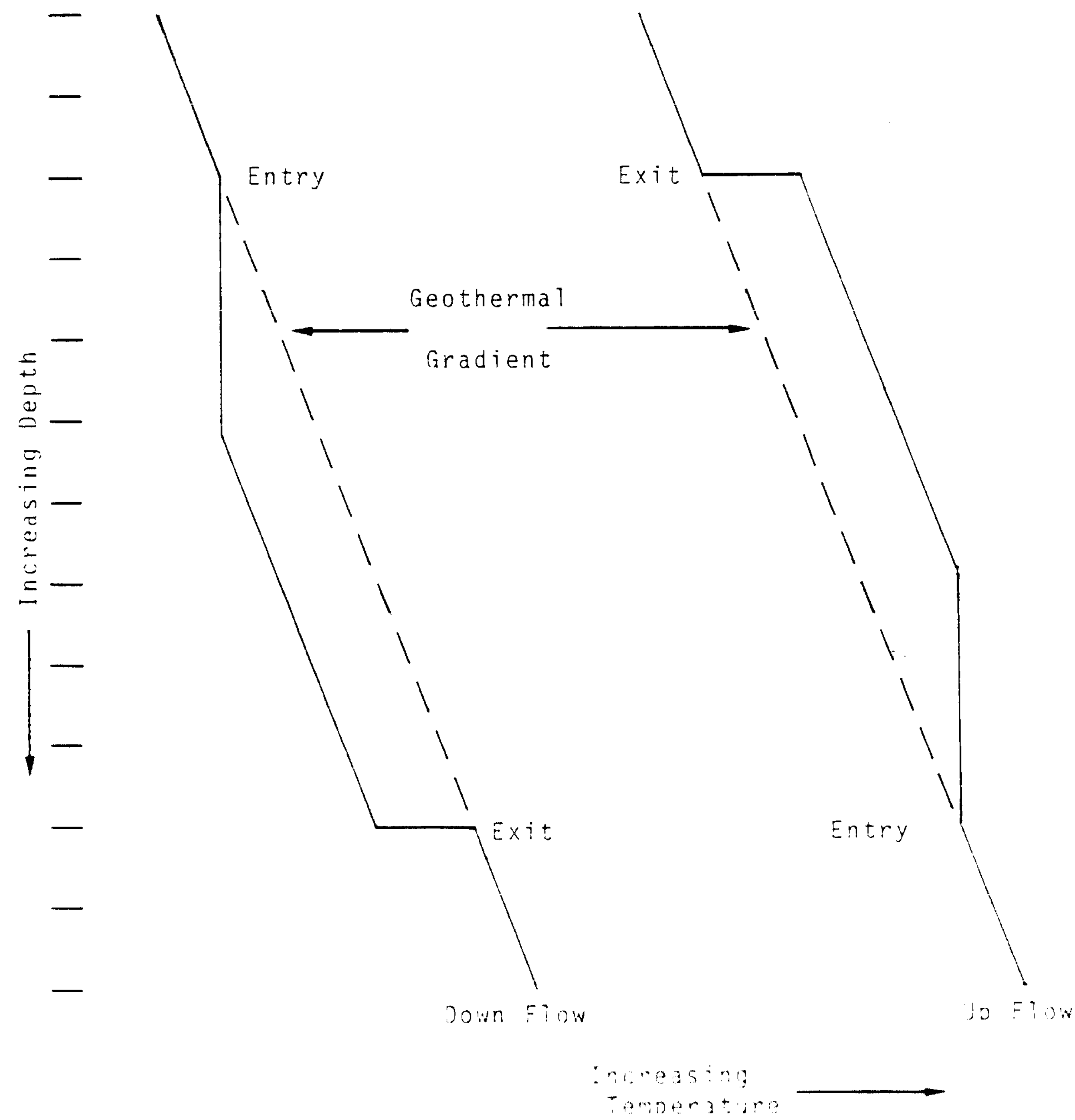

FIGURE 1

TEMPERATURE LOG SIGNATURES
LIQUID FLOW

porosity of the rock. The cement bond log (CBL) relies on the use of amplitude of the first arrival of the signal as an indicator of bonding. Also, a survey known as the Variable Density Log (VDL) is used in conjunction with the CBL in determining the condition of cement behind casing. The VDL log is the trade name used by Schlumberger Well Services; it is also known as the microseismogram (Welex), the 3D Velocity log (Birdwell Division), and the Acoustic Signature log (Dresser Atlas). All the companies refer to the bond log as the cement bond log.

