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SEALING CHARACTERISTICS OF SODIUM BENTONITE SLURRIES FOR WATER WELLS

A Report Submitted to

THE WISCONSIN DEPARTMENT OF NATURAL RESOURCES

by

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SUMMARY

A laboratory investigation of the effectiveness of sodium bentonite slurries (drilling mud type) in sealing the annular space in water wells was undertaken. "Quick-Gel" marketed by N. L. Baroid Company as a drilling fluid was studied in viscosities (based on a Marsh Funnel) of 50, 70, 90 and 170 sec/qt as a sealant. The methods of investigation included both a study of the material properties of these slurries and well model experiments in a sand container. The material properties studies included Marsh funnel viscosity, mud weight, gel strength, filtration, shrinkage and permeability (hydraulic conductivity). The well model experiments included both a small annular space model and a large well model utilizing four wells in a sand filled plexiglass container of 1.5 ft x 6 ft x 6 ft deep. In the well models, infiltration of water placed on top of the annular space sealant was studied along with the visual inspection of the sealants dissected during disassembling of the model at the end of the experiments. Additionally, a finite element computer program modeling seepage in the well experiment was developed and used in the interpretation of the experimental results.

Based on the results of the laboratory experiments and within the inherent limitations of a laboratory study of an essentially field problem, the following conclusions are advanced:

1. Quick-Gel slurries without any entrained formation materials provide varying degrees of sealing in the annular space of a well in a coarse sand formation. The infiltration rate of water through the annular space takes place primarily by exfiltration laterally into the formation through the filter cake and at a rate of 0.5 to 3.0 in/sec.

2. The coefficient of permeability (or hydraulic conductivity) of the gelled Quick-Gel slurries with Marsh funnel viscosities of 50 to 170 sec/qt was in the range of 10^{6} cm/sec.

3. Volume defects, such as cracks, however, result in infiltration rates higher than the rates consistent with the material permeability.

4. Based on the measured infiltration rates, filter cake thicknesses and

permeabilities, as well as the observations of the dissected sealants in the well experiment, it has been found that the 70 and the 90 sec/qt slurries behave significantly better than both the 50 and the 170 sec/qt slurries as an annular space sealant. The lowest and the highest viscosity slurries used in the study were more prone to cracking than the intermediate viscosity slurries.

INTRODUCTION AND OBJECTIVES

Well installation involves opening a hole in the ground extending into the acquifer. This is accomplished often by rotary drilling or percussion drilling. A well casing is subsequently placed in this hole with a screen attached to the bottom of it. The annular space between the well casing and the bore hole has to be filled and sealed in order to prevent rapid migration of the surface water or shallow ground water which may potentially be contaminated. It is clear that an opening of 3 to 4 inches wide, if not sealed properly, can conduct a considerable amount of contaminants rapidly and without any significant attenuation. Thus, it is common practice to fill the annular space in some fashion to prevent easy conduction of surface waters. The problem is important both for water supply wells and ground water quality monitoring wells.

In well drilling practice today, a variety of materials are used to seal the annular space. These include native clay slurry, sodium bentonite slurries (drilling mud type bentonite), bentonite grouts (bentonite with additives specifically developed for sealing such as "Volclay Grout" or "Benseal"), bentonite-cement grout (neat cement grout with approximately five percent sodium bentonite added), neat cement grout (a mixture with a ratio of one 94-pound sack of Portland cement and five to six gallons of water), dry granular sodium bentonite, and sodium bentonite pellets (1/4-inch diameter). The placement of the annular space sealing materials between the drillhole and the casing pipe is accomplished, in general, either by a tremie pipe from the bottom up using gravity in percussion drilling or pumping using pressure in rotary drilling.

In current practice, the materials described above are used at the discretion of the drillers with sodium bentonite slurries (drilling mud) being one of the most popular sealing material. Sodium bentonite slurries are primarilty used in well drilling in removing the cuttings during drilling and in bore-hole stabilization. However, they are left in the annular space after drilling as a sealant.

The overall objective of this study is to determine the effectiveness of various annular space sealing materials using laboratory experiments. The first phase of the investigation, which is presented in this report, is directed towards the evaluation of sodium bentonite ("Western" drilling mud type bentonite, i.e., "Quick-gel" marketed by N. L. Baroid Company) slurries with viscosity readings (based on a Marsh Funnel) of 50, 70 , 90 sec/qt and a high enough viscosity such that the slurry is just barely pumpable as annular space sealants in water wells. The methods of investigation include a study of the material properties of these slurries and well model experiments in a sand container. Additionally, a computer model of the seepage through the annular space is developed and used to help with the interpretation of the epxerimental results.

A review of the literature on the subject indicates a dearth of investigations directed at an evaluation of the effectiveness of the annular space sealing. Furthermore, there seems not to be available a widely accepted and clearly stated criterion of effective sealing. However, it is clear that permeability and stability are important factors for effective sealing. It is also possible to compare the various sealants with each other for their effectiveness. These concepts are used in the evaluation approach adopted in this report.

MATERIALS AND PROPERTY TEST PROCEDURES

In this phase of the well sealant study, a single material often used in sealing the well casings was considered, namely, a sodium bentonite drilling fluid with a trade name of "Quick-Gel" marketed by N. L. Baroid Company. It is a finely ground, premium-grade western sodium bentonite, processed to promote ease of mixing and superior mud-making qualities in fresh water. It is not toxic and does not ferment. Quick-gel has a specific gravity of 2.5. It is marketed as a viscosifier to be used as a drilling fluid for increasing hole-cleaning capabilities by removing cuttings, forming a filter cake and promoting hole stability in caving formations, and reducing water seepage and avoiding loss of circulation. Ordinarily, a slurry of quick-gel is prepared by mixing it with water and circulated in the bore hole during drilling. The slurry is pumped to the bottom of the hole in the drill rods with a return through the annular space between the drill rods and the bore hole wall. The circulated slurry picks up the cutting generated by the drill bit and carries them to the surface where the cuttings can be settled out of the slurry in a tank before the slurry is returned to the bore hole again. The viscosity of the drilling fluid is important with respect to its ability to carry the cuttings.

Additionally, the drilling fluid serves another purpose by stabilizing the bore hole. As it is introduced to the bore hole, the drilling fluid tends to penetrate the surrounding geological formation. However, it gets filtered in the pores of the formation and forms a "filter cake" of relatively low permeability. This results in application of a hydrostatic pressure on the walls of the bore hole by the drilling fluid. This pressure is used in balancing the ground-water pressure and the earth pressure tending to collapse the bore hole. The unit weight (density) of the drilling fluid is important in determining the magnitude of the hydrostatic pressure. The drilling fluid also serves other useful functions such as cooling the drill bit, lubricating the drill pipe, mitigating wear and corrosion of the drilling equipment, stopping losses into thief zones, etc.

Drilling Fluid Property Tests

How effectively the drilling fluid performs its functions depends on many physical properties. These properties are often measured periodically using some crude but practical tests during drilling to determine how well the mud will perform its function. Included among these field tests are mud weight (measures density) and Marsh Funnel viscosity (measures viscosity and gel strength). Additionally, there are tests to measure the filtration properties using a filter press, gel strength, sand content, and pH. The test procedures are described in American Petroleum Institute (API) Standard 13-B, "Standard Procedure for Testing Drilling Fluids", Fifth Edition (1974). Furthermore, the American Society for Testing and Materials (ASTM) is currently in the process of adopting some of these tests into their standards. The procedures for these tests, as summarized by the N. L. Baroid Company, are given in Appendix A.

Permeability Test for Bentonite Sealant

Quick-gel is often used in sealing the annular space between the wall casing and the bore hole subsequent to well drilling. Therefore, in addition to the basic tests to characterize it as a drilling fluid as described above, its sealing characteristics, i.e., permeability, should be determined. The coefficient of permeability or hydraulic conductivity is a property of a porous medium indicating the ease with which it conducts a fluid through its pores. It is a composite property which depends both on the characteristics of the porous medium and the permeating fluid. Soils of all types are examples of porous media and their permeability is determined by either a constant head or a variable head permeability test. There is an ASTM standard describing the constant head permeability test for coarse-grained soils (ASTM Standard D2434). However, currently there is no consensus standards for permeability testing of fine-grained soils of relatively low permeability using variable head.

Quick-gel, in slurry form, is not a solid material. When it gels, it forms a porous flexible structure which can permeate water or other liquids. There is no standard procedure known to us for testing the hydraulic conductivity of such a material. The flexible (compressible) and fragile gel structure makes sampling and permeability testing of bentonite sealants at the consistencies considered in this study rather difficult.

By trial and error, a method of permeability testing of quick-gel was developed. Two types of permeameters were developed for this purpose. Model A permeameter, shown in Figure 1, allows pouring in a slurry which then can be left to gel, in the permeater cell (about 1-1/2 inches in diameter) prior to the application of a head of water to initiate the permeation. The applied head invariably causes some compression of the gel structure and must be chosen with discretion. The suggested rule is to make it comparable to the expected head driving the water through the annular space sealant. High heads shorten the testing time but may compress the gel to change its permeability significantly. In the tests performed in this study, the initial heads were

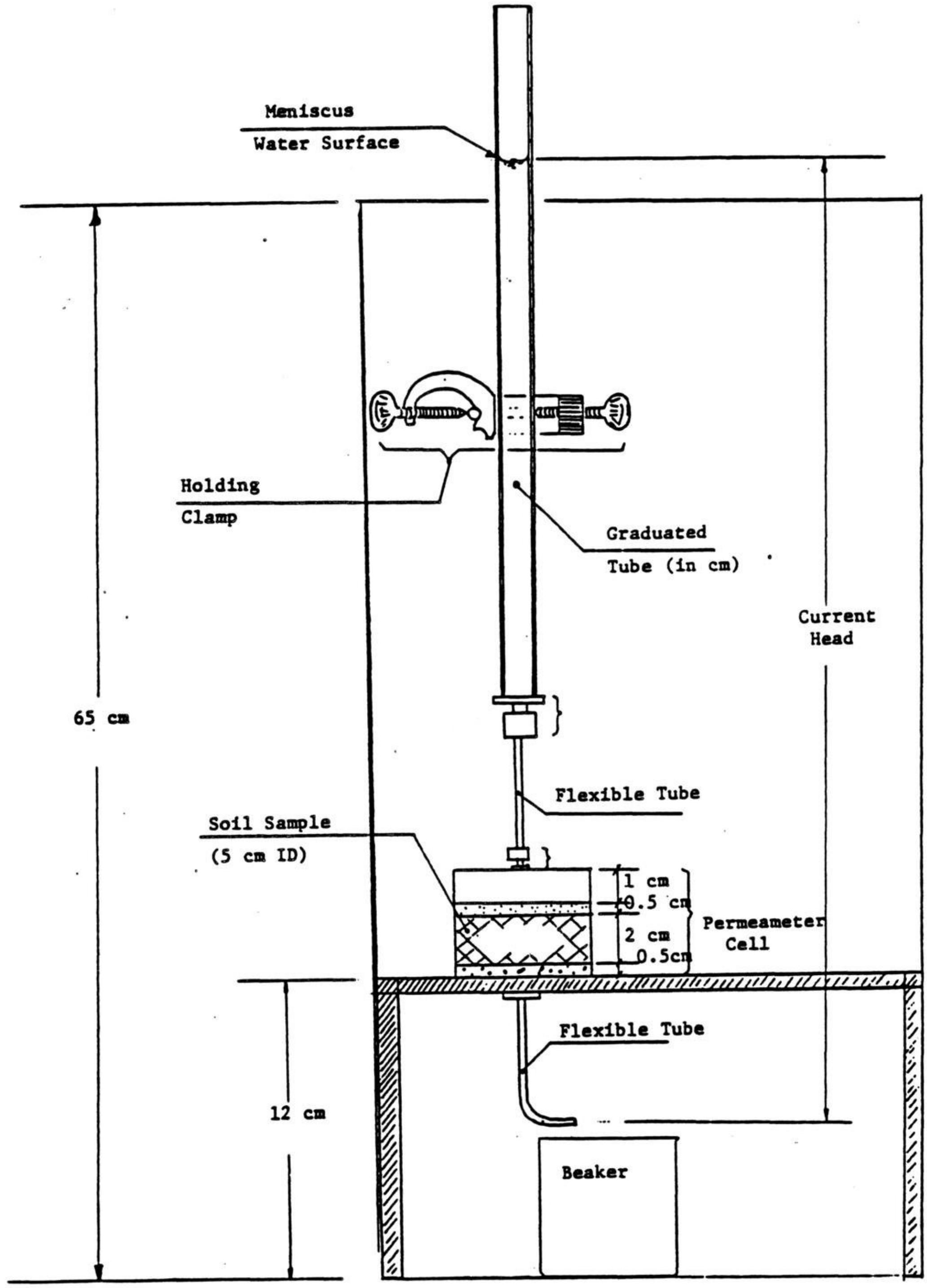

Figure 1. Model A Slurry Permeameter (Not to Scale)

kept at about 24 inches or less.

Model B permeameter, shown in Figure 2, is basically a sampling tube adapted to a permeameter. Thin-wall plastic tubing of about 3/8 inch in diameter was found to be a seemingly satisfactory means of retrieving samples from the annular space. Relatively small wall thickness (0.015 in.) of the tube is believed to cause the least disturbance during insertion. The small diameter is also believed to minimize the impact on the remaining sealant after withdrawal by leaving a reasonably small void behind which is immediately filled with the sealant. The sampling tube has an area ratio (ratio of the tube wall area to the sample cross-sectional area) of 8.2%, which is well within the suggested limits (less than 10 to 15%) for minimal soil disturbance during sampling (Hvorslev, 1949). A small vacuum is maintained on the sampling tube during withdrawal to ensure sample recovery. After sampling, the sampling tube is fitted with the plexigalss porous stone holders, one of which has a stand pipe to provide the driving head.

Permeability testing is carried out in a manner similar to the procedure described by Das (1982) for falling (variable) head permeability test, where Model A or B permeameter is used. The procedure involves setting up an initial driving head above the top surface of the specimen. The head difference, as measured from the bottom porous stone water surface, drops as water permeates through the specimen. Readings of head difference and time are taken periodically and the coefficient of permeability, k (hydraulic conductivity) is calculated from the following relationship:

$$k = \frac{aL}{A\Delta t} \ln \frac{h_1}{h_2}$$

where

a: cross-sectional area of the stand pipe

L: specimen length

A: specimen cross-sectional area

Δt: elapsed time

h_1: initial head difference

h_2: head difference after Δt

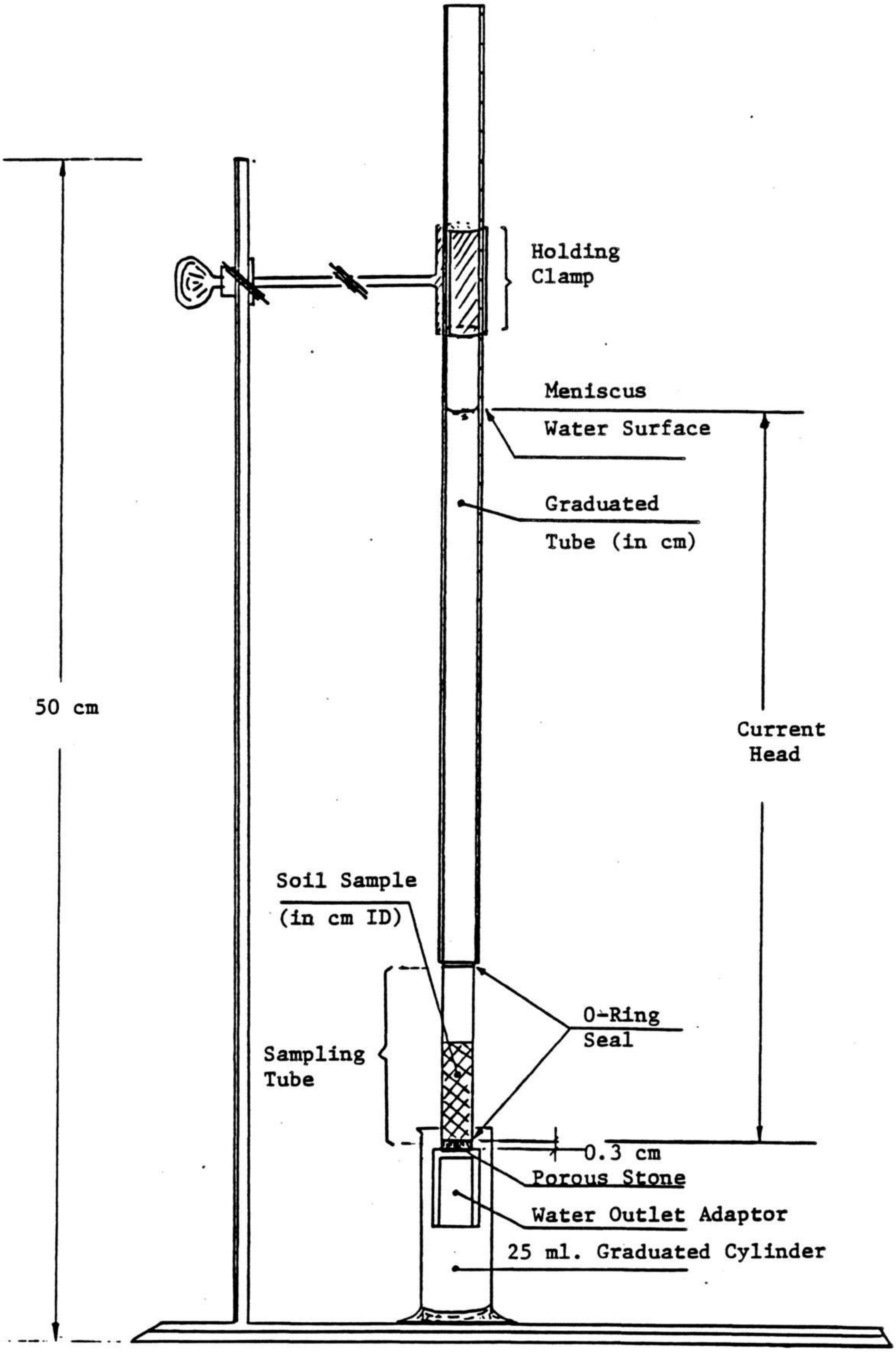

Figure 2. Model B Slurry Permeameter (Not to Scale)

Shrinkage Test

In order to obtain a relative measure of the volume change characteristics of various quick-gel slurries, shrinkage limit test is considered. This test provides the water content below which there is no more volume shrinkage due to drying. It also provides the percent volume change from the initial condition to drying. This test is performed in accordance with ASTM Standard D-427.

SMALL ANNULAR SPACE MODEL

Prior to setting up the model, it was desired to get a feel of how the sealant can be placed and is likely to perform in the annular space and how we can measure its performance can be measured as a sealant. This necessitated the construction of a small annular space model. It consisted of a 10-in. diameter PVC pipe with a porous bottom. Two other pipe sections were embedded concentrically in this pipe creating two annular spaces. The outer annular space was filled with the sand simulating the subsurface material (Portage Sand-Granusil 2040) that will be used in the large model test. The grain size characteristics of the sand is given in Figure 3. The inner annular space of the small model was filled with bentonite. Subsequently, the upper part of the middle pipe section was pulled up providing direct contact of the slurry with the sand. Water can be placed above the sealant and outfiltration from the base of the sealant in the inner annular space and from the base of the sand in the outer annular space can be monitored as shown in Figure 4.

Our first test caused a failure of the sealant, i.e., it never sealed and large water loss caused cavities. An infiltration test resulted in 1.37 cc/s outfilitration which decreased to 0.50 cc/s in half an hour. A more carefully run second test incorporated certain features which resulted in a more reasonable outcome. In the second test, the slurry was tremied into the annular space preventing possible entrapment of air. It was agitated for 15 minutes by rotating a rod in the annular space while maintaining flow of water from the slurry under a moderate head. Afterwards, the drainage was shut off and the slurry was allowed to gel for 24 hours. The sealant appeared intact the next day and drainage of access moisture was allowed. The outflow slowed and virtually stopped in a few hours. At that time, water was added above the

