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A Comparison Study of Water Well Grouting Materials

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A COMPARISON STUDY OF WATER WELL GROUTING MATERIALS

by

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A COMPARISON STUDY OF WATER WELL GROUTING MATERIALS

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To prevent contamination from occurring in water wells, and thereby groundwater, the annulus between the well casing and borehole wall must be sealed with a grout that is capable of maintaining a proper seal. Several factors and properties determine the integrity of the grout and the seal formed by that grout.

A field study discovered limitations in all of the tested grout types. Most grouts were found to vary greatly in thickness surrounding the well casing. Bentonite slurry grouts settled excessively. Cement and bentonite-cement grouts did not adhere to PVC well casing. Bentonite-cement grout fractured. The granulated bentonite was mixed with the surrounding formation in some places.

Further research, product development, and a proposed grout performance standard are recommended.

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INTRODUCTION

Statement of Problem

Groundwater is an important natural resource that requires diligent conservation and preservation. Environmental awareness has prompted many changes in regulations to help to protect groundwater. With those changes have come strict water well installation codes.

If groundwater is contaminated it can no longer be used to its fullest potential, if at all. Water wells can be a source of contamination if they have not been installed correctly, or if the grouting material used to seal the well has "failed." Water wells with either of these problems can provide a direct pathway for contamination to migrate downward from the surface, or possibly allow inter-aquifer exchange to occur. Either of these situations could cause contamination of water wells.

The numerous problems encountered in grouting water wells and the importance of a good water well seal has prompted state regulators and the water well industry to seek solutions and answers.

Many products exist for the purpose of sealing a well, as do many techniques for well installation. Most techniques have well known weaknesses that are addressed in regulations; therefore most are not in question. However, questions concerning product performance are abundant.

Water well grouting materials range from neat cement to bentonite slurries and everything in between. Each has limitations. A number of factors determine if a grout can be installed correctly and maintain its integrity. "A good grout should provide adequate percent solids to create a low-permeability seal, have a long-term physical integrity to remain intact in the hole and not settle, and have practical mixing and pumping capabilities" (Riewe, 1996, p. 29).

Properties that may affect water well grout integrity need to be understood to help to prevent groundwater contamination. To evaluate some of those properties a field study was conducted using several grouting materials.

Variability between the grouts and drillers prohibited a well-controlled study; however, the intent of this study is to compare "real world performance" of grout types and drillers. The properties of the grouts could change depending upon the driller's methods of installation, the depth of the well, and the formation in which the well is placed. In an attempt to minimize the differences between drillers, company representatives oversaw the installation of the bentonite slurry grouts used in this study. The cement grouted and the bentonite-cement grouted wells were both installed according to common drilling practices. The cable tool well was installed by the driller who developed the grouting method used. All of those involved in this study understood that the purpose of the wells was to evaluate grouting materials, and to some extent the grouting methods. The wells used in this study were intended to represent the best case scenario.

Most of the resources used in the literature review came from water well industry journals or other sources, in an attempt to utilize the knowledge and understandings of water well drillers. Michigan state codes and regulations were also important sources of information.

Purpose of Study

The purpose of this study is to evaluate the properties of the different grouting materials that may affect the integrity of a water well seal in light of findings from previously published studies and articles, and knowledge available from industrial and governmental sources.

In order to answer the questions concerning grouting problems an in-depth literature review was conducted to help define the problems. A field study was conducted to evaluate some of the properties of various grouting materials. The literature review provided insight into how grouts are applied in the water well industry and why some grouts simply do not provide an adequate seal. It also provided an extensive knowledge of the properties that are of concern in establishing a good water well seal.

The field study provided base-level information about the properties that may affect the integrity of a water well seal, and a direction for future studies.

LITERATURE REVIEW

Introduction

Grouting, as defined by the Michigan Department of Health (MDPH), means:

> The placement of grout into the annular space that surrounds a permanent casing for the purpose of sealing the annular space to prevent the entrance or migration of surface water, near surface water, and contaminants to the groundwater and to maintain the natural protection of aquifers (MDPH, 1994, p. 8).

"As it pertains to groundwater protection, the objective of grouting is 'to establish and maintain a seal, against all faces of the void, that is of equal or lower permeability than that of the best formation intersected'" (Stichman, 1990, p. 1). The best formation means the least permeable layer encountered.

Sealing of water wells has evolved over the years from the use of drill cuttings and drilling mud, to neat cement, to various bentonite-grouting materials. Each one has its own limitations.

Bentonite

Bentonite refers to a rock that contains montmorillonite as its chief mineral. Bentonite, as defined by the MDPH, is "a plastic colloidal clay which has an extensive ability to absorb fresh water and swell in volume and which is composed predominantly of the mineral montmorillonite" (MDPH, 1994, p. 6).

Although there are bentonite deposits found throughout the world, the bentonite most commonly used in the water-well industry was made by volcanic ash that was deposited during the Cretaceous period, east of Idaho, in a shallow, calm, inland sea. As the ash was deposited it began to react with the sea water (Bentonite Corp., 1997). Bentonite was formed by the alteration of the volcanic ash *in situ* (Grim, 1953). It seems that several factors must exist for the alteration of ash to bentonite to occur. The alteration from volcanic ash to bentonite takes place in saline water, not fresh water. Also, the ash must contain a moderate amount of MgO. Ash without magnesia does not alter to montmorillonite (Grim, 1953). After the ash had been deposited in the sea it was covered with silt and mud layers. This sequence of events happened several times, with over fifty layers of bentonite being deposited within one thousand feet of sediment. With continental plate movement, these beds were raised and the sea was drained. Bentonite beds are currently being mined in Wyoming and South Dakota (Bentonite Corp., 1997).

The chemical and mineral makeup of individual bentonite beds varies greatly. This is due to the complexity of the formation of bentonite. The source rock of the volcanic ash could vary in composition, thereby changing the chemical makeup of the bentonite. The salinity of the sea in which the volcanic ash was deposited could have varied over time and over regions, thus affecting the altering process. A wide assortment of variable factors played an important role in the chemical and mineral content of bentonite.

Montmorillonite is a type of smectite clay. Smectites are swelling clays that attract water between the sheet layers of its structure. The large surface area of the sheet layers allow water to be adsorbed in large quantities, thus greatly increasing the volume of the clay (Velde, 1992).

Montmorillonite contains exchangeable cations within its structure. The nature of the exchanged cation found in bentonite can affect the properties of the clay. "Water adsorption of the sodium form of montmorillonite was three times greater than that of the calcium form," (Grim, 1941, p. 9) thus making sodium bentonite more desirable for sealing wells. Large deposits of sodium bentonite are found in Wyoming.

Bentonite is used for many industrial purposes, dependent upon its properties. Bentonite is used for kitty litter and in cosmetics and pharmaceutical products. It is used to help strengthen sand molds in foundry work. It is also used as a suspension agent in insecticides, pesticides, herbicides, and fertilizer blends. Bentonite has also been found to be very useful in the oil and gas, and water well drilling industries (American Colloid Company, 1997). This is by no means a complete list of the uses of bentonite.

In the water well industry, bentonite is used in drilling mud, and it is used to seal wells. The difference between drilling mud and sealant is the bentonite solids content. In general, drilling muds have a low solids content of 3 to 9% with the remainder largely water (Stichman, 1990). Bentonite slurry grouts used to seal wells are made using 20 to 35% solids.

When properly applied, bentonite can provide an excellent seal for water wells. Bentonite has a very slight heat of hydration, and it forms a low permeability, flexible seal that will rehydrate if dried (Papp, 1994). Unlike cement it does not greatly affect the pH of groundwater. Bentonite, in general, adheres very well to all surfaces (Smith & Mason, 1985). "This ability to adsorb water and swell, exerting pressure against confining surfaces, is what gives the material its tremendous advantages over other mediums for filling void spaces in boreholes" (Stichman, 1990, p. 5). It is often assumed that bentonite does not have problems adhering to any type of casing. However, Edil et al. (1992) reported that Volclay, a brand of high solids bentonite, does not adhere to steel casing. In fact, the Volclay grout observed in Edil's study seems to form a micro-annulus similar to that noted in PVC wells grouted with cement. Edil's study does not address the adherence of Volclay to PVC casing. Is there a difference between adherence to PVC or steel well casing? Are there differences in the performance of the various grout brands?

Bentonite comes in various forms for use in the water well industry: powdered, granulated, chips and tablets. Powdered bentonite is mixed with water to form a slurry either for drilling mud or grouting. Granulated bentonite is often used in the water well industry to seal cable tool wells. Chips or tablets have been used to seal wells by dropping them into the annular space surrounding the well casing. While it is true that bentonite has the potential to provide a good seal, each of method of application has notable problems.

Bentonite Slurry Grouts

Regardless of the percent solids, bentonite slurry grouts are prone to excessive settling. The Michigan Department of Public Health Well Construction Unit, reports that well drillers and inspectors have noticed "settling of 20 to 75 feet, when products have been mixed and applied in accordance with the manufacturer's recommendations" (Gaber, 1996, p. 1).

Several theories exist that try to explain this phenomenon. One theory is that the grout is intruding into the surrounding formations. Another theory is that the grout is losing water to porous formations, thus causing settling to occur. Most literature assumes that either one or the other of these theories is true. Another theory is that additives, such as polymers and catalysts used to control bentonite swell and extend working time, affect the gel strength of the bentonite. This may cause the bentonite in deeper wells to wash out into the formation (Gaber, 1997). No published experimental studies on the settling of bentonite slurry grouts could be found.

In addition to settling problems there are several questions concerning the long-term integrity of bentonite grouts. Does bentonite provide a good seal in the vadose zone? In a field study performed by Lyndon Bucher it was found that high solids bentonite slurry grout has the ability to "maintain a high degree of hydration and provide a competent seal above the water table, even in very low moisture conditions" (Bucher, 1993, p. 40).

Another question concerning bentonite grouts is its ability to remain in place below the water table, and in flowing-well or artesian situations. Does the natural flow of water affect the integrity of a bentonite slurry grout? No literature could be found on the long-term effects of normal water flow below the water table on bentonite grouts. Does water under pressure, as in a flowing-well or artesian situation, affect the integrity of a bentonite slurry grout? Ogden and Ruff (1993, p. 249) suggest that bentonite slurry grouts do not have the strength to resist water under pressure and should not be used "in confined aquifer boundaries without additional mechanical support such as packers or adjacent cementitious seals, unless the aquitard thickness is at least two-thirds of the expected maximum drawdown." Local regulations should be checked before using packers or sealing a flowing well to determine the recommended practices for that area.

Several other questions exist regarding bentonite grouts. How do the various brands of grout compare to each other? Is long term integrity a problem for bentonite slurry grouts? How do various additives affect grout integrity? Clearly research on several aspects of bentonite grouts is badly needed.

Granulated Bentonite

Granulated bentonite can be used to seal the borehole surface and the top few feet of a dry borehole (Bertane, 1987). A more important use of granular bentonite is as a grout for cable tool wells.

To seal a cable tool driven well, granulated bentonite is heaped around the well casing at the surface and replenished as needed. As the well casing is being driven the bentonite follows the casing down the borehole. The effectiveness of this practice in providing an intact seal around the well is an ongoing research topic at Western Michigan University.

In an attempt to ensure proper grout placement, oversized sleeves may be welded to the well casing at regular intervals. These sleeves help to trap and to drag additional grout down the borehole. However, questions exist about the effectiveness of these sleeves. Does the grout become trapped only around the sleeves? Or do the sleeves help to distribute the grout evenly?

Another way to help to ensure proper grout placement for cable tool wells is to raise and lower the casing several times throughout the drilling process (see Leonard, 1985). This method is quite effective; however, it is very time consuming and there are questions as to its effectiveness with depth. Because of these problems, this method is not commonly used.

No published literature could be found about any concerns regarding this grouting method. However, researchers at Western Michigan University, speculate that if neither of the above mentioned methods of ensuring proper grout placement is used, grout thickness will diminish with depth until only a smearing of grout can be found. Further physical studies need to be conducted on the various methods of grouting cable tool wells.

In a study conducted by the MDPH Well Construction Unit (Gaber, 1997), actual volumes of dry granular bentonite needed to seal the borehole of a cable tool well were calculated, then bentonite usage was compared with the calculated volume to determine the percentage of annular space filled. Please see Figure 1 for an example of these calculations. Using these simple formulas four cable tool contractors' bentonite usage was compared. Table 1 shows a number of wells used for the Gaber (1997) study, the range

If using 4-inch casing with an outer diameter of 4.5 inches, and a drive shoe with an outer diameter of 5.2 inches, the annular space is 0.35 inches and yields an annular space volume of 0.0329 cubic feet per linear foot. A 50-pound bag of granular bentonite yields 0.7 cubic feet.

Example: A contractor installed 5754 linear feet of well casing in a year. To determine annular space volume:

5754 linear feet x 0.0329 cubic feet per linear foot

=189.3 cubic feet

189.3 cubic feet/0.7 cubic feet per bag

=270 bags of granular bentonite

The contractor reported using 240 bags of bentonite for the year.

240 bags/270 bags

=88% of the annular space volume filled

Figure 1. Example Calculation of the Percentage of Cable Tool Annular Well Space Filled (Gaber, 1997).

Table 1

Granulated Bentonite Use of Selected
Michigan Cable Tool Operators

	Contractor Data and Percentages			
Contractor Number	1	2	3	4
Number of Wells	621	165	45	15
Casing Depth Range (feet)	19-237	19-237	25-272	25-145
Average Casing Depth (feet)	83	83	84	58
Total Casing Footage	54,866	13,713	3,814	874
Total Bentonite Usage (lbs)	84,450	50,275	9,247	1,675
Bentonite Usage Rate (lbs/ft)	1.53	3.67	2.42	1.92
Percentage of Annular Space Filled	65%	156%	103%	82%

(adapted from Gaber, 1997)

of casing depth, as well as the average casing depth,and the total casing footage compared with the bentonite usage rate to determine the percentage of annular space filled by that contractor.

Although this study is not actual visual evidence of grout placement it does provide an educated guess as to whether a good seal has been established. This study does not, however, take into account any additional grout left on the surface, nor does it take into account the bentonite found in the top 1-2 feet of the borehole, which is commonly quite a bit larger than the remaining borehole diameter.

Bentonite Chips or Tablets

Bentonite chips and tablets have the capability to provide an excellent seal due to their enormous swelling potential. They can provide up to 73% solids by weight, a large difference when compared to the 20-35% provided by bentonite slurry grouts (Stichman, 1990). However, the proper installation of these products is nearly impossible in a water well. The most common method of installation is to drop the chips or tablets from the surface down the annular space between the casing and the borehole wall. As the chips or tablets fall down through the annulus, they are prone to bridging due to borehole irregularities and swelling after they hit the water table. "The introduction of bentonite pellets through standing water does not allow for packing or compaction of the seal, and the presence of voids and inhomogeneities resulting from bridging are likely" (Dunnivant et al., 1997).

In 1994, grouting of wells by pouring bentonite chips into the annulus was banned in the revised Michigan Well Construction Code (MDPH, 1994).

Drill Cuttings and Drilling Mud

Today drill cuttings and drilling mud are no longer considered viable well grouting materials. "Drill cuttings were not effective because they often bridged and could not be compacted to form a good seal. Drilling mud was not effective because of low bentonite solids concentration in the slurry" (Oliver, 1995, p. 12).

Drill cuttings, in most cases, do not meet the permeability criteria of a grout. "A grouting material should have a permeability equal to or lower than the permeability of the least permeable formation penetrated" (MDPH, 1988, p. 19). This means that the grout should transmit water at an equal or lesser rate than the native soils or rocks, thus retarding the movement of fluids (MDPH, 1988). Drill cuttings are a mixture of all formations penetrated by the drill bit. This mixture, in most cases, will have a higher permeability due to the fact that it is a mixture of all the formations, not just the least permeable formation, and because it has been disturbed it is less dense and more permeable. When a formation is disturbed the natural layering and consolidation is destroyed, resulting in a less permeable material.

Bridging is a common problem when drill cuttings are used to seal a well (Figure 2).

Because of the low solids concentration of drilling mud it cannot be used as a grout.

> A low solids [usually 3 to 9%] drilling mud or mud/cuttings combination will drop in the annulus as the mud level seeks the water table level. Settling of solids generally occurs, resulting in few or no solids in the upper portion of the annulus. Water loss to permeable formations occurs and the mud level along the casing drops, often without borehole collapse (MDPH, 1988, p. 13).

Figure 3 illustrates a well in which drilling mud has settled. "The trouble is, in some cases, that the mud slurry disappears down the annulus, leaving an open void that can allow contamination to easily flow into the well" (Riewe, 1996, p. 29).

