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GRAVEL PACK THICKNESS FOR GROUND-WATER WELLS— REPORT NO. 1

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16. ABSTRACT

Gravel packs, well screens, and well development methods are being investigated for ground-water wells through an ongoing research and development program conducted by the Bureau of Reclamation Engineering and Research Center. A well sectional model study program was designed to determine the optimum gravel pack thickness by using the high-velocity horizontal water jetting well development method. The results indicate that the thickness of a gravel pack is limited to a practical dimension. The success of the prototype well operation depends on the effective destruction of the rigid wall cake (formed by the drilling operation) during the well development phase. A minimum thickness is recommended when employing the jetting method from inside the well. However, the gravel pack should be thick enough to provide an annular space that will ensure complete surrounding of the well screen by pack material during the placement operation. Therefore, the selection of the gravel pack thickness should be based on the efficiency of the well development method used and the ease of proper placement of pack material.

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by

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June 1986

Hydraulics Branch
Division of Research and Laboratory Services
Engineering and Research Center
Denver, Colorado

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PURPOSE

Gravel pack thickness for ground-water well design was investigated in the hydraulics laboratory. The results from the well sectional model used in the study program are reported. An evaluation of the high-velocity horizontal water jetting method used for well development is also reported. The objective is to develop guidelines for well design and construction and well development procedures for fine sand aquifers.

INTRODUCTION

Coarser, artificially graded material is often placed around the ground-water well screen when the unconsolidated aquifer formation consists of fine sand material, as experienced in the Closed Basin Project in southern Colorado. The coarser material is placed during the construction phase and is usually referred to as the "gravel pack" even when it is considerably smaller than the standard classification size for gravels.

Continuous movement of the fine aquifer material into the well during the production phase eventually causes the surrounding formation to collapse, resulting in a costly well operation failure. The gravel pack acts as a filter and prevents the movement of the finer material into the well. An effective gravel pack filter enables the well screen to have wider slots, which increase its percentage of open intake area. A larger open intake area has several advantages: (1) the hydraulic efficiency increases, (2) the rate of corrosion and incrustation buildup decreases [1, 2, 3]*, and (3) the longevity of the well increases; thus, the cost of maintenance decreases.

The movement of the finer aquifer material into the gravel pack is controlled by the particle size ratio of the pack-aquifer materials, referred to as the *P/A* ratio. A *P/A* ratio of 4 will successfully control movement of the finer material with only a fraction of an inch (<25 mm) of pack material, regardless of the velocity of water flowing through the gravel pack [2, 3, 5]. Thicker (>25 mm) gravel packs will not reduce the potential for fine material movement. However, 3 inches (76 mm) is generally recommended as the minimum thickness to ensure there is enough annular space for the gravel pack to completely surround the well screen during the placement operation [2].

The permeabilities of the gravel packs can be 1,000 times greater than that of the aquifer. Therefore, thicker gravel packs can essentially increase the effective diameter of the well. Tripling the effective diameter would theoretically increase the well yield by about 20 percent [1]. However, a serious problem develops during the construction phase that makes the final development of the well extremely difficult when thick gravel packs are used.

Every method used for drilling a ground-water well causes an adverse effect on the porosity and permeability of the aquifer formation at the periphery of the drill hole [2]. When drilling through soft, unconsolidated formations, the water column inside the drill hole is maintained at a level higher than the static water level of the aquifer. Water flows from the drill hole into the aquifer and carries with it the suspended clay and silt particles caused by the drill bit agitation or the intentionally added drill mud. The outward migration of the suspended particles combined with the outward thrust of the drilling action, forces the suspended material into the pores of the aquifer formation. This forms a rigid mud deposit at the perimeter of the hole. The formation of this rigid mud deposit, referred to as the wall cake, is desirable during the drilling operation; it reduces the possibility of the hole collapsing during the construction phase. However, the wall cake has a very undesirable characteristic for the production phase. The wall cake has properties similar to an impervious core zone used in earth dams; i.e., the hydraulic gradient across the wall cake formation has a significant head loss. The high head loss caused by the wall cake must be eliminated during well development, the final step of the construction phase, before the optimum specific capacity of the well can be realized. The only way the impervious characteristics can be eliminated is by the physical destruction of the wall cake formation.

Using a thick gravel pack places the wall cake formation farther from the well screen. This makes it more difficult to effectively erase the wall cake when developing the well from the inside of the well screen.

The hydraulic laboratory investigation of gravel packs, well screens, and well development methods for ground-water wells is an ongoing research and development program. The objective of this first report is to present the results of the well sectional model study program, which is designed to determine the optimum gravel pack thickness. Only one well development method was used. It consisted of high-velocity horizontal water jetting from inside the well screen. One test run was made using low-velocity jets from outside the well screen as a preliminary test for investigating alternative well development methods planned for the future. An evaluation of the jetting well development method is made. This report also includes a summary, conclusions, details of the well sectional model design, test program, and test results. The steady-state flow conditions for certain test runs are included in the

* Numbers in brackets refer to entries in the bibliography.

appendix for those interested in pursuing mathematical model verification studies.

SUMMARY

A well sectional model (fig. 1) was designed and constructed for the ongoing research program to investigate the many different variables involved in the design and construction of prototype ground-water wells. The well sectional model was designed to determine (1) the optimum gravel pack thickness, (2) the best method of well development, and (3) other important factors needed to design efficient wells and to specify well development procedures. The study program in this report emphasizes item (1) to determine the optimum thickness of the gravel pack.

Three gravel pack thicknesses were studied: 3, 6, and 9 inches (76, 152, and 229 mm). Two different gradations for the aquifer and gravel pack materials and three different well screens, each having an 8-inch (203-mm) pipe diameter, were used. Two well screens were of the wire-wound-cage type, with slot widths of 0.020 and 0.040 inch (0.5 and 1.0 mm), and one was PVC (polyvinyl chloride), with a slot width of 0.040 inch (1.0 mm). A wall cake formation, ⅜ inch (9.5 mm) thick, was hand placed between the aquifer and the gravel pack to simulate the prototype drill hole conditions after drilling and before well development. High-velocity horizontal water jetting, using two ¼-inch (6.4-mm) diameter nozzles, was used as the method of well development.

The first 6 test runs, of the 26 completed for this report, were preliminary and were made to debug the test equipment and the well development procedure. Seven special test runs were conducted to evaluate (1) a high *P/A* ratio, (2) low-velocity horizontal water jetting outside the well screen, (3) the optimum specific capacity of the three gravel pack thicknesses without the simulated wall cake formation, and (4) the PVC well screen.

CONCLUSIONS

Based on the results of the test runs conducted on the laboratory well sectional model and included in this report, the following main conclusions can be made:

1. The effective destruction of the rigid wall cake formation at the perimeter of the drill hole is a major factor that determines the prototype ground-water well pumping capacity.

2. The wall cake formed during the drilling operation has characteristics similar to the impervious core used in earth dams; i.e., it causes a significant head loss in the ground-water flow approaching the well screen.

3. The effect of the wall cake must be erased completely before the optimum specific capacity of the well can be achieved. The efficiency of the well is proportional to the effective elimination of the wall cake formation.

4. The thickness of the gravel pack is limited to a practical dimension that allows proper placement of the gravel pack and the effective removal of the rigid, impervious characteristics of the wall cake formation by the water jetting well development method. The practical gravel pack thickness should range from a minimum of 3 inches (76 mm) to a maximum of about 6 inches (152 mm).

5. The high-velocity horizontal water jetting well development method from inside the well screen is an effective technique to physically destroy the wall cake formation characteristics and in the process expand the gravel pack. However, a large amount of fines from the aquifer are *mixed* into the gravel pack as a result of the whirling action of the water jets. The destruction of the wall cake increased the specific capacity by about 24 percent. By destroying the wall cake and expanding the gravel pack, the initial head loss caused by wall cake formation was reduced by about 75 percent. The remaining head loss is primarily caused by aquifer fines mixed into the gravel pack. The expanded gravel pack is a major factor in the recovery of the well specific capacity to within 3 percent of the ideal conditions. The high-velocity horizontal water jetting method is not an efficient technique to remove the *mixed-in* fines that occur during the first jetting pass. About five to seven jet tool passes are required to attain an optimum well specific capacity.

6. Special test runs conducted without the wall cake formation verified that thicker gravel packs could essentially increase the effective diameter of the well and thereby increase the specific capacity. The test results indicate that the specific capacity of the well would increase about 27 percent when the gravel pack thickness is increased by 3 inches (76-mm). Therefore, if the wall cake formation is ideally erased, the average specific capacity should increase by about 27 percent. The high-velocity horizontal water jetting from inside the well screen does not consolidate the gravel pack material enough to cause a significant reduction in the well specific capacity.