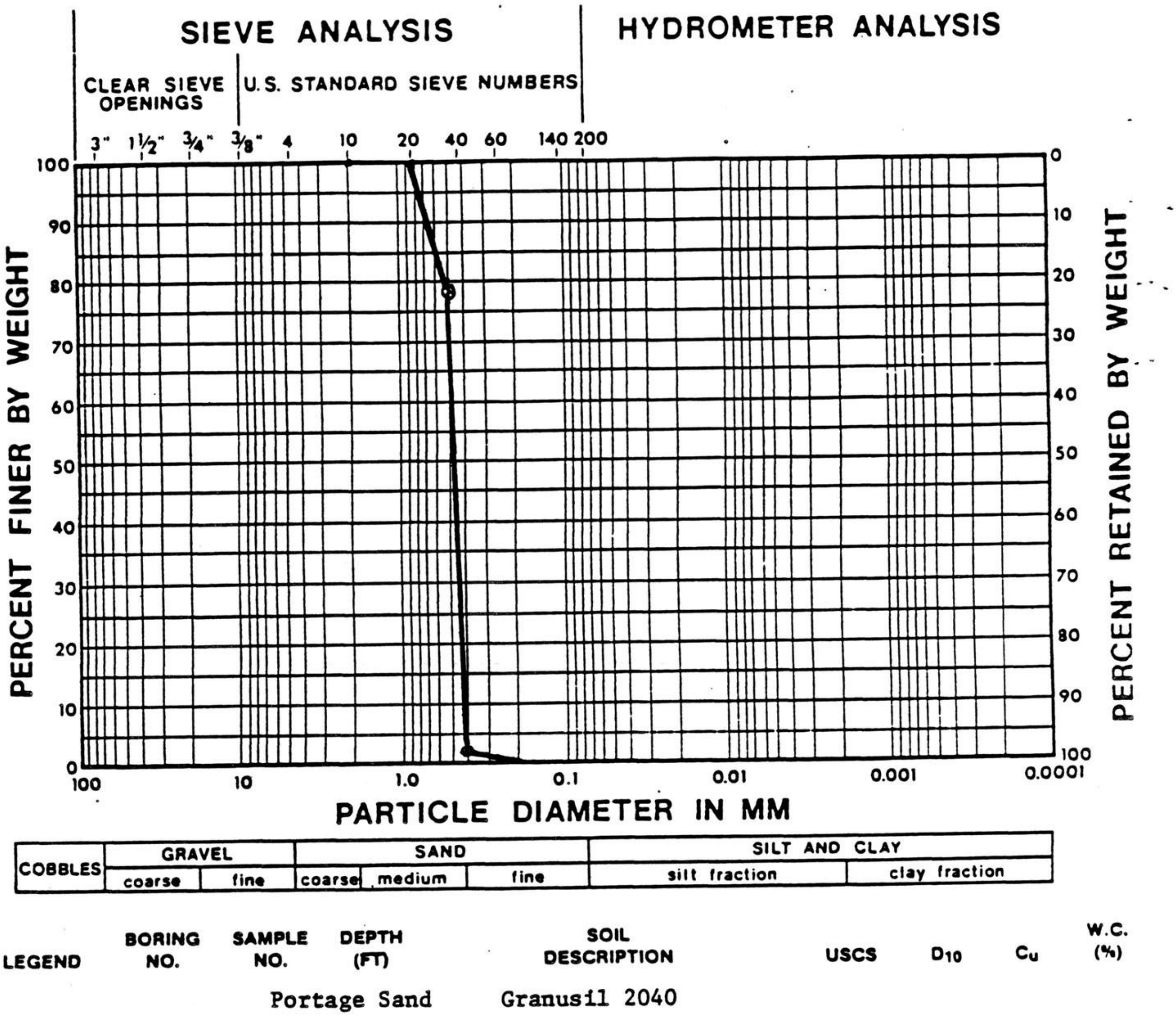

Figure 3. Grain Size Distribution of Portage Sand Granusil 2040

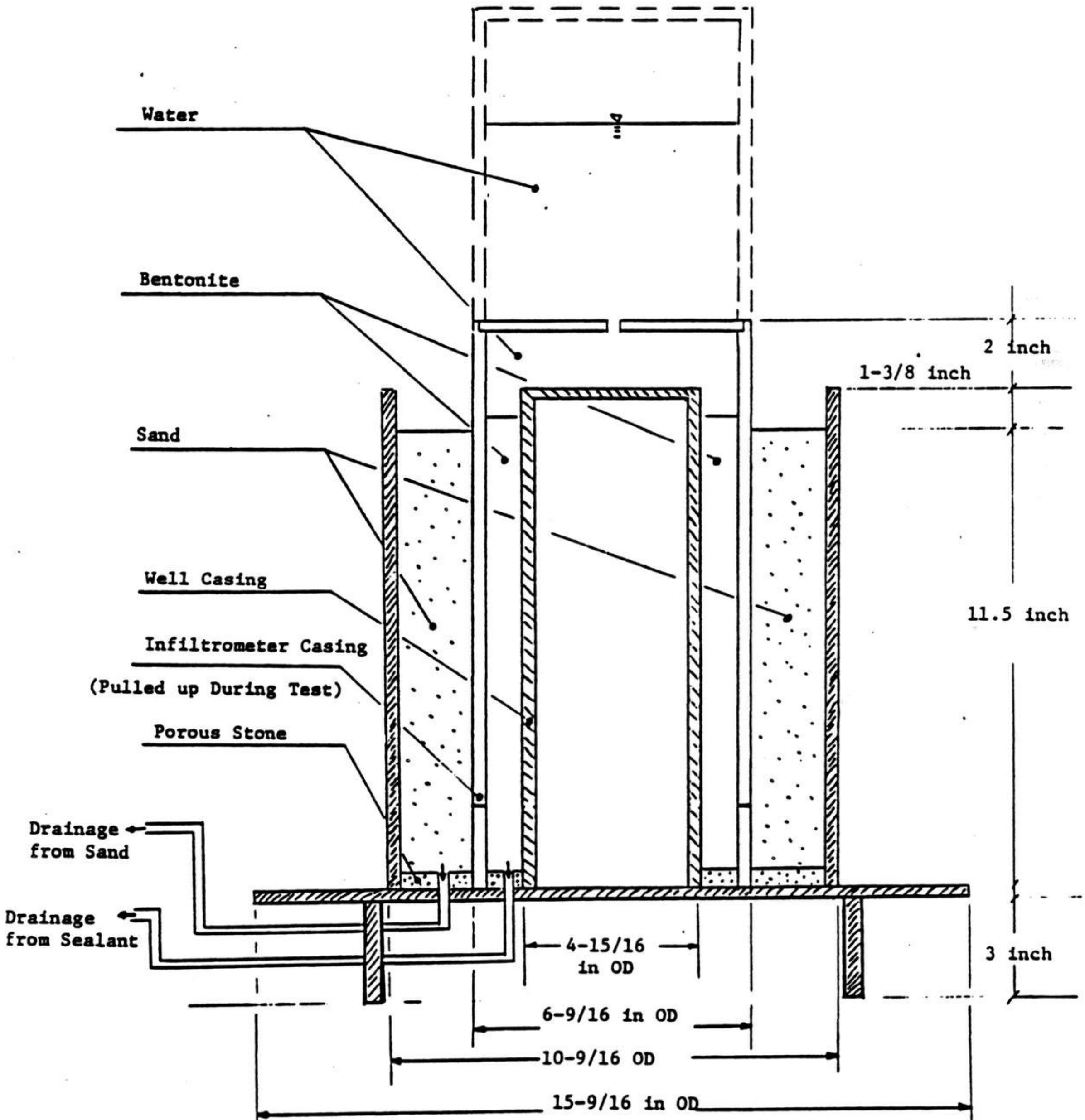

Figure 4. Small Annular Space Model (Not to Scale)

sealant to cause infiltration (and perhaps some consolidation) which caused the resumption of the outflow. Outflow from the sand in the outer annular space was about 9×10^{-5} cc/s and from the sealant in the inner annular space was about 7×10^{-4} cc/s. We believe the procedure used in the second test allowed the formation of a filter cake.

WELL MODEL EXPERIMENT

A well model utilizing four wells in a sand filled plexiglass container, 1.5 ft x 6 ft x 6 ft deep, was used in this main phase of the study. The container was built in sections, each section 2 ft high to facilitate filling and emptying of the container. Each section is reinforced at its edges and mid-height by aluminum angle sections. These angle sections also serve as the means of assembling the container sections together by bolts and nuts. The bottom section of the soil container is mounted on a hollow water tank at its base. The water tank has a series of 1/4-inch holes atop to allow water flow to and from the soil container. A porous stone covers the top of the water tank. Rubber strips are used between the tank sections to seal the joints.

In setting up the model, 8-inch diameter PVC pipes (1/3-inch in wall thickness) were placed vertically on the bottom porous stone of the first container section at equal center-to-center spacings of 1.5 ft. The sand representing the aquifer material (Portage Sand-Granusil 2040) was then shoveled into this bottom container section. After filling the bottom container section, water was applied to moisten and compact the sample. The excess water drained from the bottom. The next section of the container was then bolted on and similarly filled with sand and watered. Finally, the third section was placed and filled using a hoist.

After filling the container with sand, the metal well casings (ASTM A120 4-inch diameter steel well casing pipes with 1/4-inch wall thickness) were placed concentrically within the 8-inch diameter PVC temporary outer casing pipes. Completely mixed batches of quick-gel slurry were placed in the annular space of the four simulated wells using a tremie tube extending to the bottom of the annulus. Each well was sealed with a separately mixed slurry, each based on a Marsh Funnel viscosity of 50, 70, 90 and 170 sec/quart.

Following the emplacement of the slurry into the annular space between the well casing and the temporary outer casing pipes, the outer casings were removed by slow lifting using the hoist. This allowed direct contact of the slurry with the sand aquifer material. Subsequently, each well was fitted with a short section of 8-inch PVC casing pipe at the surface. These infiltrometer casings were pushed in 1 ft below the surface of the sand at the sand-slurry contact surface. These casings were fitted with a graduated water level burette to indicate the level of the water placed in the annular space during infiltration experiments. The sketch of the well model along with the infiltrometer casings fitted is shown in Figure 5, and a photograph of the model is given in Figure 6. The schedule of the various activities during the experiment is given in Table 1.

Following the emplacement of the slurry in the annular space, it was noted that the surface of the slurry sealant subsided. This subsidence was made up from the top by adding more slurry. The amount of the slurry added in the case of different viscosity sealants is given in Table 2. The subsidence of the sealant took place on a continuous basis over two weeks until it finally slowed down considerably. Two weeks after setting the model up, permeability samples were extracted 6 inches below the surface of the sealant using the thin-wall plastic sampling tube.

After retrieving the permeability samples, an infiltration test was initiated. Approximately 5 liters (1.3 gallons) of water adjusted to a temperature of 21°C (70°F) was placed in the annular space above the sealant between the well casing and the infiltration casing. Water level readings were taken on a periodic basis using the water level burettes. Time to time, additional 5-liters of water had to be added to replenish the infiltration water source on the sealant. Seven weeks after the initiation of the infiltration tests, remaining water in the infiltrometer was syphoned out. The sealant was examined and a second set of permeability samples were retrieved from a depth of 6 inches below the sealant surface. It was noted that the sealant continued to subside during these seven weeks. Figure 7 gives the depth of the sealant surface from the edge of the infiltrometer casing and the general description of its appearance for the four wells at different times. It is noted that the sealant in Well #3 with 90 sec/qt viscosity appeared best with basically an even surface with no visible cracks.

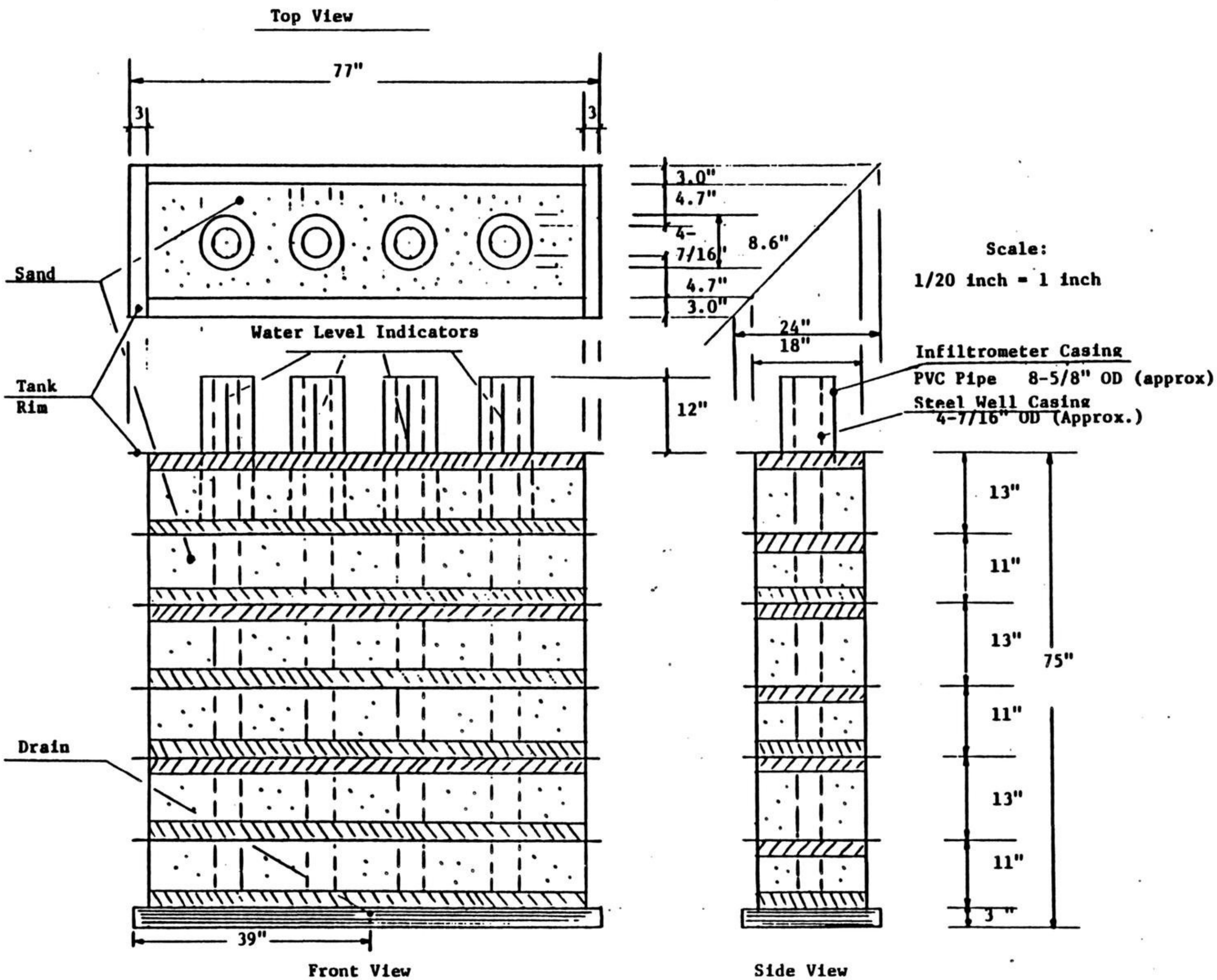

Figure 5. Sketch of Well Model

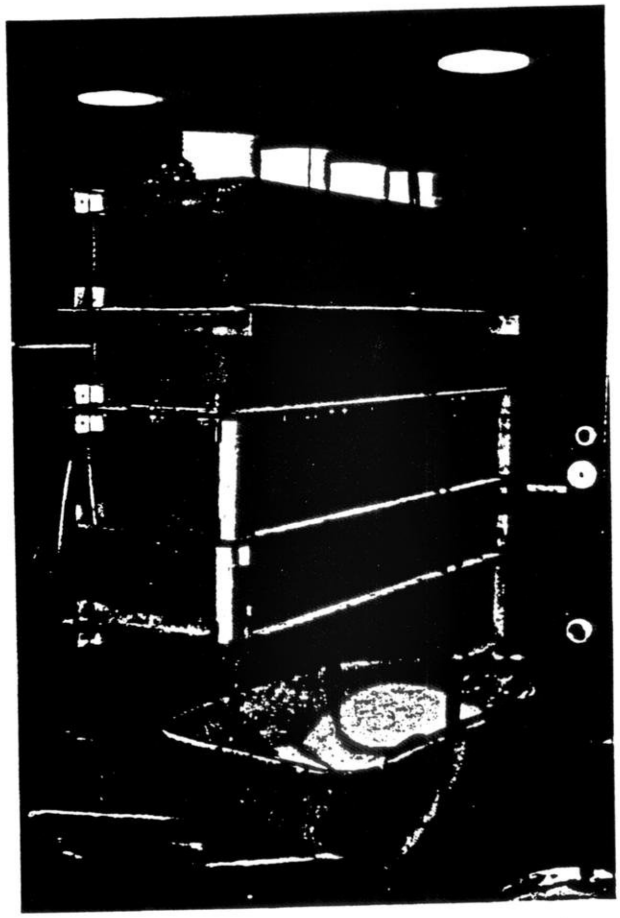

Figure 6. Well Model

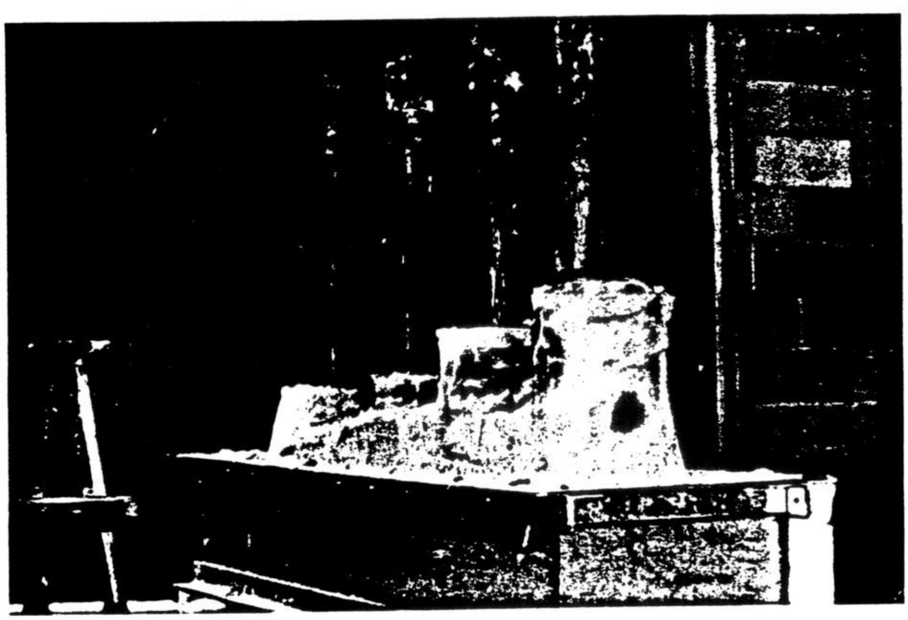

Figure 8. Disassembling the Well Model

Table 1. Schedule of Activities In the Well Model Experiment

Well	Marsh Funnel Viscosity of Sealant(sec/qt)	Emplacement of Sealant	Beginning of Infiltration Test and First Permeability Samples	Second Permeability Sampling	Beginning of Dyed Water Infiltration	Infiltrometer Casing Raised	Test Terminated
1	50	8/7/86	8/21/86	10/9/86	11/3/86	11/14/86	11/21/86
2	70	8/11/86	8/26/86	10/14/86	11/3/86	11/14/86	11/21/86
3	90	8/12/86	8/27/86	10/15/86	11/3/86	11/14/86	11/21/86
4	170	8/12/86	8/29/86	10/17/86	11/3/86	11/14/86	11/21/86

Table 2. Subsidence of Quick-Gel Sealant in the Annular Space

Well	Marsh Funnel Viscosity of the Sealant(sec/qt)	Subsidence During the First Two Weeks (in)	Addtional Subsidence During Nine Weeks Infiltration (in)	Additional Subsidence Until the Termination (in)	Total Subsidence (in)
1	50	96.5	11	6	113.5
2	70	61.5	5	6	72.5
3	90	93 or 55	>2	8.5	>65.5
4	170	72.3		7	>79.3

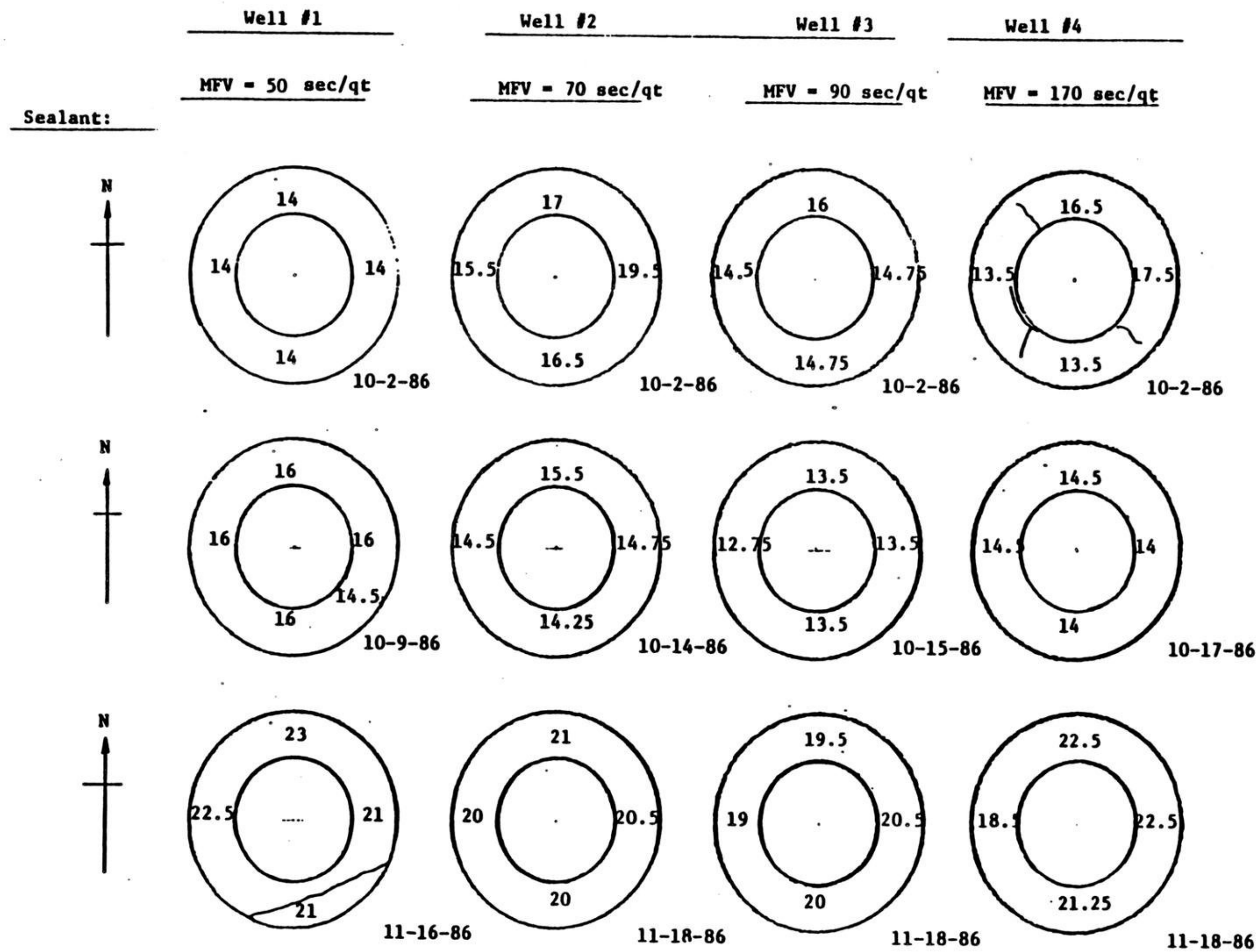

Figure 7. Sealant Surface Elevations Measured in Inches from the Top of the Infiltrometer Casing

The sealants in Wells #1 and #2 (50 and 70 sec/qt, respectively) often had uneven surfaces. The 170 sec/qt-viscosity slurry in Well #4 had often uneven surface and at times exhibited radial cracks and circumferential separation at the well casing-sealant contact. A comparison of the magnitude of subsidence during the first two weeks prior to the infiltration test as well as during the infiltration test as given in Table 2, also indicate that the 90 sec/qt subsided the least in comparison to the others.

The water infiltration tests were resumed after sampling of the sealants and continued for another four weeks to establish the long-term infiltration characteristics. At the end of this period, remaining water was again syphoned out and replaced with 5 liters of water colored with about 30 drops of Intracid Rhodamine. The objective of infiltrating the dyed water was to identify flow paths, especially the discontinuities when the model is taken apart. Infiltration of the dyed water was continued until nearly all of the liquid infiltrated after 11 days. At this point, the infiltrometer casing was pulled out about 6 inches leaving an embedment of only six inches. The infiltration test was resumed and continued for another week.

At the termination of the infiltration experiment, the model was taken apart section by section starting from the top. The sand modeling the acquifer and the bentonite seal were examined slice by slice for clues with regard to where the infiltrating water was going and the condition of the sealants. Another set of permeability samples were taken from the sealants and the filter cakes at a depth of 5 feet. Figure 8 shows the model while being taken apart. The notes taken during this operation are contained in Appendix B.

SEEPAGE ANALYSIS

In order to gain a sense of the infiltration conditions, a finite element analysis of the seepage in the well model was undertaken using a program known as ANSYS. This analysis provided a theoretical basis for the interpretation of the test results.