Edil et al. (1992) cautioned against the use of drilling mud as a grouting medium. However, their research indicated that heavy drilling muds entrained with sand, having a weight of at least 11 pounds per gallon, were capable of providing an adequate seal. Subsequent research made it quite obvious that " the use of rotary drilling mud and cutting slurries was not, in many cases, providing an adequate grout even with our new mud weight requirement" (Riewe, 1996, p. 32). It was found that

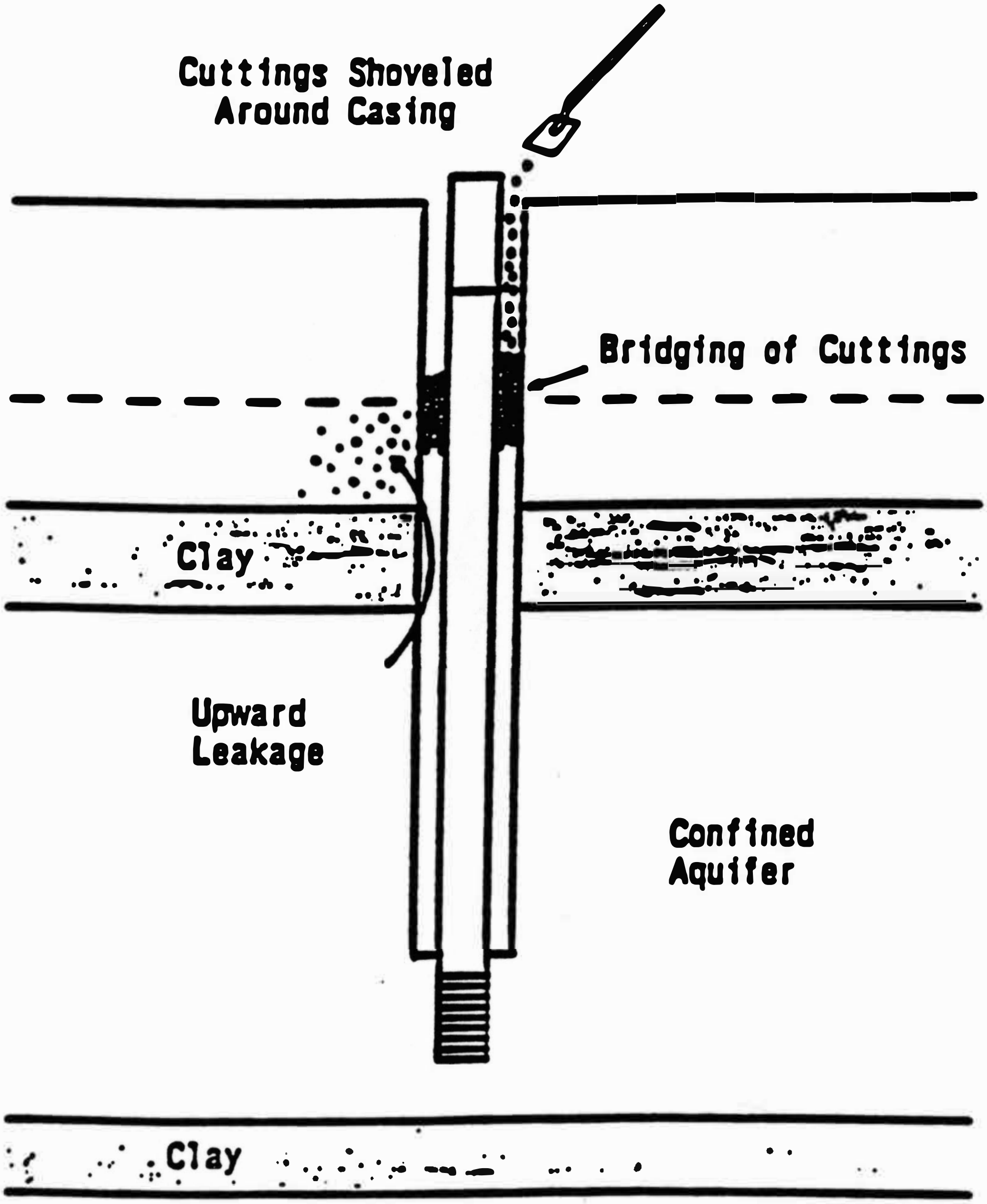


Figure 2. Drill Cuttings Bridging in Annular Space of Water Well (adapted from MDPH, 1988).

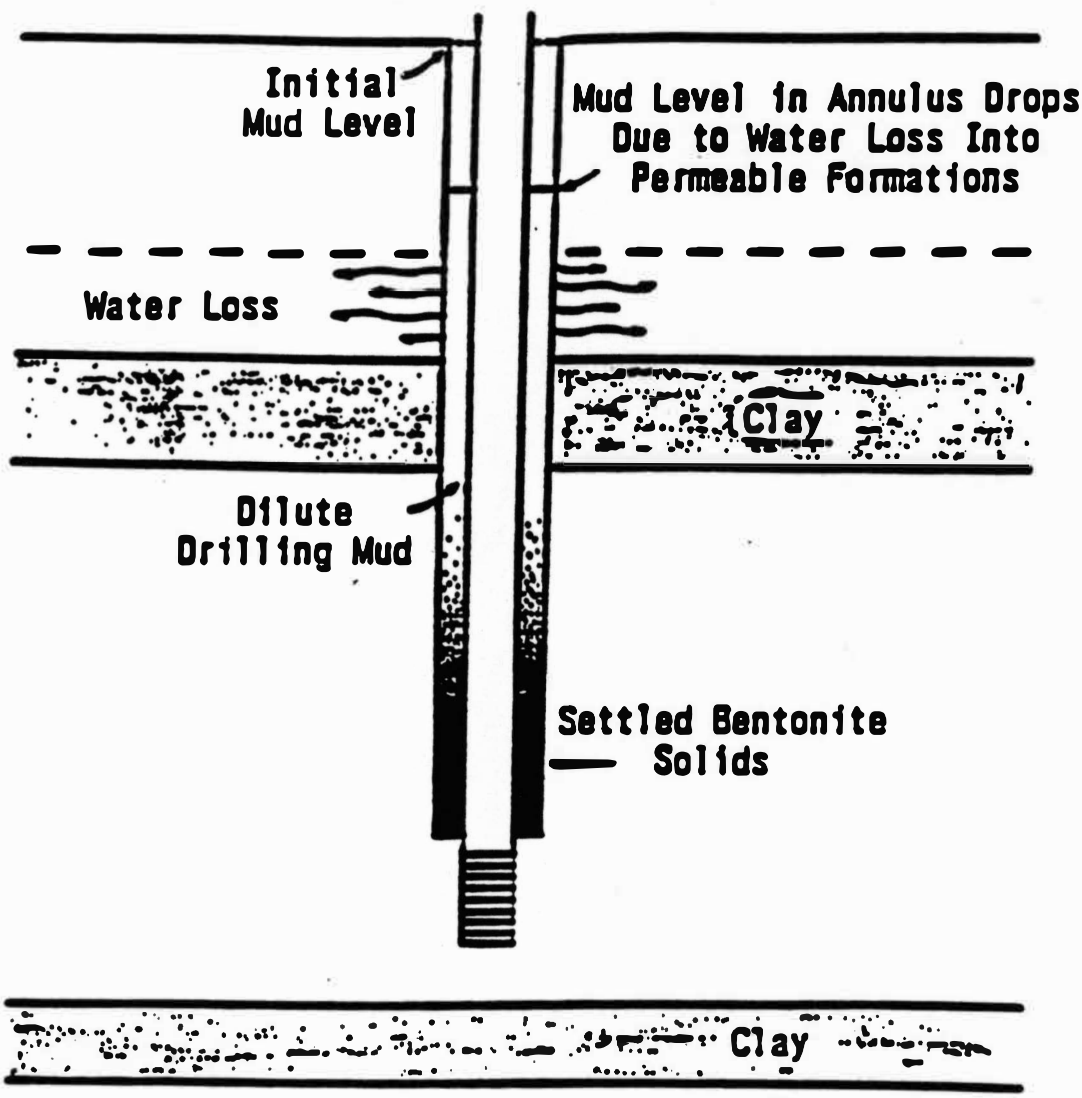


Figure 3. Drilling Mud Solids in Annular Space of Water Well (adapted from MDPH, 1988).

heavy drilling muds were difficult to pump, caused borehole instability and poor circulation, and cuttings were not dropped into the mud pit (Riewe, 1996).

The same study tested several grouting materials in the laboratory (Riewe, 1996).

> It was found that low solids drilling muds failed as grouts. They allowed excessive infiltration, exhibited decisive subsidence (in some cases greater than 100 percent by volume), and had many cracks that allowed dye to easily migrate down through them. This is not surprising when one considers the fact that these slurries are significantly greater than 90 percent water by volume (Riewe, 1996, p. 31).

Field tests confirmed laboratory results in Riewe's study.

The evidence shown in previously published studies seems to indicate that drilling mud and drill cuttings should not be used for grouting.

Cement

The most commonly used cement grout is a neat cement slurry. Neat cement is a combination of Portland cement and water. No sand or gravel is added (MDPH, 1988). Portland cement is composed of lime, silica, alumina and iron oxide (Portland Cement Association, 1965) heated to form a variety of compounds that react readily with water. These components can be derived from a number of sources. Type I Portland cement is general purpose and is the type most used in the water well industry. It should be noted that Type I cement will not resist sulfate attack. This may be important to the integrity of a seal in an area where acid rain occurs.

Neat cement has been used in the oil and gas industry successfully since the early 1900's (Smith, 1976). "Petroleum industry cementing techniques have become highly specialized and apply to water well construction, although this transfer of cementing technology has not progressed as well as in other areas" (Department of Army and Air Force, 1975, p. 288). There are several possible explanations for the lack of transfer of technology between the oil and gas industry and the water well industry:

1. As cement is mixed with water a chemical reaction occurs. This is an exothermic reaction that produces heat and is called heat of hydration. In the past it was thought that heat of hydration caused structural damage to PVC casing. Although PVC deformation is unlikely (Kurt, 1979), it may occur under certain circumstances. If a non-uniform borehole is constructed, or if washouts developed during construction, a thicker than normal column of cement can increase the chance of deformation to occur. Very few documented cases of deformation caused by the heat of hydration have been recorded in Michigan.

> Many contractors routinely cement PVC casing in Michigan. It is believed that the lower ground water temperature and relatively high static water levels contribute to a reduction in

heat of hydration damage. Michigan's minimum PVC casing size of 5 inches may also result in masking heat of hydration damage. If a slight casing deformation occurs it may not be noticed when the 4 inch submersible pump is installed, whereas if 4 inch PVC were allowed, as in other states, the deformation would be apparent (Gaber, 1997, p. 1).

2. Bentonite slurry grouts can often be mixed using the same equipment used for mixing drilling mud, whereas drillers often prefer separate mixing and pumping units for cement. To avoid pump failure, extensive flushing and cleaning is required after pumping cement. To help to assure that a working pump is found on the drill rig, a separate pump is often used for cement. Thus, cement grout requires an extra effort on the driller's part, so unless cement grout is required or requested, bentonite slurry grouts are often preferred.

3. Neat cement grout cannot be used in monitoring wells or environmentally sensitive wells because it often raises the pH of groundwater (Dumouchelle et al., 1990). Elevated pH levels may also be found in drinking water wells.

4. As neat cement cures, a micro-annulus or fracture network may develop around the well casing allowing leakage to occur down the casing (MDPH, 1988). This micro-annulus has been well documented in several studies. Cement, even cement with bentonite added to it, had the tendency "to adhere to one surface, but not the other in a borehole" (Smith and Mason, 1985, p. 36). Oliver noted that cement grouts shrink and crack after

having setup, thus "leaving areas where contaminants could migrate into the well" (Oliver, 1995, p. 12). Bertane (1987, p. 3) also noted, "Cement grout shrinks when set, creating a micro-annulus space in the borehole causing inter aquifer transfer."

The documentation of a micro-annulus is most prevalent with the use of PVC well casing and cement. No information could be found indicating if a micro-annulus forms when steel casing is sealed with cement grouts.

Not all factors affecting the formation of a micro-annulus are understood or known. Does this micro-annulus form only near the surface? Or does it extend the full length of the casing? Does hydrostatic pressure affect the adherence of cement? One study reports that the micro-annulus found in wells used in their research extended for a limited distance only (Edil et al., 1992). Oliver (1991) also reported the same results from a study he observed. Can PVC well casing be made less smooth, so that cement will adhere to it better?

Other questions also exist. How often does this micro-annulus form? Does it only form in the vadose zone? Or does it also form in saturated conditions? How does the addition of bentonite to cement affect the formation of a micro-annulus?

Understanding more about the conditions under which a micro-annulus forms would greatly improve the proper use of cement grouts in the water well industry.

Bentonite-Cement Grouts

The addition of bentonite to neat cement is alleged to augment the set volume of cement, reduce or eliminate shrinkage, inhibit water loss, and reduce the density of the cement (Smith, 1976). With all of these improvements it would seem as though bentonite-cement grouts would be the best grout ever invented. "The truth of the matter is that a cement bentonite grout is still a cement grout. Adding small amounts of bentonite to cement grout does not greatly change its properties" (McLarty, 1993, p. 29).

In fact, the field study conducted at Western Michigan University, as well as other studies, have shown that the addition of bentonite to a neat cement grout actually increases the potential for fracturing to occur. Riewe (1996) reported that bentonite-cement grouts were found more likely to fracture than cement grout. One likely reason for this phenomenon is the incompatibility of cement and bentonite.

> The introduction of cement to a bentonite can seriously effect [sic] bentonites ability to hydrate. Cement releases Ca++ and OH- ions this flocculates the bentonite clay. The clay platelets structure is destroyed and the clay looses its ability to hold water, the clay shrinks and does not provide a good seal (Bertane, 1987, p. 4).

Another theory suggests that alkalis from bentonite are released when the clay and cement are mixed, causing the pH to rise even higher than in straight cement. This rise in pH affects the alignment of the clay platelets, causing the clay particles to flocculate. A high pH also raises the solubility of the silica contained in the cement. This dissolves the quartz, an integral part of cement, causing a silica gel to form, making the cement weak. The overall effect of the above mentioned reactions are a definite concern but they are not fully understood, and it is hard to determine the exact effect that they produce in grout. Under these circumstances the addition of bentonite to cement is not advisable.

This also brings to mind questions concerning the logic of placing a cement cap on a well sealed with bentonite grout. Will a cement cap in contact with bentonite slowly change the properties of the bentonite? How will the contact between the cement and bentonite affect the long-term integrity of the bentonite seal? In a study reported by Oliver (1991), a bentonite tablet seal appeared to be damaged by leachate from cement placed above it.

> The tablets did not hydrate as much as in the other model [where only bentonite was used] and they changed color near the top. The tablets under the bentonite grout could absorb water that was in the sand below, but the tablets under the cement could not (Oliver, 1991, p. 41).

Discussion

While there is quite a bit of literature regarding water well grouting issues, there are still many unanswered questions concerning grout integrity.

Bentonite, in any of its many forms, has the potential to provide one of the best seals available at this time. Nonetheless, problems do exist that warrant further studies. Bentonite slurry grouts have been known to settle excessively. Bentonite chips and tablets when installed from the surface tend to bridge. Granular bentonite in cable tool wells may or may not be achieving a proper seal. All of the problems listed here and the questions mentioned earlier seem to argue that a lot of research remains to be conducted on the use of bentonite as a grout.

Drill cuttings and drilling mud are not, for the most part, considered to be good sealing mediums for water wells.

Cement and bentonite-cement grouts have well documented problems. Cement grouts have a tendency to form a micro-annulus around the well casing. Bentonite-cement grouts have the surprising and most disturbing propensity for developing fractures. Given the successful use of cement grouts in the oil and gas industry, more efforts should be directed to the transfer of this technology to help increase successful use of these grouts in the water well industry.

The limitations of each grouting medium must be resolved. Further research should be conducted on each grout type, and additional product development should be promoted.

FIELD STUDY

Introduction

In an attempt to answer some of the questions about grouts and to provide a baseline study for future reference, a field study was conducted on Western Michigan University campus. This study compares several different grouting materials commonly used in the water well industry and focuses on a number of properties that may affect the integrity of a water well seal.

Site Description

Location

This study was conducted on wells installed on the Western Michigan University campus, Kalamazoo, Michigan (see Figure 4). Seven wells were placed in a mini-well field (see Figure 5) in an area that was later excavated for the future basement of the new science pavilion. Four of the wells were installed as test wells, to be used by the Geology Department of Western Michigan University after the completion of the science pavilion. The three remaining wells were installed solely for the purpose of this study and have since been removed.