7. Well development procedures should not be used if the wall cake formation *does not* exist at the perimeter of the drill hole.

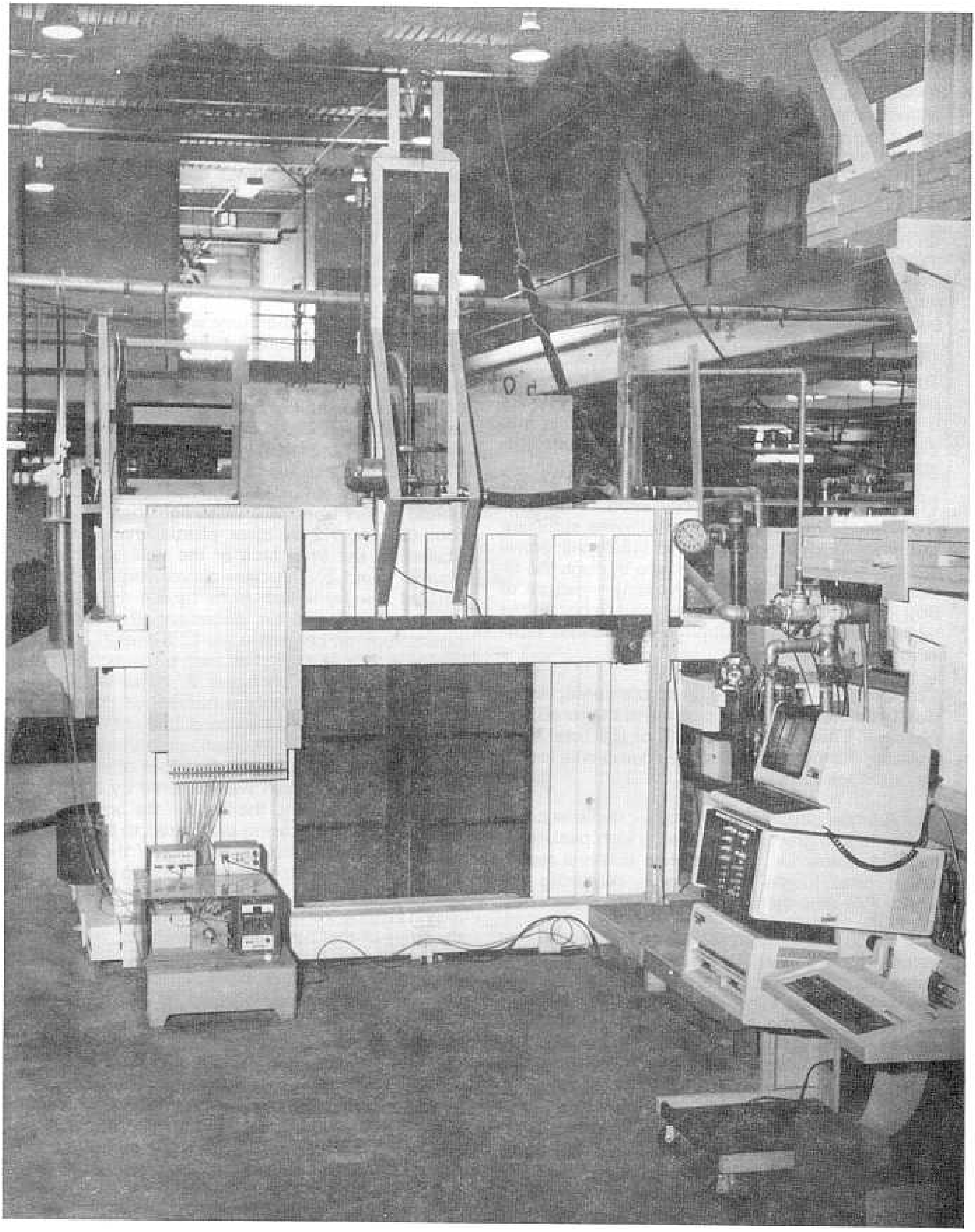


Figure 1. – General view of laboratory well sectional model. P801-D-80970

8. The special test run to evaluate the low-velocity horizontal water jetting from outside the well screen was not completely successful. A balanced low-velocity water jetting, and thus uniform jet penetration into the wall cake formation, was not accomplished. The unconventional outside the well screen water jetting can be a valid method of well development if pressures can be balanced and the water jet penetration distance can be controlled.

9. The horizontal high-velocity water jetting method of well development neither caused large cavities to remain nor directly connected the aquifer material to the well screen after jetting was completed in any of the test runs.

10. The water jet nozzle velocity is very critical. The wall cake can not be destroyed if the water jet velocity is too low. However, if the jet velocity is too high, the water jet penetrates farther into the aquifer formation and mixes a larger percentage of fines into the gravel pack.

11. The maximum jet velocity used in the test runs was 220 ft/s (67 m/s), which was sufficient to penetrate through the 6-inch (152-mm) gravel pack, but insufficient to penetrate through the 9-inch (229-mm) gravel pack. A pump pressure of 660 lbs/in^2 (4550 kPa) was required to obtain the highest water velocity through two ¼-inch (6.4-mm) jet nozzles.

12. The calibration of the jet nozzle coefficient of discharge averaged 0.49 in terms of the total head available. Therefore, about half of the total head available from the high-pressure pump was lost at the entrance to the nozzle.

13. A larger percentage of aquifer material could be mixed into gravel packs having high pack-aquifer, *P/A* ratios; i.e., greater than 6. As a result, higher head losses could occur, rendering the higher *P/A* ratio ineffective.

14. A PVC well screen requires a higher water jet velocity (greater than 15 percent) to penetrate the same distance than a wire-wound-cage type well screen having the same aquifer configuration. The mixing action of the water jet outside the PVC well screen was slightly more efficient in cleaning out the fines. This left the gravel pack material slightly coarser. The degree of clogging of the slots by the high-velocity horizontal water jetting method of well development for both the PVC and wire-wound-cage well screens was about the same magnitude. Overall, the effectiveness of the high-velocity horizontal water jetting through the PVC well screen was not significantly different from that through the wire-wound-cage well screen.

LABORATORY TEST PROGRAM

General

A well sectional model (fig. 1) was constructed in the hydraulic laboratory to facilitate the investigation of the many variables involved in the design and construction of the prototype ground-water wells. The well sectional model allows different configurations to be installed and tested in a relatively short time. A clear plastic window was installed to observe the action of the well development methods.

Well Sectional Model Design

The layout of the laboratory well sectional model is shown on figure 2, which includes the schematic arrangement of the high- and low-pressure pumps. The horizontal cross section of the aquifer and the well screen and casing is a half-circle. The aquifer is contained by a perforated CMP (corrugated metal pipe) with a Mirafi-type fabric liner at the aquifer perimeter. The CMP had a radius of 33 inches (838.2 mm) and a height of 6 feet (1.8 m). The half-cylinder CMP was bolted to the front of a watertight box. A 4- by 4-foot (1.2- by 1.2-m) clear plastic window was installed on the front face of the box, as shown on figures 1 and 2. The clear plastic window had two vertical 3/16- by ¼-inch (4.8- by 6.4-mm) slots dadoed on the inside for placement of the half-circle well screen on centerline. A 4.25-foot (1.3-m) long well screen was cut in half with a 3/16-inch (4.8-mm) offset, as shown, on figure 2, detail A. The well screen was placed on the bottom of the box with the cut edges slipped into the dadoes of the window. The bottom of the well screen was secured by a half-circle retainer ring bolted to the floor of the box. The top of the well screen was secured by a half-circle retainer ring bolted to the front of the box above the window. The well casing was fitted to the upper retainer ring and bolted to the front of the box above the well screen with rubber gaskets to prevent leakage. A heavy metal frame with two horizontal ¾- by 3-inch (19- by 76-mm) steel bars was placed against the front of the 1-inch (25.4-mm) thick window and bolted to the wooden water tight box outside frame to prevent the window from deflecting outward under hydrostatic pressure.