The principles of bond and VDL logs offered by the various companies are essentially the same. The logging sonde is usually equipped with a transmitter and two receivers. The receivers are set at different spacings; one is utilized for the CBL, the other is used for the VDL. The tool is centralized within the bore hole and is run on a wire line; a continuous record is made. The transmitter emits a signal with a ringing frequency of 20 - 25 kHz (kilohertz) that is radiated in all directions. The receiver, which is usually set three feet from the transmitter, detects and measures the amplitude of the first arrival of the sound energy. In effect, this logging method depends on the difference between the energy loss of a sound pulse travelling through casing that is standing free (no bond) in the hole and the energy loss of a pulse travelling through casing that is firmly bonded to a hard material of a low sonic velocity, such as cement. The sound pulse will travel through free casing with very little attenuation, whereas when the cement is firmly bonded to the casing the sonic pulse loses energy continuously to the cement sheath and a large signal attenuation results.

By logging the signal amplitude, it is possible to locate points in the cemented section where the bond is not adequate and a potential for fluid movement may exist. Laboratory experiments have shown that the signal attentuation in cemented pipe is proportional to the percentage of the casing circumference that is bonded with cement. Investigations by Schlumberger Well Services indicate that a decrease in attentuation to less than 70 to 80 percent of the maximum value may indicate cementing problems.

VDL Log

The VDL log, when used in conjunction with the CBL, can provide additional information on the quality of the cementing. Basically, the VDL log (microseismogram, 3D velocity, acoustic signature) is a photographically reproduced display of the arrival of the sonic signal. A special recording oscilloscope is used for the purpose. The tool is set up so that a continuous record of the wave train is made as the [illegible] tool is raised or lowered in the bore hole. A VDL display is shown on Figure 2. The normal sinusoidal trace of the wave train is shown on Figure 2a. The VDL display of the wave train is shown on Figure 2b. The VDL display is derived photographically. The troughs of the signal produce high light intensities and result in dark zones on the film. Signal peaks produce low light intensities and result in light zones on the film. The photographic record of a VDL log appears as a series of alternating light and dark bands (Figure 2). If the rock properties were the same, the VDL display on the log would appear as a series of alternating light and dark panels or broad straight lines covering the interval of the logged section. The "free pipe" signal shown on Figure 3 demonstrates this. A VDL log made in an open bore hole can be used to determine porosity and locate fractures. Detailed interpretation of the wave train makes it possible to determine various rock properties for engineering purposes.

When used in a cased hole in conjunction with a bond log, the VDL log is an aid to interpreting the condition of the cement. A typical presentation of bond and VDL logs is given on Figure 3. The logs shown on the figure were taken in a bore hole in which known portions were cemented and uncemented (the uncemented portion was gravel packed). The uncemented part