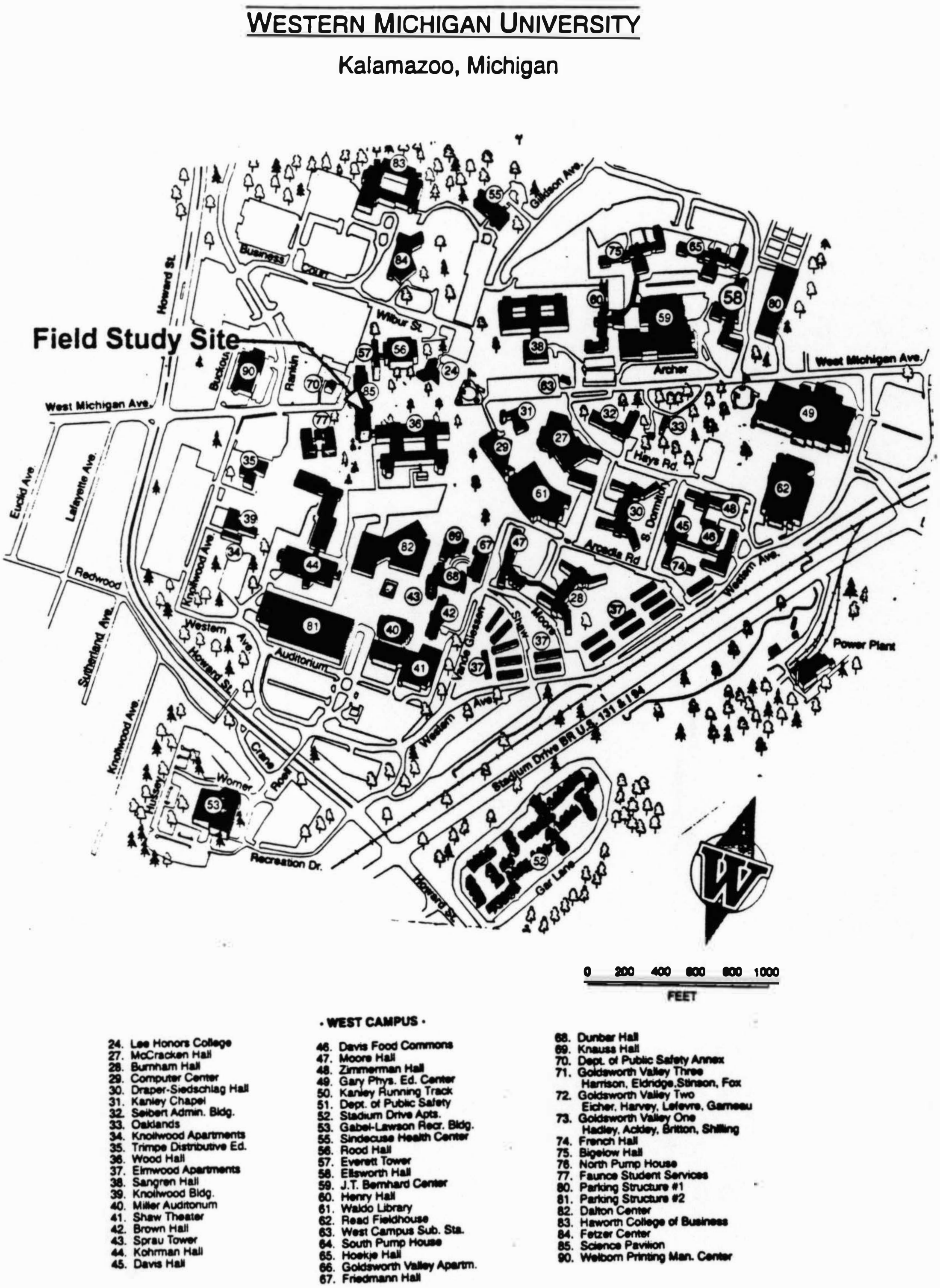


Figure 4. Site Map (adapted from Stolle, 1997).

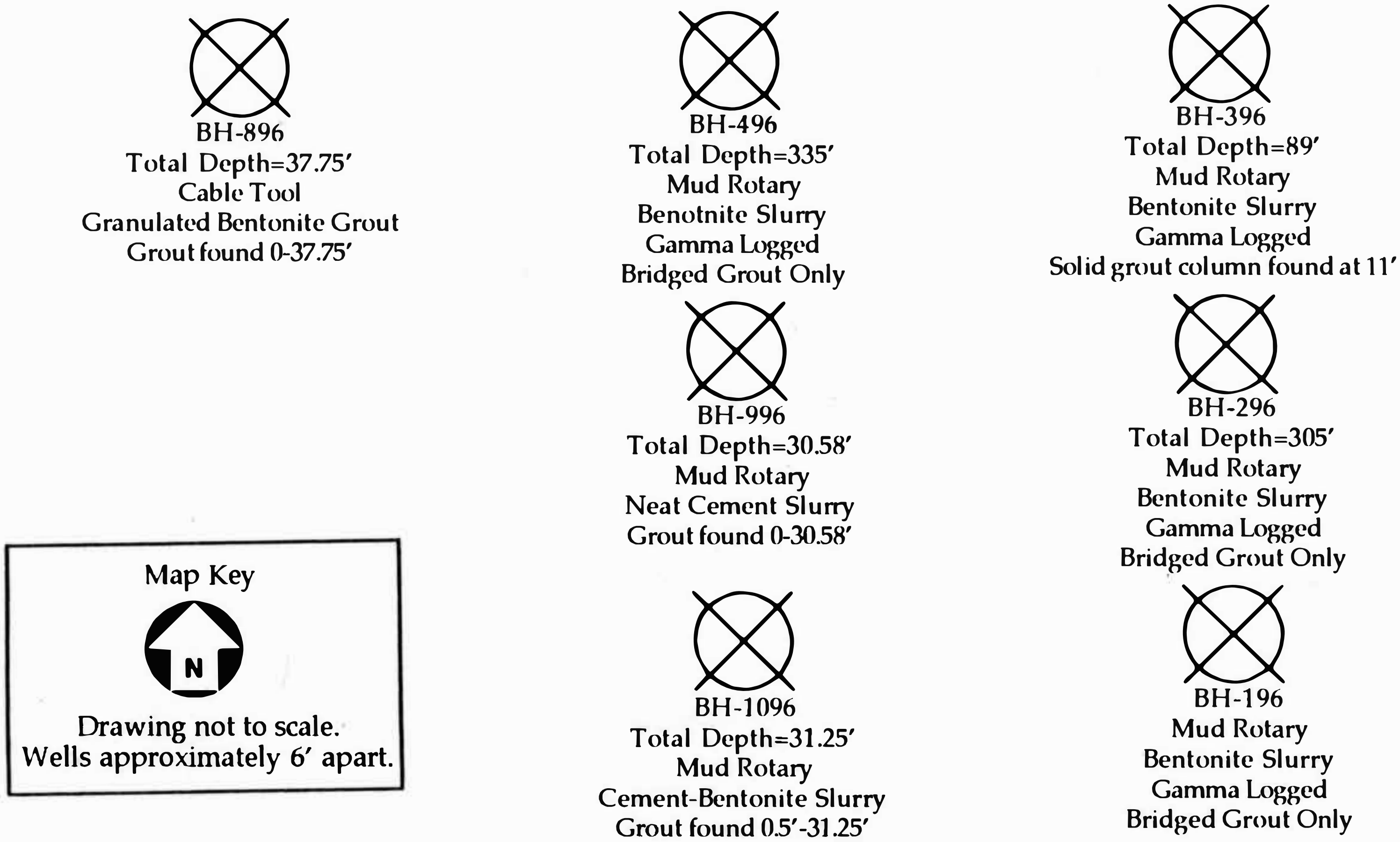


Figure 5. Well Field Diagram

Geology

The geology of this site is typical of glacial outwash deposits. Kirby (1996) logged alternating layers of sands and gravels during drilling (see Appendix A). The sands were well sorted/poorly graded, medium grained, tan, with few fines, and some small to large gravel. A gravel layer was located at approximately 8 feet below grade and was approximately 6 to 10 inches thick. The gravel was medium to large and mixed with some clay. More sand and gravel layers are present below the excavation depth, as indicated by the well logs.

The water table at this site is at approximately 80 feet. The wells were excavated to a depth of about 13 feet. Hence, this study focuses on vadose zone grouting.

Methods

Well and Grout Installation

Professional water well drillers, licensed by the State of Michigan, installed all seven wells used in this study. The drilling companies who participated in this study were: Raymer Drilling Company of Marne, Michigan; Dewind Drilling Company of Zeeland, Michigan; Stearns Drilling of Dutton, Michigan; Katz Drilling of Battle Creek, Michigan; and

Ray Leonard Cable Tool Water Well Drilling, also of Battle Creek, Michigan. Grouting materials were provided by: LaFarge, Baroid, Cetco, and Volclay. Well casing was provided by Milan Supply.

Out of the seven wells, one was installed by the cable tool drilling method. The remaining six wells were installed by the mud rotary drilling method. All seven wells were installed following State of Michigan regulations. Grout installations followed State of Michigan regulations, as well as manufacturer's recommendations.

Cable Tool Method

The cable tool well was installed by lifting and dropping a heavy drill stem and drill bit into the borehole. The drill bit loosens unconsolidated formations, and breaks up consolidated formations. Steel casing was driven into the borehole and closely followed the drill bit to prevent caving and keep the borehole open. Normally the slurry formed by drill cuttings and groundwater is periodically bailed out of the borehole. In cases, such as ours, where no water is present in the borehole, water is added to form a slurry.

The casing used was black steel. The joints of the casing were welded together. PVC casing cannot be used because it cannot withstand being driven down the borehole.

To seal cable tool wells, granular bentonite is "gravity fed" from the top of the borehole as the casing is being driven. The well casing was raised and lowered several times throughout the drilling process to ensure a good seal was achieved. No grout was found inside of the well casing during the bailing of slurry until after the casing had been raised and lowered several times at its final depth. Grout in the bottom of the well indicated that grout reached the total well depth. To read about the problems with these grouting methods please refer to the Granular Bentonite section in the Literature Review.

Mud Rotary Method

The mud rotary drilling, used to install the remaining wells, was different from cable tool in that it used drilling muds to hold the borehole open and to remove drill cuttings during the drilling process. The drill bit is located at the end of a drill string, which is rotated to loosen unconsolidated formations or break up consolidated formations (The Roscoe Moss Company, 1990).

After the borehole reached its final depth, the well string was put in place. The borehole was then flushed with fresh water to thin drilling fluids.

Two different types of tremie pipes were used to place the filter packs and grouts in the boreholes. The traditional tremie pipe is a hollow steel pipe. The other option used was disposable black tubing.

The traditional tremie pipe was placed at the bottom of the borehole between the well casing and borehole wall. The filter pack was then placed into the borehole through the tremie pipe. The tremie pipe was raised as the filter pack was installed. After the filter pack was in place, the tremie pipe was pulled back above the filter pack and grouting was begun. Grout was pumped through the tremie pipe from the top of the filter pack to the surface. When the grout reached the surface it was weighed to ensure that it has the proper weight. This grout weight may not have been the same as what was sent down the tremie pipe because the grout may have mixed with water found in the borehole. If this was the case, fresh grout was pumped down through the tremie pipe until the grout at the surface was the proper weight. After grouting was completed, the traditional tremie pipe was removed.

The disposable tremie tube was used in the cement wells. This tube was cut off at the surface and left in place. Leaving the tremie tube in place is not a recommended practice.

The grout was then allowed to set. If excessive settling occurs, it may be necessary to add more grout at a later date. However, this was not done in our study so that accurate information could be collected concerning settling data.

In the cement grouted wells formation packers were placed at the bottom of the well casing to reduce the chance of grout undercutting the formation. A formation packer is a rubber seal placed around the outside of the well casing. It is illegal in Michigan to use a formation packer to separate grout from an open borehole (MDPH, 1994).

Gamma Ray Logging

Gamma ray logs are used to measure relative radioactivity within a borehole. Lithology identification is the main use of gamma ray logging (Dresser Atlas, 1982). In trying to locate the settling depth of the bentonite slurry grouted wells, gamma ray logs were made of the following wells; BH-196, BH-296, BH-396, and BH-496. These wells were logged using a truck-mounted Keck SR 3000. All wells were logged when the probe was both descending and ascending the well.

Excavation

On January 10, 1997, approximately six months after the bentonite slurry grouted wells were installed, and approximately three months after the cement grouted wells and the cable tool well were installed; all seven wells were excavated. A large backhoe was used for the mass removal of soils, and detail digging was done by hand. The wells were excavated to a total depth of approximately 13.3 feet below the original grade. Photographs and detailed field notes were taken throughout the excavation (Callaway, 1997).

On the day of the excavation temperatures were below freezing, with wind chill factors below zero. It is not known if these extreme temperatures affected bentonite settling data, or any other grout characteristics.

Well Probing

After the excavation of the wells was completed, the new science pavilion foundation was poured. In order to protect the wells from heavy operating equipment and cement, an 8-inch steel pipe was driven down around each of the four remaining wells.

In another attempt to determine the location of the settled bentonite grouts, the annular space between the protective casing and the well casing was probed for each well with a soil probe. Unfortunately this did not work very well. It appears that as the protective casing was driven into place, the shallow grout was disturbed and mixed with the surrounding sediments. Furthermore, the probe could not penetrate beyond the depth of the protective casing, possibly because a consolidation of sediments ("hard pan") developed toward the bottom of the protective casing as it was being driven into place.

In only two of the wells was grout reached by the soil probe. In BH-196, a mixture of grout and sediment was reached at approximately 16.75 feet below the original grade. It is unclear if this is a true indicator of the final grout settling depth. During excavation, the grout in BH-396 was found at 11 below grade. When the soil probe was used, the mixed grout and sediment were not found until approximately 17.6 feet below the original grade, suggesting that the protective casing displaced the grout.

Well Completion Data

All measurements were made from the original grade, prior to excavation. Information on each well is summarized in Table 2.

BH-196 (see Appendix A) was installed by the mud rotary method, to a total depth of 135 feet. This well was screened from 130 feet to 135 feet. The filter pack was placed from 125 feet to 135 feet. Wyo-Ben Groutwell DF bentonite was used to seal this well. Eight 50-pound sacks of bentonite were used to grout from 125 feet to the surface. Neither grout weight, nor percent solids are known for this well.

BH-296 (see Appendix A) was also installed using the mud rotary method. This well was set at 305 feet below grade. It is screened from 263 feet to 305 feet, using six-foot sections of slotted pipe separated by three-foot

Table 2

Well Completion Data

Well Identification	Drilling Method	Total Well Depth	Grouted Interval	Grout Type	Grout Brand
BH-196	Mud Rotary	135'	1-125'	Bentonite Slurry	Wyo-Ben Groutwell DF
BH-296	Mud Rotary	305'	0-260'	Bentonite Slurry	Volclay
BH-396	Mud Rotary	89'	0-83'	Bentonite Slurry	Baroid Benseal w/ Baroid EZ Mud polymer
BH-496	Mud Rotary	335'	0-315'	Bentonite Slurry	Baroid Benseal w/ catalyst
BH-896	Cable Tool	37.75'	0-37.75'	Granulated Bentonite	Cetco C/S and Volclay Anti-Skid
BH-996	Mud Rotary	30.58'	0-30.58'	Neat Cement Slurry	LaFarge Type 1 Portland Cement
BH-1096	Mud Rotary	31.25'	0-31.25'	Bentonite-Cement Slurry	LaFarge and St. Mary's Type 1 Portland Cement w/ 5% Wyoming Bentonite

sections of blank riser. The filter pack was natural collapse of the surrounding formation. This well was sealed from 260 feet to the surface using Volclay Grout II. Twenty-eight 50-pound sacks were used. Grout weight was measured to be 9.6 pounds per gallon (18 gallons of water per 50-pound sack). As listed on the well log this grout contained approximately 25% solids. Calculations confirmed this percent solids (see Appendix B).

BH-396 (see Appendix A) was installed by the mud rotary method to a total depth of 89 feet. Well screen and filter pack were placed from 83 feet to 89 feet. Four 50-pound sacks of Baroid Benseal were mixed with one gallon of Baroid EZ Mud polymer to seal this well. Thirty gallons of water was used with each 50-pounds of grout mixture. This grout contained a calculated 17% solids (see Appendix B).

BH-496 (see Appendix A) was drilled using the mud rotary method. This well reached a total depth of 335 feet. From 315 to 335 feet, the borehole was left open. A 5-inch by 9-inch formation packer was placed at 315 feet. From 315 feet to the surface, the well was sealed using eleven 50-pound sacks of Baroid Benseal mixed with seven pounds of catalyst (this was used to help the grout set faster). Thirty gallons of water were used for each sack of bentonite. This grout was calculated to have 17% solids (see Appendix B).