Figure 2 also shows the schematic layout of the high- and low-pressure pump system used for the high-velocity water jetting well development method. The high-pressure pump system was designed for 1,000 lb/in^2 (6895 kPa) by using extra strength black pipe and gate valves. The high-pressure pump has a designed discharge capacity of 100 gal/min (6.3 L/s) at a pressure of 650 lb/in^2 (4482 kPa). The low-pressure pump has a capacity of 180 gal/min (11.3 L/s) at a discharge pressure of 46 lb/in^2 (317 kPa). The

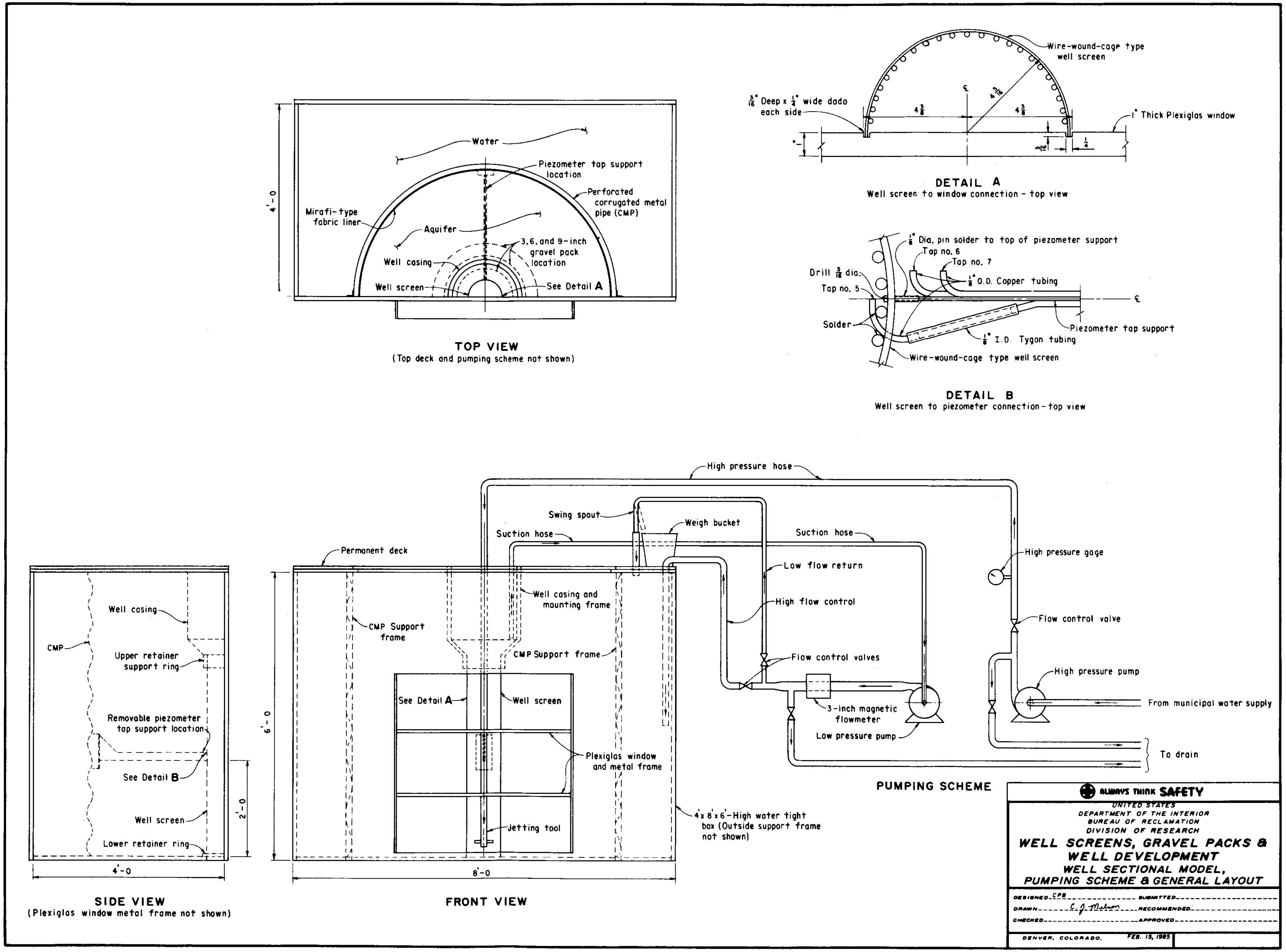


Figure 2. – Well sectional model – general layout.

low pressure suction pump was also used to establish the steady-state flow condition.

A row of piezometer taps were placed at the 2-foot (0.6-m) level (measured up from the floor of the box) to obtain the hydraulic gradient for the aquifer, wall cake, gravel pack, and well screen. The outline of the piezometer tap support is shown on figure 2. The details of the piezometer tap installation are shown on figure 3. Table 1 identifies each piezometer tap used in the well sectional model and its location for easy reference. The first and second calibration well measurements, taps No. 1, 2, and 16, 17, were used to obtain the volts per foot of water level calibration for the pressure transducer during the automatic scanning process. Tap No. 5 was located immediately inside the well screen (fig. 2, detail B). The end of each tap, located on the piezometer support (fig. 2), was wrapped with a fine 200-mesh screen and soldered ¼ inch (6.4 mm) from the end to prevent fine sand material from plugging the ⅛-inch (3.2-mm) o.d. (outside diameter) copper tubing. Flexible Tygon tubing connected each tap from the back of the piezometer support at the CMP, through the watertight box, to a manometer board, located on the upper left front corner of the box on figure 1. The piezometer support was designed for easy installation and removal to facilitate the placement and excavation of materials below the 2-foot (0.61-m) level.

Each manometer line was teed and connected to a scanner valve port. A single differential pressure transducer measured the water depth for each of the 18 piezometer taps. One side of the differential pressure transducer was connected to the center port of the scanner valve, and the other side was open to atmospheric pressure. The differential pressure transducer was of the strain-gauge type with good linear resolution and a range of 0 to 5 lb/in^2 (0 to 34.4 kPa). The scanner valve was automatically sequenced to each port by the minicomputer, and each piezometer tap was connected internally to the center port and thus the differential pressure transducer. Details of the automatic scanning, the use of the calibration wells, and the hydraulic gradient measurements for the steady-state test runs are described in subsequent paragraphs.

A 3-inch (76-mm) magnetic flowmeter was installed on the discharge side of the low-pressure pump (fig. 2). It was not used to measure the steady-state flow during the test run because the accuracy of the meter at the very low range was not satisfactory. Instead, the basic volumetric method (bucket, stop watch, and swing spout to divert the low-pressure pump discharge) was used to obtain an accurate measurement of the steady-state flow for each test run. However, the magnetic flowmeter was used to calibrate the high-velocity water jetting tool.

Four concrete blocks, each weighing 850 pounds (386 kgm), were placed on top of the aquifer at the 5.8-foot (1.8-m) level (fig. 1). These concrete blocks added to the aquifer a surcharge equivalent to about 3 feet (0.9 m) of aquifer material.

Jet Tool Design

The high-velocity water jet tool had two ¼-inch (6.4-mm) nozzles spaced 90° apart, as shown on figures 4 and 5. The jet nozzle assembly was rotated back and forth, pivoting against a vertical tee bar placed against the window because of the well screen half-circle design. As a result, the ends of the jet nozzles did not rotate concentrically around the vertical centerline of the well screen. At the midpoint of the well screen perimeter, the ends of the jet nozzles were ¼ inch (6.4 mm) closer than they were at the window edge of the screen. The rotation of the jets was limited to 85°; i.e., the jets stopped 7½° from the window to prevent direct thrust of the jet against the window boundary. High-pressure water was supplied through the vertical 1¼-inch (31.8-mm) i.d. pipe, which was plugged at the lower end, 1¼-inches (31.8 mm) below the entrances to the jet nozzles (fig. 5). The entrances to the jet nozzles were reamed to a taper of 45° to reduce entrance losses at the high water velocities.

Figure 1 shows the arrangement of the rigging used to mount and raise the jet tool assembly. The supply pipe was connected to a 1½-inch (38.1-mm) i.d. flexible high-pressure rubber hose 15 feet (4.6 m) long. The flexible hose permitted the jet tool assembly to be rotated manually by test personnel during the jetting well development procedure. A quick disconnect (jet supply pipe to the hose connection) was used so that the assembly could easily be disconnected and removed from the well sectional model when materials were placed or excavated. The jet tool assembly was raised during the well development procedure at a speed of 1 foot (0.3 m) per minute using a geared motor, pulley, and hoist cable attached to the jet tool supply pipe near the upper end.