Program Description

ANSYS program is known as one of the most powerful programs using the finite element method in solving several kinds of engineering problems. The ANSYS has been developed for engineering applications since 1970, and has been used by many consulting firms. The available types of elements in this program are more than fifty in static and dynamic analyses, and more than twenty in heat transfer. Because of the many choices in element type, the program is widely used including seepage problems. Generally, this program is divided into three phases: preprocessing phase, solution phase, and postprocessing phase. The data input for the ANSYS program has been designed to make the problem definition as easy as possible. In the preprocessing phase, mesh generation, setting of the boundary conditions, and defining the material properties are easily performed. In the postprocessing phase, results can be subjected to algebraic modification, differentiation, and integration.

The basic governing equation in the thermal analysis (heat flow) is

$$\frac{\partial}{\partial x}\left(k_{xx}\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_{yy}\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_{zz}\frac{\partial T}{\partial z}\right) + \dddot{q} = \rho C \frac{\partial T}{\partial t} \tag{1}$$

where

k_{xx}, k_{yy}, k_{zz} = thermal conductivities

T = temperature

$\dddot{q}$ = internal heat generation per unit volume

ρ = density

t = time

C = specific heat

In the finite element formulation, this governing equation could be formulated as follows:

$$\{\underline{C}\}\ \{\underline{\dot{T}}\}\ \{\underline{K}\}\ \{T\} = \{Q\} \tag{2}$$

where

$\{\underline{C}\}$ = specific heat matrix

$\{\underline{K}\}$ = conductivity matrix

$\{\underline{Q}\}$ = nodal heat flow

The governing equation of water flow through porous medium is given as:

$$\frac{\partial}{\partial x}\left(k_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_{zz}\frac{\partial h}{\partial z}\right) + \dot{q} = C\frac{\partial h}{\partial t} \quad (3)$$

where

k_{xx}, k_{yy}, k_{zz} = permeability
h = hydraulic load
t = time
C = porosity
$\dot{q}$ = internal flow injection rate

There is one-to-one analogy between Equations (1) and (3). Therefore, using the ANSYS in analyzing a seepage problem, the following substitutions have to be made:

T for h: temperature replaced by hydraulic head
q for q: nodal heat flow rate replaced by discharge rate

There are two different types of boundary conditions:

a. impervious boundary requires zero normal velocity since $v_s = -k\frac{\partial H}{\partial s}$

this boundary condition requires $\frac{\partial h}{\partial s} = 0$

b. pervious boundary: this boundary condition requires h = constant

The following steps generally describe how the ANSYS is used in solving the seepage problems:

1. Select the kind of problem that will be dealt with.
Because the governing equation of heat transfer problem, chooseoose KAN=
-1 in this program first.

2. Define the kind of element that will be used in the analysis.
In the ANSYS, there are more than twenty four heat transfer analyses. The isoparametric thermal element (ET = 55) was used in this analysis. The element has four nodal points with a single degree of freedom,

head, at each node.

3. Define properties of each material such as permeability.
   In order to simplify this problem, the anisotropic properties of soils was not considered here, i.e., the permeabilities, k_{xx}, k_{yy}, and k_{zz} all are equal.

4. Mesh generation.
   Include the coordinates of nodes and the connection order of the elements.

5. Determine whether a steady state or a transient flow problem to be solved.
   Because the experiments of this project have been carried out for a considerable period of time, steady state was assumed to be reached.

6. Prescribe the boundary conditions.
   Constant flow rate and constant hydraulic head options at the inflow boundary can both be employed in this analysis.

7. Get into the solution phase.

8. Print the results.

An example of the output of the ANSYS for the well experiment is shown in Figure 9. This figure shows the equipotential lines in the annular space and portion of the sand surrounding the annular space.

The bentonite sealant permeability samples were retrieved from the annular space at three different times after the emplacement and are referred as 2-Week, 9-Week, and 15-Week samples. The first two samples were taken from a depth of 6 inches below the surface. The 15-Week samples were taken at a depth of 5 to 6 ft along with the samples of the filter cake. Similarly, 50 sec, 70 sec, 90 sec, and 170 sec refer to the Marsh Funnel viscosity of different bentonite slurries used. In the seepage analysis, the first item that should be defined is the permeabilities of the sand, the bentonite sealant, and the filter cake. These permeabilities were estimated based on

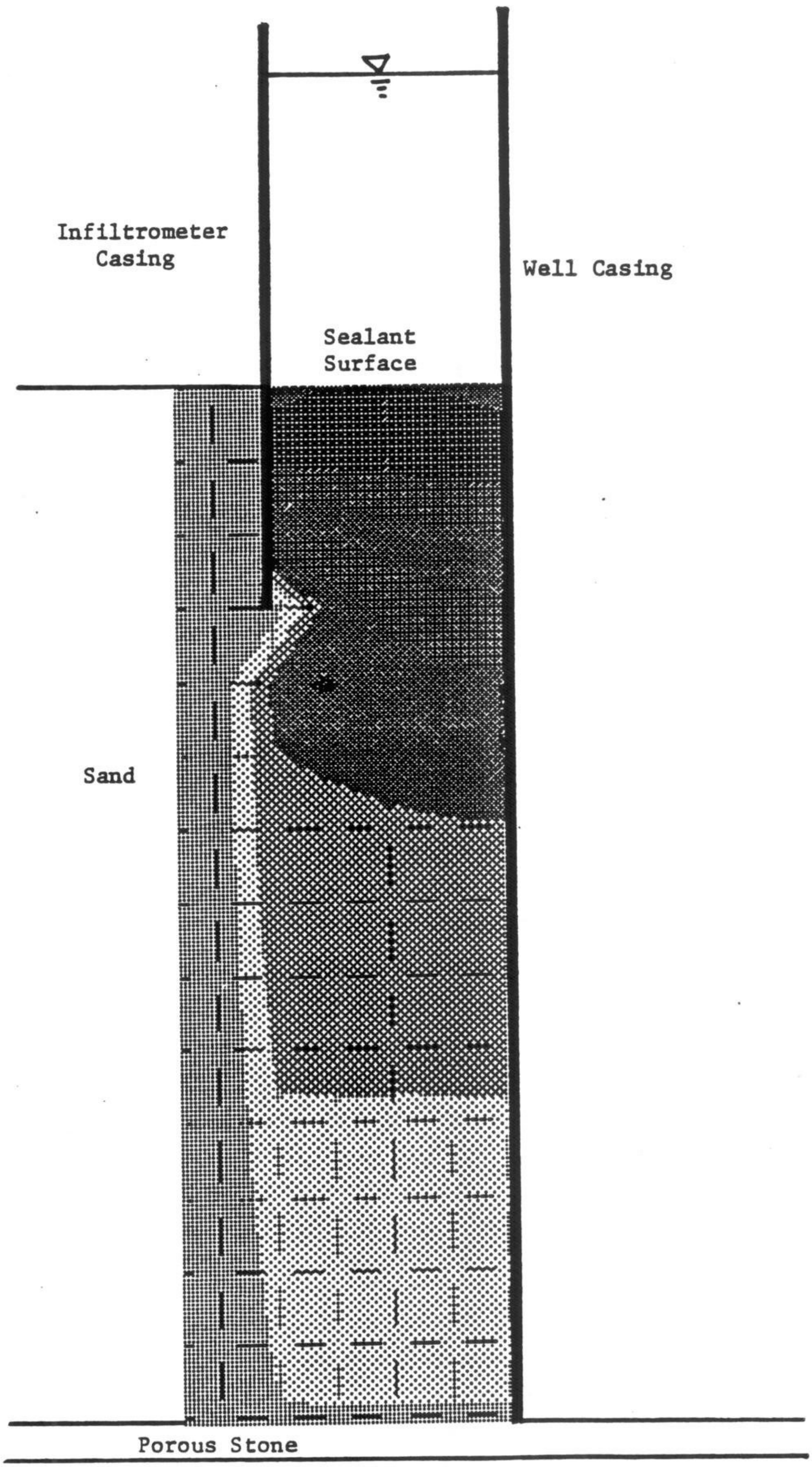

Figure 9. Zones of Equipotentials in Well Model from the ANSYS

the laboratory permeability tests performed on the samples. Another important item is to decide whether the boundary condition along the top surface of the sealant is a constant head or a constant flow rate boundary. The plots of water level versus time in the model experiment showed basically straight lines. That means $\Delta h/\Delta t$ is a constant. Therefore, the boundary condition on the top surface of the sealant can be taken as a constant flow rate boundary. Actually, the hydraulic head varies with time and would theoretically influence the flow rate. In order to more confidently use the constant flow rate assumption, first, a constant head boundary with different values was used in the analyses. As shown in Figure 10, the variable head does not exert a significant influence on the flow rate within the range it varied in the well experiment.

Sensitivity Analyses

Sensitivity analyses are employed to detect the influence of various factors. First of all, the sensitivity of the infiltration rate with respect to the permeability of the various zones, i.e., the sand, sealant, and filter cake were analyzed. The results are shown in Figure 11. We can conclude that the variation of the permeabilities of the sand and the filter cake do not impact the flow rates but changes in the permeability of the bentonite will result in appreciable changes in the flow rates.

The actual thickness and shape of filter cake was not precisely known. Therefore, the thickness and location of filter cake are varied in a reasonable manner as shown in Figure 12. In order to study the influence of the filter cake thickness, it was varied from 0.5 in. to 0.75 in. Moreover, it was assumed to be at different locations for the 0.5 in.-thick filter cake. The results are shown in Table 3. Because the difference between the permeabilities of the filter cake and the bentonite is small, the influence of thickness and location of filter cake on the results is not significant.

The impermeable boundary in the sand in the model experiment is not a circle. But in the computer analysis, this boundary was assumed to be circular for simplified axisymmetric analysis. The longest distance from the wall of the soil container to the center of the wells is 30.48 cm, and the shortest distance is 22.86 cm. All the computer program analyses assumed

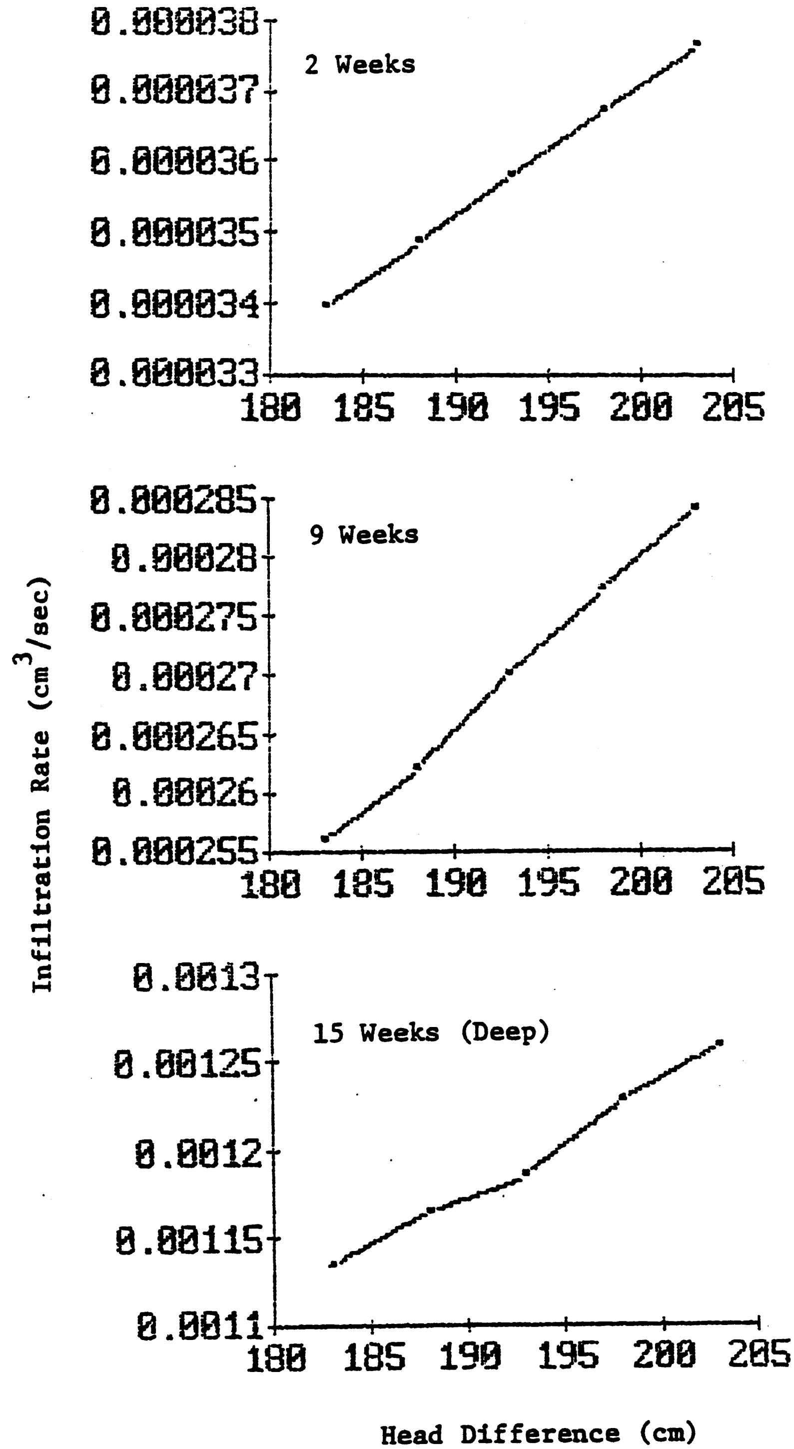

Figure 10. Infiltration Rate versus Head Difference in Well Model Experiment Using Permeabilities Measured at Different Times for Well #3

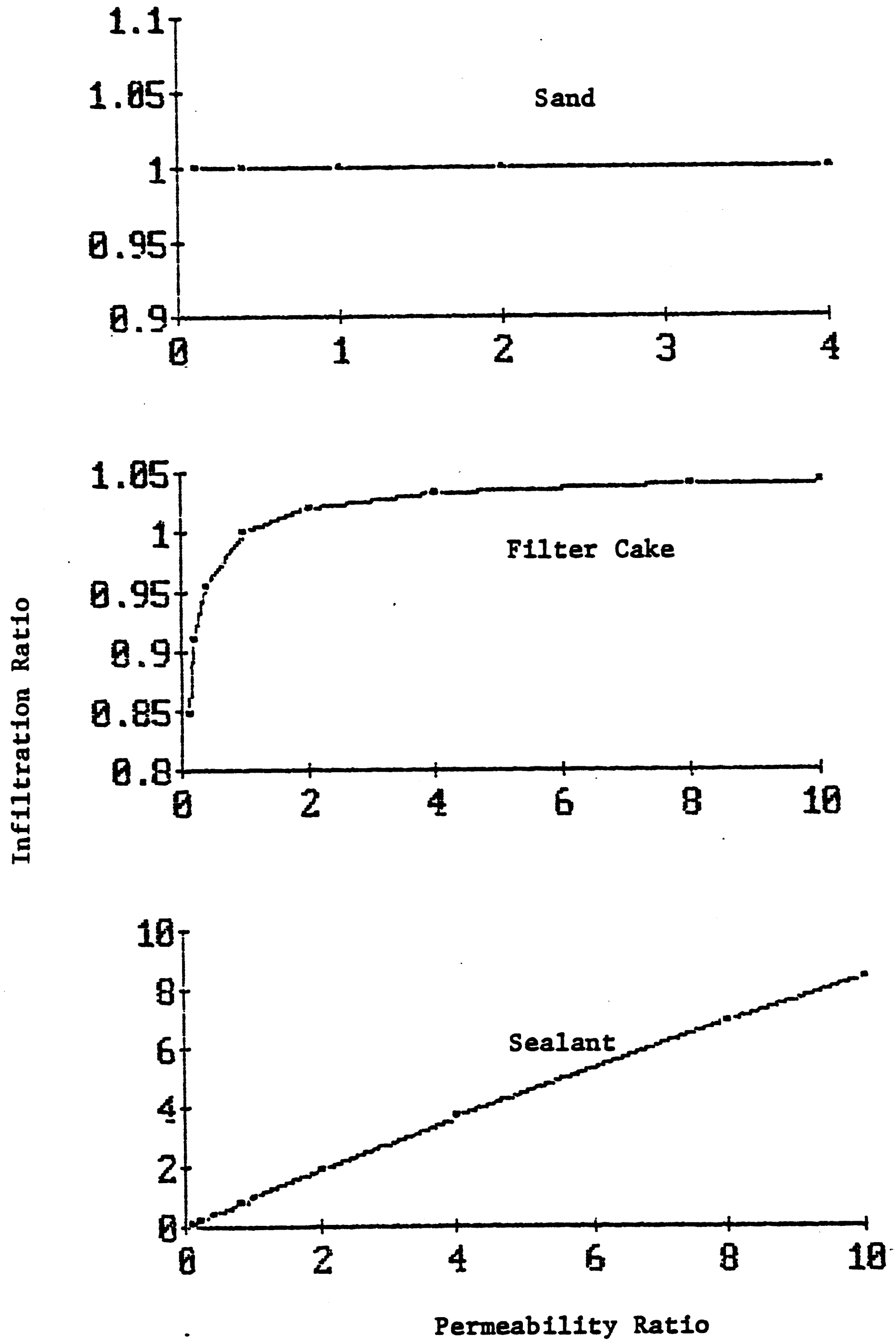

Figure 11. Sensitivity of Infilitration Rate to Permeabilities of Sand, Filter Cake and Sealant (Head Difference 193 cm, Reference Permeabilities: Sand 2.1x;0^{-1} cm/sec, Filter Cake 2.1x10^{-6} cm/sec and Sealant 5.0x10^{-6} cm/sec)

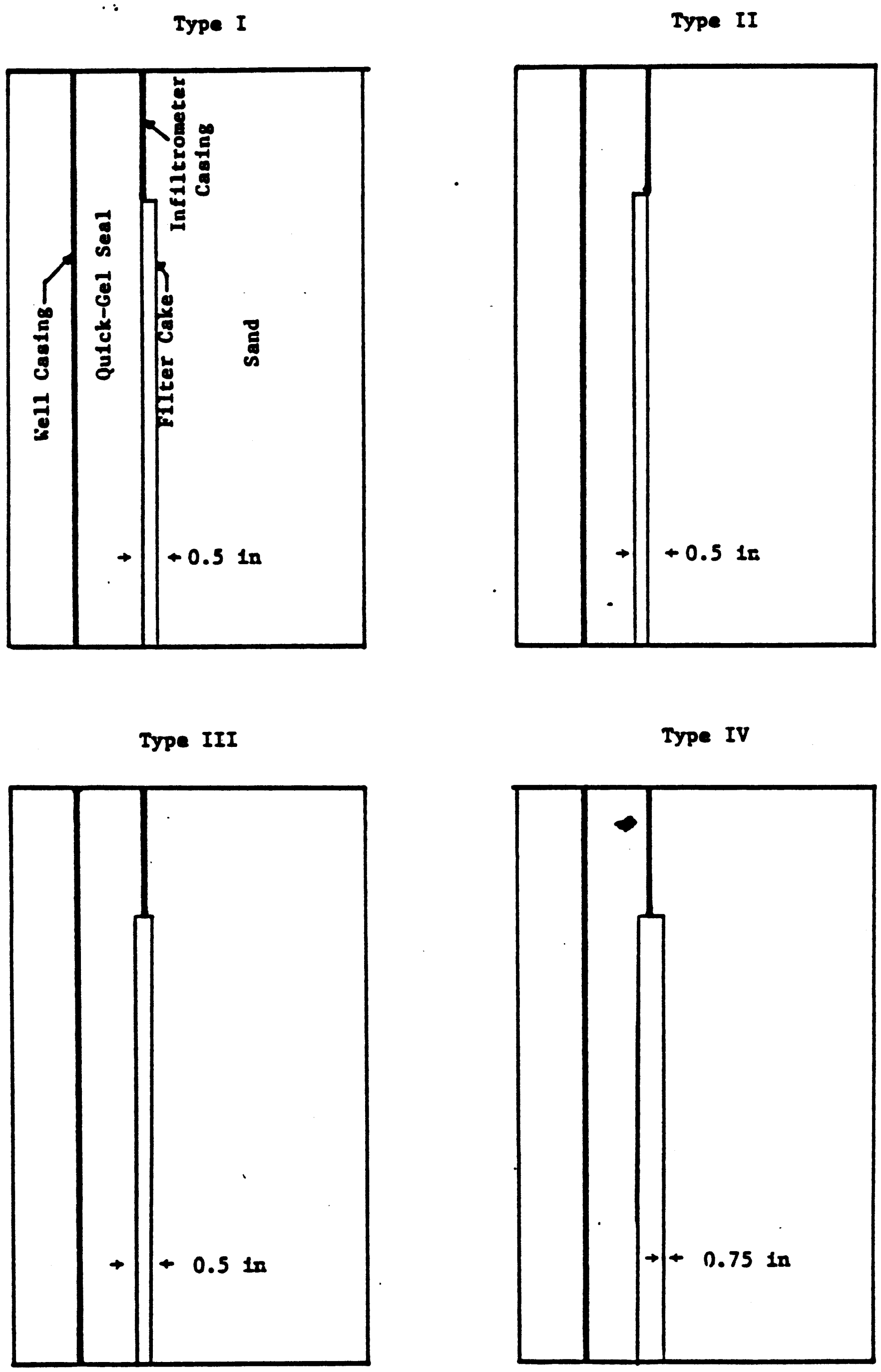

Figure 12. Filter Cake Locations and Thicknesses Used in the Sensitivity Analysis

Table 3. Sensitivity of Infiltration Rate to Thickness and Location of Filter Cake

	Type 1	Type II	Type III	Type IV
Infiltration Rate (cm^3/sec)	8.02×10^{-4}	8.32×10^{-4}	8.16×10^{-4}	8.09×10^{-4}

Note: Head Difference: 193 cm; Permeabilities: Sealant 4.0×10^{-6} cm/sec, Sand 2.1×10^{-1} cm/sec, Filter Cake 5.1×10^{-6} cm/sec.

30.48 as the distance to the impermeable lateral boundary. To understand the effect of this boundary, different distances to this boundary were assumed. As the results in Table 4 show, the assumption regarding the position of the impermeable lateral boundary in the ANSYS is acceptable.

RESULTS

The results of the material property tests, the infiltration tests in the well model experiment, and the analysis of seepage by the finite element method are presented in this section.