BH-896 (see Appendix A) was installed by the cable tool method. Total depth of this well was 37.75 feet. Five and one half 50-pound sacks of granular bentonite (Cetco C/S and Volclay Anti-Skid) were used to seal this well from 37.75 feet to the surface. This dry grout was gravity fed from the surface.

BH-996 (see Appendix A) was installed using the mud rotary method. Total depth of this well was 30.58 feet. This well was sealed from 30.58 feet to the surface using six 94-pound sacks of LaFarge Type I Portland cement and a disposable tremie tube. This tremie tube was left in place after grouting was completed. The grout mixture was 5.6 gallons of water per sack of cement, giving a water to cement (w/c) ratio of 0.5. Grout weight was 15.3 pounds per gallon.

BH-1096 (see Appendix A) was installed using the mud rotary method. Total depth of this well was 31.25 feet. It was sealed from 31.25 feet to the surface with five 94-pound sacks of LaFarge Type I and St. Mary's Type I Portland cement mixed with one half bag of Wyoming (PDS Company) bentonite. A disposable tremie tube was used to install the grout, and was left in place after grouting was completed. This grout contained approximately 5 percent bentonite. For each sack of cement used, 5.6 gallons of water was added, resulting in a w/c of 0.5. Grout weight was 15.3 pounds per gallon.

Observations

As the wells were excavated, the grouts were evaluated for the following properties: depth of settling, grout consistency, fracturing, thickness of grout surrounding the casing, intrusion into the surrounding formation, adherence to the well casing, adherence to the surrounding formation, and bridging. Filter cake was also noted, if present. Table 3 summarizes the observations on the excavated grouts.

Grout Descriptions

BH-196: (See Appendix C) No grout, other than bridged grout, was found in this well. Filter cake was noted in the grout-free annular space of this well. This filter cake varied in thickness from 0.125 inch to 0.5 inch. Some lineations were noted in the filter cake. The filter cake was still moist; therefore, these cracks did not seem to occur due to the drying out of the filter cake. It is not known what caused these lineations. Settling rates for this well are as follows: 1.83 feet after 1 hour, 10.83 feet after 10 hours, and 10.83 feet at 15 hours. During excavation, no grout was found at 10.83 feet, indicating that the grout had continued to settle after 15 hours (see Appendix D). Total depth of settling could not be determined during excavation.

BH-296: (See Appendix C) No grout, other than bridged grout, was found in this well during excavation. Filter cake was found in the grout-

Table 3

Grout Comparison Table

Wells	BH-196	BH-296	BH-396	BH-496	BH-896	BH-996	BH-1096
Grout Brand	Wyo-Ben Groutwell DF Bentonite	Volclay Grout II Bentonite	Baroid Benseal Bentonite w/ Baroid EZ Mud Polymer	Baroid Beseal Bentonite w/ catalyst	Cetco C/S Granular & Volclay Antiskid Granular Bentonite	LaFarge Type I Neat Portland Cement	LaFarge & St. Mary's Type I Neat Portland Cementw/ PDS Co. Wyoming Bentonite
Adherence to the Casing	yes	yes	yes	yes	yes	no	no
Adherence to the Formation	yes	yes	yes	yes	yes	yes	yes
Bridging	yes	yes	yes	yes	no	no	no

Table 3-continued

Wells	BH-196	BH-296	BH-396	BH-496	BH-896	BH-996	BH-1096
Consistency	stiff petroleum jelly	stiff petroleum jelly	stiff petroleum jelly	stiff petroleum jelly	leather-like	hard and stiff	hard and stiff
Fracturing	unknown	unknwon	no	unknown	no	no	yes
Grouted Interval	1-125'	0-260'	0-83'	0-315'	0-37.75'	0-30.58'	0-31.25
Settling Depth	13.3'+	25.5'+	11.0'	13.5'+	none	none	0.5'
% Settling	10.64%+	9.80%+	13.25%	4.30%+	0%	0%	1.92%

Table 3-continued

Wells	BH-196	BH-296	BH-396	BH-496	BH-896	BH-996	BH-1096
Predicted Depth of Settling (13%)	16.25'	33.80'		40.95'			

(+) Indicates that further settling occurred or is suspected.
Underlined text indicates exact readings or calculations.

free annulus, and did not have any fractures that were evident to the unaided eye. The thickness of the filter cake varied from 0.125 inch to 0.5 inch. The settling data for this well are as follows: 2.25 feet after 25 minutes, 4.42 feet after 2 hours, 21.25 feet after 11.5 feet, and 25.5 feet after 14 hours. It is assumed that settling continued after the last reading, as it did in BH-196 and BH-396 (see Appendix D).

BH-396: (See Appendix C) Grout was found in this well at a depth of 11 feet. Bridged grout was found above 11 feet. A filter cake was found throughout the exposed length of this well. The filter cake had no evident fractures, and varied in thickness from less than 0.125 inch to 0.75 inch. The grout, found at 11 feet, had the consistency of stiff petroleum jelly, and appeared to be fully hydrated. It did not penetrate or intrude into the surrounding formation. It did adhere to the well casing and the filter cake. Thickness of the grout was evenly distributed between the well casing and annular wall. No fractures or gaps were found in the grout. Settling data for this well are as follows: 7.7 feet at 14.5 feet, and 11 feet at excavation. Once again the settling had continued after the last reading at 14.5 hours (see Appendix D).

BH-496: (See Appendix C) No grout, other than bridged grout, was found in this well. Filter cake was noted in the grout-free annular space. This filter cake had no apparent fractures in it, and varied in thickness from 0.125 inch to 0.75 inch. Settling data are as follows: 1 foot after 2.5

hours, 2.58 feet after 3.5 hours, 6.67 feet after 12.5 hours, and 13.5 feet after 15.25 hours. Grout had continued to settle past the 13.5 feet as was discovered during excavation, when no grout was reached (see Appendix D).

BH-896: (See Appendix C) Grout was found in this cable tool well from the surface. No settling of grout occurred in BH-896. No filter cake was found in this well. Grout thickness varied from less than 0.125 inch to 0.75 inch. Thickness did not appear to decrease with depth. In two areas the grout appeared to have mixed with the surrounding formation. These areas measured approximately 4 inches by 4 inches. The grout had not swelled, but the individual grains of bentonite were adhering to each other. The grout adhered to the well casing and the surrounding formation. No fractures or gaps were found in this grout. The grout did not intrude into the surrounding formation.

BH-996: (See Appendix C) No settling of grout occurred in this well. Grout was found at the surface. No grout had penetrated or intruded into the surrounding lithology. No fractures were evident in this grout. This grout adhered to the surrounding formation. It did not adhere to the well casing, as was evidenced during excavation, when the well casing was pulled out of the grout with little or no effort. Also, the grout did not adhere to the tremie tube that had been left in place during well installation. However, the grout inside of the tremie tube did seem to be adhering to the tube, it did not fall out of the tube when manipulated. Grout thickness varied from less than 0.125 inch to 6 inches. No filter cake was found in this well.

BH-1096: (See Appendix C) The grout in this well was found near the surface. Only six inches of settling occurred. The grout did not adhere to the well casing or the tremie tube that had been left in place; it did, however, adhere to the surrounding formation. A large fracture was found in this grout at almost 10 feet from the surface. This fracture surrounded the entire well casing. Excavation activities did not cause this fracture to occur. This is known because mud was found between the plates of the fracture. No mud was found in the surrounding formation or along the well casing, indicating that the mud was present prior to the excavation. This mud most likely came from the mid-winter thaw that occurred one week prior to excavation. No other fracturing was found. The grout did not intrude or penetrate into the surrounding formation. Grout thickness varied from less than 0.125 inch to 6 inches. No filter cake was found in this well.

Gamma Log Interpretations

Unfortunately, gamma ray logging did not help to locate the depth of settling in the bentonite slurry grouted wells of this study (see Appendix E for well logs). The influence of a small layer of bentonite located so near the well casing was not enough to make a difference within the total range of influence detected by the logging probe. In most logging instruments the "effective depth of investigation" is calculated and set to minimize the disturbance surrounding the borehole (Telford et al., 1976, p. 773). Therefore the influence of grout is minimal. For proper evaluation of grout placement, gamma ray logs should have been made prior to grout installation to be used for comparison to the logs run after grout installation (Ground-Water Survey TNO, 1976). Various factors affecting drift, such as instrument warm up time, and significant temperature differences between the surface and borehole, could have skewed the gamma ray data. Inexperienced users of the logging equipment could also play a part in the apparent lack of information gained from the upper 14 feet of these particular logs. Deeper portions of the logs do show consistent intensity changes due to lithologic changes.

Other methods may have worked better in this situation. Ultrasonic probes have been successfully used in the oil and gas industry to log cement seals. The University of Wisconsin has been researching the use of a slim-hole version of this probe for water wells and observation wells with success. The ultrasonic probe can be used in steel or PVC casings to detect the integrity of cement and bentonite grout seals (Edil et al., 1995). However, ultrasonic probes detect the presence of a micro-annulus, not the presence of grout.

Temperature logging can be used to detect heat of hydration in cement grouted wells. Temperature logging can be quite accurate when used within 48 hours of installing cement grout (Kwader, 1986).

Clear casing in combination with a downhole camera would have been extremely useful. Locating and obtaining clear casing at an affordable price is difficult and prevented it from being incorporated into this study.

Although gamma ray logging was of no use in this study, it has the potential to provide the most useful approach for grout detection. If it could be determined which brands of grout emit radioactive particles, and if the type of particles being emitted could be isolated, gamma ray logging could be very useful in detecting the placement of grout. Another possible solution to this dilemma is to obtain permission from the proper authorities to legally spike grout with a natural, innocuous, known radioactive substance, such as some shale formations. Doing this would provide an economical and effective means of tracing grout.

Comparisons

All of the following properties were observed as the wells were being excavated. The observations made for each well is described in detail in the Observations section. This section makes general comparisons between the different grout types.

Adherence

An important characteristic of a grout is the ability to adhere to the well casing and to the formation. If adherence does not occur, the void between the grout and well casing, or between the grout and formation, could become an avenue for contamination migration. Concerns for both cement and bentonite grouts exist. "Cement grouts can shrink during the curing processes and separate from the well casing or at the borehole-formation interface" (Dunnivant, 1997, p. 140). In using bentonite grouts, "...the smooth surface of thermoplastic casing (PVC) provides a potential path for vertical leakage between the casing and the grout material" (Dunnivant, 1997, p. 141).

All of the bentonite slurry grouts used in this study adhered to both the PVC well casing and the surrounding formation. In wells where grout was not found above the excavation depth, the bridged grout was evaluated for this property. The dry granulated bentonite used to grout the cable tool well (BH-396) adhered to the well casing and surrounding formation surprisingly well considering the fact that the only water it came in contact with was that water found in the vadose zone. BH-396 was the only other well in which a solid column of bentonite grout was found. This grout had Baroid EZ Mud polymer mixed into it. The grout of this well adhered very well to the PVC well casing. It also adhered to the filter cake lining of the borehole wall. In all of the bentonite slurry grouted wells the bridged bentonite grout adhered to the well casing and surrounding formation.

Neither the neat cement grout nor the bentonite-cement grout adhered to the PVC well casing. Several sections of intact grout and casing were cut. The PVC casing from these sections was pulled out of the grout with little to no resistance. These grouts did not adhere to the tremie tube either, thus providing two possible avenues for contamination migration. Both the cement and bentonite-cement grouts adhered to the formation.

In defense of cement grouts it must be remembered that they have been used in the oil and gas industry successfully since the early 1900's.

Bridging

Bridging of grout is an obstruction that occurs between the well casing and the borehole wall (refer to Fig. 1). This obstruction may or may not surround the entire casing. Bridging can possibly prevent the downward movement of additional grout.

Bridging can sometimes cause problems when grouting. If a well is grouted from the surface bridging can block grout from sealing a well properly. Tremming the grout from the bottom of the well to the surface corrects this problem. It would be thought that no bridging would occur if this method were used; however, this study shows otherwise. Bridging was found in all of the bentonite slurry grouted mud rotary wells. This bridging had to occur as the settling of the grouts took place. It did not surround the entire well casing and did not block the downward movement of settling grout. It is not known, however, if bridging in the deeper wells might have prevented further settling of the grouts. This type of bridging could cause problems in determining exactly how deep the grout has settled. Problems could also develop if the well must be regrouted. The bridged grout could build up even more and prevent the additional grout from properly sealing the annular space, leaving voids and gaps.

The bridged grouts that were found in the bentonite slurry grouted wells were fully hydrated. They had the same consistency as the grout found in BH-396; i.e., stiff petroleum jelly. The bridged grout did not appear to be any different than the grout found in BH-396. No apparent reason for the occurrence of bridging could be determined. No borehole anomalies were found where bridging occurred. No well casing joints or well casing anomalies were found where bridging was located.

Neither the cement grouts nor the granular bentonite had bridging problems, because they did not settle.

Consistency

Consistency may range from fluid to hard and stiff. This property is used to describe the state of the material.

Consistency is a characteristic that can affect how well a grout will hold up to stresses that may be applied to it over time. Elements of stress may include, but are not limited to; fluctuations in the water table level, flowing water, excavation and earth moving activities, and the natural movement and shifting of surrounding formations.

The two bentonite grout types, observed in this study, had different consistencies. The cable tool well grout was not fully hydrated and individual grains of the granular grout could be seen. The individual grains were adhering to each other. This grout could be manipulated by hand. It was quite elastic and could be bent almost in half before breaking. It had a leather-like feel to it. In the mud rotary well (BH-396), the grout was fully hydrated and had the consistency of stiff petroleum jelly. It was very ductile.

Both of the cement grouts were very hard, non-elastic, and non-ductile. Because of these properties it may be prone to fracturing.

Filter Cake

Filter cake develops during the mud rotary process as a result of the drilling fluids used. Suspended particles from drilling fluids are deposited along the porous borehole wall, building up a low-porosity film (Driscoll, 1986). Filter cake is beneficial to mud rotary drilling in that it helps to hold the borehole open during drilling and grouting.

Filter cake was found in all of the bentonite slurry grouted, mud rotary wells. The thickness of this filter cake varied from less than 0.125 inch to almost 0.75 inch. The filter cake prevented any connection between the grout solids and the surrounding formation, thus preventing any intrusion into the surrounding formation.

No filter cake was found in the cement grouted, mud rotary wells. Several explanations exist that could explain why no filter cake was found in connection with these wells. The first explanation may be that these wells were flushed more thoroughly than the deeper, bentonite slurry grouted wells. Another explanation could be that since the cement grout is so much heavier than bentonite grouts it could have possibly eroded away the filter cake as it was being installed. One other explanation could be the chemical reaction that occurs between bentonite and cement.

The cable tool well also lacked a filter cake lining of the borehole wall. This is not surprising, since no drilling fluids were used to install this well. A possible smearing of granular bentonite along the borehole wall could be expected; however, none was detected in the well used for this study.

Fracturing

Fracturing refers to any crack, break, or joint found in a grout (Bates, 1984).

Fracturing can create serious problems in protecting groundwater quality. If fracturing and non-adherence are found together, a direct conduit may be created for possible contamination to enter the well annulus and thereby the aquifer.

In this study, as well as others (Riewe, 1996), it has been found that the bentonite-cement grout is more likely to fracture than the cement grout. One possible explanation for this is the chemical reaction that takes place between cement and bentonite (Bertane, 1987).

Fracturing was found in the bentonite-cement grouted well of this study. No fracturing was found in the bentonite grouted wells, or the neat cement grouted well.

Intrusion

Intrusion refers to grout penetrating into the surrounding formation. This would lessen the amount of grout available to seal the borehole.

Several theories have been suggested to explain the large settling depths of bentonite slurry grouts. One such theory is that the grout was intruding or penetrating into the surrounding formation. No evidence of this was found in this study. However, it does not mean that it did not occur at deeper levels. Another theory is that as the grout sets it loses water to the surrounding formations in the vadose zone. This theory seems more plausible for the settling that occurred in this study. A theory suggested for wells placed in bedrock is that the grout is penetrating into formation fractures. This theory seems highly likely in those situations.

In this field study, the bentonite slurry grouts would have had to penetrate the filter cake lining of the borehole wall before coming in contact with the surrounding formation. This was not seen in the excavated length of the wells used in this study.

In the cement grouted wells very little settling occurred, indicating that no grout was lost by intrusion or penetration into the surrounding formation; nor was any intrusion seen when these wells were excavated.

Settling

Settling refers to the "rate at which suspended solids subside and are deposited." (Bates, 1984, p. 460). This specifically applies to bentonite slurry grouts.

Settling of grouts is a serious problem. Settling may occur in any slurry grouted well. If excessive settling occurs, the integrity of the well seal is affected. Excessive settling requires a driller to return to the site to add more grout in order to seal the well properly. This is costly and labor intensive. Please refer to Appendix E for a graphical representation of the following settling data.