Jet Tool Calibration

The jet tool was placed inside the well screen at the 1-foot (0.3-m) level (measured up from the floor). The watertight box, without aquifer formation materials, was filled with water to the 5.7-foot (1.7-m) level. The jet nozzles were calibrated by balancing the flow from the jet nozzles into the box (using the high-pressure pump system with the intake connected to the laboratory's municipal water supply) with the flow to the outlet of the box (using the low-pressure pump system connected to the laboratory drain). When the flow into the box from the jets balanced the flow to the drain, measurements of the magnetic

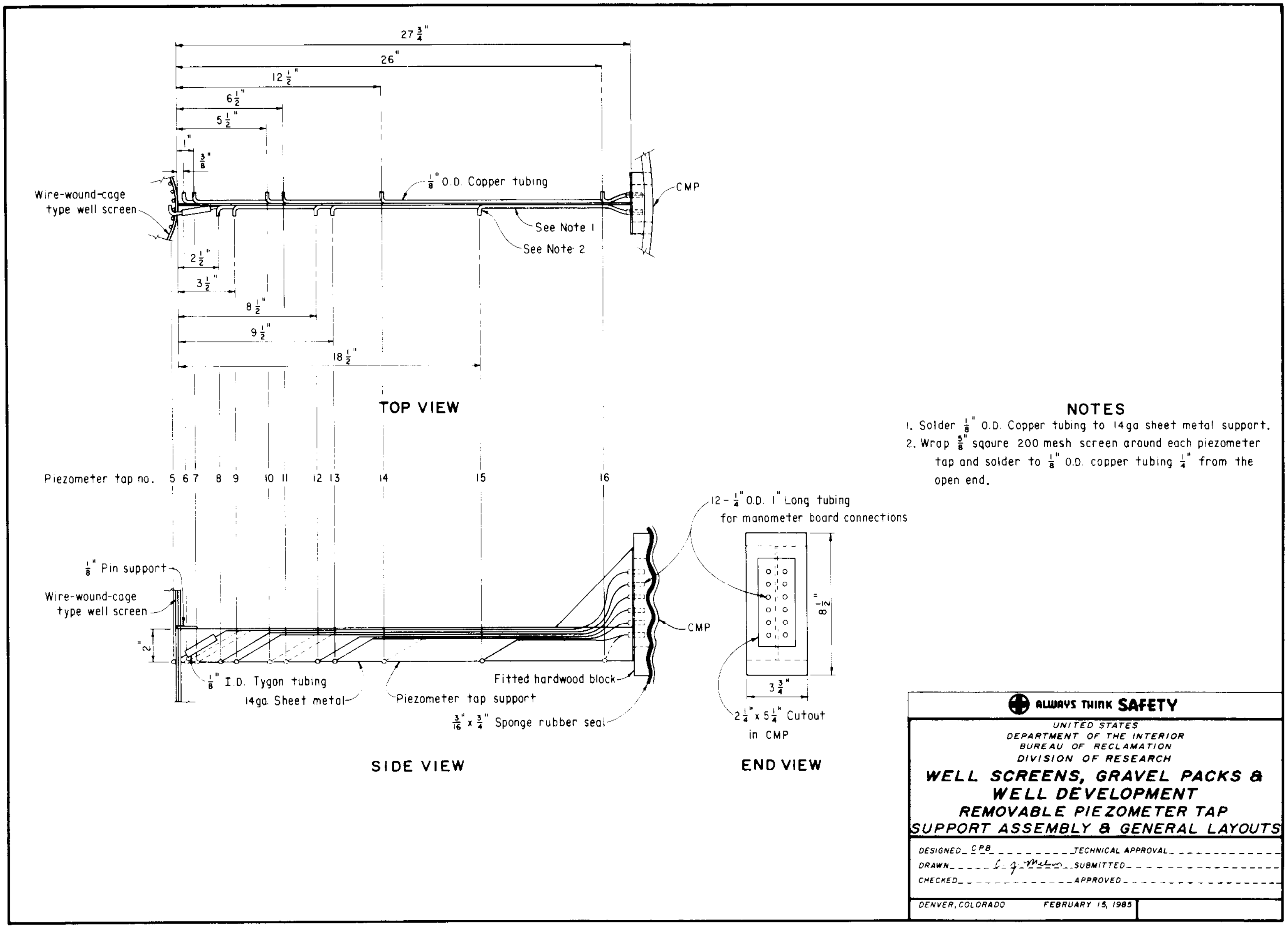


Figure 3. – Details of piezometer tap installation.

Table 1. – Piezometer tap locations.

Tap No.	Location*			Remarks
	Inches			
	fraction	decimal	mm	
1	–	–	–	Stilling wells for first calibration
2	–	–	–	
3	–	–	–	Static water level inside box
4	–	–	–	Static water level inside well casing
5	–	–	–	Located immediately inside well screen
6	3/8	0.38	9.6	For 1/2-in gravel pack
7	1	1.00	25.4	
8	2 9/16	2.56	65.0	For 3-in gravel pack
9	3 9/16	3.56	90.4	
10	5 1/2	5.50	139.7	For 6-in gravel pack
11	6 1/2	6.50	165.1	
12	8 9/16	8.56	217.4	For 9-in gravel pack
13	9 9/16	9.56	242.8	
14	12 9/16	12.56	319.0	For aquifer formation
15	18 9/16	18.56	471.4	
16	26 9/16	26.06	661.9	
17	–	–	–	Stilling wells for second calibration
18	–	–	–	

* Measured from outside edge of well screen.

flowmeter and the high-pressure gauge on the jet tool supply pipe (fig. 2) were taken. The high-pressure gauge measurement was used for the total head on the jet nozzle. Several balanced flow conditions at various jet tool supply line pressures were accomplished to develop a jet tool calibration, pressure versus jet nozzle velocity. Table 2 summarizes the jet tool calibration tests and includes the calculation of the jet nozzle coefficient of discharge, K_e, in terms of the total head. The test runs provided an average K_e of 0.49, which is considered to be typical for a sharp-edge entrance condition. Apparently, the 45° taper provided at the nozzle entrance did not streamline the entrance enough to reduce the head loss from that of the sharp-edge entrance design.

Figure 6 graphically shows the jet nozzle velocity versus the high-pressure gauge value. This graph was used extensively in the test program to establish the required pump pressure for the selected jet nozzle velocity.

Test Procedure

General. – A typical aquifer configuration setup and the test run procedure is described in detail to assist in the understanding of terms used in the test results discussed in subsequent paragraphs. The well screen was set in place and sealed with tape from the well casing down to the 2.5-foot (0.8-m) level, as explained later.

Preparation. – With the inside of the CMP (fig. 2) clean of sand materials, the first step in the filling operation was to place a sheet metal form [14 ga by 2.5 feet (2.4 mm by 0.8 m) high, having a half-circle shape in cross section] concentrically with the well screen and butting against the window. The annular space between the well screen and the sheet metal form represents the gravel pack thickness. Three sheet metal forms were required, each having a different radii, to represent the gravel pack thicknesses of 3, 6, and 9 inches (76, 152, and 229 mm) used