Marsh Funnel Viscosity, Mud Weight and Gel Strength

One of the earliest tasks in the study involved the determination of the characteristics of the Quick-gel slurries and developing reproducible procedures for preparing slurries at a given viscosity. Figure 13 gives the relationship between Marsh Funnel Viscosity (MFV) versus percent solids or mud weight. These determinations were made at different times after mixing of Quick-gel and fresh water to study the effects of aging. The slurry was mixed again prior to MFV measurement after the waiting period. Figure 13 shows that Quick-gel is an effective viscosifier building viscosity rapidly at solid percentages of 5% to 7%. The shape of the curves and the quantities involved are very similar to the ones reported in the literature (Driscoll, 1986). Aging tends to increase viscosity, with the effect being more pronounced at higher solid contents. The range of this effect is less than 5 sec/qt to about 15 sec/qt. Table 5 gives the percent solids used in preparing the various viscosity slurries used in the well experiments based on the MFV determinations made immediately after the initial mixing.

The effect of temperature on the measured MFV of drilling fluids was reported (Driscoll, 1986). For the typical laboratory conditions, the water temperature may vary about 10° F. Figure 14 shows the MFV determinations made at 60°F or 70°F and at different solid contents. The influence of temperature on measured MFV appears to be negligible in this range of temperatures.

The Marsh funnel has been used to some degree to obtain a measure of the gel strength of muds as well as viscosity (Rogers, 1963). In making the gel

Table 4. Sensitivity of Infiltration Rate to Distance to Impermeable Boundary

Distance (cm) to Impermeable Boundary	30.48	27.94	20.54
Infiltration Rate (cm^3/sec)	9.66×10^{-4}	9.66×10^{-4}	9.66×10^{-4}

Note:
Head Difference: 193 cm/s; Permeabilities: Sealant 5.0×10^{-6} cm/sec, Sand 2.1×10^{-1} cm/sec, Filter Cake 2.1×10^{-6} cm/sec.

Table 5. Percent Quick-Gel versus Marsh Funnel Viscosity Used in Preparing Slurries

Percent Quick-Gel*	Marsh Funnel Viscosity (sec/qt)
5.4	50
6.3	70
6.7	90
7.2	170

* Weight of Quick-Gel as a percentage of the weight of water it is mixed with.

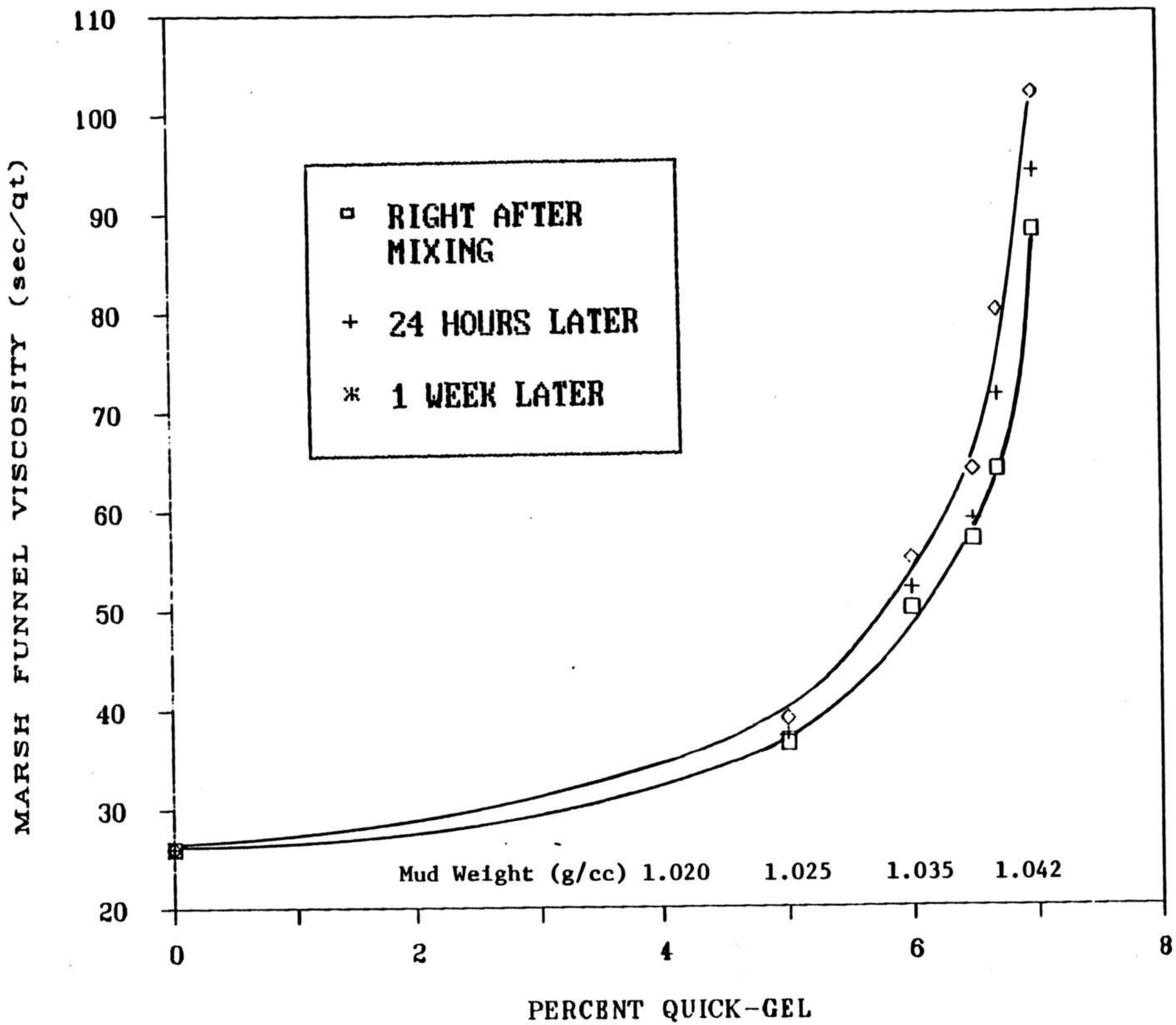

Figure 13. Marsh Funnel Viscosity versus Percent Quick-Gel

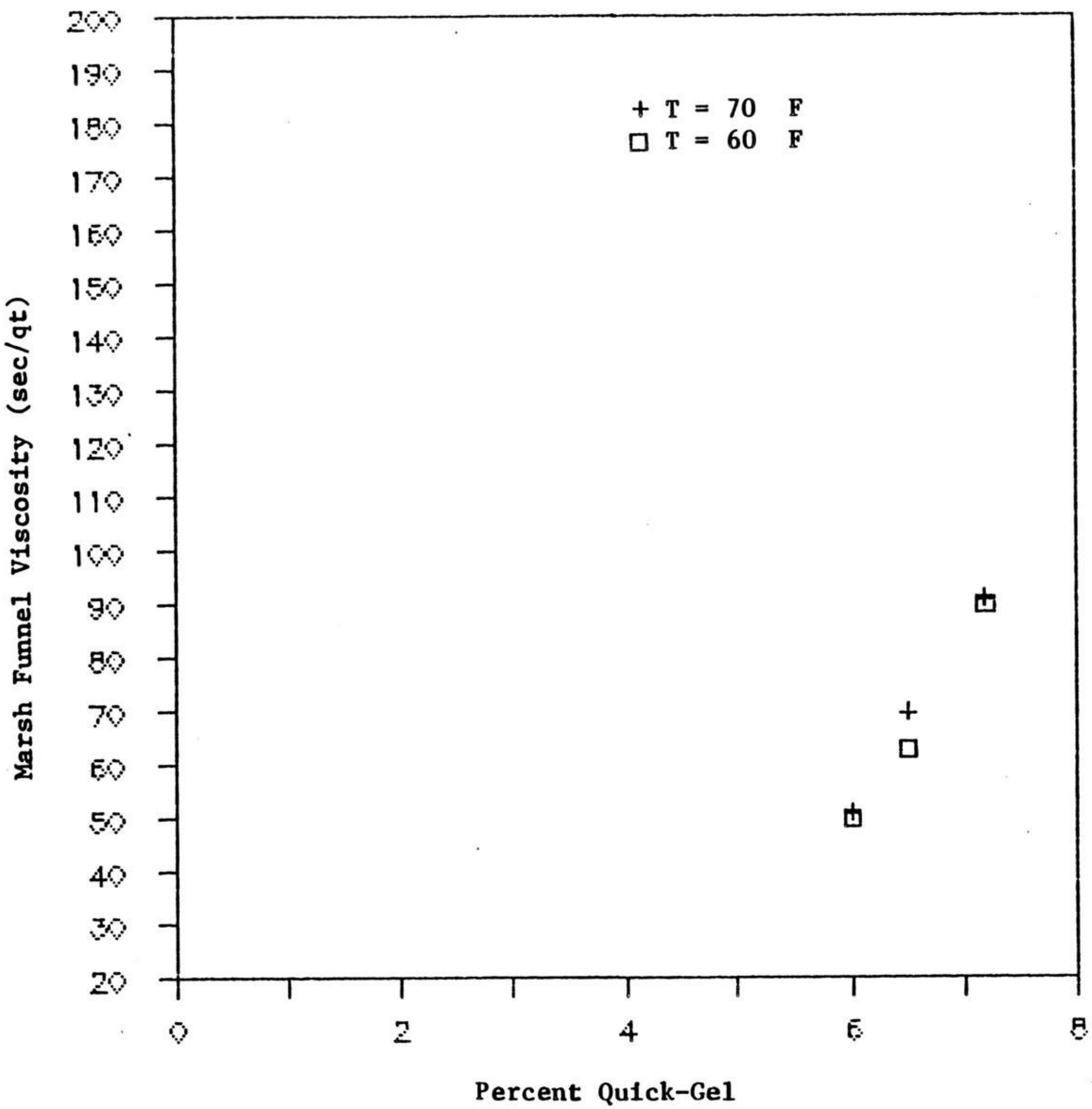

Figure 14. Marsh Funnel Viscosity versus Percent Quick-Gel at Two Temperatures

strength tests, the viscosity time in seconds is first determined with minimum delay between filling the funnel and making the measurement. The funnel is then refilled and allowed to stand quiet for 10 minutes after which the viscosity is again measured. The time difference in seconds between the first and second measurements gives the gel strength in seconds. This method has been largely supplanted by the Stormer viscosimeter in recent years. The shearometer is also used in obtaining a measure of the gel strength. In this method, a standard aluminum cylinder is placed on the slurry and allowed to sink into it for 10 minutes in the shearometer cup. The gel strength is read at the end of this period from the scale attached to the center of the shearometer cup in lb/100 sq ft. The gel strength of slurries with varying MFV's was determined by both of these methods. The results are given in Tables 6 and 7.

Filtration

The ability of the Quick-gel to rapidly form a filter cake of low permeability on a porous formation is a desirable property, not only important for hole stability, but also important for the sealing qualities. The thickness of the filter cake is related to the type and concentration of solids suspended in the mud. Two muds, both having a MFV of 45 sec/qt but different mud weights, are known to form filter cakes varying 36 times in volume on sandstone. As soon as bridging of the openings in the formation has occurred, the sealing property of the mud becomes dependent upon the amount and physical state of the clay in the mud, and not on the permeability of the formation. The wall building test consists of determining the rate at which fluid is forced from a filter press containing the mud sample under specified conditions of pressure and time (usually 100 psi and 30 minutes) and measuring the thickness of the residual solids film deposited on the filter paper by the loss of liquid. The results of the infiltration tests using the Baroid low pressure filter press are given in Figures 15 and 16 in terms of filter loss (filtrate volume accumulated in 30 minutes) and filter cake thickness as a function of percent solids. The slurries were prepared at appropriate solid concentrations to yield 50, 70, 90 and 170 sec/qt MFV's.

Shrinkage Characteristics

Table 6. Marsh Funnel Gel Strength of Quick-Gel

Percent Quick-Gel (%)	Mud Weight (lb/gal)	Marsh Funnel Viscosity (sec/qt)	Temperature (°F)	Marsh Funnel 10-min Gel Strength (sec/qt)
5.5	8.60	51	70	54
6.2	8.63	70	70	77
6.7	8.66	93	70	106
7.2	8.70	165	70	188

Table 7. Shearometer Gel Strength

Percent Quick-Gel (%)	Marsh Funnel Viscosity (sec/qt)	Shearometer 10-min Gel Strength (lb/100 sq ft)
5.3	48	56 sec* 56 sec**
6.3	72	7.0* 7.5**
6.7	90	9.3* 10.0**

* Immediately after mixing.

** 10 minutes after mixing.

If the cylinder settles at the bottom before 1 min., the time it takes to settle is entered as in the case of 5.3% Quick-Gel.

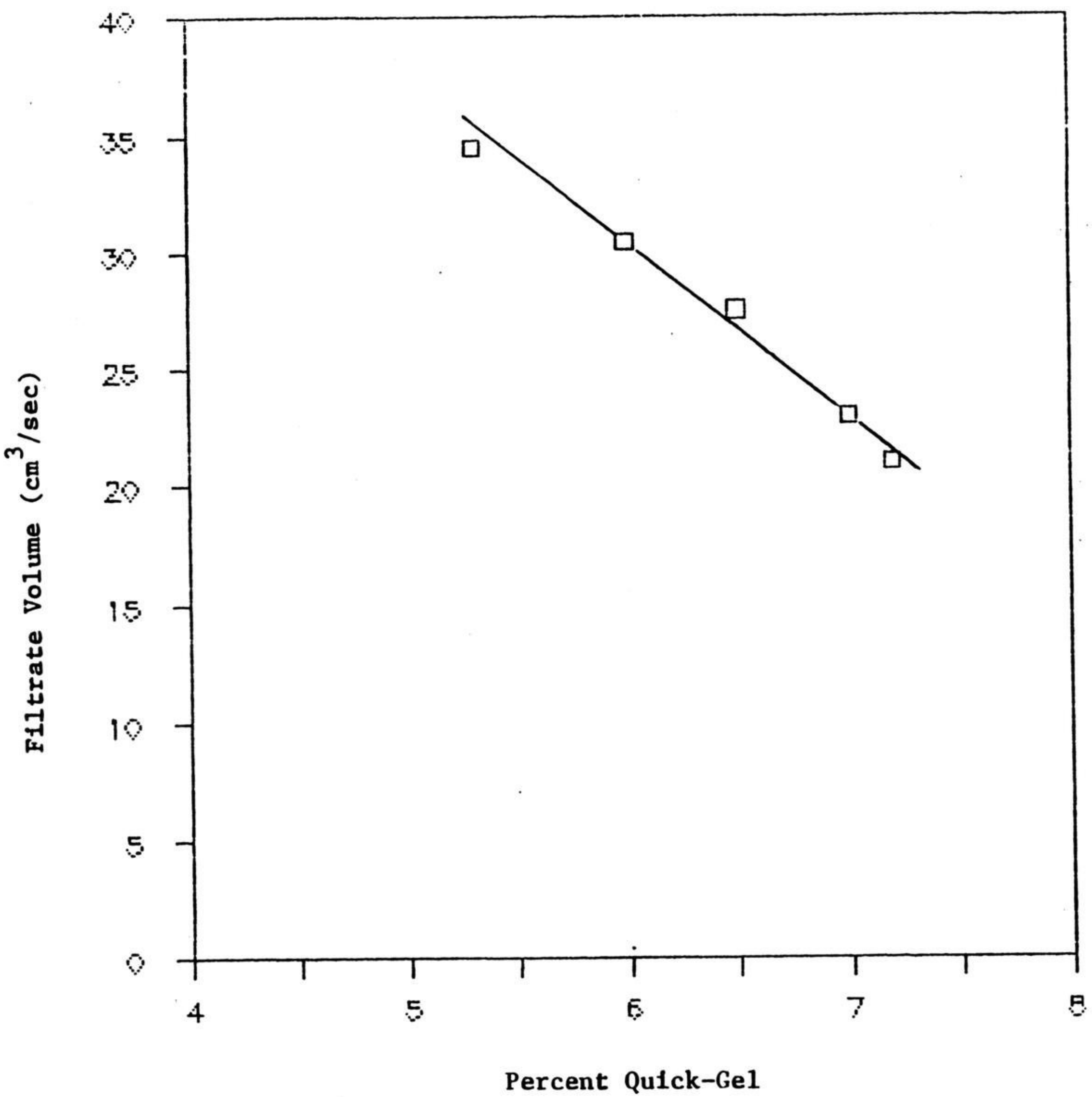

Figure 15. Filtrate Volume versus Percent Quick-Gel

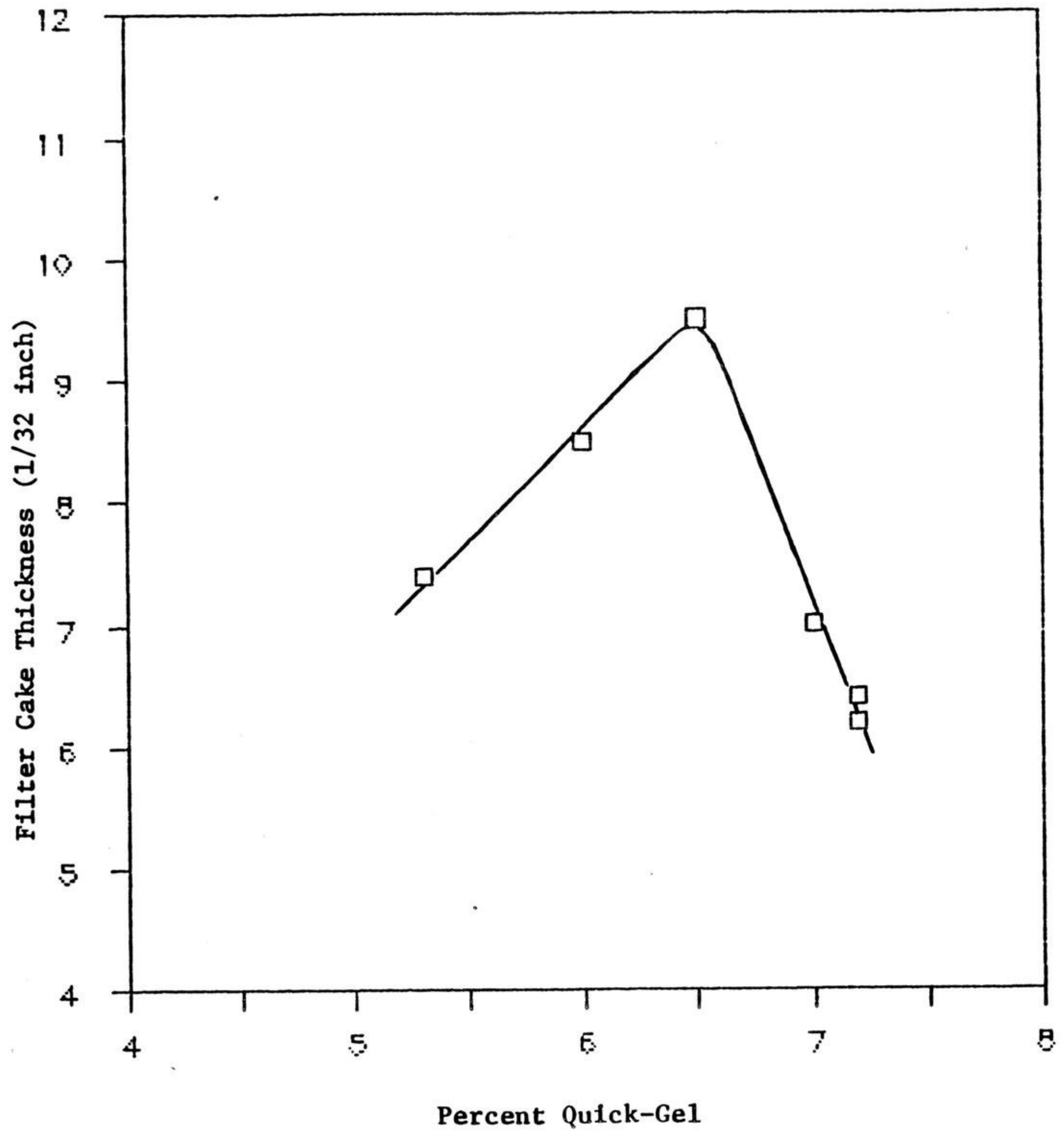

Figure 16. Filter Cake Thickness versus Percent Quick-Gel

The shrinkage limit test results are given in Table 8 in terms of percent Quick-gel in the mud. Shrinkage limit decreases considerably from 116% at a MFV of 43 sec/qt to 22% at 90 sec/qt. These values are very high when compared with the shrinkage limit of soils. Degree of shrinkage (volume change as percentage of the initial volume) and volumetric shrinkage (volume change as percentage of the final volume) follow the same trend of decrease with increasing percent Quick-gel. There is about 97% reduction in volume as a result of complete drying of the mud. The ratio of volume change to water content change (or the dry unit weight at the shrinkage limit) i.e., shrinkage ratio, is in excess of 2.

Coefficient of Permeability (Hydraulic Conductivity)

Measurement of the permeability of Quick-Gel slurries with a MFV's of 48 to 146 sec/qt in Model A permeameters indicated final coefficients of permeability in the range of 1 to 3 x 10^{-6} cm/sec as given in Table 9. The rest of the permeability tests were carried in Model B permeameters on samples obtained from the annular space and the filter cakes. There were four sets of such samples in each of the four viscosity slurries used in the well model experiments. Two sets of samples were retrieved from a depth of 6 inches below the surface of the sealant in the well model at the end of 2 and 9 weeks after the emplacement of the sealant. Another set of sealant samples were taken on the day the well experiment model was taken apart (nearly 15 weeks after the emplacement) at a depth of 5 to 6 ft below the sealant surface. At the same time, samples of the filter cake were also retrieved. Coefficient of permeability was computed both in terms of the cumulative inflow and the incremental inflow quantities corresponding to different elapsed times from the beginning of the test. The head difference in the permeability tests was mostly in the range of 15 to 20 inches with the largest value of 24 inches. Permeability specimen lengths varied between 2 and 5 inches with a few specimens as short as over an inch in length. The permeability test data are given in Appendix C.

In general, the coefficient of permeability of the sealant slurries exhibited a decrease soon after the application of the driving head, as shown in Figure 17, accompanied by some shortening of the specimen length. This is attributed to the compression of the gel structure. However, the computed

Table 8. Shrinkage Characteristics of Quick-Gel

Percent Quick-Gel (%)	Marsh Funnel Viscosity (sec/qt)	Initial Water Content (%)	Shrinkage Limit (%)	Degree of Shrinkage (%)	Volumetric Shrinkage (%)	Shrinkage Ratio (g/cc)
5.5	43	1823	116	97.3	3605	2.02
6.0	49	1645	108	97.2	3437	2.24
6.5	58	1511	56	97.0	3215	2.21
7.2	90	1383	22	96.4	2665	2.05

Table 9. Coefficient of Permeability of Quick-Gel

Percent Quick-Gel (%)	Marsh Funnel Viscosity (sec/qt)	Coefficient of Permeability (cm/sec)x10^6	
		Initial*	Final**
5.3	48	13.6	3.2
6.3	72	17.7	2.6
6.7	90	14.7	1.8
6.9	146	11.3	1.4

* The first measurement at the beginning of the test.