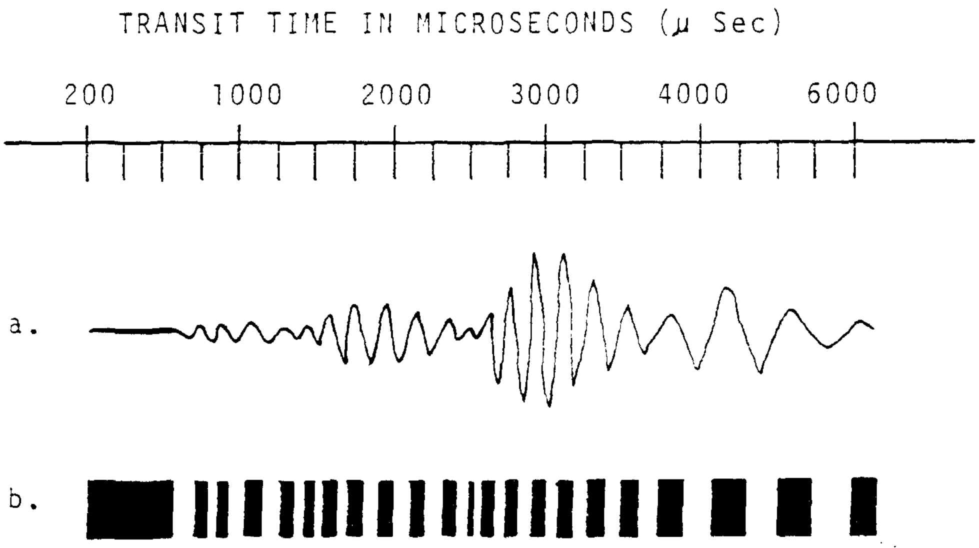

FIGURE 2

VARIABLE DENSITY LOG DISPLAY

a. Sound Wave Display

b. VDL Display

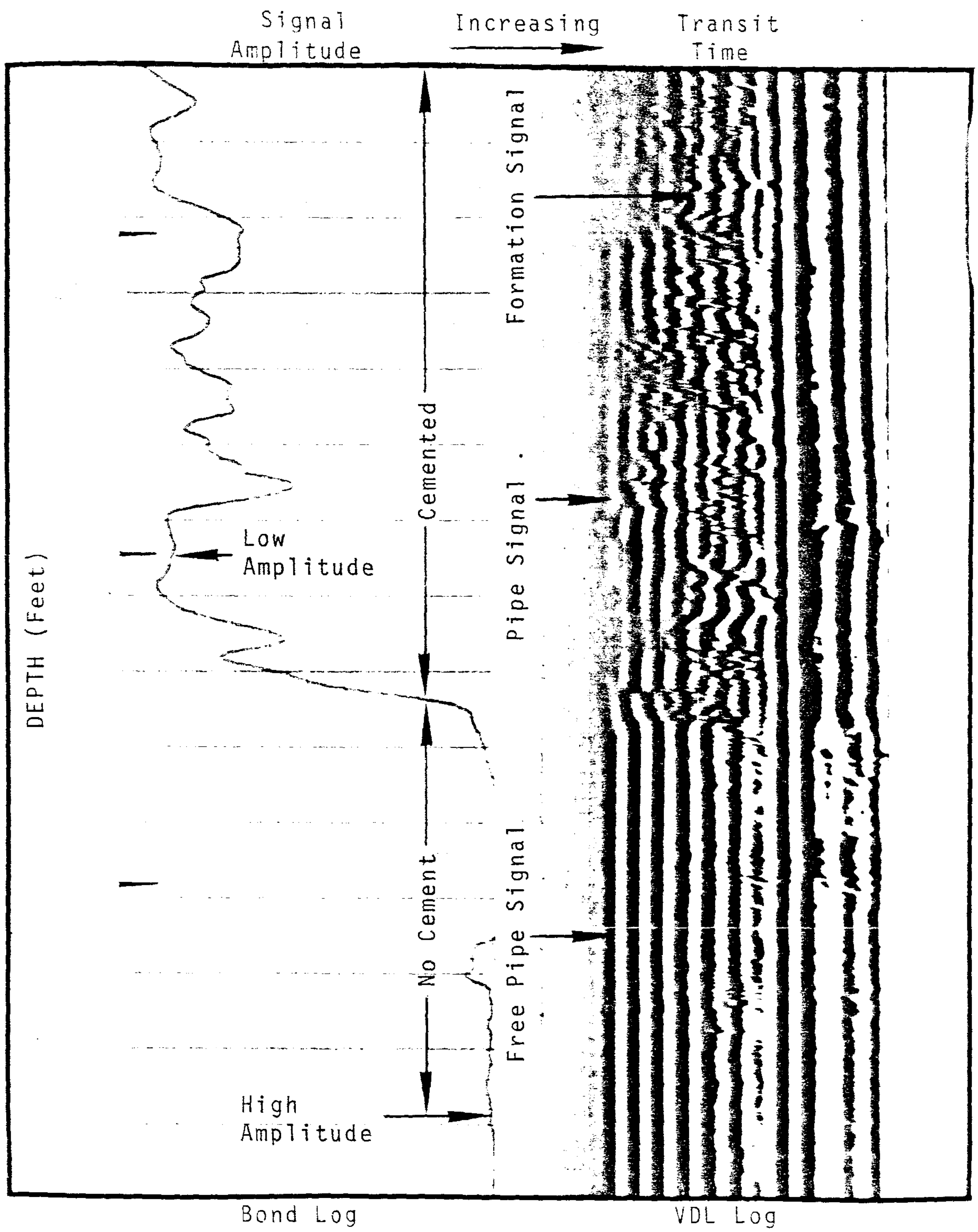

FIGURE 3
TYPICAL BOND LOG AND VDL DISPLAYS

shown on the log (below 2058 feet) is shown by a high amplitude signal on the bond log (no signal loss to the formation), whereas the cemented portion of the casing (above 2058 feet) is indicated by the low amplitude of the signal.

The VDL display below 2058 feet shows a characteristic, strong, free pipe signal which gives the appearance of the undistorted alternating light and dark bands. No signal strength is being lost to the formation, which accounts for the rather sharp display on the VDL display.

The cemented portion of the casing is characterized by (1) the low amplitude signal; (2) the weak, almost indistinguishable pipe signal; and (3) the wavy, irregular formation signal. The low amplitude of the signal is due to the loss of acoustic energy to the formation and indicates that the cement is bonded to the pipe. The amplitude of the pipe signal also is low because of the loss of strength to the formation. The presence of the irregular, wavy formation signals on the VDL display indicates that cement is bonded to the formation.

The combined use of both the cement bond log and the VDL log makes it possible to obtain some idea as to whether or not cement is bonded to the pipe and to the formation. However, it should be pointed out that this only indicates the presence or absence of an adequate bond, but [illegible] migration behind the casing; it only indicates whether such a potential exists. Other tests, such as temperature or noise logging, would be required to establish this.

Noise Logging

Within the past 20 years or so, the oil industry has developed the noise log as another tool which can be used to detect and locate fluid movement behind casing, cross-flow between zones, and relative flow rates from perforated intervals. The noise log can be of significant help in locating "leaks" that would be associated with fluid movement behind casing due to channeled cement. Research has shown that the frequency of sound generated by this type of leak is distinctive and can be utilized effectively to detect fluid movement.