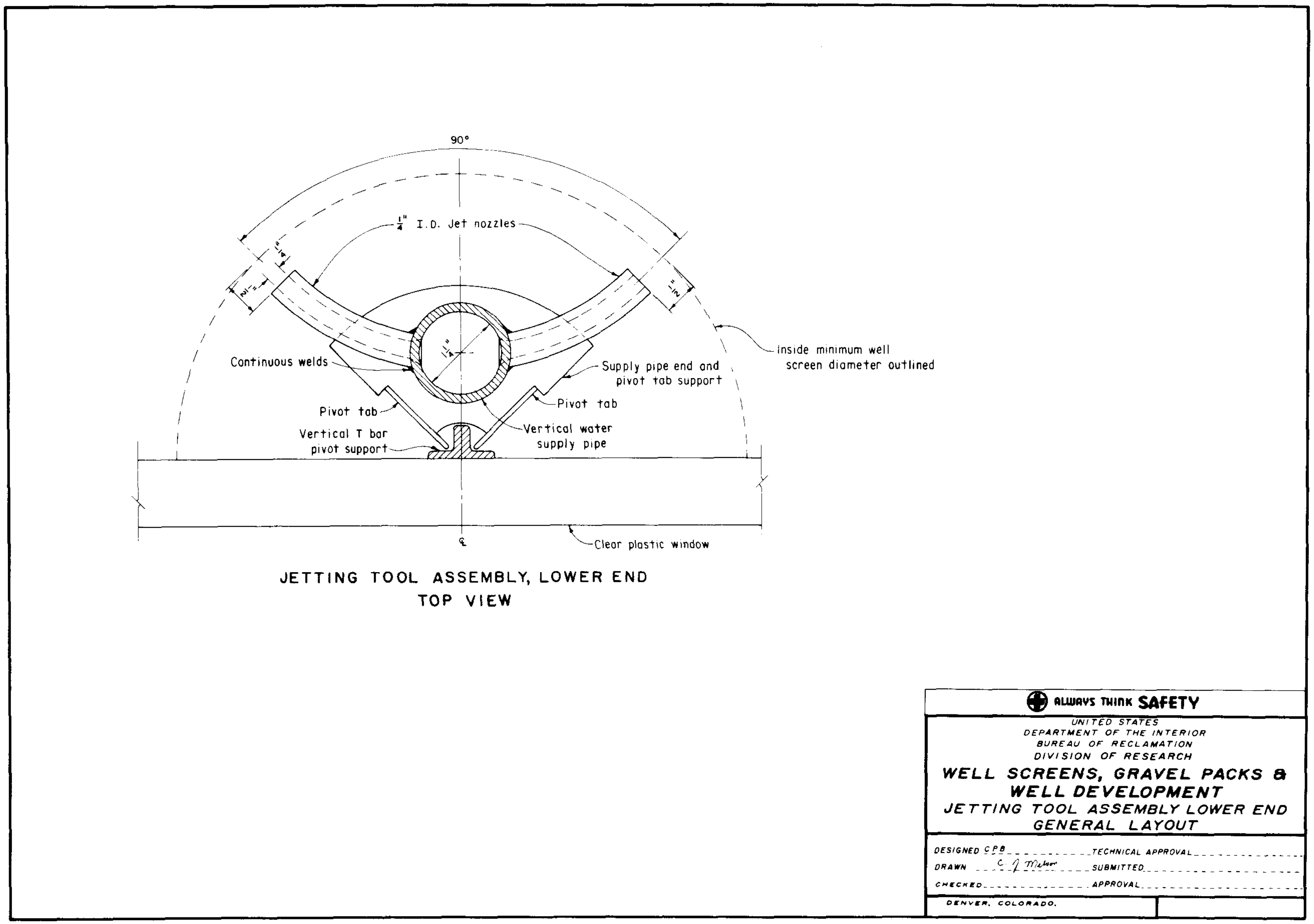


Figure 4. – High-velocity water jetting tool assembly – lower end top view.

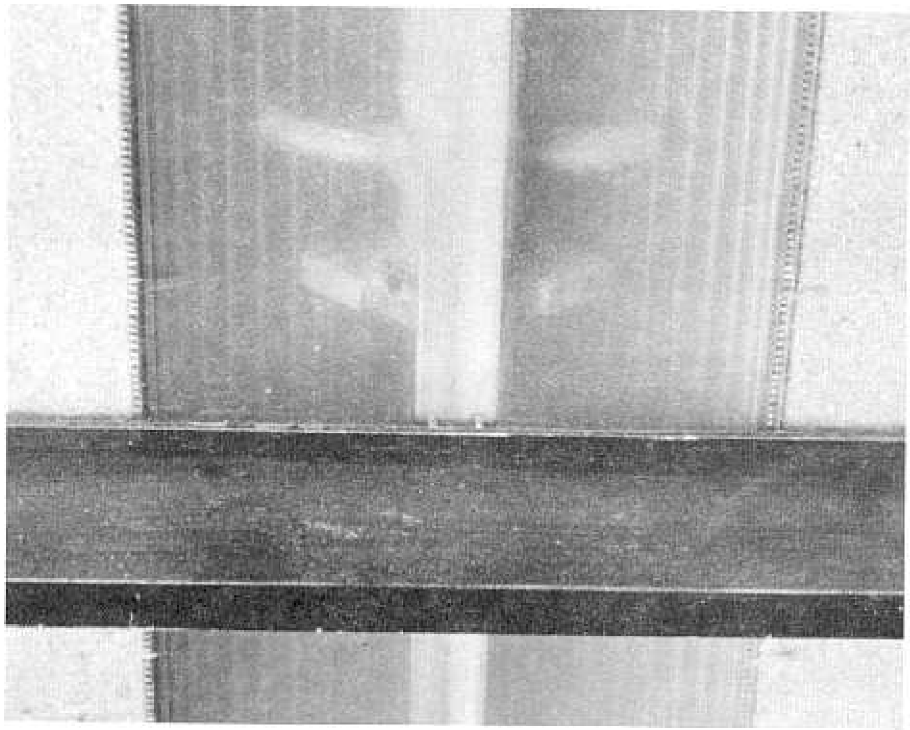


Figure 5. – General view of jet tool nozzles and lower end assembly inside well screen. P801-D-80971

Table 2. – Summary of jet tool calibration test runs.*

Run No.	Avg. gauge pressure, lb/in² (kPa)	Total head *HT*, ft (m)	Discharge *Q*, ft³/s	Discharge Q, gal/min (L/min)	Jet velocity V, ft/s (m/s)	Discharge coefficient, K_e
1	100 (689)	230.8 (70.3)	0.0588	26.39 (100.0)	86.5 (26.4)	0.50
2	250 (1724)	577.0 (175.9)	0.0952	42.73 (161.8)	140.0 (42.7)	0.47
3	300 (2068)	692.4 (211.0)	0.1060	47.57 (180.1)	155.9 (47.5)	0.46
4	400 (2757)	923.2 (281.4)	0.1151	51.66 (195.6)	169.3 (51.6)	0.52
5	500 (3447)	1154.0 (351.7)	0.1323	59.38 (224.8)	194.6 (59.3)	0.49
6	630 (4344)	1454.0 (443.2)	0.1452	65.17 (246.7)	213.5 (65.1)	0.51
Average						0.49

*Total area of the two ¼-inch jet nozzles = 0.00068 ft²,
HT = gauge pressure × 2.308,
V = computed jet nozzle velocity,
g = gravitational constant, and

$$K_e = \frac{HT - (V^2/2g)}{HT}.$$

in the study program. Next, a second sheet metal form [14 ga by 1 foot (2.4 mm by 0.3 m) high, also having a half-circle shape in cross section] was placed concentrically outside the gravel pack sheet metal form. The annular space between the first and second sheet metal forms represents the thickness of the simulated wall cake formation of the prototype ground-water well. A shorter sheet metal form was required to obtain the annular space for the ⅜-inch (9.5-mm) thick wall cake formation for each of the three gravel pack thicknesses used in the study. These shorter forms were coated on the inside with

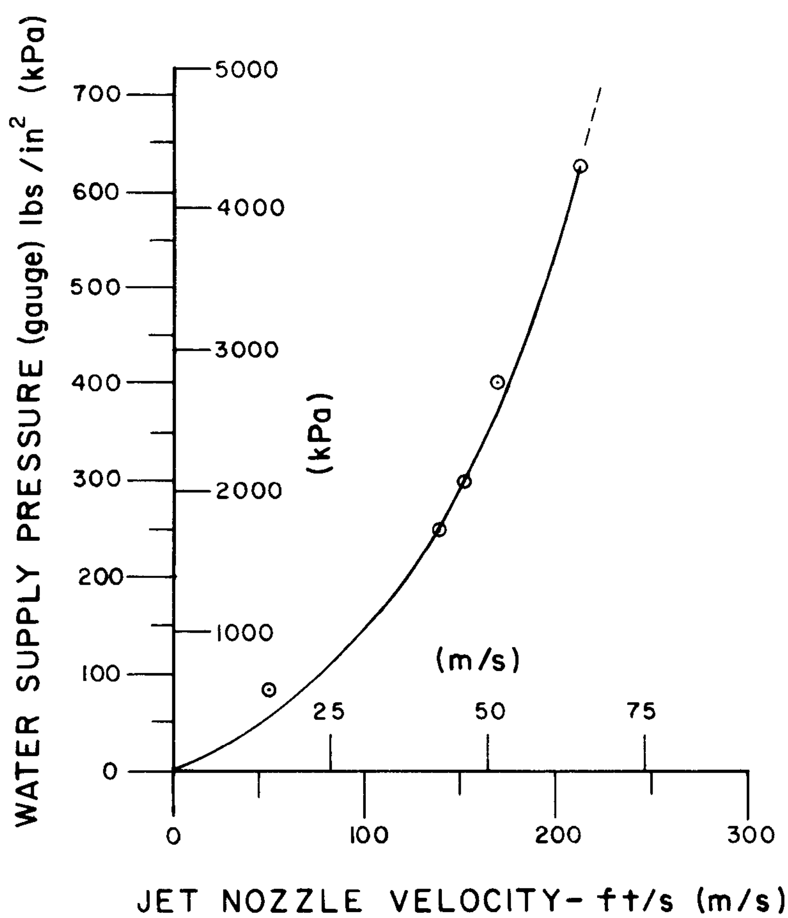


Figure 6. – Jet tool calibration of inlet gauge pressure vs. jet nozzle velocity.

a molybdenum disulfide base lubricant known as "Dry Slide" to prevent the wall cake material from sticking to them when they were slipped out later.