** The average final values after the permeability decreased.

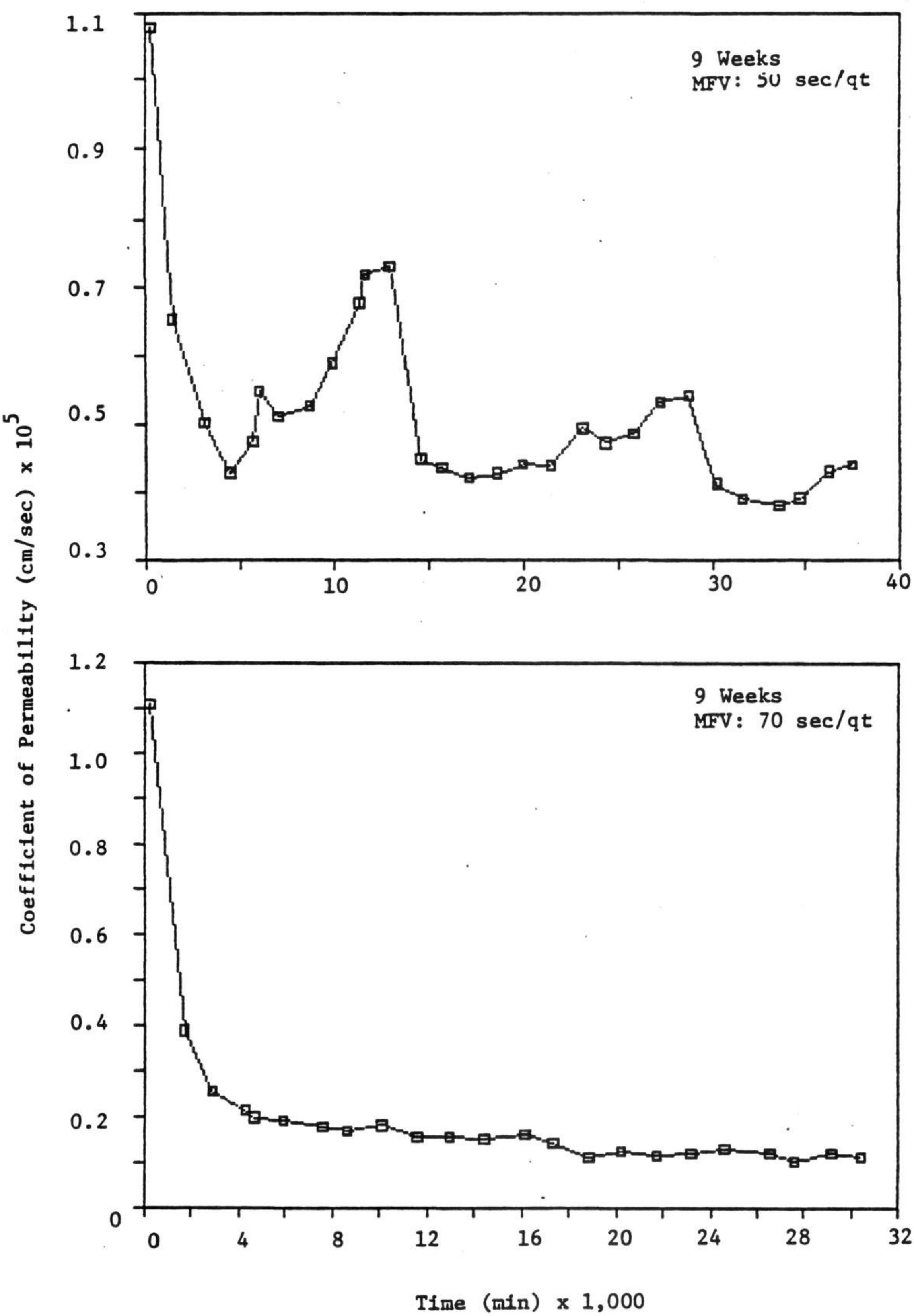

Figure 17. Coefficient of Permeability versus Time

values stabilized after some time elapsed. The initial and final values of the coefficient of permeability for the three sets of sealant samples and the filter cake samples are given in Table 10. The test duration for the filter cake samples was about 10 days, whereas it was 15 to 30 days for the sealant samples. Because of the shorter testing period and the presence of the sand grains in the samples, the filter cake samples did not exhibit noticeable compression during the permeability tests. Thus, the systematic decrease in permeability observed in the sealant samples is not evident for the filter cake samples.

For comparison purposes, the final permeabilities should be used since they are more likely to be representative of the stable gel structure of the sealants in the annular space. The permeabilities of the two and nine-weeks samples are quite comparable to each other. These samples were taken 6 inches below the sealant surface. Since the sealant was replenished once between the two sampling periods, these specimens represent the permeability characteristics of fresh and unconsolidated slurry encountered near the top of the annular space. The fifteen-week samples were taken from a depth of 5 to 6 feet; therefore, they would be subjected to some consolidation and aging. This is reflected in decidedly lower (nearly one order of magnitude) coefficients of permeability of these samples.

It is also noted that there are some differences in the final coefficients of permeability of the slurries with varying viscosity or solid content. These differences become negligible in the case of deep samples, perhaps due to the overriding influence of consolidation and aging. The other sealant samples and the filter cake indicate higher permeabilities for the slurries with MFV values of 50 and 170 sec/qt than the slurries with 70 to 90 sec/qt. It is interesting to note that the slurry with the highest solid content (MFV of 170 sec/qt) is not necessarily the sealant with the lowest permeability.

Infiltration in Well Model

The results of the infiltration tests conducted in the well model, as described earlier, are given in Figure 18 in terms of the elevation of the water surface above the annular space sealant versus time. The infiltrating water was replenished time to time as its elevation dropped. This situation

Table 10. Coefficient of Permeability, k (cm/sec) x 10^6 of Sealant and Filter Cake Samples

Sealant Viscosity (sec/qt)	Two Weeks (surface)		Nine Weeks (surface)		Fifteen Weeks (deep)		Filter Cake
	Initial	Final	Inital	Final	Initial	Final	Final
50	8.25	4.37	10.80	4.07	0.62	0.22	5.09
70	4.12	2.60	11.10	1.14	0.87	0.16	1.28
90	11.30	7.09	3.94	1.43	0.28	0.18	0.42
170	7.43	0.65	5.92	5.04	0.25	0.15	2.12

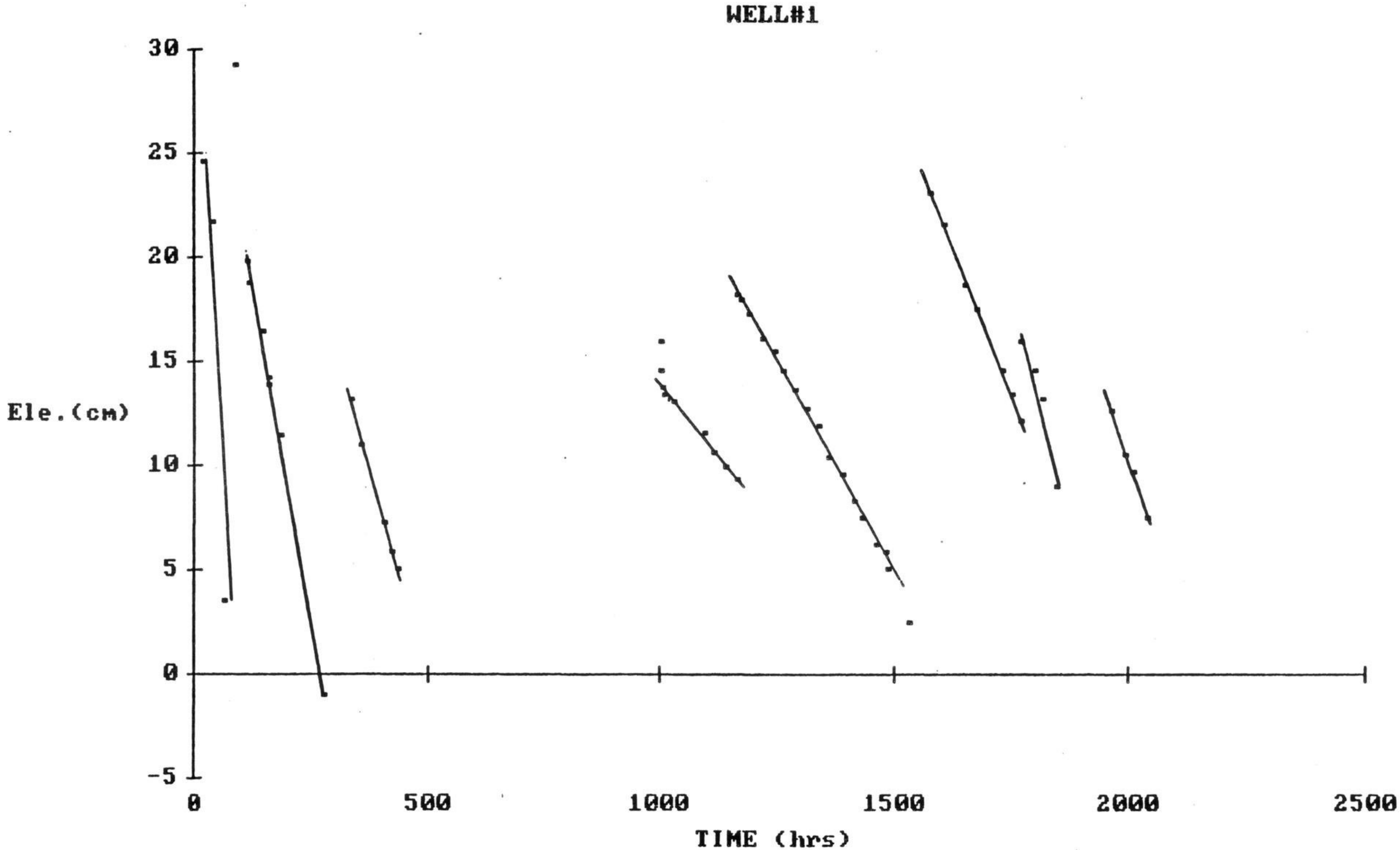

Figure 18(a). Infiltration Rate in Well Model Experiment (Sealant MFV = 50 sec/qt)

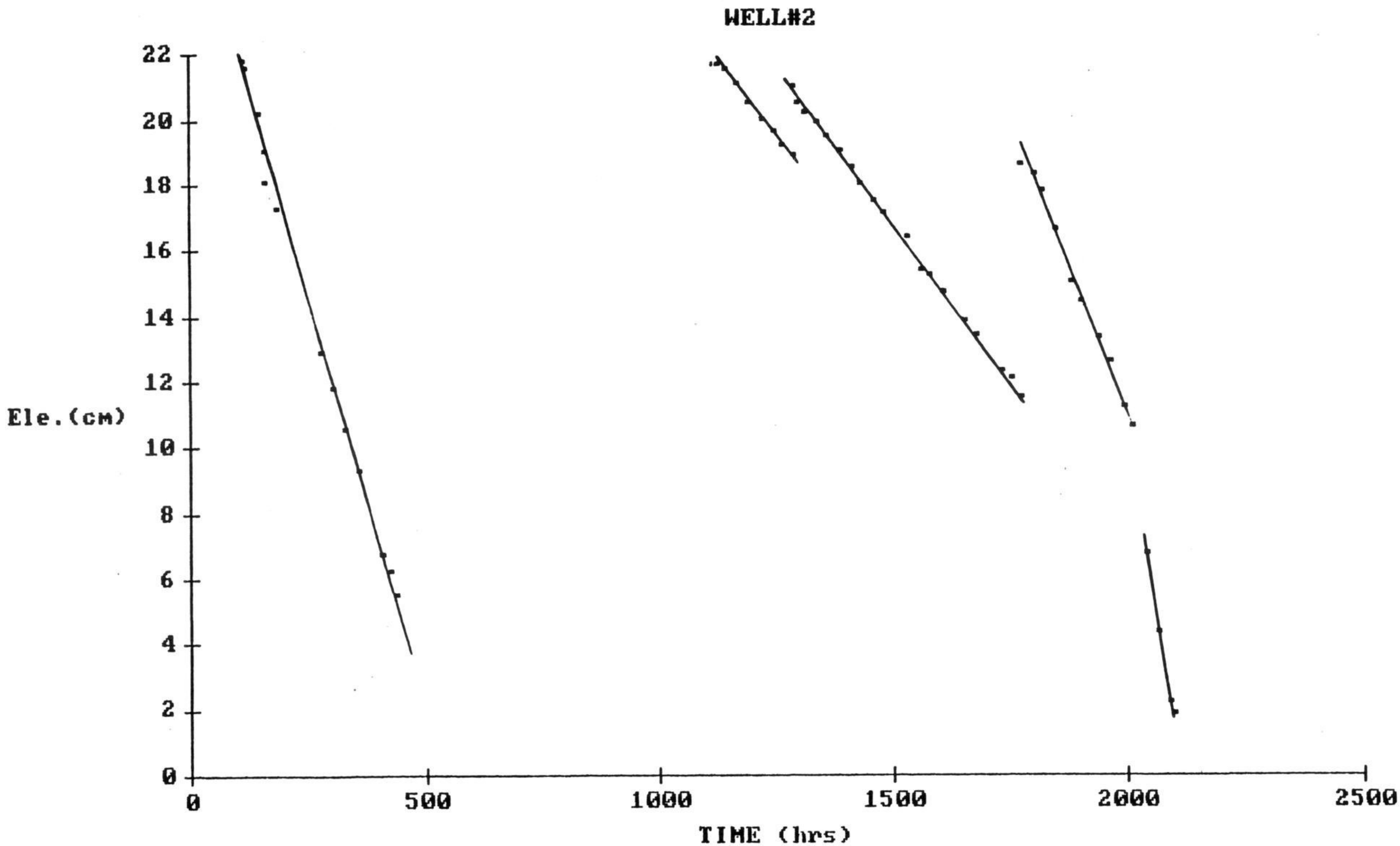

Figure 18(b). Infiltration Rate in Well Model Experiment (Sealant MFV = 70 sec/qt)

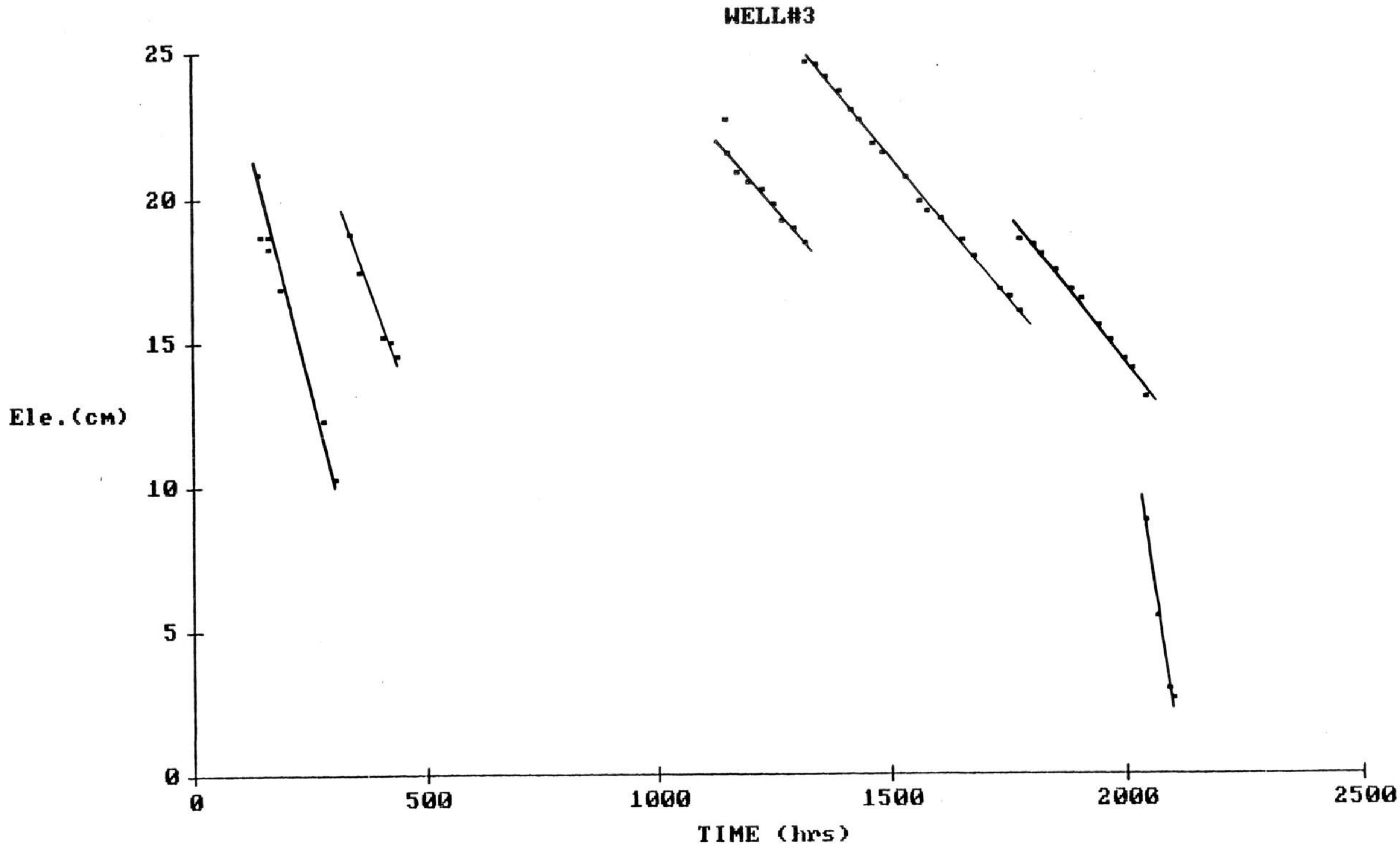

Figure 18(c). Infiltration Rate in Well Model Experiment (Sealant MFV = 90 sec/qt)

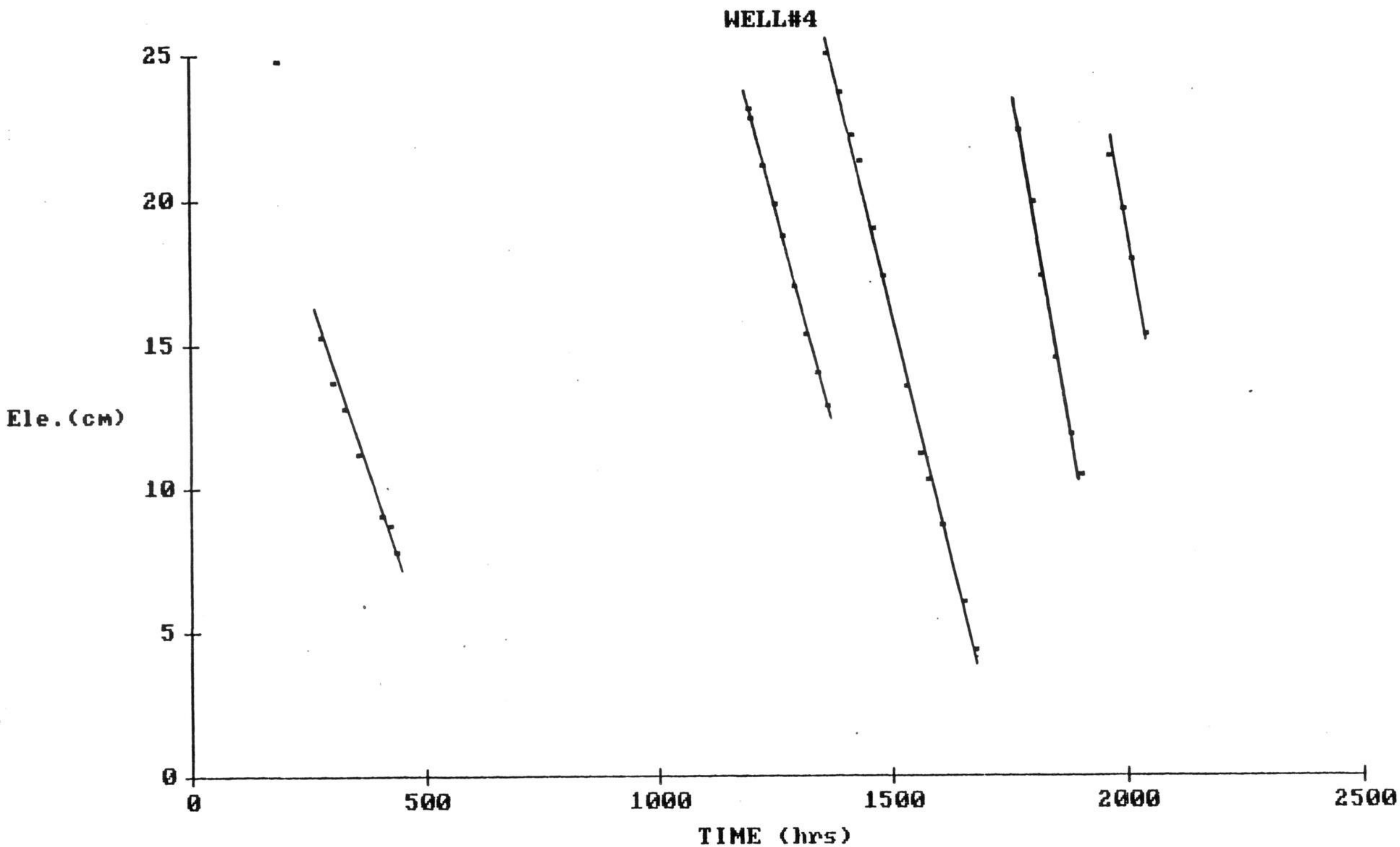

Figure 18(d). Infiltration Rate in Well Model Experiment (Sealant MFV = 170 sec/qt) is reflected by the sudden jumps in the elevations shown in Figure 18. The average slopes of the water surface elevation-time curves are given in Table 11 along with the infiltration rates obtained by multiplying these slopes by the annular space cross-sectional area (221.7 cm^2).

The infiltration of water starts at a rapid rate in Well #1. After some time, the infiltration rate drops and stabilizes around 3 to 4 x 10^{-3} cm^3/sec. When the infiltrometer casing was pulled out, reducing its embedment from 12 inches to 6 inches, the infiltration rate increases again almost doubling. Wells #2 and #3 start at decidedly lower rates of infiltration than Well #1. The stabilized values of infiltration rates for these wells are quite comparable at about 1 to 2 x 10^{-3} cm^3/sec. Well #4 has an initial and a stabilized infiltration rate higher than in Wells #2 and #3. While the initial infiltration rate is lower than in Well #1, the stabilized infiltration rate is quite comparable to Well #1. The infiltration rates of all four sealants are comparable after the casing was pulled out; however, due to disturbances, this portion of the test is not very reliable. The 6-12 weeks or 12-14 weeks (with the dye) infiltrations are believed to be representative values. Based on the infiltration rates, it is evident that Wells #2 and #3, with slurries having MFV of 70 and 90 sec/qt, seal better than Wells #1 and #4 with respectively lower and higher MFV's.