Cement Grouts

The cement grouts tested in this study settled very little. The neat cement grout did not settle at all. The bentonite-cement grout settled only 6 inches. This yields a 1.9% settling for the entire grouting length of this well.

Bentonite Grouts

The granular bentonite used to seal the cable tool well did not settle at all. The bentonite slurry wells all had excessive settling. The average settling percentage for the bentonite slurry grouts was approximately 13%. BH-396 was the only well in which bentonite slurry grout was reached during excavation. It occurred at 11 feet below grade, which is 13.25% of the total grouting length of the well.

In trying to determine the settling depths of the remaining three, bentonite slurry grouted wells, they were gamma ray logged and probed. The probing did not produce any conclusive results. The gamma ray logs were also found to be inconclusive.

The reasons behind such a large settling rate in slurry grouts are not fully understood. The intrusion/penetration theory did not prove to be true in this study. Another theory suggests that because grout can only be made to contain up to a certain solids percentage due to pumping and mixing restrictions, the fully hydrated bentonite solids settle out and leave the remaining water to be absorbed into the surrounding lithology. This theory seems plausible for the wells of this study. Grout additives may also play a role in how much a grout settles.

Thickness

Varying thickness of the grouts surrounding the well casing were found in all of the wells, except for BH-396. The grout in BH-396 appeared to be evenly distributed through out the annular space. Grout thickness varied from less than 0.125 inch thick to almost 6 inches thick in the mud rotary, cement grouted wells, and less than 0.125 inch thick to 0.75 inch thick in the cable tool well. Although thickness varied, the void between the well casing and surrounding formation was filled with grout. This fulfills State of Michigan regulations; however, questions are raised as to whether less than 0.125 inch of grout is sufficient to protect ground water quality.

If stabilizers or centralizers are used to place the well casing in the center of the borehole annulus the grout would be more evenly distributed. However, these tools make tremming grout with the traditional steel pipe, from the bottom of the grouting depth to the surface, very difficult. Drillers do not like to use stabilizers because of the problems they can cause during grout installation. However, if a disposable tremie tube is used along with stabilizers or centralizers the problem is solved, since the tubing is taped to the bottom of the grouting length of the well casing.

Discussion

Many factors can affect the integrity of a water well seal. In this field study several properties of different grouts were compared to each other. Table 4 summarizes the data for this study.

The lack of adherence to either the borehole wall or the well casing may provide a void, which could become an avenue for contamination migration. In this field study all of the bentonite grouts adhered to the well casing and the surrounding formations. The cement grouts adhered to the surrounding formations, but did not adhere to the well casing.

The occurrence of bridging is not considered to be a serious problem if a well is grouted from the bottom of the well to the surface. However, in cases where bridging occurs when a grout settles from the surface, false readings could occur in the inspection of a well, and it could cause problems should the well need to be regrouted. Bridging of this type occurred in all of the bentonite slurry grouted wells used in this study.

Consistency may affect how well a grout holds up to the various stresses that may be applied to it. The granular bentonite grout was observed to be quite elastic. The bentonite slurry grouts were observed to be very ductile. Both cement grouts were seen to be hard and stiff.

Table 4

A Comparison of Water Well Grouting Materials

	Bentonite Slurry Grouts	Dry Granular Bentonite	Neat Portland Cement	Bentonite-Neat Cement Mixture
Adherence to PVC Well Casing	yes	yes (Steel Casing)	**no***	**no**
Adherence to Surrounding Formation	yes	yes	yes	yes
Bridging Occurred During Settling	**yes**	no	no	no
Consistency	petroleum jelly	leather-like	hard and stiff	hard and stiff
Fracturing	no	no	no	**yes**
Intrusion into Surrounding Formation	no	no	no	no
Percent Settling	**~13%**	0%	0%	~2%

Table 4-continued

	Bentonite Slurry Grouts	Dry Granular Bentonite	Neat Portland Cement	Bentonite-Neat Cement Mixture
Thickness Surrounding Well Casing	~2"	**<1/8"-3/4"**	**<1/8"-6"**	**<1/8"-6"**
Presence of a Filter Cake	yes	no	no	no
Cost	moderate	low	high	high

*** Bold type indicates an area of special concern.**

Filter cake is an interesting sideline to this study. Filter cake was found in the bentonite slurry wells, but not in the granular bentonite well, nor in the cement wells. The presence of filter cake may provide an added measure of contamination protection, especially in those wells in which settling may be a problem. Although the filter cake cannot prevent contaminants from entering an open borehole from the surface, the low permeability of the filter cake may help to slow or stop horizontal migration of contaminants within the vadose zone or groundwater from entering the borehole. The filter cake may be able to provide just enough protection from contaminants until the well can be regrouted. Filter cake however, should not be thought of as a grout replacement. It is not known if filter cake can provide any protection whatsoever from contaminants. If excessive settling does occur, more grout should be added as soon as possible. Future studies should include the ability of filter cake to withstand contaminants.

Another possible function of filter cake is to prevent the intrusion of bentonite slurry grouts into surrounding formations. It would be interesting to compare wells with filter cake versus wells without filter cake in combination with settling problems and the role that intrusion may play in the settling of grouts.

Fracturing of a grout can seriously jeopardize the integrity of the seal of a water well. Fracturing was found in only one well, the bentonite-cement grouted well. This correlates with other studies.

Intrusion of grout into the surrounding formation did not occur at shallow levels in the wells used in this study. All of these wells were placed in medium sands, and a filter cake was present in the bentonite slurry grouted wells. Perhaps in a gravel aquifer, or in a well in which no filter cake is present, intrusion could occur.

From data collected in this field study, settling of approximately 13% can be expected in wells sealed with bentonite slurries. The cement grouts settled very little to none. The granular bentonite used to seal the cable tool well did not settle.

Efforts to determine the total depth of settling for the bentonite slurry grouts were unsuccessful. The soil probe could not penetrate the hard pan created by the driving of protective casings down around the wells. The gamma ray logs did not provide any conclusive results for this study. A number of factors could have played a part in the apparent lack of information gained from gamma ray logging the wells in this study.

All of the grouts varied in the thickness surrounding the well casing, except for the bentonite slurry grout found in BH-396. In the cement wells, thickness varied from less than 0.125 inch to almost 6 inches. In the cable tool well grout thickness varied from less than 0.125 inch to

0.75 inch. Varying thickness of a grout surrounding a well may or may not affect the integrity of a well seal.

This field study cannot begin to cover all questions concerning grouts, and should be used as a precursor to further studies. Tremendous amounts of testing and product development remain to be conducted.

CONCLUSIONS

Stricter well installation codes have been developed because of concerns about our groundwater resources. Improperly installed or grouted water wells can be potentially dangerous to groundwater quality. They can become direct pathways for the downward migration of contaminants to groundwater.

This study has focused on water well grouting issues. It summarizes previously published studies, and gives data concerning several properties of grout evaluated in a field study conducted on Western Michigan University Campus.

Various forms of bentonite, drill cuttings, drilling mud, neat cement, and bentonite-cement and have all been used to seal water wells with varying degrees of success. Each grouting medium has limitations; however, each has its purpose and place in the water well industry.

Bentonite comes in many forms; powdered, granulated, chips or tablets, etc. In the water well industry it is used for drilling mud and grouting purposes. In use as a grout, bentonite has the capability of providing the best water well seal available at this time. Its swelling properties, its low permeability, its ability to adhere to well casings and surrounding formations, and its ability to rehydrate, all add to the integrity of a water well seal made by a bentonite grout.

With all of the good qualities come limitations and many unanswered questions about bentonite. Bentonite slurry grouts tend to settle excessively and there are many questions concerning its ability to withstand the forces of moving water, and its ability to maintain its integrity over a long period of time.

Granulated bentonite when used to seal a cable tool well appears to provide a very good seal, but it is uncertain how deep that seal actually extends. Calculations have been developed to help answer this question; however, these calculations are not physical evidence. Another area of concern surrounding grouting cable tool wells is the mixing of the surrounding formation with the granulated bentonite. This is not considered to be a serious problem because the areas of mixing found during the excavation were small, and it is thought that when the bentonite is hydrated and swells the mixture of bentonite and the surrounding formation will provide an adequate seal.

No standard method of application has been developed to effectively apply chips or tablets as a grout, and they have been banned from use in Michigan as a result. This form of bentonite has the capability of providing the highest solids content, thus the best seal, however it tends to bridge, leaving voids and gaps.

The use of drill cuttings and/or drilling muds have been shown, for the most part, to be unreliable grouting agents. Drill cuttings when shoveled into the annular space between the well casing and the borehole wall have the tendency to bridge, and may not satisfy the permeability requirement of a grout. Drilling muds usually only contain 3 to 9% solids, meaning that over 90% is water. Because of the low solids content, drilling muds settle excessively, tend to crack, and allow tracer dyes to pass through them.

Cement grouts have been available for quite some time and have been successfully utilized in the oil and gas industry. There seems to be a lack of transfer in technology between the oil and gas industry and the water well industry. Perhaps this is because of problems encountered when using cement grouts for grouting water wells. Cement grouts have been shown to raise the pH of nearby groundwater, form a micro-annulus around PVC well casings, and may require additional equipment for mixing and installation.

The addition of bentonite to cement was thought to solve the micro-annulus problem and any settling concerns. It has been shown in this study as well as others that the addition of 5% bentonite increases the likelihood of fracturing to occur. This is most likely due to the chemical reaction that takes place between cement and bentonite.

The field study conducted on Western Michigan University campus focused on several properties of commonly used grouting mediums thought to affect a water well's seal integrity. These properties were adherence, bridging, consistency, filter cake, fracturing, intrusion, settling, and thickness. Table 4 summarizes the data collected for the various grout types.

Each grouting medium, mentioned in this study, was found to be lacking in some aspect of providing an adequate well seal. The lack of adherence in the cement wells is a major concern. Fracturing, found in the bentonite-cement grout, seriously jeopardizes the integrity of a well. Settling of bentonite slurry grouts leaves an open borehole for the possible migration of contaminants to occur. The best performing grout evaluated in the field study was the granular bentonite used to seal the cable tool well. However, this well was installed by an atypical driller, who developed the grouting method used to install the well for this study. Therefore, the results seen in this study may be skewed. Questions still exist about the ability to provide a seal along the entire length of a cable tool well.

Recommendations

Groundwater resources will continue to be compromised if research efforts are not promoted and supported. A very important aspect of this study is to provide direction for future studies. Suggestions for future studies are as follows:

1. Each grout property discussed earlier in this paper could be a research project in and of itself. Detailed, well controlled studies of each property could provide a tremendous amount of information, could help to explain the deficiencies found in grouting materials and how to remedy those deficiencies. Both laboratory and field studies are needed.

2. A better understanding of why and how bentonite slurry grouts settle is essential. Settling studies should also address the role that filter cake plays in this process.

3. Grout integrity below the water table needs to be investigated more thoroughly.

4. Detailed studies of how to prevent a micro-annulus from forming in cement grouts could provide a solution to this problem.

5. Grouting information and techniques from the oil and gas industry should be collected and related to the water well industry.

6. A way to trace and detect all grouting materials through the well casing should be developed. Perhaps a grout additive would work in connection with a geophysical method. One possible additive is an innocuous substance, such as shale, that produces a significant kick on the gamma ray logger.

7. The development of a standardized method of application of bentonite chips and tablets could produce the most effective grout yet.

8. Mixing cement with bentonite should be discouraged, if not banned, until further investigations are performed.

9. Perhaps the most significant suggestion is the development of a grouting performance standard. This standard would help raise the awareness of inadequacies now found in grouting materials, and promote further product development. This standard could be seen as a challenge to the grouting industry to take on the task of making the changes needed to protect ground water resources.

Regardless of who performs the research or produces a grout performance standard, it is quite apparent that more in-depth and conclusive research is needed in the area of water well grouting. Proper well grouting and grout integrity are important issues when considering how to protect groundwater quality. All questions surrounding grouting issues are important, yet there are no easy ways to answer them.

Appendix A

Lithologic Well Logs

Lithologic Well Log

Well Identification: BH-196
Date Drilled: 7-8-96
Location: Western Michigan University, Basement of Science Pavilion, Kalamazoo, MI
Drill Company: Raymer Co., Marne, MI
Driller: Rich Bloom and Craig Merlington
Drilling Method: Mud Rotary
Geologist: M. Kirby

Well Diagram	Depth (ft)	Description
	8	medium to coarse, tan (10YR7/6) sand w/ chert pebbles, well graded
	18	as above, w/ large pebbles (1/2" dia.) of greenstone, quartz, jasper, and chert, well graded
	38	as above, w/ finer pebbles
	48	fine to medium, tan (10YR6/6) sand w/ well rounded pebbles of chert, greenstone, quartz, and jasper
	53	as above, w/ black shale fragments, increasing amount of pebbles
	58	tan (10YR6/6) sandy gravel w/ pebbles as described above
	68	tan (10YR6/6) gravelly sand
	73	tan (10YR6/6) sandy gravel, pebbles 1/2" dia.
	78	as above, w/ increasing gravel, brown sandstone pebbles, clay
	83	as above, slight color change (10YR7/6)
	88	as above, becoming gravelly clay, sandier at 90'
	93	tan (10YR7/6) gravelly clay, pebbles consist of quartz, chert, granite, greenstone, black shale, and tan sandstone
	98	tan, clayey gravel, pebbles as above w/ jasper
	103	as above w/ less clay, pebbles mostly chert and other igneous rock fragments
	108	as above, gravels fine to pebbles (3/8" dia.)
	113	as above, less clay, gravel is mostly chert
	123	grey (5B6/1) clay, gravel in sample suspected slough (per driller)
	133	as above, w/ medium quartz sand
	138	as above, end of borehole

Completion Data

Depth (ft)	Description
0-125'	8 - 50 lb bags of Wyo-Ben Groutwell DF bentonite tremmied to the surface through well annulus
0-130'	blank 5" ID PVC riser pipe, 2.5' stick-up at surface
125-135'	6 - 50 lb bags of Flat Rock 20/40 filter sand
130-135'	5' of 20-slot 5" ID PVC screen with PVC bottom cap

Grout Settling Data

Elapsed Time (hrs)	Depth (ft)
1	1.83
10	10.83
15	10.83
Excavation	Unknown

Additional Comments:
3' of collapse in hole, 135-138'.

Lithologic Well Log

Well Identification: BH-296
Date Drilled: 7-9-96
Location: Western Michigan University, Basement of Science Pavilion, Kalamazoo, MI
Drill Company: Dewind Drilling Co., Zeeland, MI
Driller: Jeff Dewind and Jay Currie
Drilling Method: Mud Rotary
Geologist: M. Kirby

Well Diagram	Depth (ft)	Description
	5	medium to coarse, tan (10YR7/6) sand w/ chert pebbles, well graded
	10	as above, w/ pebbles to 3/8" dia.
	15	as above, pebbles to 1" dia., consisting of greenstone, granite, chert and jasper
	20	coarse tan sand w/ fine chert gravel
	40	as above, pebbles to 1/2" dia.
	50	as above, w/ fine gravel
	55	as above, pebbles to 1/2" dia.
	58	as above, coarser gravel
	65	as above, increasing gravel 3/8" dia.
	80	coarse sand w/ fine gravel
	85	fine gravel w/ coarse sand
	90	medium gravel as above, w/ black shale fragments
	95	as above, w/ increasing shale fragments
	100	sandy gravel w/ grey clay, pebbles to 1/2" dia.
	105	fine gravel, no clay in sample (stone in bit)
	120	as above, clay becoming abundant
	132	as above w/ gravel layer
	135	grey clay
	160	50% grey clay, 50% quartz-chert fine gravel
	165	fine gravel as above
	180	fine-medium gravel w/ chert, black shale, jasper, and quartz
	185	medium gravel as above
	187	fine gravel w/ grey clay
	200	fine gravel w/ grey clay
	205	grey clay w/ fine gravel
	210	fine gravel w/ grey clay
	215	grey clay
	230	grey clay w/ fine pebbles
	240	as above w/ black shale chips
	245	fine gravel w/ grey clay
	250	fine gravel as above w/ black shale chips
	260	as above, w/ some limestone chips
	265	black and red shale w/ limestone (Coldwater Shale?)
	285	clay and sand streaks, shale and limestone
	295	as above, increasing shale and clay
	305	as above w/ soft blue clay. End of Borehole.

Completion Data

Depth (ft)	Description
0-260'	5" OD blank PVC riser pipe. 28 - 50 lb bags of Volclay Grout II used to grout by tremmimg from bottom to top. Grout weight = 9.6 lbs/gal (18 gallons water per 50 lb bag of grout) Approximately 25% solids

260-305'	45' of 4" OD 20-slot PVC screen. Each joint consisted of 6' slotted pipe at bottom and 3' of blank riser at top. 3x5 K-Packer installed at 260'.