With the two sheet metal forms in place, the filling operation began by placing the wall cake material (a special blend of aquifer sand and fines having a 15 percent moisture content, described in subsequent paragraphs) between the forms and against the window. The material was compacted by tamping with a ¼- by ¾-inch (6.4 by 19.0-mm) metal bar. The filling and tamping continued at 2-inch (51-mm) lifts until a 10-inch (254-mm) depth was obtained at the window on both sides of the half circle. Filling the annular wall cake space at the window first prevented the fine sand aquifer material from leaking around the edges of the sheet metal form when it was placed inside the CMP. The annular spaces of the pack and wall cake were then covered to prevent fine material from settling inside when the aquifer material was poured into the CMP from the top. A dump bucket on the front of a forklift was used to lift and pour the very dry aquifer material. The quantity poured in provided an 8- to 9-inch (203- to 229-mm) lift of the aquifer formation when leveled out. The dust covers were then removed and the placement and tamping of the wall cake material around the remaining unfilled perimeter continued in 2-inch (51-mm) lifts until the height matched the level of the aquifer material. Then the outside sheet metal form was carefully lifted up and out of the material. The removed slip form was then recoated with "Dry Slide" for the next lift. It was repositioned at the higher level in the same concentric half circle. The filling process was repeated for the second 8- to 9-inch (203- to 229-mm) lift of the wall cake and aquifer materials. The third lift brought the formation to the 2-foot (0.6-m) level.

When the placement of the wall cake and the dry aquifer was completed to the 2-foot (0.6-m) level, the watertight box was slowly filled with water to the 1.7-foot (0.5-m) level. At the same time, water was added to the inside of the well screen to balance the hydraulic gradient across the wall cake until a depth of about 1.5 feet (0.46 m) was reached. Then the gravel pack material (dry) was poured from a bucket into the annular space between the well screen and the first sheet metal form until the depth reached 2 feet ¾ inches (0.63 m). The sheet metal form was lightly tapped with a hammer, causing the gravel pack to settle about ½ inch (13 mm). Then the sheet metal form was lifted, using an overhead crane hoist, and taken out of the CMP. For the 3-inch (76-mm) gravel pack sheet metal form, the well casing had to be removed to provide clearance when the form was slipped out. The removal of the gravel pack sheet metal form would cause the pack material to settle an additional ¼ inch (6.4 mm), bringing the top of the pack material down to the 2-foot (0.6-m) level.

The next step was to take material samples of the gravel pack and aquifer at the 2-foot (0.6-m) level for mechanical analysis. These samples, referred to as the "in place" samples, were taken along a line 45° from the window on the well's right side (looking into the well). Two samples, one on each side of the 45° line about 2 inches (51 mm) apart were taken at selected distances from the well screen. Figure 7 shows the soil sample pattern for the three gravel packs used in the study. Each sample was 1 inch (25.4 mm) in diameter and about 3½ inches (89 mm) deep. Standard procedures were employed in the mechanical analysis of materials; except that 3-inch (76-mm) diameter sieves were used for the small samples. The gradations of the two opposite samples on the 45° line were averaged.

After the soil samples were taken, the row of piezometer taps mounted on the piezometer support frame was slipped into place. The two sheet metal forms for the gravel pack and wall cake were then set into the proper half-circle concentric positions; each form had a slot at the midpoint of its perimeter to fit over the piezometer support frame. These slots were taped when the forms were used at other levels to prevent leakage of the sand materials. The work accomplished to this stage usually took 1 day.

On the second day, the filling procedure was repeated to the 3.33-foot (1.0-m) level. With the gravel pack, wall cake, and aquifer formation saturated with water, a layer of wall cake ½-inch (13 mm) thick was placed and compacted on top of the gravel pack. It extended from the well screen to the outside edge of the vertical wall cake half-circle edge. The well screen was sealed with duct tape above the 2.5-foot (0.8-m) level. Therefore, an impervious boundary was set up to the 3.33-foot (1.0-m) level, and the flow of water into the well screen was limited to the lower 2.5 feet (0.8 m) of the gravel pack and aquifer formation. The taped well screen, from the well casing at the top down to the 2.5-foot (0.8-m) level, allowed the gravel pack and aquifer to slump, (as material was removed and the gravel pack expanded during the water jetting well development phase) and prevented the aquifer material from making contact with the open slots of the well screen. A typical aquifer, wall cake, and gravel pack completed configuration is shown on figure 8(a) for a 6-inch (152-mm) gravel pack thickness.

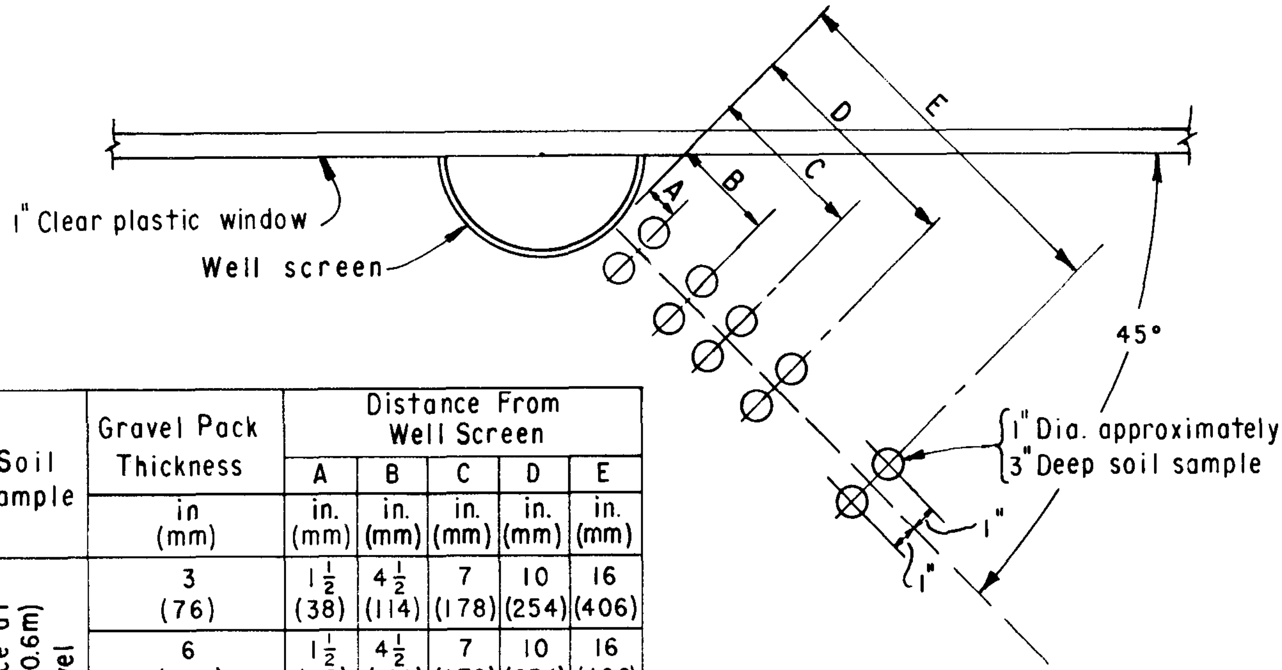
If the well casing had been removed for the 3-inch (76-mm) gravel pack placement, it was replaced at this time. Even though gaskets were used to prevent leakage into the well casing, it was necessary to seal the lower end around the well screen with modeling clay for added protection.

A load of dry aquifer material was poured in for another lift on top of the gravel pack lid. This brought the aquifer formation up to about the 4-foot (1.2-m) level. If material having the same gradation was available from a previous test run (used materials were stockpiled separately from unused materials), it was used to fill the CMP from the 4-foot (1.2-m) up to the 5.8-foot (1.8-m) level. The top of the aquifer was screeded to obtain a very flat surface for the concrete blocks.

The reused material included a mixture of gravel pack and wall cake materials. It was thought that the mixed materials would not significantly affect the performance of the aquifer when placed near the top. The material would also be wet and would have to be hand tamped into place to achieve the same relative density as the material below. The water level was then raised to the 5.7-foot (1.7-m) level, completing the work on the second day of the filling operation. The water was drained out of the box slowly overnight to consolidate the aquifer gravel pack formation.