Infiltration Analyses

In the analyses, both the constant flow rate and the constant head boundaries were employed. The constant flow rates as shown on Table 11 were determined from the curves of head versus time by using the linear regression method. For all the tests, the water table mostly changes in the range from 203 cm to 184 cm. Hence, 193 cm was chosen as the constant head when modeling using the constant flow rate analysis.

In the experimental model, we are concerned with where the water is lost most: through the bentonite, the filter cake, or the sand. As shown in Table 12, almost all of the outflow is through the sand. Also the flow lines of this analysis indicate the same tendency.

The constant head model was used to predict the infiltration rate

Table 11. Infiltration Rates in Well Model Experiment

Sealant Marsh Funnel Viscosity (sec/qt)	50		70		90		170	
	$\Delta h/\Delta t$*	q**	$\Delta h/\Delta t$	q	$\Delta h/\Delta t$	q	$\Delta h/\Delta t$	q
2-6 Weeks	13.20	29.3	1.40	3.1	1.58	3.5	1.31	2.9
	3.48	7.7			1.17	2.6		
	2.26	5.0						
6-12 Weeks	0.63	1.4	0.50	1.1	0.50	1.1	1.76	3.9
	2.98	6.6	0.54	1.2	0.86	1.9	1.90	4.2
12-14 Weeks (Dye)	1.57	3.5	1.04	2.3	0.59	1.3	2.66	5.9
	2.54	5.6						
15 Weeks (Casing Pulled Up)	1.83	4.0	2.44	5.4	3.07	6.8	2.30	5.1

* in cm/sec x 10^5 ** in cm^3/sec x 10^3

Table 12. Constant Flow Rates (cm^3/sec) Analyses by Using ANSYS

Sealant Viscosity (sec/qt)	2 Weeks		
	Inflow	Outflow	
		sealant & filter cake	sand
50	$2.9x10^{-2}$	$7.2x10^{-8}$	$2.9x10^{-2}$
70	$3.4x10^{-3}$	$3.9x10^{-9}$	$3.1x10^{-3}$
90	$3.5x10^{-3}$	$1.1x10^{-8}$	$3.5x10^{-3}$
170	$2.9x10^{-3}$	$1.5x10^{-9}$	$2.9x10^{-3}$
	9 Weeks		
50	$1.4x10^{-3}$	$3.3x10^{-9}$	$1.4x10^{-3}$
70	$1.1x10^{-3}$	$7.2x10^{-10}$	$1.1x10^{-3}$
90	$1.1x10^{-3}$	$7.3x10^{-10}$	$1.1x10^{-3}$
170	$3.9x10^{-3}$	$1.0x10^{-8}$	$3.9x10^{-3}$

consistent with the estimated permeabilities of the materials involved. Therefore, a certain hydraulic head, 193 cm at the top of the sealants was chosen and the resulting infiltration rates are calculated (Table 13). The computed infiltration rates corresponding to the permeabilities of the sealant samples taken at different times and places given in Table 13 bracket the range of values consistent with the boundary conditions and the material characteristics of the well model. A coefficient of permeability of 2.0×10^{-1} cm/sec was assumed for the sand and the filter cake permeabilities were taken as the measured values given in Table 10. The filter cake thickness was assumed to be 0.5 inch as described by Type I in Figure 12.

The computed infiltration rates of Table 13 are seen to be about an order of magnitude less than the corresponding actual infiltration rates measured at different times as given in Table 11. The difference becomes even greater when the computed infiltration rates based on the permeability of the 15-weeks samples taken at a depth of 5 feet below the sealant surface are considered. The computed infiltration rates corresponding to the 15-weeks permeabilities show almost no variation between the sealants of different viscosity slurries consistent with the permeability values of Table 10. It has to be noted that the analysis assumes a uniform material without cracks, joints and other defects. However, this was hardly the case when the model was taken apart and the sealant was dissected.

When the model was disassembled, it was noted that the dye applied in the infiltration test migrated down not only by permeating through the bentonite sealant (leaving a general pink hue in the sealant and the surrounding sand) but also traveling through the cracks in the sealant and along the casing-sealant interface (refer to the notes in Appendix B). In the case of Well #1, the 50 sec/qt slurry failed with a crack carrying the dye to at least the 53-inch depth, where the dye broke into the sand as shown in Figure 19.

The 70 and 90 sec/qt slurry seals performed adequately in preventing excessive downward movement of dye. There were no apparent cracks. Migration of water seemed to be through permeation and possibly along the casing-sealant interface.

The 170 sec/qt slurry appeared to be better than the 50 sec/qt slurry, but

Table 13. Computed Infiltration Rates $(cm^3/sec)x10^3$

Sealant Marsh Funnel Viscosity (sec/qt)	50	70	90	170
2 Weeks*	0.86	0.50	0.12	0.13
9 Weeks*	0.80	0.22	0.27	0.97
15 Week (Deep)*	0.04	0.03	0.04	0.03

Note: A constant head difference of 193 cm is assumed.

* This refers to the coefficient of permeability of the sealant sample used in the analysis; see Table 10.

Figure 19. Cracking in 50 sec/qt Slurry as Indicated by the Dye

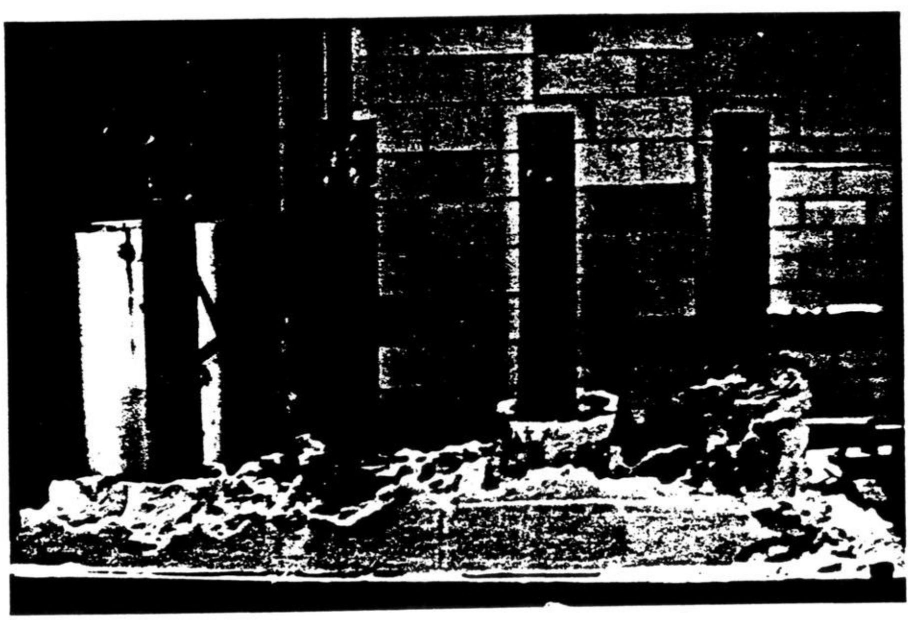

Figure 20. Coloration of Sand by Seeping Dye

significantly worse than the 70 and 90 sec/qt slurries. Some dye migrated to a depth of 3 to 4 feet and broke into the sand. The coloration of the sand shown in Figure 20 is indicative of the excessive exfiltration around Well #1 (50 sec/qt) extending in front of Well #2 (70 sec/qt) and Well #4 (170 sec/qt) with the breaking of the dye into the sand. A close-up of Well #3 (90 sec/qt) and Well #4 (170 sec/qt) contrasts the difference in the behavior of these two sealants in Figure 21.

The observations made from the examination of each sealant, in general, are supported by the quantitative data obtained in the course of this investigation. For instance, the infiltration rates during the period from 6th to 14th week when the sealants should have stabilized indicate comparable higher rates for 50 to 170 sec/qt slurries relative to comparable but 2 to 5 times lower rates of 70 and 90 sec/qt slurries as shown in Table 11. Similar trends of optimization of the sealant characteristics between 50 and 170 sec/qt and at about 70 or 90 sec/qt were observed with respect to the sample permeabilities (Table 10) and the wall building properties, i.e., filter cake thickness (Figure 16).

The reason for higher actual infiltration rates compared to the theoretically expected values is attributed to the presence of cracks and the casing-sealant interface flow which are not modeled in the seepage analysis. The Quick-Gel slurries have a material coefficient of permeability in the 10^{-6} cm/sec range or less when they are gelled and stabilized. However, volume defects such as cracks alter the overall water infiltrate rate and the effective sealing of the annular space. Occurance of volume defects is believed to be dependent on the structural stability of the bentonite slurry. An increase in the mud weight, especially with entrainment of native formation solids may be beneficial in some ways. However, an optimization of inherent permeability and structural stability for satisfactory sealant qualities could not be made based on the results of this phase of the investigation.

CONCLUSIONS

Based on the results of this phase of the laboratory investigation on the sealing characteristics of sodium bentonite slurries used in sealing the annular space of water wells, the following conclusions can be advanced:

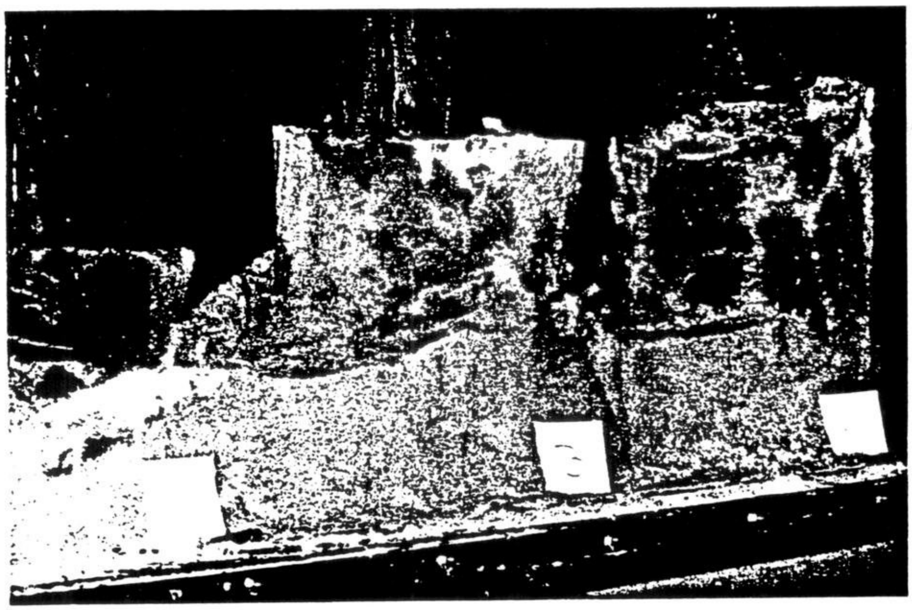

Figure 21. Close-ups of Wells #3 and #4 (Note the breaking of dye through the sand in Well #4)

1. Quick-Gel slurries without any entrained formation materials provide varying degrees of sealing in the annular space of a well in a coarse sand formation. The infiltration rate of water through the annular space takes place primarily by exfiltration laterally into the formation through the filter cake and at a rate of 0.5 to 3.0 in/sec.

2. The coefficient of permeability (or hydraulic conductivity) of the gelled Quick-Gel slurries with Marsh funnel viscosities of 50 to 170 sec/qt was in the range of 10^{6} cm/sec.

3. Volume defects, such as cracks, however, result in infiltration rates higher than the rates consistent with the material permeability.

4. Based on the measured infiltration rates, filter cake thicknesses and permeabilities, as well as the observations of the dissected sealants in the well experiment, it has been found that the 70 and the 90 sec/qt slurries behave significantly better than both the 50 and the 170 sec/qt slurries as an annular space sealant. The lowest and the highest viscosity slurries used in the study were more prone to cracking than the intermediate viscosity slurries.

RECOMMENDATIONS

The model well experiments and the material property studies are useful in eliminating the unsuitable sealants and procedures. However, they are not adequate for establishing the types of sealants and the procedure that will work in the field. However, reasonable ease of testing under controlled conditions is an attractive option in studying numerous variables. It appears that intimate material characteristics of the sealants in terms of permeability, stability, and volume change control the resulting performance as a sealant. Therefore, it is only appropriate to study these factors. A likely factor to affect these characteristics is the entrainment of cuttings in the bentonite slurry. Additional non-bentonite solids increases the mud-weight and perhaps stability without necessarily affecting viscosity or permeability. This may be a logical next variable to be considered. Other variables include other type of commonly available sealants such as bentonite and cement grouts, and perhaps placement techniques.

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APPENDICES

APPENDIX A

PROPERTIES AND PERFORMANCE OF DRILLING MUD

NL Baroid

PROPERTIES AND PERFORMANCE OF DRILLING MUD

The reason for additives to water in making a rotary drilling fluid is to improve performance in hole cutting, hole cleaning, hole stability, and productivity. Properly formulated and maintained drilling fluids enable the driller to carry out his operations with increased efficiency and improved results. The drilling fluid should be thought of by the driller as a useful tool at his disposal.

The circulating (drilling) fluid performs many functions in rotary drilling applications:

FUNCTION

Primary Functions

- Lubricate drill pipe
- Cool the bit
- Clean the cuttings from the bit and the bottom of the hole
- Remove the cuttings from the hole

Secondary Functions

- Drop the cuttings at the surface
- Facilitate the movement of the drill string (and casing)
- Prevent caving and wash outs
- Stop losses into thief zones
- Control formation pressures
- Mitigate wear and corrosion of the drilling equipment

How effectively the circulating fluid performs its functions depends on many physical properties. These properties can and should be measured periodically to determine how well the mud will perform its functions.

The test procedures described conform to American Petroleum Institute Standard 13-B, "Standard Procedure For Testing Drilling Fluids," Fifth Edition, February, 1974.

MUD WEIGHT: DENSITY

The most significant, yet simple measurement the driller can make is that of mud weight or density. No visual estimate can be made. Density must be measured by weighing a known volume. Density can be stated in any convenient units, such as lb/gal, lb/ft^3 grams/cm^3.

To prevent the flow of formation fluids into the hole, the drilling mud must exert a greater pressure than that of the fluids in the porous rocks that are penetrated by the bit. The pressure exerted by the drilling mud at any depth is related directly to its density.

Hydrostatic pressure, psi = [lb/gal x 0.052] depth

Loss of circulation may result from excessive pressure due to mud that is too dense or heavy.

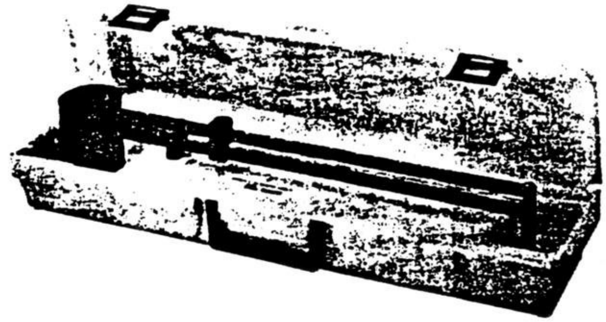
With simple water-base muds, density is a reliable measure of the amount of suspended solids.

EFFECT OF SOLIDS CONTENT ON MUD WEIGHT
(Assumed Solids Specific Gravity = 2.65)

Percent Solids	Mud Weight lbs/gallon
0	8.33
1	8.47
2	8.60
3	8.74
4	8.88
5	9.02
6	9.15
7	9.29
8	9.43
9	9.57
10	9.70
11	9.84
12	9.98
13	10.12
14	10.25
15	10.39
16	10.53
17	10.67
18	10.80
19	10.94
20	11.08

Solids that do not contribute useful properties (i.e., most drilled solids) are definitely objectionable. Abrasive solids, like sand, cause excessive wear on pumps, drill string and bit. The drilling rate is reduced; a thick filter cake is deposited on permeable formations, and the pump does unnecessary work recirculating solids which have been allowed to collect in the mud.

For the water well driller, a most objectionable effect of useless solids is the formation of a thick filter cake on the water-bearing section. The thick filter cake on the water-bearing formation may not be removed completely and consequently impairs the flow of water. By weighing the mud regularly, the solids content can be estimated so that corrective steps can be taken before damage is done.



Procedure for using the Baroid Mud Balance:

1. Fill the cup to capacity with fresh, screened mud.
2. Replace lid and rotate until firmly seated, making sure some mud is squeezed out the vent hole. Wipe or wash excess mud from the exterior of the balance, and dry. Then seat the balance with its knife edge on the stand and level it by adjusting the rider.
3. Read mud density from the inside edge of the rider as indicated by marker on the rider. Use any of the four scales to express the mud density as required. (Pounds per gallon is the normal scale.)
4. Calibration can be checked by filling the cup with fresh water. It should read 8.34 lb/gal.

WEIGHT—(Density)

Measures	Hydrostatic pressure in the bore hole, and solids content of unweighted muds
Affects	Drilling rate, hole stability, transportation and settling rate of cuttings Useless solids accumulation slows drilling rate, wastes fuel, causes equipment wear, loss of circulation, differential sticking, and damages the productive formation
Desirable Limits	Below 9.0 lb/gal (water is 8.34 lb/gal)
Control	BAROID® to increase weight; water dilution to decrease weight Good mud pit design Shale shakers, desander cones

VISCOSITY

Flow Properties

The removal of rock chips from the cutting face of the bit and the carrying of these cuttings to the surface depend on the flow properties (viscosity) and the velocity of the drilling fluid.

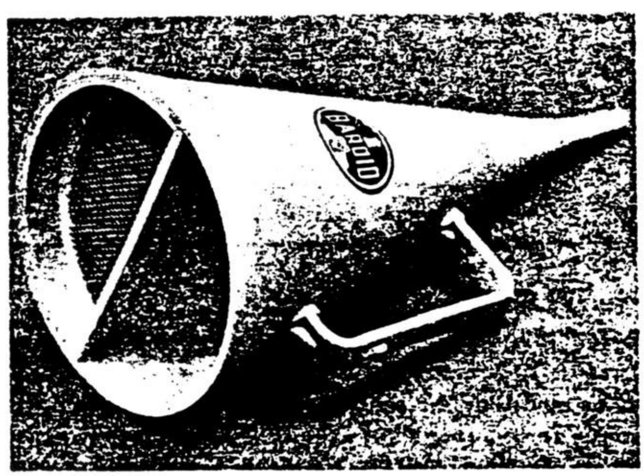
Viscosity is defined as the resistance offered by a fluid (liquid or gas) to flow. The well driller recognizes this as thickness.

The Marsh funnel is a simple means of making comparative viscosity measurements which with experience becomes very useful. "Low viscosity" is favored for effective cleaning at the bit face and rapid settling of cuttings at the surface. "High viscosity" may be necessary to remove coarse sand from the hole or to stabilize gravel but will retard settling of the cuttings at the surface.

Gel Development

The property of gel development is associated closely with the flow properties of most water-base muds. When the mud stops moving it tends to thicken or "gel." The force necessary to break the gel is called the "gel strength." High gel strength may require such high pump pressure to break circulation after a period of shutdown that the mud can be lost to a weak formation. Rapid gel development retards settling of cuttings. Gel strength can be used to advantage to hold loose sand and gravel in place during shutdowns.

High viscosities and gel strength result in increased circulating pressures that can result in loss of circulation and increased pumping costs.



Procedure For Using The Baroid Marsh Funnel:

1. Hold or mount the funnel in an upright position and place a finger over the outlet.
2. Pour the test sample, freshly taken from the mud system, through the screen in the top of the funnel until the level just reaches the under side of the screen.
3. Immediately remove the finger from the outlet tube and measure the number of seconds for a quart of mud to flow into the measuring cup.
4. Record time in seconds as "funnel viscosity." NOTE: Calibration time for fresh water at 70 F is 26 seconds.
5. The funnel viscosity measurement obtained is influenced considerably by the gelation rate of the mud sample and its density. Because of these variations, the viscosity values obtained with the Marsh Funnel cannot be correlated directly with other types of viscometers and/or rheometers.

The 1000cc measuring cup, graduated in cubic centimeters and fluid ounces, is designed specifically for use with the Baroid Marsh Funnel Viscometer. A quart volume is clearly marked on the measuring cup.

VISCOSITY—(Thickness)

Measures	Carrying capacity and gel development
Affects	Hole cleaning, drilling rate, hole stability, cuttings settling rate, circulating pressure
Desirable Limits	Thin as practical and still retain formation stability and cuttings lifting capacity Usual range 32 to 38 sec/qt higher when necessary (water is 26 sec/qt)
Control	QUIK-GEL®, QUIK-TROL™, or CELLEX® to thicken. Water or BARAFOS® to thin

FILTRATION AND CAKE THICKNESS

The ability of the solid components of the mud to rapidly form a thin filter cake of low permeability on a porous formation is a desirable property closely related to hole stability, freedom of movement of the drill string, and the information and production derived from the hole.

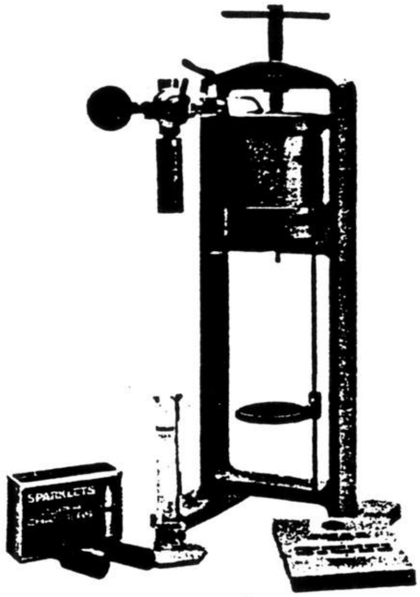
When water, carrying suspended solids, comes into contact with a porous, permeable formation such as sandstone, the solid particles immediately enter the openings. As the individual pores become bridged by the larger particles, successively smaller particles are filtered out until only a small amount of the liquid passes through the openings into the formation.

Thus, the mud solids are deposited as a filter cake on the hole wall. The thickness of the cake is related to the type and concentration of solids suspended in the mud. As soon as bridging of the openings has occurred, the sealing property of the mud becomes dependent upon the amount and physical state of the clay and other colloidal materials in the mud, and not on the permeability of the formation.

While the mud is being circulated, part of the cake is continually eroded away. The amount of liquid (filtrate) entering the porous rock depends on the sealing qualities of the thin sheath at the bore wall. Several problems (often attributed to other causes) may then arise if the mud has a high solids content and a high filtration rate.

If, when rotation is stopped, the drill pipe is in direct contact with filter cake on permeable, porous rock, the pipe may be held firmly in place by the differential pressure. The pipe becomes wall-stuck and cannot be rotated, even though there is free circulation of the mud. Even if the pipe is not stuck, severe swabbing may occur as the pipe is being pulled from the hole. On going back into the hole, the cake may be encountered and reported as "tight spots" or "bridges." The texture as well as the thickness of the filter cake is significant. A gritty, sticky texture indicates more frictional drag on the pipe than that of a smooth, slick cake.