Grout Settling Data

Elapsed Time (hrs)	Depth (ft)
0.42	2.25
2	4.42
11.5	21.25
14.5	25.5
Excavation	Unknown

Additional Comments:

Lithologic Well Log

Well Identification: BH-396
Date Drilled: 7-10-96
Location: Western Michigan University, Basement of Science Pavilion, Kalamazoo, MI
Drill Company: Stearns Drilling, Dutton, MI
Driller: n/a
Drilling Method: Mud Rotary
Geologist: M. Kirby

Well Diagram	Depth (ft)	Description
	5	fine gravel w/ coarse sand, pebbles of black shale, chert, quartz fine sand in sample
	8	gravel layer
	10	same as 5', becoming coarser w/ chert, jasper, greenstone, limestone, and quartz
	15	fine gravel, as above
	20	fine to medium gravel, as above, well graded, up to 3/8" dia. gravel
	25	as above w/ jasper
	30	as above w/ black shale chips
	52	medium gravel as above w/ wood chips
	57	fine gravel, as above
	72	fine to medium gravel, mostly chert and quartz w/ wood chips
	77	grey clay w/ wood, some gravel
	82	fine to coarse gravel, mostly chert, quartz, and jasper, no wood chips
	84	gravel layer
	89	medium to coarse gravel as above w/ wood. End of borehole.

Completion Data

Depth (ft)	Description
0-83'	5" ID blank PVC riser pipe. 4' stick-up. 4- 50 lb bags of Baroid Benseal bentonite w/ 1 gallon of Baroid EZ Mud Polymer. Grout tremmied from bottom of interval to top. Mix was 30 gallons water per 50 lb bag bentonite and 12 oz. of EZ Mud
83-89'	4.38" 20-slot 5" ID PVC screen w/ 1.625' blank PVC riser pipe. 2 - 50 lb bags of Flat Rock 20/40 filter sand.

Grout Settling Data

Elapsed Time (hrs)	Depth (ft)
14.5	7.58
Excavation	11

Additional Comments:

Lithologic Well Log

Well Identification: BH-496
Date Drilled: 7-11-96
Location: Western Michigan University, Basement of Science Pavilion, Kalamazoo, MI
Drill Company: Katz Water Well Drilling, Battle Creek, MI
Driller: Moe McKeague and Leo Van Valkenburg
Drilling Method: Mud Rotary
Geologist: M. Kirby

Well Diagram	Depth (ft)	Description
	5	coarse gravel (greenstone, chert and quartz), w/ coarse tan sand
	10	as above w/ coarser gravel
	15	as above w/ finer gravel
	30	as above w/ coarse pebbles (up to 1/2" dia.)
	40	medium sand w/ fine gravel
	50	as above w/ coarse gravel
	55	fine gravel and coarse sand
	65	as above w/ red sand
	72	gravel layer
	75	gravel w/ soft grey clay
	80	medium sand and medium gravel w/ clay
	85	as above w/ coarse gravel
	100	fine gravel w/ coarse sand
	105	as above w/ wood chips
	110	as above, medium gravel instead of fine
	115	as above, w/ limonite in addition to quartz, chert, and greenstone pebbles
	120	as above w/ grey clay (driller calls this "Kalamazoo Grey")
	125	as above w/ brown clay
	130	as above w/ grey clay
	135	grey clay w/ medium to coarse gravel
	145	coarse sand w/ minor clay
	155	medium to coarse quartz, chert, greenstone sand w/ fine gravel
	165	coarse tan quartz, chert, jasper sand
	170	sand as above w/ medium gravel, some black shale fragments
	180	medium to coarse sand
	190	medium gravel (chert, greenstone, and quartz), no fines
	200	medium sand
	210	fine to medium sand
	215	as above w/ grey clay
	225	as above w/ grey fine sand and silt
	230	medium to coarse sand
	235	medium sand w/ fine grey silt
	240	fine to medium sand w/ grey clay
	255	as above w/ some black shale fragments
	270	medium sand to fine gravel (mostly chert and quartz)
	275	gravel w/ limestone and clay fragments
	280	blue/grey clay w/ medium sand
	300	black and grey shale w/ grey limestone (driller thinks bedrock encountered at 298'
	305	grey clay and shale
	310	grey shale
	315	blue/grey sandy shale
	318	blue/grey shale
	320	black and grey shale and grey limestone chips
	321	as above w/ abundant grey limestone
	332	as above w/ red shale
	335	as above. End of borehole.

Completion Data

Depth (ft)	Description
0-315'	5" ID PVC riser pipe. Pipe glued w/ PVC cement. 16" stabilizer installed at 10' below ground surface. 11-50 lb bags of Benseal bentonite and 7 lbs of catalyst. Grout tremmied from bottom of interval to top. Mix was 30 gallons water per 50 lb bag of bentonite. 5x9 formation packer installed at 315'.
315-335'	Open hole

Grout Settling Data

Elapsed Time (hrs)	Depth (ft)
2.5	1
3.5	2.58
12.5	6.67
15.25	13.5
Excavation	Unknown

Additional Comments:

Lithologic Well Log

Well Identification: BH-896
Date Drilled: 11-23-96
Location: Western Michigan University, Basement of Science Pavilion, Kalamazoo, MI
Drill Company: Ray Leonard Cable Tool Well Drilling, Battle Creek, MI
Driller: Ray Leonard
Drilling Method: Cable Tool
Geologist: S. Callaway

Well Diagram	Depth (ft)	Description
	5	sand
	8	gravel layer
	37.75	sand. End of borehole.

Completion Data

Depth (ft)	Description
0-37.75'	4" Steel casing. Welded at joints. No screen. 5.5 - 50 lb bags of Cetco C/S and Volclay AntiSkid granular bentonite.

Grout Settling Data

Elapsed Time (hrs)	Depth (ft)
Excavation	0

Additional Comments:
Grout was applied dry, from the surface.
Well casing raised and lowered several times throughout the drilling process to aid in grout placement.
This well was removed after excavation.

Lithologic Well Log

Well Identification: BH-996
Date Drilled: 12-3-96
Location: Western Michigan University, Basement of Science Pavilion, Kalamazoo, MI
Drill Company: Katz Water Well Drilling, Battle Creek, MI
Driller: Moe McKeague
Drilling Method: Mud Rotary
Geologist: S. Callaway

Well Diagram	Depth (ft)	Description
	2	medium grained. tan sand w/ small gravel
	8	gravel layer, medium sized, small amount of clay
	9	medium grained sand w/ small gravel
	30.58	same as above. End of borehole.

Completion Data

Depth (ft)	Description
0-30.58'	5" PVC casing 6 - 94 lb bags of LaFarge Type I Neat Portland cement, tremmied to to the surface. No screen. Mix was 5.6 gallons water per 94 lb bag cement.

Grout Settling Data

Elapsed Time (hrs)	Depth (ft)
Excavation	0

Additional Comments:
A disposable tremie tube was used to grout this well. The tremie tube was cut off at the surface and left in place.
This well was removed after excavation.

Lithologic Well Log

Well Identification: BH-1096
Date Drilled: 12-3-96
Location: Western Michigan University, Basement of Science Pavilion, Kalamazoo, MI
Drill Company: Katz Water Well Drilling, Battle Creek, MI
Driller: Moe McKeague
Drilling Method: Mud Rotary
Geologist: S. Callaway

Well Diagram	Depth (ft)	Description
	2	medium grained, tan sand w/ small gravel
	8	gravel layer, medium sized, small amount of clay
	9	medium grained sand w/ small gravel
	31.25	same as above. End of borehole.

Completion Data

Depth (ft)	Description
0-31.25'	5" PVC casing 5 - 94 lb bags of LaFarge and st. Mary's Type I Neat Portland cement, mixed w/ 1/2 bag PDS Co. Wyoming bentonite, tremmied to the surface. No screen. Mix was 5.6 gallons water per 94 lb bag cement. Contained 5% bentonite.

Grout Settling Data

Elapsed Time (hrs)	Depth (ft)
Excavation	0.5

Additional Comments:
A disposable tremie tube was used to grout this well. The tremie tube was cut off at the surface and left in place.
This well was removed after excavation.

Appendix B

Percent Solids Calculations

Percent Solids Calculations

Formula (Stichman, 1990)

$$\frac{\text{Total Weight Bentonite Used}}{\text{Total Weight Water Used} + \text{Total Weight Bentonite Used}} \times 100$$

= Percent Solids

BH-296

Materials Used:
- 28 - 50 lb bags of bentonite
- 18 gallons of water per bag bentonite
- Weight of Water = 8.33 lbs per gallon

Total Weight Bentonite Used
28 bags bentonite x 50 lbs = 1400 lbs

Total Weight Water Used
18 gallons x 28 bags bentonite x 8.33 lbs per gallon
=4198.3 lbs

Percent Solids

$$\frac{1400 \text{ lbs}}{4198.3 \text{ lbs} + 1400 \text{ lbs}} \times 100 = 25\%$$

BH-396

Materials Used:
- 4 - 50 lb bags bentonite
- 30 gallons of water per bag bentonite

Total Weight Bentonite Used
4 bags x 50 lbs = 200 lbs

Total Weight Water Used
30 gallons x 4 bags bentonite x 8.33 lbs per gallon
=999.6 lbs

Percent Solids

$$\frac{200 \text{ lbs}}{99.6 \text{ lbs} + 200 \text{ lbs}} \times 100 = 17\%$$

BH-496

Materials Used:
11 - 50 lb bags bentonite
30 gallons water per bag bentonite

Total Weight Bentonite Used
11 bags x 50 lbs = 550 lbs

Total Weight Water Used
30 gallons x 11 bags bentonite x 8.33 lbs per gallon
2748.9 lbs

Percent Solids

$$\frac{550 \text{ lbs}}{2748.9 \text{ lbs} + 550 \text{ lbs}} \times 100 = 17\%$$

Appendix C

Excavation Well Logs

Excavation Well Logs

Well Identification: BH-196
Date Excavated: 1-11-97
Grout Brand / Type: Wyo-Ben Groutwell DF / bentonite slurry
Total Grout Interval: 0 - 125'

Depth (ft)	Description
0 - 3.67	No grout. Slough from surface.
3.67 - 5.67	No grout. Filter cake found lining the borehole wall, ranges in thickness from .125" to .75". Lineations noted in filter cake.
5.67	Bridged grout approximately 3"x4" in size. Bridged grout adhered to the well casing and surrounding formation. Filter cake as noted above w/o lineations.
5.67 - 13.3	Periodically bridged grout. Filter Cake as noted above.
13.3	End of Excavation. No solid column of grout found.

Well Identification: BH-296
Date Excavated: 1-11-97
Grout Brand / Type: Volclay Grout II / bentonite slurry
Total Grout Interval: 0 - 260'

Depth (ft)	Description
0 - 13.3	Periodic bridging found. Filter cake lined entire exposed length of borehole and varied in thickness from .125" to .75". Bridged grout adhered to the well casing and surrounding formation.
13.3	End of Excavation. No solid column of grout found.

Well Identification: BH-396
Date Excavated: 1-11-97
Grout Brand / Type: Baroid Benseal w/ Baroid EZ Mud Polymer / bentonite slurry
Total Grout Interval: 0 - 83'

Depth (ft)	Description
0 - 11.4	Periodic bridging found throughout excavated length of well. Filter cake found along entire exposed length of borehole w/ varying thickness of .125" to .75".
11.4	Solid column of grout begins.
11.4 - 13.3	Solid column of grout continued. Grout has the consistency of thick petroleum jelly. No fractures or seams were noted for the grout. Grout is consistently 3" thick around the casing. Grout adhered to the well casing and the surrounding formation.
13.3	End of Excavation. Solid column of grout found.

Excavation Well Logs (continued)

Well Identification: BH-496
Date Excavated: 1-11-97
Grout Brand / Type: Benseal w/ catalyst / bentonite slurry
Total Grout Interval: 0 - 315'

Depth (ft)	Description
0 - 13.3	Periodically bridged grout found throughout the excavated length of well. Filter cake noted along entire exposed borehole wall. Filter cake varied in thickness from .125" to .75". Bridged grout adhered to the well casing and surrounding formation.
13.3	End of Excavation. No solid column of grout found.

Well Identification: BH-896
Date Excavated: 1-11-97
Grout Brand / Type: Cetco C/S and Volclay AntiSkid / granular bentonite
Total Grout Interval: 0 - 37.75'

Depth (ft)	Description
0 - 13.3	Solid column of grout found the entire length of the excavated well casing. Grout was not fully hydrated, but adhered to the well casing, surrounding formation and to itself. Had a leather-like flexibility. No fractures, seams, or bridging were found. Two 4"x4" areas had mixed with surrounding formation. Thickness of grout varied from less than .125" to approximately 2".
13.3	End of Excavation. Solid column of grout for entire exposed length of well casing.

Well Identification: BH-996
Date Excavated: 1-11-97
Grout Brand / Type: LaFarge Type I Portland Cement / cement slurry
Total Grout Interval: 0 - 30.58'

Depth (ft)	Description
0 - 13.3	Solid column of grout found entire length of exposed well casing. Grout was hard and stiff. Grout did not appear to adhere to the well casing or disposable tremie tube. Grout varied in thickness from less than .125" to approximately 6". No fracturing or bridging was seen.
13.3	End of Excavation. Solid grout column found from 0 - 13.3'.

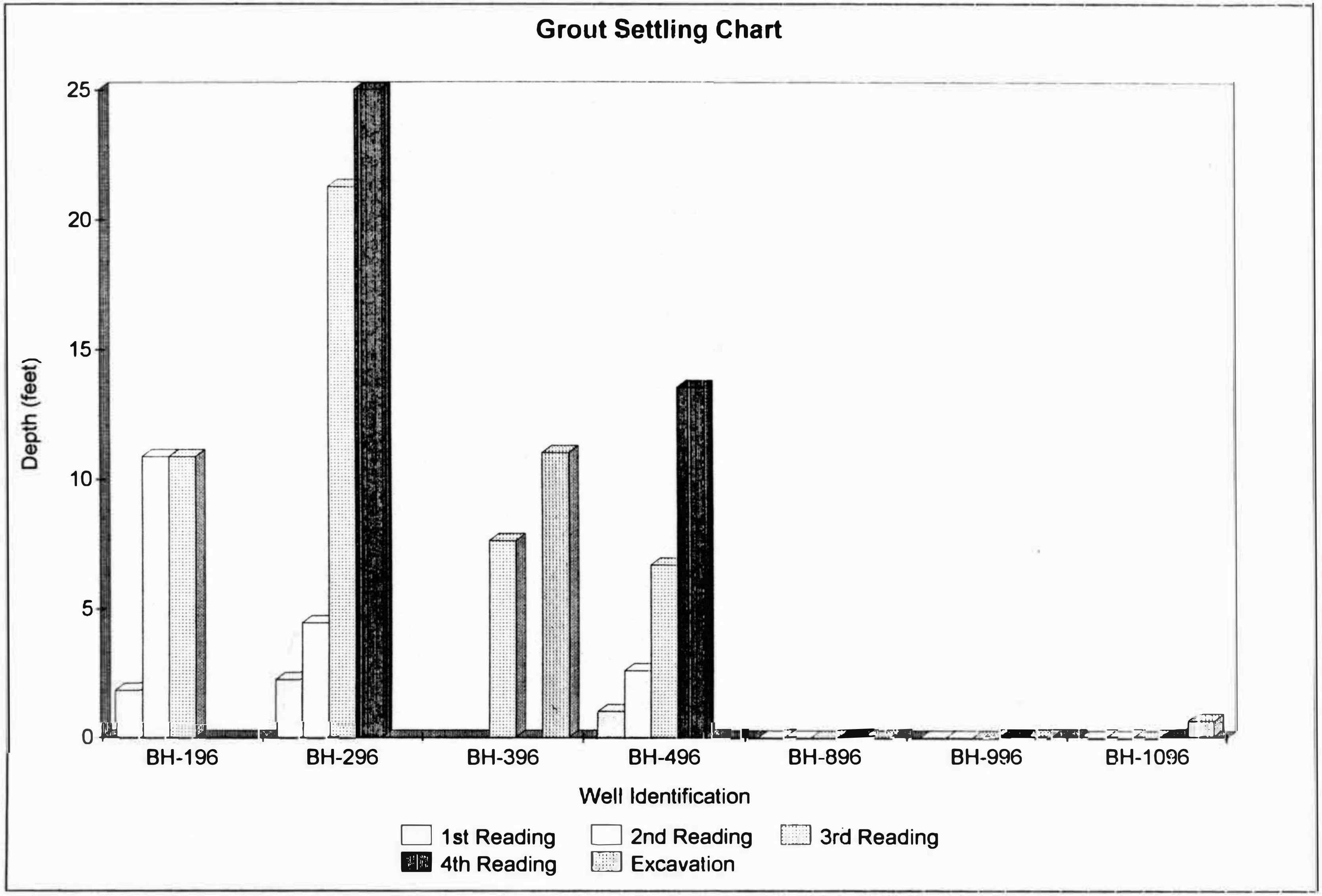
Excavation Well Logs (continued)

Well Identification: BH-1096
Date Excavated: 1-11-97
Grout Brand / Type: LaFarge and St. Mary's Type I Portland Cement w/ PDS Wyoming Bentonite / bentonite-cement slurry
Total Grout Interval: 0 - 31.25'

Depth (ft)	Description
0 - 0.6	Surface slough. No grout.
0.6 - 8.25	Solid column of grout, varying in thickness from less than .125" to approximately 6". Grout was hard and stiff. Grout did not appear to adhere to the well casing or disposable tremie tube.
8.25	Horizontal fracture surrounding the entire well casing. Had mud in between the upper and lower plate indicating that it had occurred prior to excavation.
8.25 - 13.3	Solid column of grout as noted above.
13.3	End of Excavation. Grout found from 0.6' to 13.3' with fracture noted at 8.25'.