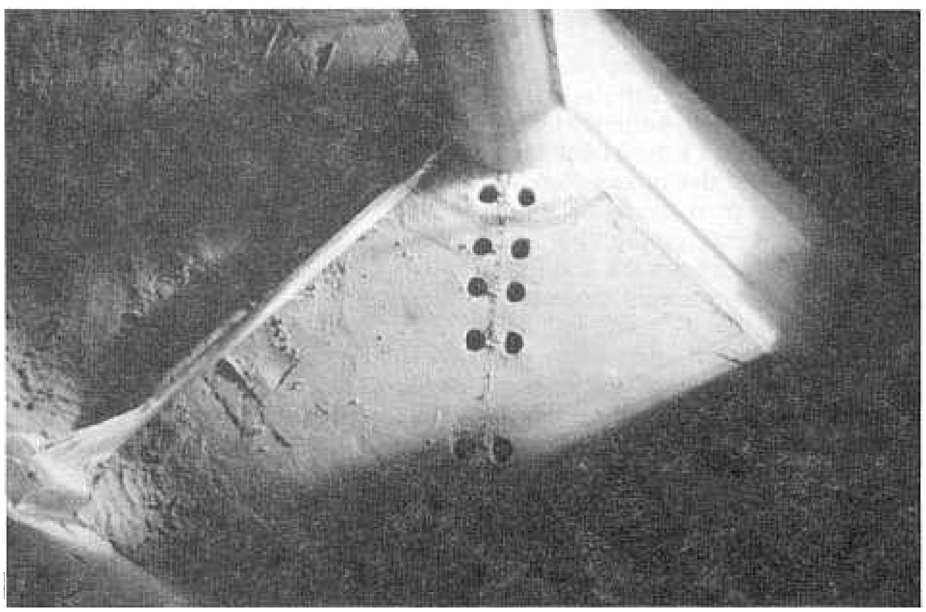
The next day, the formation was refilled with water slowly. A Mirafi-type fabric cloth was placed on top of the aquifer material inside the CMP. Then the four concrete blocks, each weighing 850 pounds (385 kgm), were placed on top for a surcharge, which was equivalent to about 3 feet (0.9 m) of additional aquifer material. The jet tool rig was installed and the necessary hose connections made to the high and low pump systems. The piezometer lines were purged of air by bleeding water slowly back through the piezometer taps from the top of the manometer board tubes. The teed line connections to the scanner valve, including the pressure transducer, were also bled before each test run. Periodically, the water inside the four dead-end calibration wells was drained and replaced with fresh water to prevent the growth of black algae. The sediment deposited inside the well screen during the filling operation settled to the bottom and was siphoned out. A ¼-inch (6.4-mm) i.d., 6-foot (1.8-m) long aluminum tube connected to a flexible Tygon tube was used to siphon the sediment water mixture into a bucket placed on the laboratory floor outside the well box. At this time, the filling operation was completed and the aquifer configuration was ready for the test run.

Steady State. – The test sequence began with a steady-state flow condition to establish the initial



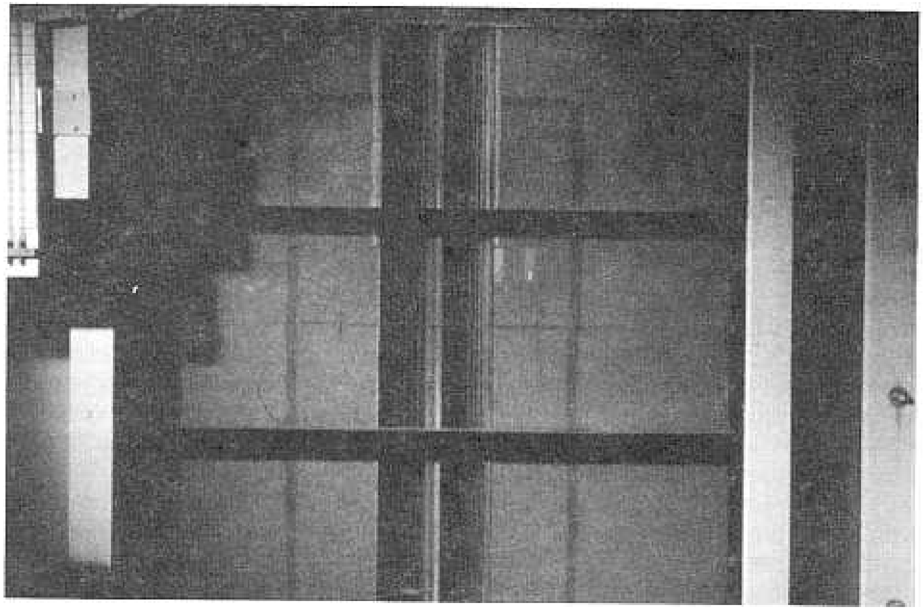
Soil Sample	Gravel Pack Thickness	Distance From Well Screen				
		A	B	C	D	E
	in (mm)	in. (mm)	in. (mm)	in. (mm)	in. (mm)	in. (mm)
Inplace at 2'-0" (0.6m) level	3 (76)	1 1/2 (38)	4 1/2 (114)	7 (178)	10 (254)	16 (406)
	6 (152)	1 1/2 (38)	4 1/2 (114)	7 (178)	10 (254)	16 (406)
	9 (229)	1 1/2 (38)	5 (127)	8 (208)	10 1/2 (267)	16 (408)
After jetting at 1'-6" (0.5m) level	3 (76)	1 1/2 (38)	5 (127)	7 (178)	10 (254)	16 (406)
	6 (152)	1 1/2 (38)	5 (127)	7 1/2 (190)	10 (254)	16 (406)
	9 (229)	1 1/2 (38)	5 (127)	8 (203)	10 1/2 (267)	16 (406)

(a) Top view.

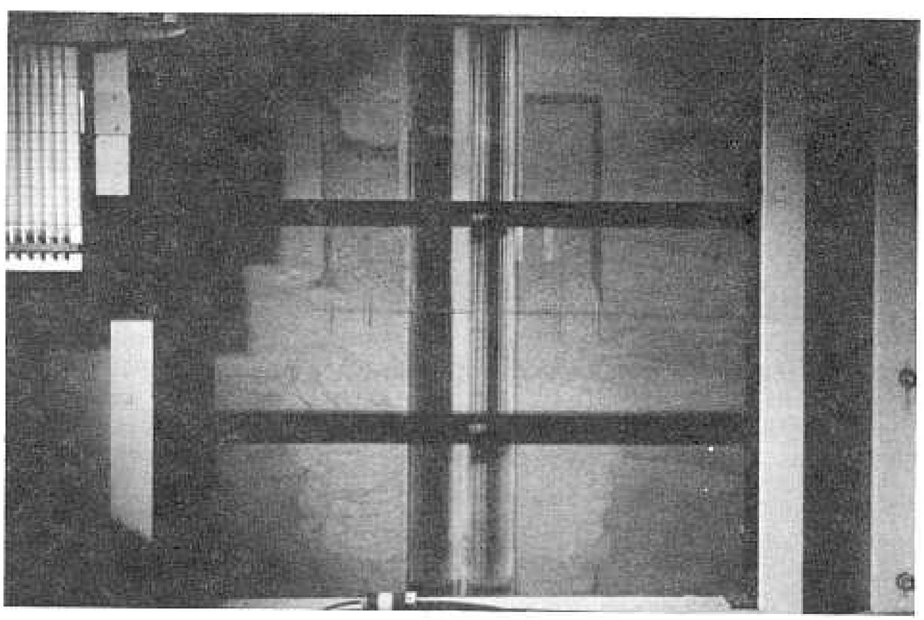


(b) General view at 2-foot (0.6-m) level (including piezometer support installation).