Because the filter cake must be removed from an aquifer before unhindered flow of water can occur, the presence of filter cake may seriously affect the results of the water-well driller's efforts. For example, consider two muds—one made from natural mud, the other from premium-grade bentonite (AQUAGEL® or QUIK-GEL), both having a funnel viscosity of 45 seconds. The natural mud weighs 10.3 lb per gallon, the AQUAGEL (or QUIK-GEL) weighs 8.6 lb per gallon. For the same time of filtration on a sandstone, the volume of filter cake formed from the natural mud is *36 times* as much as that from the AQUAGEL or QUIK-GEL!



Procedure for Using the Baroid Filter Press:

Pressure can be applied with any nonhazardous gas (never use oxygen). The photograph shows the small CO^2 cartridge used to supply pressure.

Turn the T-screw on the pressure regulator to the maximum outward position. Insert a CO^2 cartridge into the knurled thimble. Make it tight on the threaded connector to perforate the cartridge.

Assemble the cell. Fill with mud nearly to the top, and fit the cap into place. Place the assembled cell in the frame and secure with the T-screw. Put a graduated cylinder under the filtrate tube. Open the valve to the pressure source. Adjust the regulator T-screw until the gauge registers a pressure of 100 pounds per square inch. Maintain the pressure for 30 minutes. Turn the regulator T-screw on the pressure regulator, to the maximum outward position. Slowly open the relief valve and relieve the pressure. Note the volume of filtrate to the nearest tenth of a cubic centimeter.

Remove the cell from the frame. Discard the mud. Disassemble the cell. Wash the filter cake formed on the paper with a gentle stream of water, to remove excess mud. Measure the thickness to the nearest 1/32 inch. Feel the cake for gritty material, stickiness, or other features of texture that may relate to performance of the mud.

FILTRATION PROPERTIES—
(Wall Cake and Filtrate)

Measures	Ability of the mud to form a controlled filter cake on the wall of the hole under static conditions
Affects	Hole stability, freedom of movement of the drill string, formation damage, and well development time
Desirable Limits	Cake very thin (less than 2/32 inch), slick, low permeability, easily removed on back flow
Control	Maintain high ratio of effective colloidal solids. QUIK-GEL and/or QUIK-TROL

SAND CONTENT

Measurement of the sand content of mud should be made regularly because excessive sand makes a thick filter cake, causes abrasive wear of pump parts, bit and pipe, may settle when circulation is stopped and interfere with pipe movement or setting of casing. Sand content (API method) is defined as the percentage by volume of solids in the mud that are retained on a 200-mesh sieve. Abrasiveness is not dependent on size alone, however, but upon the hardness and shape of the particles and may be severe with particles even smaller than 200-mesh (74 microns).

Procedure For Using The Baroid Sand Content Set:

1. Pour mud into the tube to the mark labeled "Mud to Here." Then add water to the mark labeled "Water to Here." Cover the mouth of the tube and shake.
2. Pour this mixture through the screen, and wash the solids from the tube with clean water onto the same side of the screen. Wash the sand on the screen with clean water to remove any residual mud.
3. Fit the funnel down over the top of the screen (side containing the sand) and invert, with the neck of the funnel in the mouth of the tube. Wash the sand back into the tube with clean water sprayed on the screen, and allow the sand to settle.
4. Observe the quantity of sand settled in the calibrated tube as sand content in percent by volume of the mud.

SAND CONTENT

Measures	Solids content of particles over 200 mesh size
Affects	Mud weight, equipment life, bit footage, drilling rate, formation damage and drilling problems
Desirable Limits	Less than 2% by volume
Control	Water Dilution Good pit design with maximum settling time and suspend pump suction off bottom of pit Mechanical separation (shakers, desanders) Thin with BARAFOS

pH MEASUREMENT

Alkalinity or acidity is commonly expressed as pH. On the scale 7 is neutral, less than 7 is acid and greater than 7 is alkaline. Each unit represents a tenfold change in hydrogen-ion concentration (for example, a pH of 5 means ten times as acid as a pH of 6; or a pH of 10 means ten times as alkaline as a pH of 9).

The optimum performance of some mud systems is based on control of pH. The effectiveness of bentonite is greatly reduced in an acid environment. Before mixing bentonite, pH of the water should be adjusted to 8 to 9. Contamination of mud by cement will raise the pH to 10 - 12. Sodium bicarbonate can be used to treat for cement contamination and reduce the pH of the mud to the desired range.

The Procedure for Using pHydrion Dispenser

In each pHydrion dispenser is a roll of test paper treated with a dye which undergoes changes in color with pH to correspond to the reference color strips on the side of the container. The broad-range test paper can be used in most cases to estimate to one pH unit. Narrow-range indicators are available for estimation to one-tenth pH unit.

Remove a one-inch strip of paper from the pHydrion Dispenser. Place the strip on the surface of the water or mud and allow it to remain until the surface has become wet and the color has stabilized (30 seconds to a minute). Estimate the pH by comparison of the color of the upper side of the paper with the chart on the dispenser from which the paper was taken.

pH

Measures	Alkalinity or acidity of mixing water and drilling fluids
Affects	Mud mixing, viscosity, gel and filtration of mud, hole stability, corrosivity of mud
Desirable Limits	8.5 to 9.5 (Neutral solutions pH = 7.0)
Control	Raise with soda ash (1 to 2 lb/100 gal), lower with sodium bicarbonate (for cement contamination)

WATER FOR DRILLING

Water is the primary constituent of most drilling fluids. The quantity, quality and on-site cost of the water used for drilling influences the types and amounts of mud additives necessary to control drilling fluid properties. The properties of bentonite in water are seriously impaired by dissolved acidic or salty substances. When water is acidic, it may carry traces of such heavy metals as copper and zinc and be unsatisfactory for use in mud without preliminary treatment. Hard water, caused by dissolved calcium and magnesium salts, impairs the suspending and sealing qualities of bentonite.

A few simple tests will establish the suitability of the water. Measurement of pH by means of indicator paper strips (pHydrion paper) and a semiquantitive test for hardness (Baroid Calcium Indicator) usually are sufficient.

If the water is acidic it should be treated with soda ash to raise the pH to 8 or 9 prior to the addition of any mud-making materials. Hardness is removed by soda ash but, if more convenient, treatment for hardness can be made along with the addition of the mud-making materials. Usually between 1 and 5 lb of soda ash per 100 gal of water is sufficient; however, the simple tests for pH and calcium should be made on the treated water. Strongly acidic water may require treatment with caustic soda. If sulfides are present, pH should be maintained above 10 to counteract corrosion.

Knowledge of the source of the water usually serves to indicate the possibility of contamination by other salts, such as halite. There is no treatment which will remove sodium and potassium salts. Consequently the mud program must be adapted to the composition of the salty water to be used. Organic polymers are used instead of bentonite in salty water.

If drilling is to be to or through the potable water zones, care should be taken to insure that the mud make-up water is not contaiminated with micro-organisms or other pollutants. The source of much aquifer bacterial contamination can be traced back to the introduction of micro-organisms during the drilling process.

HARD WATER

Hard water is a frequent cause of unsatisfactory performance of mud. Hard water contains dissolved calcium and magnesium salts. Calcium salts, such as anhydrite or gypsum, seriously impair the suspending and sealing properties of bentonite. A simple test for calcium ion in the makeup water will show the need for treatment, if the water is hard. After addition of soda ash to the water, a test should be made to make certain the water has been softened.

Procedure for Using Calcium Indicator Solution

The Baroid Calcium Indicator gives an approximation of the hardness of water due to dissolved calcium salts. To 2 cc of the water, or filtrate, add 2 drops of Baroid Calcium Indicator. Shake well and let stand two minutes. Estimate the calcium ion concentration from the amount of turbidity as follows:

Suspension	Approximate ppm Calcium	Soda Ash Treatment lb/100 gal
Translucent	100 to 200	0.5 to 1
Milk White	200 to 400	1 to 2
Dense White	Above 400	2 to 5

If a dense white precipitate forms, repeat the test with a smaller sample and make the appropriate correction in the estimation.

CALCIUM INDICATOR

Measures	Hardness of mixing water due to dissolved calcium salts
Affects	Mud mixing, increases filtration, wall cake; suppresses viscosity and gel development
Desirable Limits	Less than 100 ppm calcium
Control	Pre-treat mixing water with soda ash (1-5 lb/gal)

CHLORIDE CONTENT

Frequently it is desirable to know the salt content of muds to account for certain aspects of their performance. Filtration, suspension, viscosity, and gel properties are adversely affected by salt unless the mud is specifically designed to withstand salt contamination. Organic polymers, such as QUIK-TROL and LOLOSS, must be used to replace bentonite in salty waters.

To determine the chloride content, a sample of the makeup water or mud filtrate is titrated with a standard silver nitrate solution, using potassium chromate as an indicator. When the chloride is completely titrated, the addition of more silver nitrate produces a red color which is taken as the end point. Results are reported in parts per million of chloride ion.

Procedure for Using Chloride Content Kit

Apparatus and Reagents:

- Pipette, 1 cc
- Pipette, 10 cc
- Silver nitrate solution, 1 cc equivalent to .001 g Cl
- Distilled water
- Potassium chromate solution
- Polyethylene or porcelain titration dish
- Polyethylene or glass stirring rod

METHOD:

1. Pipette 1.00 cc of sample into the titration dish and dilute to 40 or 50 cc with distilled water.
2. Add four or five drops of potassium chromate indicator solution.
3. Add standard silver nitrate solution from a pipette dropwise and slowly, all the while stirring continuously with a stirring rod, until the sample just turns from yellow to orange or brick red.

RESULTS:

1. The number of cc of standard silver nitrate solution used to obtain this end point is multiplied by 1,000 when the 0.001 g silver nitrate solution is used to obtain parts per million (ppm) of chloride (Cl) ion.
2. The salt content in the sample is expressed as ppm Cl. Multiply ppm Cl by 1.65 for ppm NaCl.

CHLORIDE CONTENT (SALT)

Measures	Dissolved chlorides (usually salt)
Affects	Mud mixing, increases filtration and wall cake thickness; suppresses viscosity and gel development when present in makeup water; thickens fresh water mud
Desirable Limits	Less than 500 ppm
Control	Dilution with fresh water

ROUTINE TESTING PROGRAM

Time and money can be saved by keeping records of mud properties. The simple measurements of mud weight and funnel viscosity in many cases furnish sufficient information for adequate control of mud properties. Mud weight should be measured at the ditch and at the pump suction to determine how effectively the cuttings are being separated. Too much emphasis cannot be placed on the measurement of density. An increase of solids from cuttings means slower drilling; more wear on the bit; thicker filter cake and higher pressure downhole with greater danger of sticking the drill pipe, and more likelihood of losing circulation.

Funnel viscosity should be no higher than is necessary to carry the cuttings and provide a stable hole. Based on experience with mud of simple composition, limits can be set for weight and funnel viscosity which will assure satisfactory filtration properties. For example, if a fresh-water bentonite mud has a funnel viscosity of 32 to 38 seconds, and weighs less than 9.0 lb per gal, satisfactory performance usually can be expected for average drilling.

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SHEAR OR GEL STRENGTH

The gel strength of drilling muds is a measure of the minimum shearing stress necessary to produce slip-wise movement.

Two readings are generally taken: the first, immediately after agitation of the mud in the cup; the second, after the mud in the cup has been quiescent for a period of ten minutes. The readings are referred to as the initial gel strength and the ten-minute gel strength respectively. Both gel strength readings so determined will be zero for true fluids no matter how viscous, e.g., clarified honey, but the difference in the readings may be appreciable for suspensions such as drilling muds. This difference is considered to be a measurement of the thixotropy of the mud system. Hole size, type of formations, depth, temperature and pressure of formation fluids or gases, and amount of weight material in the mud are factors that must be considered in prescribing desirable gel-strength properties of the mud.

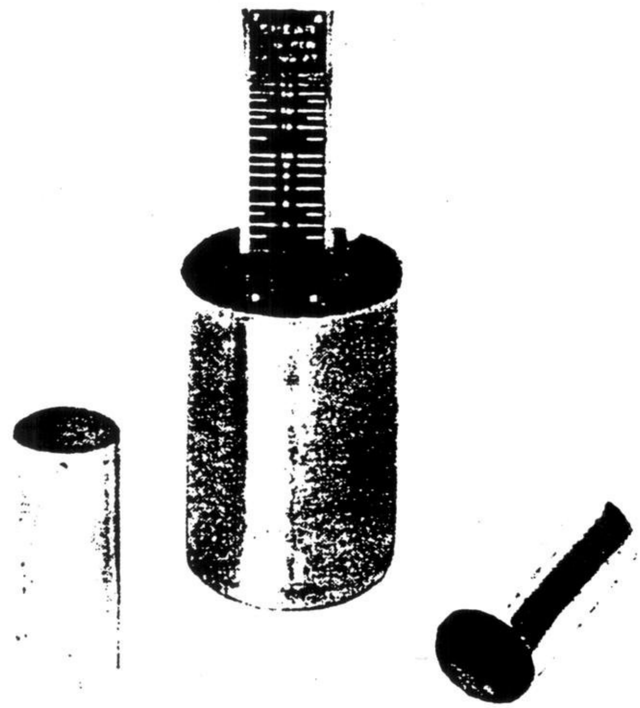
SHEAROMETER

The Shearometer is an auxiliary instrument for use in determining gel strengths of drilling muds. The readings are obtained directly from a calibrated scale and give gel strength in pounds per 100 square feet of area. The readings cannot be correlated with those obtained with the Baroid Viscometer or the Baroid Rheometer. The Shearometer is not recommended for use with very low or very high gel strength muds.

The Shearometer consists of a duraluminum tube 3.5 inches long, 1.4 inches in internal diameter, and weighing 5.0 grams; a special scale graduated in pounds per 100 ft^2 of shear; and a sample cup which also serves to support the scale.

PROCEDURE:

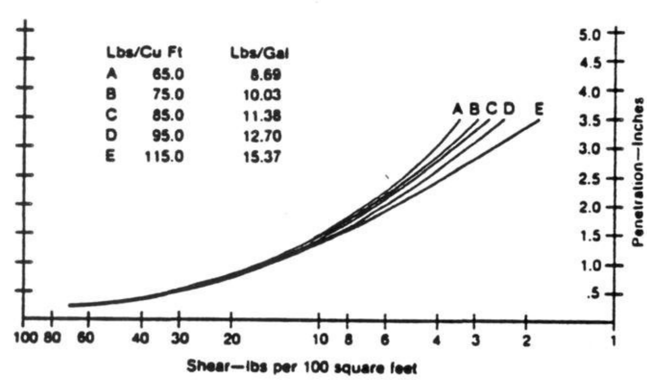
1. Wet the tube with water and wipe off excess water.
2. Lower the Shearometer tube over the scale support and place it on the surface of the freshly agitated mud which has been poured into the container to bottom line across scale. Allow the tube to sink vertically, guided by the fingers only if necessary.
3. With a stopwatch measure the time from the instant the tube is released. After allowing the tube to sink for one minute, read the scale directly opposite the top of the tube and record the shear strength in pounds per 100 ft^2.
4. Wait 10 minutes and repeat procedure to measure 10-minute shear.



Shearometer Set.

RESULTS:

1. Report the shear strength in pounds per 100 ft^2.
2. If the tube sinks to bottom in one minute or less, report the shear strength as zero with a superscript indicating the number of seconds of fall. (Example: Initial shear, lb/100 ft^2 0^6.)



Shearometer Calibration Curves, 5 gram.

APPENDIX B

NOTES TAKEN WHILE DISASSEMBLING THE WELL MODEL
(observation on 11-21-86)

Four wells - Well #1 (50 sec/qt seal)
Well #2 (70 sec/qt seal)
Well #3 (90 sec/qt seal)
Well #4 (170 sec/qt seal)

Remarks:
1. 20 liters water with 30 drops dye was introduced onto the annular space seals on 11-3-86.
2. Rust as well as 'black stains' (?Mn) reacted with bentonite.
3. Circumferential positions in terms of hours are from north, i.e., 12 o'clock is north, 6 o'clock is south, etc.

WELL #1

1. General diffusion of the dye into the sand (south).
2. After removing the top 24" of sand, 1/4"-thick pink-hued zone at pipe-bentonite contact existed on WEST side.
3. The dye came out of the seal down to the infiltrometer casing bottom.
4. The bentonite leaked around the bottom of the casing, some flowed out.
5. At 8" below the tank edge, radial crack was noticed at 1 o'clock position.
6. Crack continued at 12" below the edge.
7. At 13" below the edge, the crack no longer was observed.
8. At 12" below the top of tank (original base of the infiltrometer casing), sand intruded into bentonite at 4 o'clock position.
9. The thickness of the bentonite seal is: 2-1/2" on West side, 1" on East side, 1-1/2" on South side, and 2-1/2" on North side.
10. Circumferential pink-hued bentonite was found at the same level described in (5).
11. Pipe rust intruded 1/2" into bentonite.
12. At 56" below the top of the pipe, 1/4" pink-hue existed in bentonite and stopped at the 69" level (from top of pipe).
13. At 62", rupture of dye through bentonite into the sand was observed.
14. At 69", the filter cake thickness was 2-1/4".

WELL #2

1. After removing the top 24" section, stratified dye shown, which dipped from east to west (south).
2. The top of the pipe, 36" from the joint (between top and second tank), was 12" above the sand surface.
3. At 24" below the top of the pipe, 3" deep, decomposed material was found at 4 o'clock position.
4. At the same level, bentonite thickness is: 2" N, 2-1/4" E, 2" S, 2" W.
5. Lots of pipe rust was found in the bentonite at 4 o'clock position, 24" below the top of the pipe.
6. At 27" below the top of the pipe:
   a. rust stain was at 7 o'clock position
   b. circumferential crack was at 8 o'clock with dye in it
   c. the crack went all the way out to the filter cake
7. At 29" below the top of the pipe:
   a. pink-hue existed in the 3 o'clock to 7 o'clock area
   b. from 3 to 4 o'clock, pink-hue distributed within the area, but extended to the edge at the 5 o'clock position
8. At 60", pink-hue disappeared and filter cake thickness was 1-1/2".
9. At 68" below the top of the pipe, pink hues existed in bentonite on NORTH side.
10. At 70", pink-hue vanished in bentonite.

WELL #3

1. After removing the top 24" section of the container, it is well-sealed (south), however, the dye ran down the pipe-bentonite interface at 4 o'clock (not diffused).
2. 36" below the top of the sand surface, pink-hue existed in bentonite (SOUTH).
3. At 60" below the top of the pipe, the thickness of the filter cake was 1-1/4".

WELL #4

1. After removing the top 24" section of the container, cracks were shown in bentonite with streaks of dye (south); however, no trace of the dye was found at layer 1.5 to 2" below.
2. Pink zone at the pipe-bentonite contact at 10 - 12 o'clock area.
3. At 36" below the top of the sand surface, pink-hue existed in the bentonite (NORTH).
4. At 68" below the top of the pipe, break-thru of dye in sand was at 11 o'clock position.
5. At 69", the filter cake thickness was 1-1/4".
6. At 73", pink-hue in the filter cake (NORTH).

Prepared by Michael Chang M.K.
(December 19, 1986 draft)
(February 19, 1987 revised)

APPENDIX C

****
* PERMEABILITY TEST * 2-WEEK SAMPLES
****

Bentonite sample : 50 seconds
Initial head : 34.50 cm
Conversion factor : 3.27 cm/cc
Diameter of sample : 1.0720 cm

TIME (MINUTES)	LENGTH (CM)	HEAD (CM)	PERMEABILITY (CM/SEC)	INCREMENTAL K (CM/SEC)
30	3.00	34.00	.825E-05	.825E-05
195	3.00	32.80	.439E-05	.369E-05
1215	3.00	28.90	.247E-05	.210E-05
1550	3.00	27.70	.240E-05	.215E-05
2645	3.00	22.90	.263E-05	.295E-05

****
* PERMEABILITY TEST *
****

Bentonite sample : 50 seconds
Initial head : 34.50 cm
Conversion factor : 3.27 cm/cc
Diameter of sample : 1.0720 cm

TIME (MINUTES)	LENGTH (CM)	HEAD (CM)	PERMEABILITY (CM/SEC)	INCREMENTAL K (CM/SEC)
75	2.75	34.20	.181E-05	.181E-05

****
* PERMEABILITY TEST *
****

Bentonite sample : 50 seconds
Initial head : 34.80 cm
Conversion factor : 3.27 cm/cc
Diameter of sample : 1.0720 cm

TIME (MINUTES)	LENGTH (CM)	HEAD (CM)	PERMEABILITY (CM/SEC)	INCREMENTAL K (CM/SEC)
150	2.75	32.30	.772E-05	.772E-05
350	2.75	28.90	.825E-05	.864E-05

****
* PERMEABILITY TEST *
****

Bentonite sample : 50 seconds
Initial head : 37.30 cm
Conversion factor : 3.27 cm/cc
Diameter of sample : 1.0720 cm

TIME (MINUTES)	LENGTH (CM)	HEAD (CM)	PERMEABILITY (CM/SEC)	INCREMENTAL K (CM/SEC)
45	2.75	36.90	.372E-05	.372E-05

255	2.75	33.50	.655E-05	.715E-05

****
* PERMEABILITY TEST *
****

Bentonite sample : 50 seconds
Initial head : 35.00 cm
Conversion factor : 3.27 cm/cc
Diameter of sample : 1.0720 cm

TIME (MINUTES)	LENGTH (CM)	HEAD (CM)	PERMEABILITY (CM/SEC)	INCREMENTAL K (CM/SEC)
229	2.75	31.90	.629E-05	.629E-05

****
* PERMEABILITY TEST *
****

Bentonite sample : 50 seconds
Initial head : 45.50 cm
Conversion factor : 3.27 cm/cc
Diameter of sample : 1.0720 cm

TIME (MINUTES)	LENGTH (CM)	HEAD (CM)	PERMEABILITY (CM/SEC)	INCREMENTAL K (CM/SEC)
360	2.75	38.90	.676E-05	.676E-05
1635	2.75	24.30	.596E-05	.573E-05

****
* PERMEABILITY TEST *
****

Bentonite sample : 50 seconds
Initial head : 46.20 cm
Conversion factor : 3.27 cm/cc
Diameter of sample : 1.0720 cm

TIME (MINUTES)	LENGTH (CM)	HEAD (CM)	PERMEABILITY (CM/SEC)	INCREMENTAL K (CM/SEC)
180	2.75	43.10	.599E-05	.599E-05

****
* PERMEABILITY TEST *
****

Bentonite sample : 50 seconds
Initial head : 47.50 cm
Conversion factor : 3.27 cm/cc
Diameter of sample : 1.0720 cm