A noise logging tool detects sound energy created by the turbulent flow of fluids (single phase) or water-and-gas (two-phase) moving through channels, perforations, and leaks. The sound generated ranges in frequency from 200 to 6000 Hz. Single and two-phase flows generate typical frequencies and, by examining the frequency of the noise, it is possible to estimate whether it is gas or liquid that is in motion. The logging tool or sonde is basically a sophisticated microphone. Sound energy from a noise source is detected through cement, casing, and bore hole fluids (or gas, in the event the bore hole is

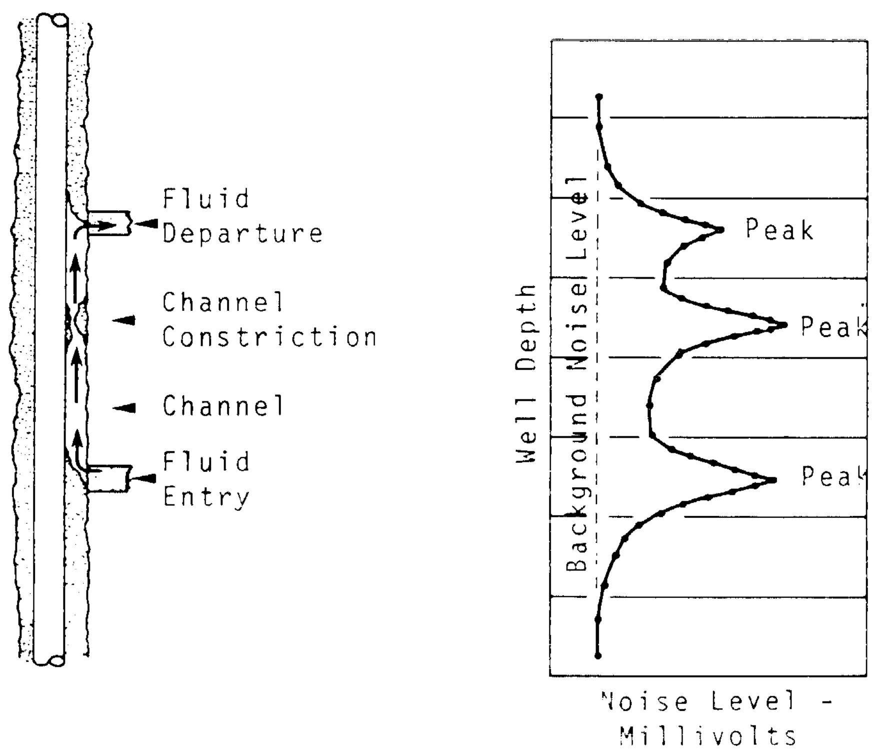

FIGURE 4

TYPICAL NOISE LOG DISPLAY

empty). The resultant electrical signal is transmitted via cable to surface electronic equipment where it is recorded.

The noise signal has an alternating frequency wave form composed of a number of frequencies. The intensity of the signal is an indication of the presence (or absence) of fluid movement, leaks, etc. The noise log measures (and records) the amplitude of the signal, which is expressed in AC millivolts, and is sensitive to any flow that can be "heard." Noises associated with movement of the tool and wire-line in the bore hole will mask out noise produced by leaks, movement, etc. Consequently, a noise log is usually made with the tool in a stationary position. The noise log is a survey taken on a STATION by STATION basis, in contrast to other logs which provide a continuous record with respect to depth of the parameter being measured.

Recently, noise logging tools have become available which can make a continuous record. By eliminating the frequency response generated by tool movement, the log can be made without stopping the sonde at a station, recording the noise level of the signal, and moving on to the next point.

Figure 4 illustrates the results of a typical noise log. In this example, fluid is entering a channel at a point opposite a permeable bed, moving upward, departing the channel, and entering another permeable bed. The noise log reveals a number of important facts. First, noise levels are greater than background values over the entire length of the channeled section where fluid is moving, giving an indication of the entire section which has been affected. Second, the top and bottom peaks indicate the points of entry and departure. These two peaks indicate only points of entry and departure; they do not indicate direction of flow. The flow could have been shown in the opposite direction and the log would have looked essentially the same. However, flow direction could be determined using a temperature log in conjunction with the noise log. Third, the middle noise peak on the log is shown as being the result of a constriction in the cement channel. It could have been shown as another point of entry or departure and the result would have been the same. Any of these causes will produce a noise that will be detected.

The noise log is another tool which can be used individually or in conjunction with other logs to aid in detecting fluid movement behind casing. It also can be applied successfully in locating leaks. It is a wire line service offered by a number of the commercial logging companies such as Schlumberger Well Services, McCullough, and Dresser Atlas.