Appendix D

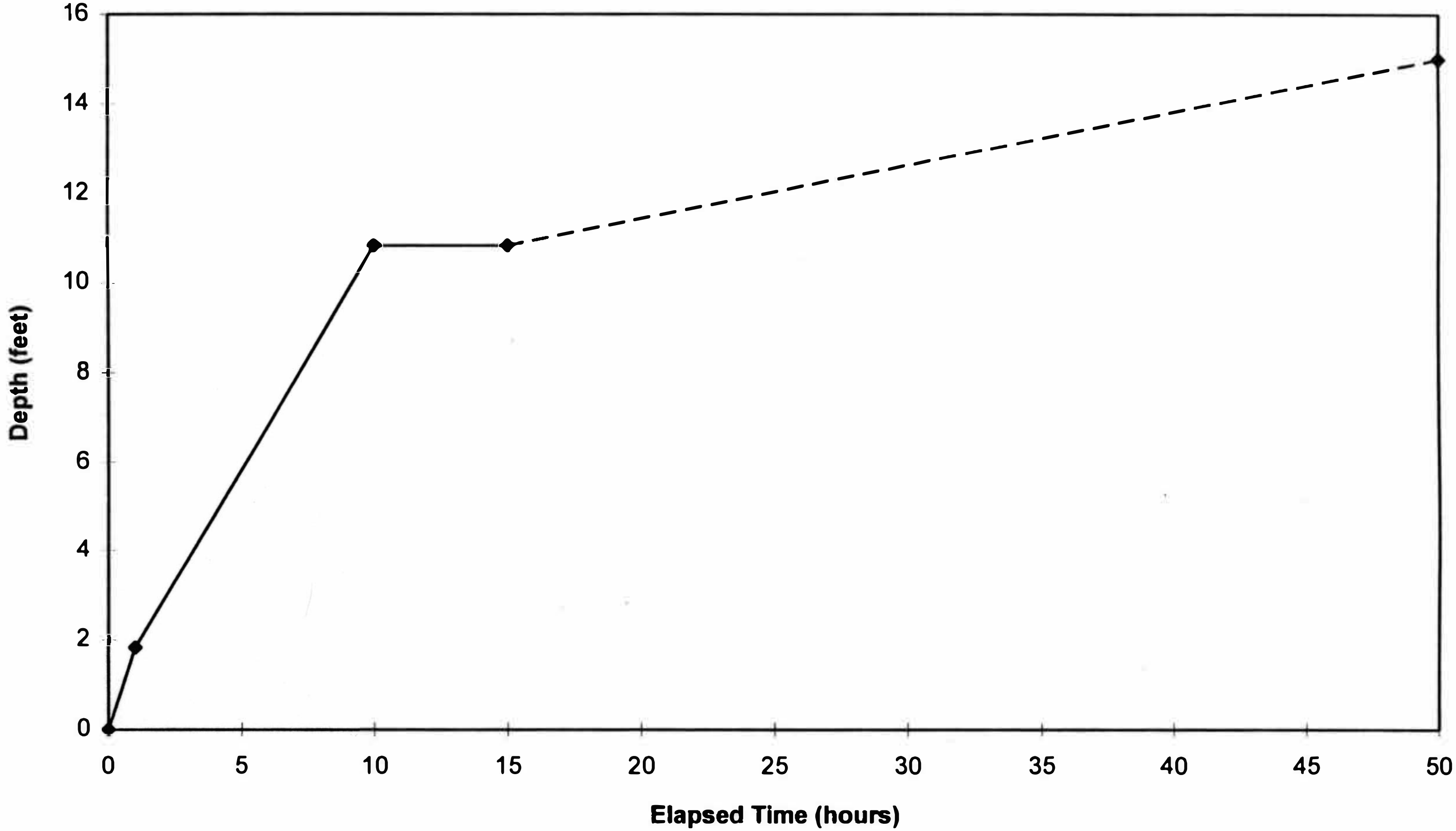
Settling Charts


Grout Settling Chart
Depth (feet)
25
20
15
10
5
0
BH-196
BH-296
BH-396
BH-496
BH-896
BH-996
BH-1096
Well Identification
1st Reading
2nd Reading
3rd Reading
4th Reading
Excavation

BH-196 Settling Graph

50 Hours = Excavation

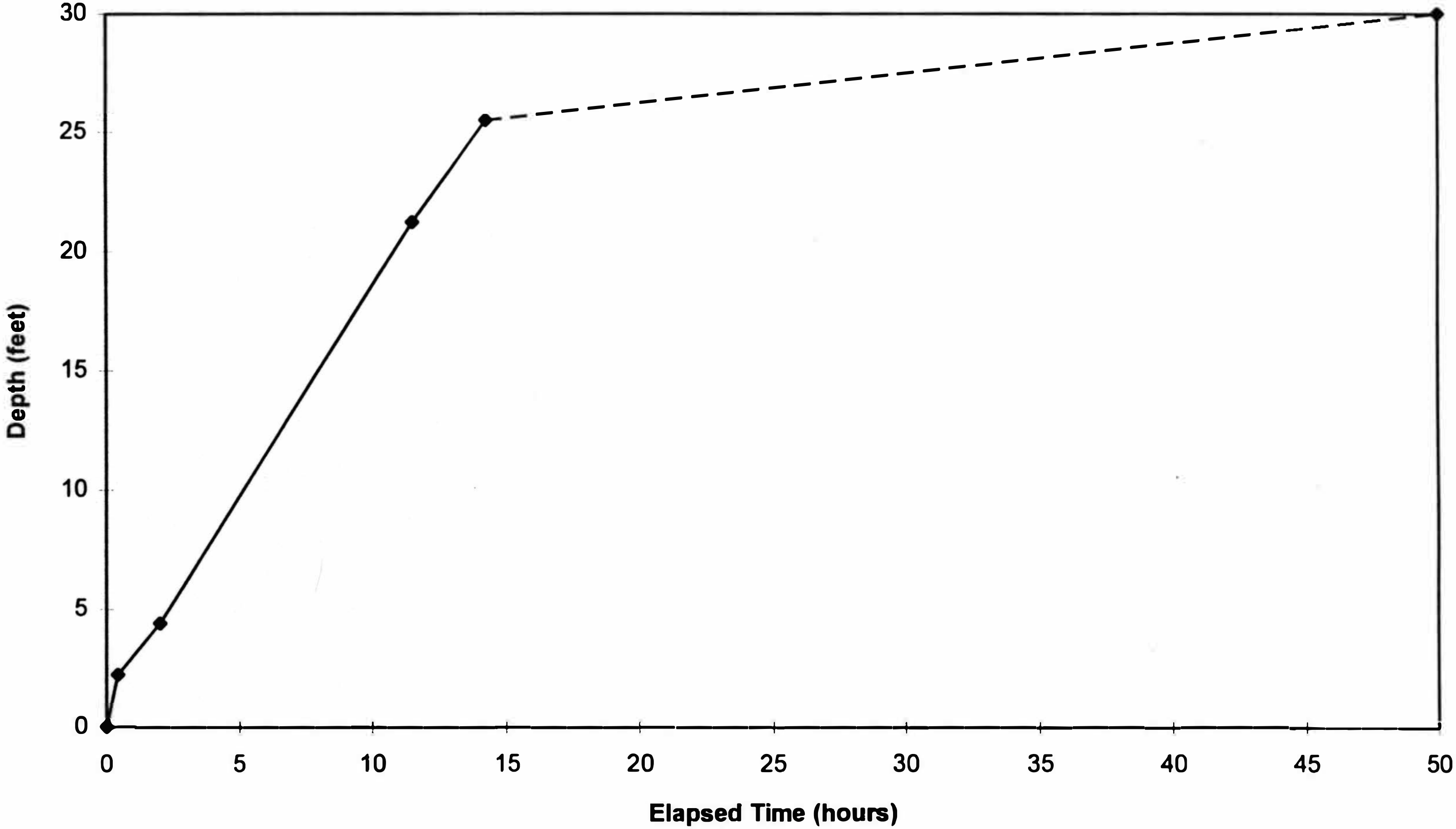
Dashed Line Indicates Unknown Settling Depth

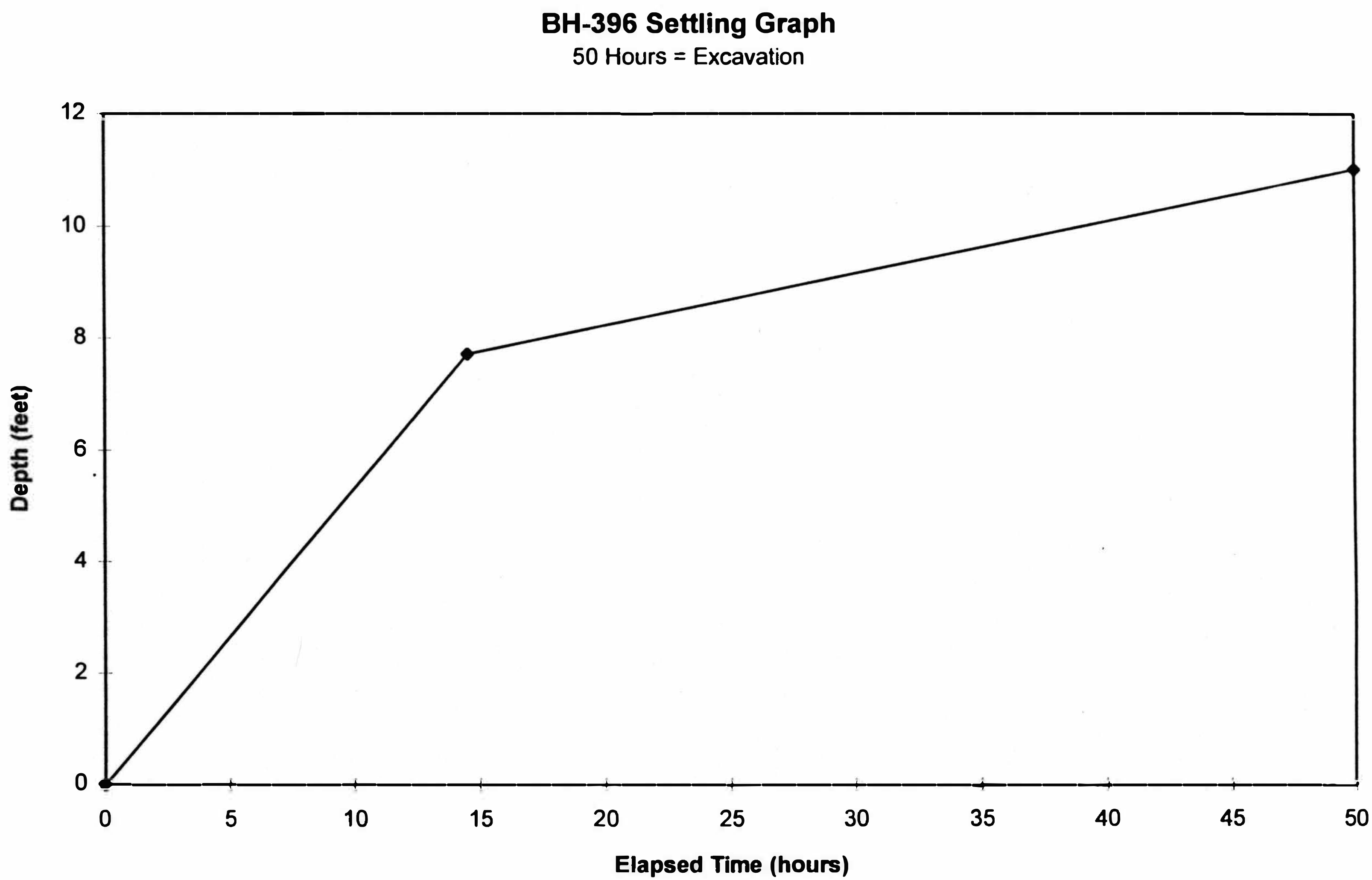


BH-296 Settling Graph

50 Hours = Excavation

Dashed Line Indictes Unknown Settling Depth

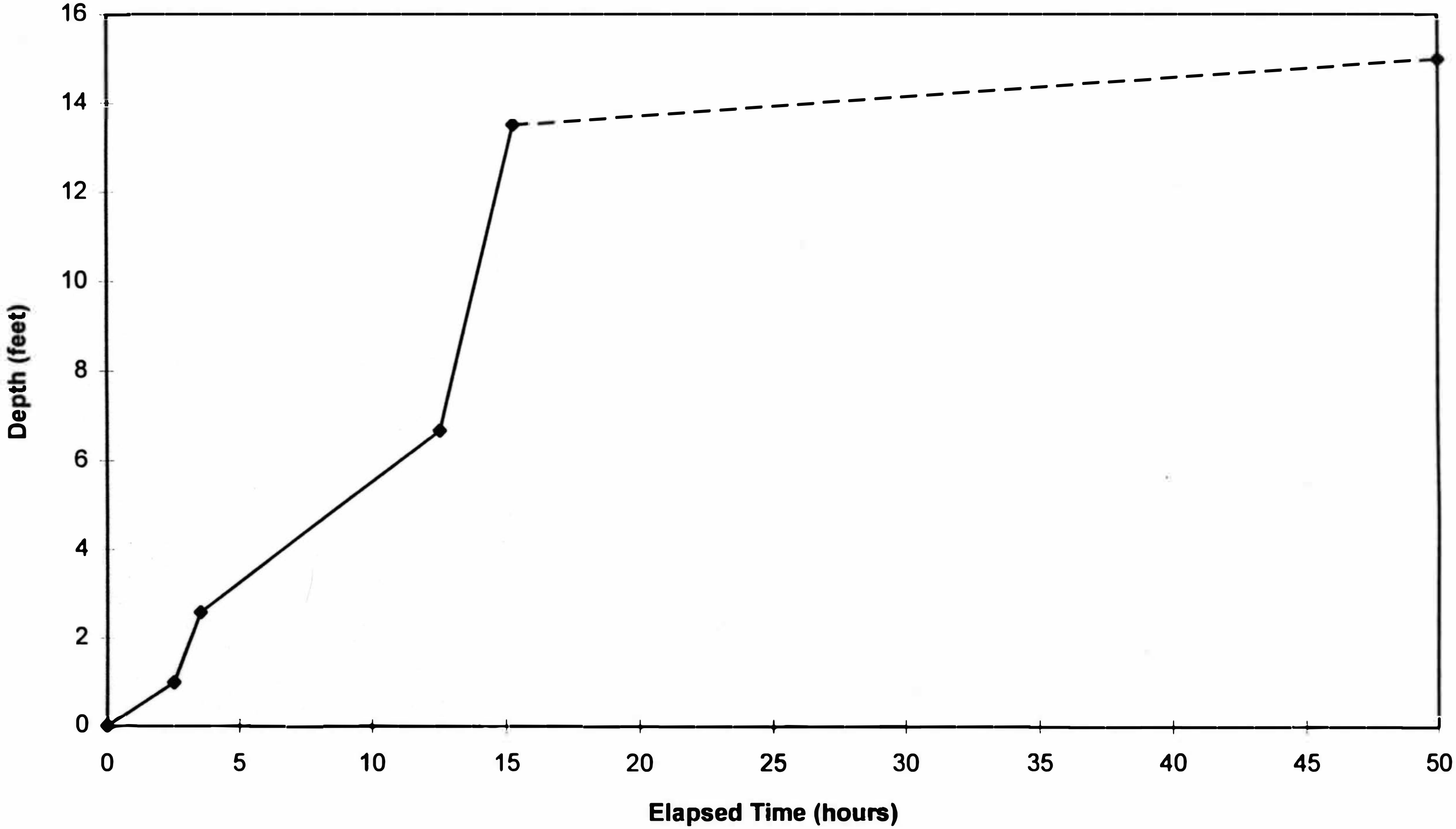



BH-396 Settling Graph
50 Hours = Excavation
Depth (feet)
12
10
8
6
4
2
0
0
5
10
15
20
25
30
35
40
45
50
Elapsed Time (hours)