TIME (MINUTES)	LENGTH (CM)	HEAD (CM)	PERMEABILITY (CM/SEC)	INCREMENTAL K (CM/SEC)
1260	2.75	32.80	.457E-05	.457E-05
1500	2.75	30.70	.452E-05	.428E-05
2815	2.75	21.50	.437E-05	.421E-05

****
* PERMEABILITY TEST *
****

Bentonite sample : 50 seconds
Initial head : 47.50 cm
Conversion factor : 3.27 cm/cc
Diameter of sample : 1.0720 cm

TIME (MINUTES)	LENGTH (CM)	HEAD (CM)	PERMEABILITY (CM/SEC)	INCREMENTAL K (CM/SEC)
1200	2.75	34.00	.433E-05	.433E-05
2640	2.75	23.10	.424E-05	.417E-05

****
* PERMEABILITY TEST *
****

Bentonite sample : 70 seconds
Initial head : 61.50 cm
Conversion factor : 3.00 cm/cc
Diameter of sample : .9525 cm

TIME (MINUTES)	LENGTH (CM)	HEAD (CM)	PERMEABILITY (CM/SEC)	INCREMENTAL K (CM/SEC)
5410	14.50	50.50	.412E-05	.412E-05
6920	14.50	48.60	.385E-05	.287E-05
7280	14.50	48.10	.382E-05	.325E-05
8555	14.50	46.70	.364E-05	.262E-05
8740	14.50	46.50	.362E-05	.262E-05
14170	14.50	41.00	.323E-05	.262E-05
15610	14.50	39.80	.315E-05	.233E-05
15910	14.50	39.50	.315E-05	.285E-05
17020	14.50	38.50	.311E-05	.261E-05
18365	14.50	37.40	.306E-05	.244E-05
19805	14.50	36.10	.304E-05	.278E-05

****
* PERMEABILITY TEST *
****

Bentonite sample : 90 seconds
Initial head : 48.70 cm
Conversion factor : 2.82 cm/cc
Diameter of sample : .9906 cm

TIME (MINUTES)	LENGTH (CM)	HEAD (CM)	PERMEABILITY (CM/SEC)	INCREMENTAL K (CM/SEC)
140	14.20	48.00	.113E-04	.113E-04

****
* PERMEABILITY TEST *
****

Bentonite sample : 90 seconds
Initial head : 48.50 cm

Conversion factor : 2.82 cm/cc
Diameter of sample : .9906 cm

TIME (MINUTES)	LENGTH (CM)	HEAD (CM)	PERMEABILITY (CM/SEC)	INCREMENTAL K (CM/SEC)
5465	14.20	34.90	.656E-05	.656E-05
6970	14.20	31.10	.694E-05	.834E-05
7330	14.20	30.30	.699E-05	.788E-05
8605	14.20	27.70	.709E-05	.766E-05

****
* PERMEABILITY TEST *
****

Bentonite sample : 90 seconds
Initial head : 49.90 cm
Conversion factor : 2.82 cm/cc
Diameter of sample : .9906 cm

TIME (MINUTES)	LENGTH (CM)	HEAD (CM)	PERMEABILITY (CM/SEC)	INCREMENTAL K (CM/SEC)
180	14.20	49.10	.978E-05	.978E-05
5610	14.20	30.50	.956E-05	.955E-05

****
* PERMEABILITY TEST *
****

Bentonite sample : 90 seconds
Initial head : 52.50 cm
Conversion factor : 2.82 cm/cc
Diameter of sample : .9906 cm

TIME (MINUTES)	LENGTH (CM)	HEAD (CM)	PERMEABILITY (CM/SEC)	INCREMENTAL K (CM/SEC)
300	14.20	51.30	.839E-05	.839E-05
1550	14.20	36.40	.257E-04	.299E-04
2755	14.20	31.90	.197E-04	.119E-04
4195	14.20	28.40	.159E-04	.879E-05

****
* PERMEABILITY TEST *
****

Bentonite sample : 170 seconds
Initial head : 56.50 cm
Conversion factor : 3.10 cm/cc
Diameter of sample : .9525 cm

TIME (MINUTES)	LENGTH (CM)	HEAD (CM)	PERMEABILITY (CM/SEC)	INCREMENTAL K (CM/SEC)
140	15.50	56.00	.743E-05	.743E-05
5600	15.50	52.30	.161E-05	.146E-05
7110	15.50	51.80	.143E-05	.744E-06
7470	15.50	51.60	.142E-05	.126E-05
8745	15.50	51.20	.132E-05	.714E-06

8930	15.50	51.00	.134E-05	.247E-05
14360	15.50	49.20	.113E-05	.774E-06
15800	15.50	48.80	.108E-05	.663E-06
16100	15.50	48.70	.108E-05	.800E-06
17350	15.50	48.40	.104E-05	.578E-06
18555	15.50	48.10	.101E-05	.603E-06
19995	15.50	47.80	.978E-06	.508E-06

****
* PERMEABILITY TEST * 9-WEEK SAMPLES
****

Bentonite sample : 50 seconds
Initial head : 41.20 cm
Conversion factor : 3.27 cm/cc
Diameter of sample : 1.0720 cm

TIME (MINUTES)	LENGTH (CM)	HEAD (CM)	PERMEABILITY (CM/SEC)	INCREMENTAL K (CM/SEC)
235	14.00	39.90	.108E-04	.108E-04
1415	14.00	36.20	.723E-05	.652E-05
3110	14.00	32.50	.603E-05	.503E-05
4465	14.00	30.20	.550E-05	.428E-05
5665	14.00	28.10	.534E-05	.475E-05
6030	14.00	27.40	.535E-05	.547E-05
7020	14.00	25.70	.532E-05	.512E-05
8750	14.00	22.90	.531E-05	.527E-05
9915	14.00	21.00	.538E-05	.588E-05
11335	14.00	18.60	.555E-05	.676E-05
11695	14.00	18.00	.560E-05	.720E-05
12965	14.00	16.00	.577E-05	.733E-05

****
* PERMEABILITY TEST *
****

Bentonite sample : 50 seconds
Initial head : 42.20 cm
Conversion factor : 3.27 cm/cc
Diameter of sample : 1.0720 cm

TIME (MINUTES)	LENGTH (CM)	HEAD (CM)	PERMEABILITY (CM/SEC)	INCREMENTAL K (CM/SEC)
1670	13.00	38.10	.449E-05	.449E-05
2720	13.00	35.80	.444E-05	.435E-05
4140	13.00	33.00	.436E-05	.421E-05
5660	13.00	30.20	.434E-05	.428E-05
7040	13.00	27.80	.435E-05	.441E-05
8480	13.00	25.50	.436E-05	.440E-05
10205	13.00	22.70	.446E-05	.495E-05
11410	13.00	21.00	.449E-05	.474E-05
12920	13.00	19.00	.454E-05	.487E-05
14295	13.00	17.20	.461E-05	.532E-05
15795	13.00	15.40	.469E-05	.541E-05

****
* PERMEABILITY TEST *
****

Bentonite sample : 50 seconds
Initial head : 37.70 cm
Conversion factor : 3.27 cm/cc
Diameter of sample : 1.0720 cm

TIME (MINUTES)	LENGTH (CM)	HEAD (CM)	PERMEABILITY (CM/SEC)	INCREMENTAL K (CM/SEC)

=========	======	====	============	=============
1475	13.00	34.70	.413E-05	.413E-05
2880	13.00	32.20	.402E-05	.391E-05
4825	13.00	29.10	.394E-05	.382E-05
5885	13.00	27.50	.394E-05	.392E-05
7440	13.00	25.10	.402E-05	.431E-05
8675	13.00	23.30	.407E-05	.442E-05

****
* PERMEABILITY TEST *
****

Bentonite sample : 70 seconds
nitial head : 58.50 cm
onversion factor : 3.00 cm/cc
Diameter of sample : .9525 cm

TIME (MINUTES)	LENGTH (CM)	HEAD (CM)	PERMEABILITY (CM/SEC)	INCREMENTAL K (CM/SEC)
=========	======	====	============	=============
210	15.80	57.40	.111E-04	.111E-04
1685	15.80	54.80	.478E-05	.387E-05
2850	15.80	53.50	.386E-05	.254E-05
4270	15.80	52.20	.329E-05	.213E-05
4630	15.80	51.90	.318E-05	.197E-05
5900	15.80	50.90	.291E-05	.189E-05
7575	15.80	49.70	.265E-05	.175E-05
8625	15.80	49.00	.253E-05	.166E-05
10045	15.80	48.00	.243E-05	.179E-05
11565	15.80	47.10	.231E-05	.153E-05
12945	15.80	46.30	.223E-05	.153E-05
14385	15.80	45.50	.215E-05	.149E-05
16110	15.80	44.50	.209E-05	.159E-05
17315	15.80	43.90	.204E-05	.139E-05
18825	13.10	43.20	.164E-05	.109E-05
20200	13.10	42.50	.162E-05	.121E-05
21700	13.10	41.80	.158E-05	.113E-05
23175	13.10	41.10	.156E-05	.117E-05
24580	13.10	40.40	.154E-05	.125E-05
26525	13.10	39.50	.151E-05	.118E-05
27585	13.10	39.10	.149E-05	.981E-06
29140	13.10	38.40	.148E-05	.119E-05
30375	13.10	37.90	.146E-05	.108E-05

****
* PERMEABILITY TEST *
****

entonite sample : 90 seconds
Initial head : 56.30 cm
onversion factor : 3.10 cm/cc
iameter of sample : .9525 cm

TIME (MINUTES)	LENGTH (CM)	HEAD (CM)	PERMEABILITY (CM/SEC)	INCREMENTAL K (CM/SEC)
=========	======	====	============	=============
340	14.20	55.60	.394E-05	.394E-05
1610	14.20	53.90	.290E-05	.262E-05
3275	14.20	52.10	.254E-05	.219E-05
4335	14.20	51.10	.240E-05	.196E-05

5755	14.20	49.90	.225E-05	.179E-05
7275	14.20	48.60	.217E-05	.186E-05
8655	14.20	47.50	.210E-05	.178E-05
10095	14.20	46.40	.205E-05	.174E-05
11820	14.20	45.20	.199E-05	.163E-05
13025	14.20	44.30	.197E-05	.179E-05
14535	12.80	43.30	.174E-05	.146E-05
15905	12.80	42.40	.172E-05	.148E-05
17410	12.80	41.40	.171E-05	.153E-05
18885	12.80	40.60	.167E-05	.128E-05
20290	12.80	39.60	.167E-05	.171E-05
22235	12.80	38.50	.165E-05	.140E-05
23295	12.80	38.00	.163E-05	.119E-05
24850	12.80	37.20	.161E-05	.132E-05
26085	12.80	36.50	.160E-05	.149E-05

****
* PERMEABILITY TEST *
****

entonite sample : 170 seconds
nitial head : 52.00 cm
Conversion factor : 2.82 cm/cc
iameter of sample : .9906 cm

TIME (MINUTES)	LENGTH (CM)	HEAD (CM)	PERMEABILITY (CM/SEC)	INCREMENTAL K (CM/SEC)
295	14.70	51.20	.592E-05	.592E-05
1565	14.70	48.60	.487E-05	.463E-05
3240	14.70	45.40	.472E-05	.458E-05
4290	14.70	43.20	.487E-05	.533E-05
5710	14.70	40.60	.489E-05	.493E-05
7230	14.70	38.10	.485E-05	.471E-05
8610	14.70	35.80	.489E-05	.509E-05
10050	14.70	33.60	.490E-05	.496E-05
11775	14.70	30.90	.498E-05	.547E-05
12980	14.70	29.10	.504E-05	.561E-05

****
* PERMEABILITY TEST *
****

Bentonite sample : 170 seconds
nitial head : 48.10 cm
Conversion factor : 2.82 cm/cc
Diameter of sample : .9906 cm

TIME (MINUTES)	LENGTH (CM)	HEAD (CM)	PERMEABILITY (CM/SEC)	INCREMENTAL K (CM/SEC)
1510	13.30	45.70	.346E-05	.346E-05
2880	13.30	43.30	.372E-05	.402E-05
4385	13.30	40.70	.389E-05	.420E-05
5860	13.30	38.10	.406E-05	.456E-05
7265	13.30	35.70	.419E-05	.472E-05
9210	13.30	32.60	.431E-05	.476E-05
10270	13.30	31.10	.433E-05	.453E-05
11825	13.30	28.50	.451E-05	.573E-05

****
* PERMEABILITY TEST *
****

15-WEEK (DEEP) SAMPLES

Bentonite sample : 50 seconds
Initial head : 43.70 cm
Conversion factor : 3.27 cm/cc
Diameter of sample : 0.9525 cm

TIME (MINUTES)	LENGTH (CM)	HEAD (CM)	PERMEABILITY (CM/SEC)	INCREMENTAL K (CM/SEC)
365	5.50	43.45	0.619E-06	0.619E-06
1327	5.50	43.10	0.410E-06	0.331E-06
7135	5.50	41.70	0.258E-06	0.224E-06
8305	5.50	41.35	0.262E-06	0.283E-06
9655	5.50	41.05	0.255E-06	0.212E-06
16795	5.50	39.15	0.258E-06	0.261E-06
18235	5.50	38.80	0.257E-06	0.245E-06
19675	5.50	38.50	0.253E-06	0.212E-06
21235	5.50	38.15	0.252E-06	0.230E-06
22615	5.50	37.90	0.248E-06	0.187E-06
26875	5.50	37.00	0.244E-06	0.222E-06
28375	5.50	36.75	0.240E-06	0.178E-06
31195	5.50	36.20	0.238E-06	0.210E-06
32695	5.50	35.90	0.237E-06	0.218E-06
35935	5.50	35.30	0.234E-06	0.205E-06
38635	5.50	34.75	0.233E-06	0.229E-06
39955	5.50	34.50	0.233E-06	0.215E-06
41385	5.50	34.20	0.233E-06	0.240E-06

****
* PERMEABILITY TEST *
****

Bentonite sample : 70 seconds
Initial head : 38.80 cm
Conversion factor : 2.82 cm/cc
Diameter of sample : 0.9525 cm

TIME (MINUTES)	LENGTH (CM)	HEAD (CM)	PERMEABILITY (CM/SEC)	INCREMENTAL K (CM/SEC)
376	5.10	38.50	0.873E-06	0.873E-06
1336	5.10	38.20	0.493E-06	0.345E-06
7146	5.10	36.90	0.297E-06	0.252E-06
8316	5.10	36.70	0.283E-06	0.196E-06
9666	5.10	36.50	0.267E-06	0.171E-06
16806	5.10	35.45	0.227E-06	0.173E-06
18246	5.10	35.35	0.216E-06	0.830E-07
19686	5.10	35.20	0.209E-06	0.125E-06
21246	5.10	34.90	0.211E-06	0.232E-06
22626	5.10	34.80	0.203E-06	0.880E-07
26886	5.10	34.20	0.199E-06	0.173E-06
28386	5.10	34.00	0.197E-06	0.165E-06
31206	5.10	33.65	0.193E-06	0.155E-06
32706	5.10	33.50	0.190E-06	0.126E-06
35946	5.10	33.10	0.187E-06	0.157E-06
38646	5.10	32.80	0.184E-06	0.143E-06
39966	5.10	32.60	0.184E-06	0.196E-06

41396	5.10	32.40	0.184E-06	0.182E-06

****
* PERMEABILITY TEST *
****

Bentonite sample : 90 seconds
Initial head : 44.00 cm
Conversion factor : 3.10 cm/cc
Diameter of sample : 0.9525 cm

TIME (MINUTES)	LENGTH (CM)	HEAD (CM)	PERMEABILITY (CM/SEC)	INCREMENTAL K (CM/SEC)
2374	6.50	43.40	0.284E-06	0.284E-06
2726	6.50	43.30	0.289E-06	0.321E-06
3564	6.50	43.15	0.268E-06	0.203E-06
3745	6.50	43.10	0.271E-06	0.314E-06
4079	6.50	43.05	0.262E-06	0.170E-06
5471	6.50	42.70	0.269E-06	0.288E-06
6883	6.50	42.40	0.264E-06	0.245E-06
7370	6.50	42.30	0.262E-06	0.238E-06
8332	6.50	42.10	0.260E-06	0.242E-06
14140	6.50	40.95	0.249E-06	0.234E-06
15310	6.50	40.70	0.250E-06	0.257E-06
16660	6.50	40.50	0.244E-06	0.179E-06
23800	6.50	39.25	0.235E-06	0.215E-06
25240	6.50	39.02	0.233E-06	0.200E-06
26680	6.50	38.90	0.226E-06	0.105E-06
28240	6.50	38.60	0.227E-06	0.243E-06
29620	6.50	38.40	0.225E-06	0.185E-06
33880	6.50	37.80	0.220E-06	0.181E-06
35380	6.50	37.60	0.218E-06	0.173E-06
38200	6.50	37.20	0.216E-06	0.186E-06
39700	6.50	37.00	0.214E-06	0.176E-06
42940	6.50	36.55	0.212E-06	0.185E-06
45640	6.50	36.20	0.210E-06	0.175E-06
46960	6.50	36.00	0.210E-06	0.206E-06
48390	6.50	35.85	0.208E-06	0.143E-06

****
* PERMEABILITY TEST *
****

Bentonite sample : 170 seconds
Initial head : 48.00 cm
Conversion factor : 3.00 cm/cc
Diameter of sample : 0.9525 cm

TIME (MINUTES)	LENGTH (CM)	HEAD (CM)	PERMEABILITY (CM/SEC)	INCREMENTAL K (CM/SEC)
2369	6.00	47.40	0.248E-06	0.248E-06
2721	6.00	47.30	0.253E-06	0.281E-06
3559	6.00	47.15	0.235E-06	0.177E-06
3740	6.00	47.10	0.237E-06	0.274E-06
4074	6.00	47.05	0.230E-06	0.149E-06
5466	6.00	46.80	0.217E-06	0.179E-06
6878	6.00	46.55	0.209E-06	0.177E-06
7365	6.00	46.45	0.208E-06	0.207E-06

8327	6.00	46.25	0.209E-06	0.210E-06
14135	6.00	45.35	0.188E-06	0.158E-06
15305	6.00	45.10	0.190E-06	0.221E-06
16655	6.00	44.90	0.188E-06	0.154E-06
23795	6.00	43.95	0.173E-06	0.140E-06
25235	6.00	43.70	0.174E-06	0.185E-06
26675	6.00	43.55	0.171E-06	0.112E-06
28235	6.00	43.30	0.171E-06	0.173E-06
29615	6.00	43.10	0.170E-06	0.157E-06
33875	6.00	42.60	0.165E-06	0.128E-06
35375	6.00	42.40	0.164E-06	0.147E-06
38195	6.00	42.00	0.164E-06	0.157E-06
39695	6.00	41.80	0.163E-06	0.149E-06
42935	6.00	41.40	0.161E-06	0.139E-06
45635	6.00	41.05	0.160E-06	0.147E-06
46955	6.00	40.90	0.159E-06	0.130E-06
48385	6.00	40.70	0.160E-06	0.160E-06

****
* PERMEABILITY TEST *
****

FILTER CAKE SAMPLES

Bentonite sample : 50 seconds
nitial head : 41.10 cm
onversion factor : 3.27 cm/cc
Diameter of sample : 1.0720 cm

TIME (MINUTES)	LENGTH (CM)	HEAD (CM)	PERMEABILITY (CM/SEC)	INCREMENTAL K (CM/SEC)
50	5.70	39.20	0.305E-04	0.305E-04
2576	5.70	12.90	0.145E-04	0.142E-04
3940	5.70	10.40	0.112E-04	0.509E-05

****
* PERMEABILITY TEST *
****

entonite sample : 50 seconds
Initial head : 41.30 cm
onversion factor : 3.27 cm/cc
iameter of sample : 1.0720 cm

TIME (MINUTES)	LENGTH (CM)	HEAD (CM)	PERMEABILITY (CM/SEC)	INCREMENTAL K (CM/SEC)
1575	5.70	17.00	0.181E-04	0.181E-04
2241	5.70	13.30	0.163E-04	0.119E-04
2899	5.70	11.70	0.140E-04	0.627E-05

****
* PERMEABILITY TEST *
****

entonite sample : 70 seconds
nitial head : 44.50 cm
Conversion factor : 2.82 cm/cc
iameter of sample : 0.9906 cm

TIME (MINUTES)	LENGTH (CM)	HEAD (CM)	PERMEABILITY (CM/SEC)	INCREMENTAL K (CM/SEC)
124	4.60	44.30	0.128E-05	0.128E-05

****
* PERMEABILITY TEST *
****

entonite sample : 90 seconds
Initial head : 58.10 cm
onversion factor : 3.10 cm/cc
iameter of sample : 0.9525 cm

TIME (MINUTES)	LENGTH (CM)	HEAD (CM)	PERMEABILITY (CM/SEC)	INCREMENTAL K (CM/SEC)
124	6.40	58.05	0.335E-06	0.335E-06

1519	6.40	57.40	0.385E-06	0.390E-06
4493	6.40	55.80	0.434E-06	0.459E-06
6063	6.40	55.00	0.437E-06	0.444E-06
6118	6.40	54.95	0.440E-06	0.799E-06
8644	6.40	53.75	0.435E-06	0.422E-06
10008	6.40	53.20	0.425E-06	0.364E-06
11588	6.40	52.50	0.422E-06	0.405E-06
12253	6.40	52.20	0.422E-06	0.416E-06
12911	6.40	51.90	0.422E-06	0.423E-06
14394	6.40	51.30	0.418E-06	0.379E-06

****
* PERMEABILITY TEST *
****

Bentonite sample : 170 seconds
Initial head : 57.30 cm
Conversion factor : 3.00 cm/cc
Diameter of sample : 0.9525 cm

TIME (MINUTES)	LENGTH (CM)	HEAD (CM)	PERMEABILITY (CM/SEC)	INCREMENTAL K (CM/SEC)
125	7.70	57.10	0.168E-05	0.168E-05
1520	7.70	54.60	0.191E-05	0.193E-05
4494	7.70	48.90	0.212E-05	0.223E-05
6063	7.70	45.30	0.233E-05	0.293E-05
6119	7.70	45.10	0.235E-05	0.474E-05
8645	7.70	34.40	0.354E-05	0.644E-05
10009	7.70	28.20	0.425E-05	0.875E-05

****
* PERMEABILITY TEST *
****

Bentonite sample : 170 seconds
Initial head : 60.40 cm
Conversion factor : 3.00 cm/cc
Diameter of sample : 0.9525 cm

TIME (MINUTES)	LENGTH (CM)	HEAD (CM)	PERMEABILITY (CM/SEC)	INCREMENTAL K (CM/SEC)
1576	7.70	44.30	0.118E-04	0.118E-04
2241	7.70	38.90	0.118E-04	0.117E-04
2899	7.70	34.20	0.118E-04	0.117E-04
4384	7.70	27.70	0.107E-04	0.852E-05