Tracer Log

A radioactive tracer log can be used to locate fluid movement behind casing (assuming that a leak exists in the casing) or at the bottom of the casing to establish the integrity of the cement seal at that point. Basically, the survey is quite simple. A fluid containing a radioactive substance with a very short half life is injected into the well. As it moves downward it will leave the casing where leaks exist (assuming the material outside of the casing will permit fluid movement).

After the fluid is injected, a gamma-ray tool is lowered in the hole. At the point of the leak, where radioactive fluid has accumulated, a zone of comparatively intense radioactivity will exist; it will be detected by the tool and shown on the log as an anomaly. The log presentation is in essentially the same format as other logs.

In the case of fluid movement behind the casing at a leak or at the shoe, the zone of radioactivity will move as the fluid migrates and will be shown at different positions in successive surveys. In the case of upward movement at the shoe, radioactivity will be shown at points above the shoe where the only way this can occur would be for the fluid to migrate upward behind the casing.

A summary of the various logs and their applicability to determining fluid movement is given on Table 1.

COSTS

The costs for performing the various wire-line surveys used in determining mechanical integrity will, of course, depend on a number of factors. The commercial logging companies have a rather complex method of calculating charges which is based on: (1) the distance from the company office to the well, (2) standby charges, (3) an operations charge or depth charge, and (4) the type of survey. A minimum charge also is applied for depth and type of survey. Most companies allow the customer some "free standby" time before charges for this item will apply. Also, there will be differences in the charge for performing a specific survey within the same company, dependent on the geographic area. As noted previously, each of the major logging companies has subdivided the country into areas. The breakdown of service areas is remarkably similar between the various companies. Costs for a given survey will vary depending on the area and will vary between companies. The difference could be as much as $1,000.00, depending on the depth and type of survey.

Thus, the development of costs for a typical survey is complex and depends not only on the well depth [illegible]

TABLE 1

SUMMARY OF VARIOUS LOGS AND THEIR APPLICABILITY TO DETECTING FLUID MOVEMENT BEHIND CASING

Type of Log	Parameter Measured	Area of Investigation (1)	Presentation (2)	Applicability (3)	Principal Use
Sonic	Travel time of generated sonic signal	360^{o} Centralized Tool	Record of travel time of sound in μsecs/ft	No	Porosity
Cement Bond	Amplitude of sonic signal	360^{o} Centralized Tool	Record of signal amplitude in millivolts	Indicates Potential	Condition of cement behind casing
VDL	Time of travel and behavior of the signal wave train	360^{o} Centralized Tool	Photographic record of wave train, transit time in usec/ft	Indicates Potential	Condition of cement, rock properties, fracturing, porosity
Temperature	Temperature of cement, formation, and fluid	360^{o}	Record of temperature in ^{o}F, also record of temperature gradient	Yes	Leak detection, fluid movement, cement top
Density	Electron density	Partial (contact tool)	Bulk density of formation in grams/cc	No	Porosity tool
Neutron	Emitted gamma ray	Partial (contact tool)	Porosity in percent	No	Porosity tool

TABLE 1 - Continued

Type of Log	Parameter Measured	Area of Investigation (1)	Presentation (2)	Applic-ability (3)	Principal Use
Noise	Sound generated by fluid or gas movement	360°	Amplitude of the noise signal - amplitude of more than 1 frequency can be examined	Yes	Leak detection
Tracer	Radioactivity	360°	Radioactive highs	Yes	Leak location, detection

NOTES:

1. Refers to whether or not the tool investigates all or a portion of the circumference of the bore hole or casing

2. All surveys are presented as a continuous record of the value of the parameter being measured versus depth

3. Refers to whether or not the survey can be used in determining fluid movement

and the type of survey, but on the same factors noted for pressure testing as well.

To develop estimated costs for the various surveys, assumptions similar to those used in costing out pressure testing were used. Depths ranged from 2,000 to 6,000 feet; the well was a 300-mile trip from the service company office, and no standby time was required. Also, none of the logging company's special equipment or services were needed. The logs were performed over the entire cased portion of the bore hole and no provisions for dealing with a hostile environment were necessary. The estimated costs, rounded to the nearest $100.00, for temperature, cement bond-VDL, and noise logs are shown on the following table. These are average values converted to 1977 dollars.

Logged Depth	Temperature	Cement Bond-VDL	Noise
2000	$1,600	$1,500	$1,500
3000	1,900	1,800	1,800
4000	2,200	2,100	2,100
5000	2,400	2,400	2,400
6000	2,700	2,800	2,800

These figures are average values and could vary as much as $500.00 depending on the survey, company, and geographic location.

ELEMENTS OF STATE UIC PROGRAMS RELATED TO WELL INTEGRITY

This portion of the report summarizes the results of a review of the underground injection control practices of 12 states. The objective of this part of the assignment was to:

1. Determine the range of requirements applicable to assuring the mechanical integrity of wells designated Classes I and II by the proposed Federal Underground Injection Control Regulations.