BH-496 Settling Graph

50 Hours = Excavation

Dashed Line Indicates Unknown Settling Depth



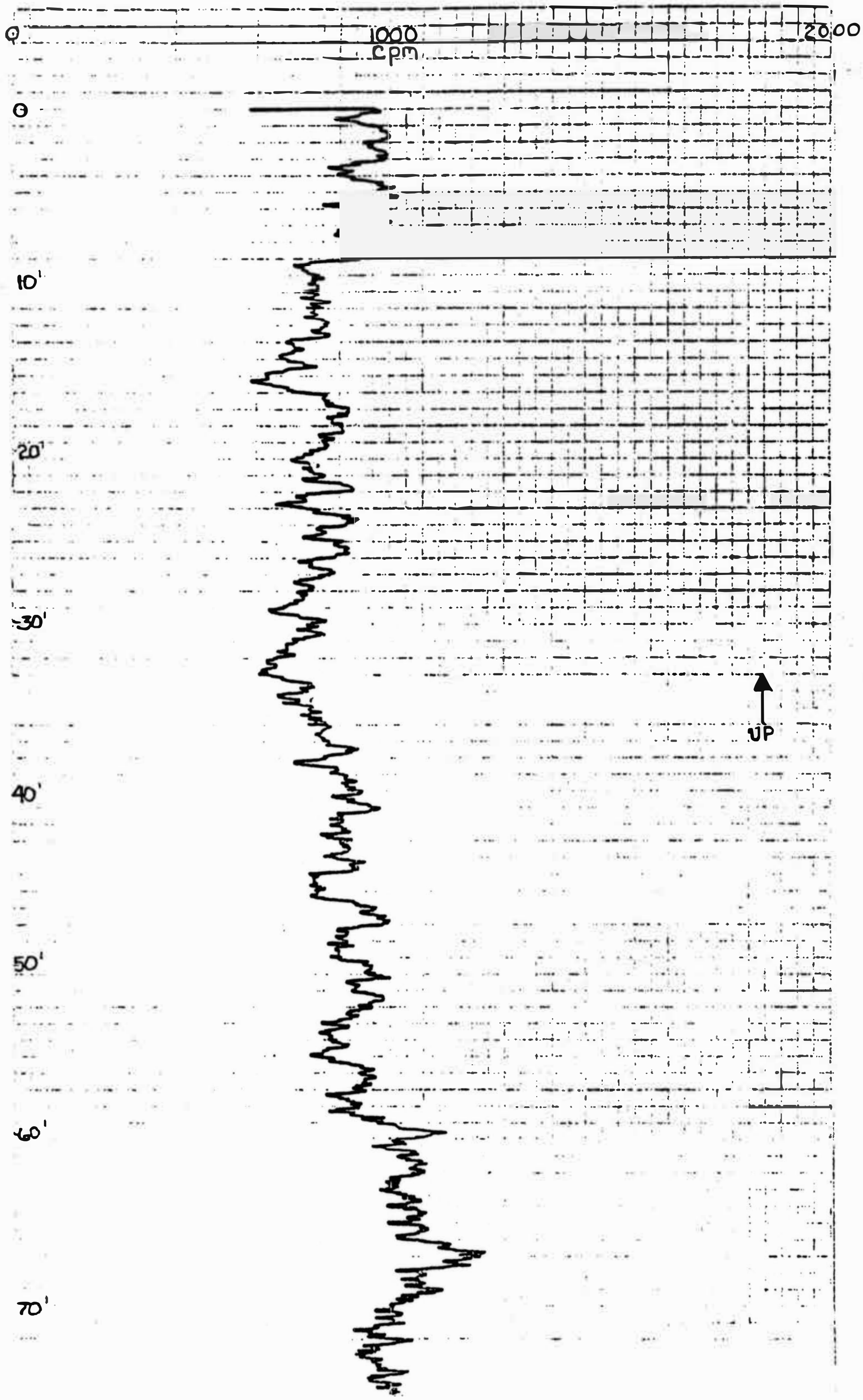
Appendix E

Gamma Ray Logs

Gamma Ray Log

Well: BH-196
Equip: Keck Model SR-3000
Oper: Callaway/Gardner
Scale: 2000 cpm f.s.
Logging up

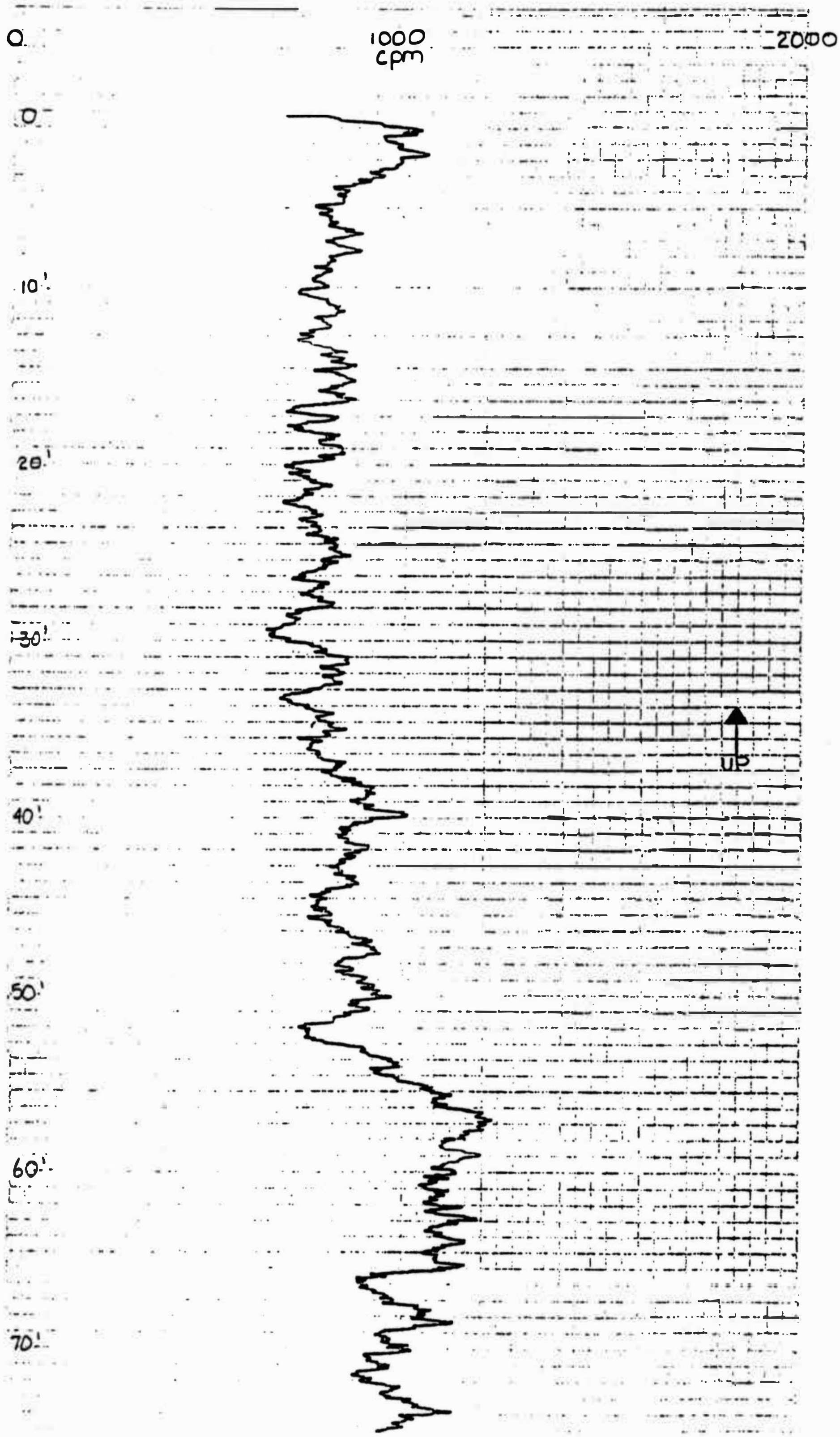
Date: 11/16/96
Casing: 5" PVC Casing
Time Constant: 10 sec
Velocity: 6 ft/min



Gamma Ray Log

Well: BH-296
Equip: Keck Model SR-3000
Oper: Callaway/Gardner
/Montgomery
Scale: 2000 cpm f.s.

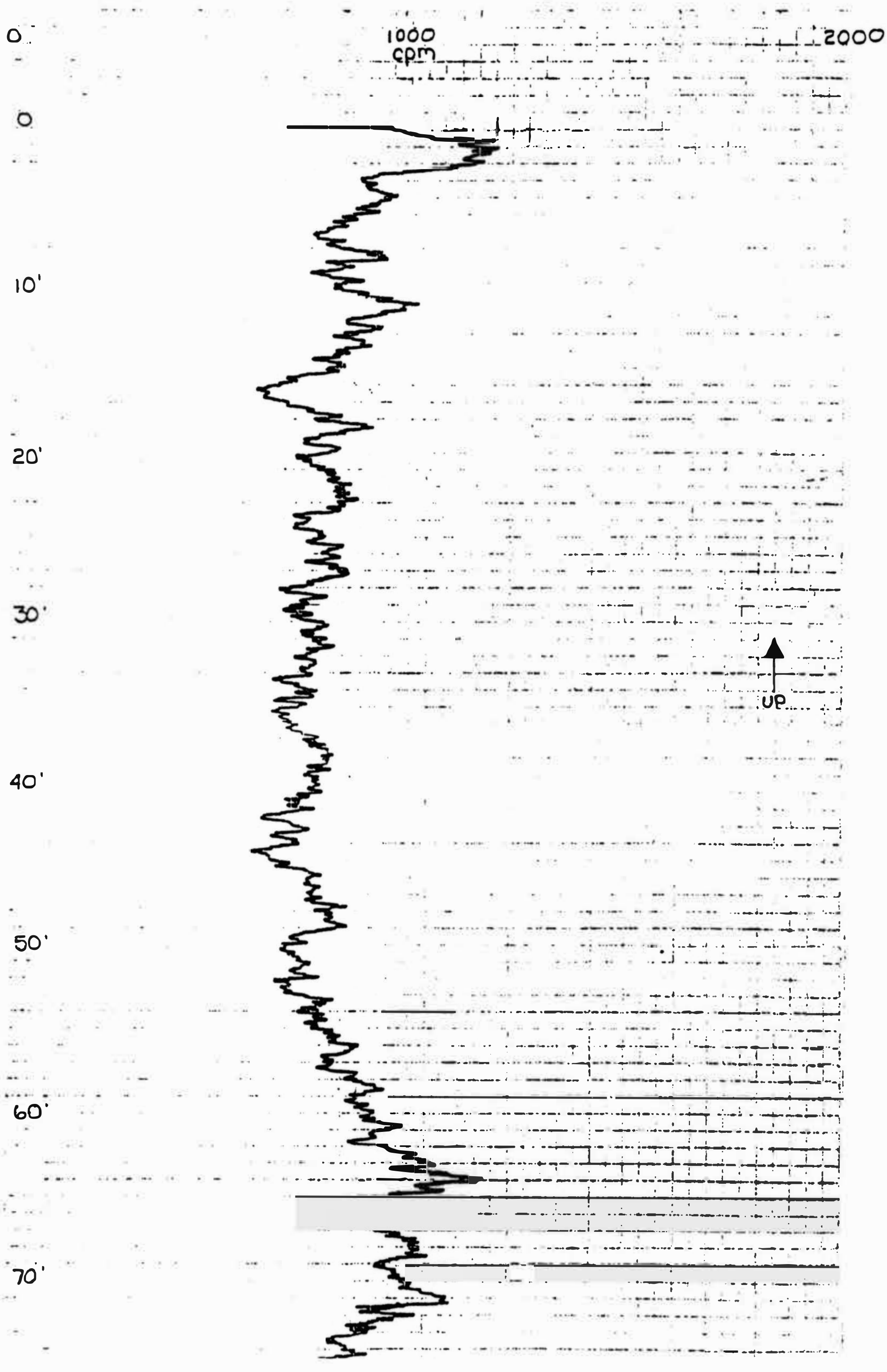
Date: 11/15/96
Casing: 5" PVC Casing
Time Constant: 10 sec
Velocity: 6 ft/min
Logging up



Gamma Ray Log

Well: BH-396
Equip: Keck Model SR-3000
Oper: Callaway/Gardner
Scale: 2000 cpm f.s.
Logging up

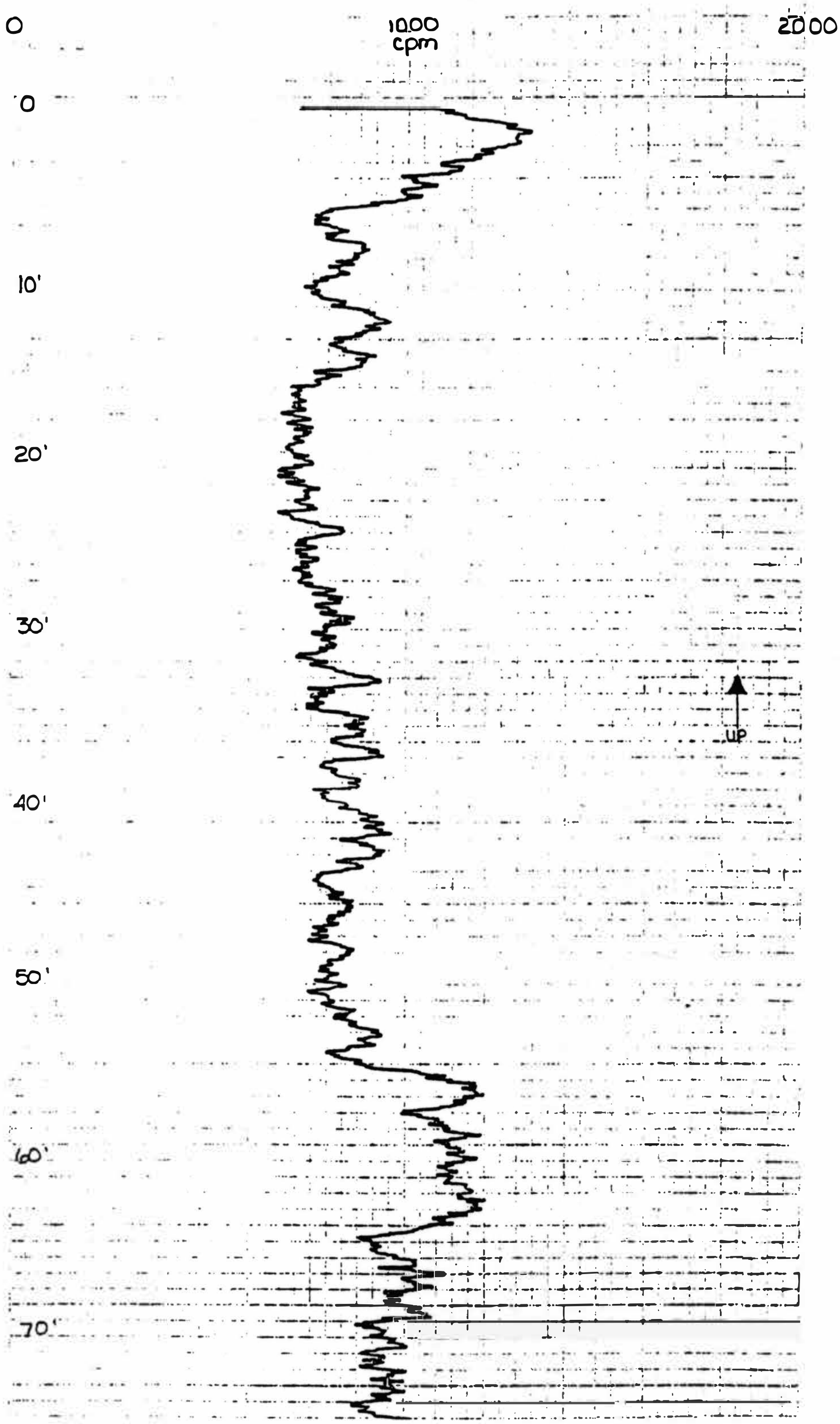
Date: 11/16/96
Casing: 5" PVC Casing
Time Constant: 10 sec
Velocity: 6 ft/min



Gamma Ray Log

Well: BH-496
Equip: Keck Model SR-3000
Oper: Callaway/Gardner
Scale: 2000 cpm f.s.
Logging up

Date: 11/16/96
Casing: 5" PVC Casing
Time Constant: 10 sec
Velocity: 6 ft/min



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