2. Ascertain the compatability of the state requirements with the process and performance standards for well integrity and abandonment expressed in the proposed EPA regulations.

The states of interest are: California, Illinois, Kansas, Louisiana, New Mexico, New York, Michigan, Oklahoma, Ohio, Pennsylvania, Texas, and Wyoming.

Geraghty & Miller's regulatory files and library were analyzed and updated through contacts with state agency representatives and assessment of data from regulatory and technical reports. It was also necessary to undertake a limited review of the supporting legislation in each state to determine the philosophy of the agency with respect to control of underground injection.

Table 2 shows that the principal sources of information concerning well integrity assurance are related to: (a) the regulatory emphasis or objectives of the permit; (b) the pre-permitting engineering report submitted by the applicant; (c) the actual permit application requirement for logs and surveys of well construction and operation; (d) on-going operational monitoring; and (e) record keeping and reporting.

Regulatory Approach

Examination of the regulatory approach of the state agency was necessary to determine the overall minimum standard for regulation of underground injection.

For instance, New York, Oklahoma, and Pennsylvania each follow the case-by-case permitting procedure, but each agency has special considerations, rules, or policies which influence this individual assessment and address well integrity either directly or by inference.

The New York Department of Environmental Conservation uses construction procedures required for Class II wells as minimum standards, as does California, Texas, Oklahoma, Ohio, Michigan,

TABLE 2

WELL INTEGRITY ELEMENTS OF STATE UIC REQUIREMENTS

	CA	IL	KS	LA	NM	NY
Regulatory Approach						
Case-by-Case	X	X	X			X[8,9]
Compliance With Performance Standards (Environmental)	X	X[6]	X	X		X
Compliance With Process Standards (Technical)						
Judgement of Contents of Engineering Report	X	X	X			
Pre-Permitting Report						
Area of Review (in Miles)		2		2[3]	2[1]	
Contingency Plans		X		X		
Technical Report on Disposal Zone	X	X	X			
Well Construction Drawings	X	X	X	X		X
Casing Specs	X	X		X		X
Cementing Specs	X	X		X		X
Tubing Installation	X	X				
Packer Installation	X	X				
Permit Application						
Logs and Surveys						
1. Driller's Log		X[8]	X[3]	X[3]		X
2. Cement Bond Log		X	X			
3. Porosity Survey			X			
4. Resistivity		X	X	X		X
5. Faulting Potential Survey						X
6. Gamma-Ray Neutron		X		X		X
7. Casing Log						
8. Bottom Hole Pressure Test		X				X
Monitoring of Well Integrity						
Continuous Annulus Monitoring	X	X				X
Injection Pressure	X	X		X		X
Periodic Well Integrity Testing "Program"	X[11]	X				X
Monitor Wells	X	X				
Record Keeping						
Site Inspection	X	X				
Monitoring Data		[illegible]*		[illegible]*		[illegible]*
Reporting						
1. [illegible]						
2. [illegible]	[illegible]	X				X
3. [illegible]	[illegible]			X		
4. [illegible]	[illegible]					

TABLE 2 - Continued

WELL INTEGRITY ELEMENTS OF STATE UIC REQUIREMENTS

	MI	OK	OH	PA	TX	WY
Regulatory Approach						
Case-by-Case	X	X[10]	X	X[9]	X	
Compliance With Performance Standards (Environmental)	X	X			X	
Compliance With Process Standards (Technical)						
Judgement of Contents of Engineering Report	X	X	X		X	
Pre-Permitting Report						
Area of Review (in Miles)	2[1]				2.5	
Contingency Plans	X	X			X	
Technical Report on Disposal Zone	X	X			X	
Well Construction Drawings	X	X	X		X	
Casing Specs	X	X			X	
Cementing Specs	X	X			X	
Tubing Installation	X	X			X	
Packer Installation	X	X			X	
Permit Application						
Logs and Surveys						
1. Driller's Log		X	X[3]		X	
2. Cement Bond Log		X			X	
3. Porosity Survey		X			X	
4. Resistivity		X			X	
5. Faulting Potential Survey		X			X	
6. Gamma-Ray Neutron		X			X	
7. Casing Log		X				
8. Bottom Hole Pressure Test					X	
Monitoring of Well Integrity						
Continuous Annulus Monitoring	X[5]	X	X		X	
Injection Pressure	X	X	X		X	
Periodic Well Integrity Testing "Program"	X	X				
Monitor Wells	X	X	X		X	
Record Keeping						
Site Inspection		/Da*				
Monitoring Data		/We*	/Mo*			
Reporting						
1. Weekly						
2. Monthly		X			X	
3. Quarterly						
4. Annually		X	X			

TABLE 2 - Continued

WELL INTEGRITY ELEMENTS OF STATE UIC REQUIREMENTS

NOTES

1. Oklahoma requires extensive testing of wells within one mile radius of each injection well. This area is designated as the "Potentially Affected Zone." State requires integrity test program for inspection wells every five years.

2. Texas offers most comprehensive guidance through extensive permit requirements.

3. Prescribes log requirements on case-by-case basis.

4. Michigan requires applicant to make "exhaustive search" to locate "penetrations" in "expected area of influence."

5. Michigan will accept results of continuous monitoring of the well in lieu of integrity testing quarterly.

6. Uses Class II regs for salt-water disposal as minimum standards for permitting all well injection.

7. Agency "may" request data on nearby wells and other facilities in the area of review.

8. Policy is to use Class II well construction procedures as minimum standards. Division of oil and gas must approve specifications and engineering plans for all injection wells.

9. Applicant required to demonstrate that no alternative disposal method is available.

10. Well owner must submit estimate of the "life-time expectancy" of the injection well (Rule 5.10).

11. Agency has the option of requiring periodic well integrity tests including temperature testing, radioactive tracer and/or spinner test. Testing is done by specially equipped mobile unit.

12. Agency may follow oil and gas regs requiring "periodic" temperature, radioactive tracer, and/or spinner tests.

* We (Weekly)
* Da (Daily)
* Mo (Monthly)

and Kansas. However, both New York and Pennsylvania discourage the use of injection wells for industrial and municipal use. In New York, "the injection of liquid wastes by deep wells is considered a last resort after all other methods have been evaluated." This practice is regarded as "a method for gaining long-term storage rather than treatment." In New York, the applicant must demonstrate that injection is the optimal approach, and has the least effect to the total environment. Pennsylvania also views underground injection as a "last resort." Case-by-case evaluation for Class I wells in Oklahoma involves judgment of the applicant's projection of the "life-time expectancy" of the well.

The case-by-case review usually involves one of two different regulatory approaches. One approach stresses compliance with established environmental standards and requires all parts of the facility to operate so that this standard is maintained. This approach always relies heavily upon long-term monitoring and stops short of imposing detailed technical construction and testing regulations. Although guidance is provided, the technical process standards are not written as regulations, but rather inferred by the contents of the permit application. The other approach uses specific technical requirements or testing procedures to meet the established standard for environmental protection, and is usually more rigorous with respect to prevention of problems. Monitoring is required as a secondary checking mechanism of operational integrity.

For instance, the Kansas Department of Health uses the regulations for oil and gas salt-water disposal wells as the minimum standard for permitting all well injection. Agency rules simply say that underground injection must protect "usable water," defined as all water containing not more than 5,000 ppm chlorides. The technical details of how to construct a well that will meet this standard are not provided as regulations by the agency. Hence, when the applicant submits the required engineering report, the reviewer must consider principally whether the proposed well has or will have sufficient integrity to protect "usable water" regardless of the techniques used for construction, testing, or maintenance. Technical guidance offered and testing procedures imposed allow for site-specific judgment.

Conversely, Michigan regulations emphasize the initial determination of the site containment potential and well construction to assure integrity of the total operation, but reinforce this reliance through rigorous pre-permitting investigations, prescribing specific testing procedures to be completed periodically. Oklahoma's Rules and Regulations for

Industrial Waste Management also prescribe specific well integrity tests as a condition of permitting. These tests are comparable to those required by Sec. 146.08 of the proposed regulations.

Pre-permitting Engineering Report

The technical data collection requirements related to well integrity are to be found to one degree or another as data submission items in the applicant's site evaluation, well construction, and operational engineering report, which each of the states uses to initiate the permitting process. Procedural guidance and permit forms used by the Texas Department of Water Resources stipulate the variety of tests needed. However, the agency reported that monitoring is considered to be the most important indicator of problems. It was pointed out that "other tests are redundant." The degree to which pre-construction data is relied upon by the states is indicated by the fact that, of the states reviewed, only California, New York, Michigan, and Oklahoma formally require subsequent periodic well integrity testing (Table 2).

It also should be noted that the contents of the pre-permitting report for Class I wells in Illinois, Michigan, and Oklahoma are particularly rigorous, requiring considerable preliminary fiscal investment by the potential operator with no guarantee that the results will not lead to a request for additional investigation.

Logs and Surveys

The logs and surveys required for the actual permit application indicate that Illinois, Oklahoma, and Texas requirements are the most consistent with respect to start-up testing programs which test the validity of the initial permit application data (Table 2). The other states prescribe logging and surveying activities on a case-by-case basis without apparent regulatory reference to the pre-permitting tests.

Monitoring of Well Integrity

Oklahoma and Texas rules are noteworthy because of the degree to which fairly rigorous log and survey requirements are supported by equally explicit monitoring requirements. As previously mentioned, most of the other states, including California, Ohio, Illinois, Michigan, and New York, place heavy reliance on post-operational monitoring to confirm the integrity of the well.

Continuous annulus monitoring and regular checks of injection pressure are the two most common requirements for checking day-to-day operational integrity of the well. However, some states, notably Texas, Kansas, and California, [illegible] additional testing on a case-by-case basis in conjunction with the issuance of the operational permit. In California, the State Water Resources Control Board retains the option of requiring periodic well integrity tests including temperature testing, radioactive tracer and/or spinner testing. The tests are run by a specially equipped mobile unit.

In Texas, the applicant for an injection well must: "Describe provisions for continuing activities necessary for proper well operation and qualifications of personnel who will operate and supervise the injection well and related facilities." The agency policy is to rely on well monitoring to indicate problems. Other tests, although they are sometimes requested, are regarded as "redundant" in the context of the total permitting process for injection wells. It should be noted that Texas and Oklahoma regulations for well design, construction, and operation are probably the most comprehensive of those reviewed. They prescribe casing, construction materials, pressure gradients, emergency facilities, qualifications of operators, and also offer considerable regulatory guidance to permit applicants.

In Kansas, the frequency of checking disposal operations is dictated by the Division of Environment's "knowledge of the potential for problems in the region." The state requires a spinner survey if problems with the well are "suspected." Radioactive tracers are used "occasionally" and the installation of an annulus pressure gauge is "preferred but not mandatory." The state philosophy is to "use rules and policy requirements based upon laws rather than uniform regulations."

Periodic Well Testing Programs

Oklahoma and Michigan prescribe periodic testing of operating wells in a fashion similar to the proposed EPA regulations (Sec. 146.24(3)). The Oklahoma regulation (5.6.10.1) requires that

> "At least once during each five (5) years, the operator shall conduct such tests, such as cement bond logs or tracer surveys, as are necessary to insure the continued integrity of the cementing..."

The operator also is advised that:

> "Formation pressure decay tests as specified shall be conducted annually and the results submitted to the Department.
>
> 5.6.11.1 Such formation pressure decay tests shall be conducted by pressurizing the well to its maximum normal injection pressure for a length of time sufficient to establish stable conditions, then closing off the well and monitoring the decay in well head pressure. The test may be terminated when the well head pressure changes no more than three (3) p.s.i. in one (1) hour, or at the end of the twenty-four (24) hours, whichever comes first."

Michigan's Rule 67 covers "Periodic testing of storage and disposal wells." This quarterly testing specifies the use of the variable-rate input method, the pressure fall-off test, "or any other performance test specified." The rule stipulates that:

> "Sufficient data shall be collected during each calendar year to facilitate analysis of static and injection formation pressures, storage zone limits or boundaries, changes in formation characteristics, and other information commonly derivable from such tests."

However, the agency advises the operator that continuous monitoring data may be an acceptable substitute for "some" periodic testing.

New York State Department of Environmental Conservation policy with respect to deep well injection declares that:

> "It is incumbent upon the applicant to obtain a competent geologist and a professional engineer for the necessary studies, design and preparation of reports and plans. This should include, but not be limited to the environmental, economical and technical implications."

The well testing program required by the Illinois Division of Land/Noise Pollution Control also goes beyond continuous monitoring (Table 2). The specific tests to be run are determined on an individual basis for each well and are performed six months after initial operation and then either annually or every two years.

Existing state regulatory practices and policies are designed to assure the integrity of wells used to inject municipal or industrial wastes into the subsurface.

Controls are based upon practices established by the oil and gas industry for Class II wells. These oil and gas waste disposal regulations are minimum standards for other injection wells.

The states incorporate a number of elements of the proposed Federal regulations into their practices. However, no state program is organized in a categorical fashion similar to the proposed EPA standards. The state emphasis is on assessing the likelihood that the well will be secure rather than upon prevention of problems sometime in the future.

The lack of uniformity for data requirements directed at well integrity for Class I wells exists because of the special nature of the practice. Injection of industrial and municipal wastes is sufficiently limited nationally to allow state agencies to issue permits on a case-by-case basis. The tendency to regard underground injection as a "last resort" management practice is sufficiently prevalent to encourage this approach. For instance, the New York Department of Health "Statement of Policy" declares that "the injection of liquid wastes by deep wells is considered a last resort after all other methods have been evaluated." The same policy exists in Pennsylvania.

The potential operator, not the regulatory agency, is principally responsible for proposing technical design, operation, and monitoring details. Permit forms ask questions and rarely dictate specific standards other than those related to the quality of water to be protected. Judgment concerning the applicant's data submission with respect to well integrity is the basis for the permitting agency's selection of testing procedures as a condition of permitting.

Philosophically, the principal difference between the Federal approach to well integrity assurance and related testing and the state practices relates to the reluctance of state agencies to standardize technology. Instead, performance standards are emphasized.

Re-permitting of Class I injection wells every five years is not the practice of any of the states whose regulations were reviewed in this assessment. However, Oklahoma does require the operator to undertake a formal program of well integrity testing every five years.

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