Figure 7. – Gravel pack and aquifer soil sample locations. P801-D-80972



(a) Completed aquifer configuration. P801-D-80973



(b) After water jetting well development. P801-D-80974

Figure 8. – Typical aquifer, wall cake, and 6-inch (152-mm) gravel pack.

specific capacity of the aquifer configuration before the jetting well development method was started. The steady state was accomplished by lowering the water level inside the well casing about 1 foot (0.3 m) by using the suction of the low-pressure pump system. The pump discharge was then returned to the well box outside the CMP (fig. 2) through the ¾-inch (19-mm) return pipe. The flow was controlled by a ¾-inch (19-mm) gate valve. When the water level inside the well casing remained constant for a period of 5 minutes, a steady-state flow condition was achieved. Then the automatic scan of the analog outputs of the pressure transducer and the magnetic flowmeter was initiated from the minicomputer keyboard. The scan began with piezometer tap No. 1 obtaining 1,000 values of analog pressure transducer output at 0.001-second intervals. Next, 1,000 values of the magnetic flowmeter analog output were obtained at the same 0.001-second interval. Both sets of 1,000 quantities of analog data were converted to digital values and stored in buffers. When the scan was completed, the scanner valve was stepped to the next port. Then the data were converted to floating point values, summed, and averaged. The averaged analog output of the magnetic flowmeter was converted to flow in gal/min; and both averaged quantities, water depth and flow, were stored in an array. After a 1-second delay, the second piezometer tap pressure transducer and another magnetic flowmeter average outputs were obtained in a similar manner. However, before proceeding to scan the third port, the average output of the pressure transducer for taps No. 1 and 2 was used to calculate the first calibration of the pressure transducer linear equation for volts per foot of water depth.

The scanning sequence continued through the 18 piezometer taps. The average output of the pressure transducer for taps No. 17 and 18 were used to calculate the second calibration of the pressure transducer linear equation for volts per foot of water depth. The first and second calibrations were then summed and averaged. The purpose of averaging the two calibrations was to average out any drift in the pressure transducer and amplifier that might have occurred during a test run scan, which took about 36 seconds.

After the scanning was completed, the average output for piezometer taps No. 3 through No. 16 was converted from volts to feet of head by the average calibration linear equation. At this point in the steady-state test run, an option was given to enter a volumetric calibration of the steady-state flow or to continue with the magnetic flowmeter output. A volumetric calibration was always made for the steady-state flow conditions. The 3-inch (76-mm) magnetic flowmeter did not have the required accuracy (±2 percent) at the very low flow range of about 2 gal/min (0.13 L/s). The volumetric flow calibration was obtained by swinging the ¾-inch (19-mm) return pipe and diverting the return flow into a water bucket. The diverted flow was timed by a stopwatch, and the water was then weighed. The weight (lbs) and time (s) were entered into the minicomputer from the keyboard. The computer program converted the volumetric data into the flow in gal/min. The program then calculated the specific capacity of the well, using the volumetric flow calibration in gal/min per foot of drawdown. The drawdown was measured from piezometer taps No. 3 and No. 5, which are located in the watertight box outside the CMP and inside the well screen, respectively. Therefore, the drawdown includes the head loss across the CMP and the Mirafi-type fabric cloth boundary. The values of all the data were then printed out on hard copy and stored on the computer system disk.

Well Development. – After completing the first steady-state scan, the jetting tool was lowered to the bottom of the well to the 3-inch (76-mm) level. The high-pressure pump was turned on, and the 2-inch (51-mm) control gate valve was cracked open to bleed the air out of the jet nozzle supply line. At this time, test personnel began rotating the jet nozzle back and forth (85°) at about one rotation per 2 seconds. At the same time, the low-pressure pump was turned on, discharging the flow to the laboratory drain, to lower the water level inside the well screen by about 6 inches (152 mm). After bleeding all the air out of the jet nozzle supply line, the high-pressure control valve was slowly opened, bringing the pressure on the jet nozzles up to the desired value. At this time, the electric hoist motor was turned on, raising the jet tool at a speed of 1 foot (0.3 m) per minute. When the jet nozzles reached the 9-inch (229-mm) level, the pressure had to be reduced to maintain a constant penetration distance into the gravel pack wall cake formation. The pressure reduction continued until the jet tool reached the 2-foot (0.6-m) level, at which time the high- and low-pressure pumps (including the control valves) were turned off, and one jet tool pass was completed. Figure 8(b) shows the results of a typical 6-inch (152-mm) test run after jetting is completed.

After waiting at least 15 minutes to allow the heavier suspended particles in the water inside the well screen to settle, the steady-state scan was repeated as described above. Before the next jet tool pass was made, the materials deposited on the bottom of the well screen were siphoned out into a bucket. Later, these samples were dried and weighed, and a mechanical analysis was performed on them. Usually four jet tool passes were made on the first day, and three more were made on the second day. Therefore, typically each well configuration had seven jet tool passes, seven inside the well screen material samples, and eight steady-state scans.

Excavation. – The first step of the excavation phase of the test run was to remove the jet tool rig and concrete blocks. Then the deformation of the aquifer, wall cake, and gravel pack [fig. 8(b)] on the window was measured. Because material was washed into the well screen during well development, a sinkhole occurred at the top of the aquifer around the well casing. Contours of this sinkhole were plotted. Then the aquifer was excavated by hand to the top of the gravel pack at the 3.33-foot (1.0-m) level. Measurements were taken of the deformed wall cake and gravel pack boundaries. The excavation continued, and measurements of the formation were taken every 6-inches (152 mm). At the 2-foot (0.6-m) level, the piezometer tap support was removed. At the 1.5-foot (0.46-m) level, soil samples were taken on the 45° line, as shown on figure 7. These samples were referred to as the "after" gradations, and were compared with the "before" gradation.

It usually took 1 day to excavate and clean out the inside of the CMP. Therefore, allowing 1 more day for data analysis and test run summary, and 1 day for an average turnaround time, a typical test run took 8 working days. Twenty-six test runs were completed for this report.

Limitations. – The well sectional model is not capable of representing the prototype well conditions in all respects. In the tests, the high jet nozzle velocity and discharge caused liquefaction problems, limiting the jetting to the lower 2 feet (0.6 m) of the aquifer formation. The jet nozzle velocity had to be decreased above the 9-inch (229-mm) level to maintain a constant penetration distance. Because the wall cake formation had to be hand placed in the well sectional model, it probably did not represent the true bore hole conditions after drilling the prototype well. The maximum velocity of water flowing into the well screen could not be achieved during the steady-state conditions because of the minimum head drawdown [about 1.5 feet (0.5 m)] available in the well sectional model. The window at the front of the half-circle well formation provided an unusual boundary condition when jetting was performed at high velocities. The splash of the jet against the window depended on the rotation of the jet tool and the geometry of the well screen next to the window.

During the well development phase, the low-pressure pump discharge to the laboratory drain (while maintaining a drawdown to the well screen) transported suspended materials caused by the jetting method. Therefore, the gradation of the material siphoned from the bottom of the well after each jet tool pass may be biased to the larger particle sizes.

Material Gradations

Two different gradations for the aquifer and gravel pack materials were used for the test runs included in this report. These are designated as SA No. 1 and SA No. 2. The first gradation, SA No. 1, used a fine sand for the aquifer and fine to medium sand for the gravel pack. The second gradation, SA No. 2, was slightly coarser: from fine to medium sand for the aquifer and medium sand for the gravel pack. The gravel pack aquifer *P/A* ratios for SA No. 1 and SA No. 2 were 3.6 and 4.0, respectively. A well screen slot width of 0.020 inch (0.51 mm) was used for the SA No. 1 gravel pack material, and a slot width of 0.040 inch (1.02 mm) was used for the SA No. 2 gravel pack material. All well screens had an 8-inch (203-mm) nominal pipe size diameter. The wire-wound-cage, stainless steel well screens were used in all the test runs except Nos. 25 and 26, where a PVC slotted well screen having a 0.040-inch (1.02-mm) slot width was used. Figure 9 shows the well screen slot widths versus the sieve analysis for the SA No. 1 and SA No. 2 materials.

Also shown on figure 9 is the gradation of the wall cake material used. The wall cake material consisted of the SA No. 1 aquifer material blended with 30 percent fines. The fines were gray in color, with 100 percent passing the No. 100 sieve and 52 percent passing the No. 200 sieve. The gray color was very helpful in tracing the wall cake material during the well development and excavation phases of the test run. The blend was used for all tests that included the wall cake formation for both SA No. 1 and SA No. 2 aquifer configurations.

A summary of the principal parameters of the materials used in this report is listed in table 3.

LABORATORY TEST RESULTS

Preliminary Test Runs

The first six test runs were conducted to debug test equipment and procedures. However, several important decisions and conclusions were made based on the results of these preliminary test runs.

The aquifer configuration for test runs No. 1 through No. 6 had a 3-inch (76-mm) gravel pack thickness and used the SA No. 1 gradation for the aquifer and gravel pack materials. The top of the gravel pack extended to the 4.33-foot (1.3-m) level, which was 4 inches (102 mm) above the well screen onto the lower portion of the well casing. The upper portion of the well screen was not taped as discussed previously for a typical aquifer configuration. The wall cake formation was not included in test runs No. 1

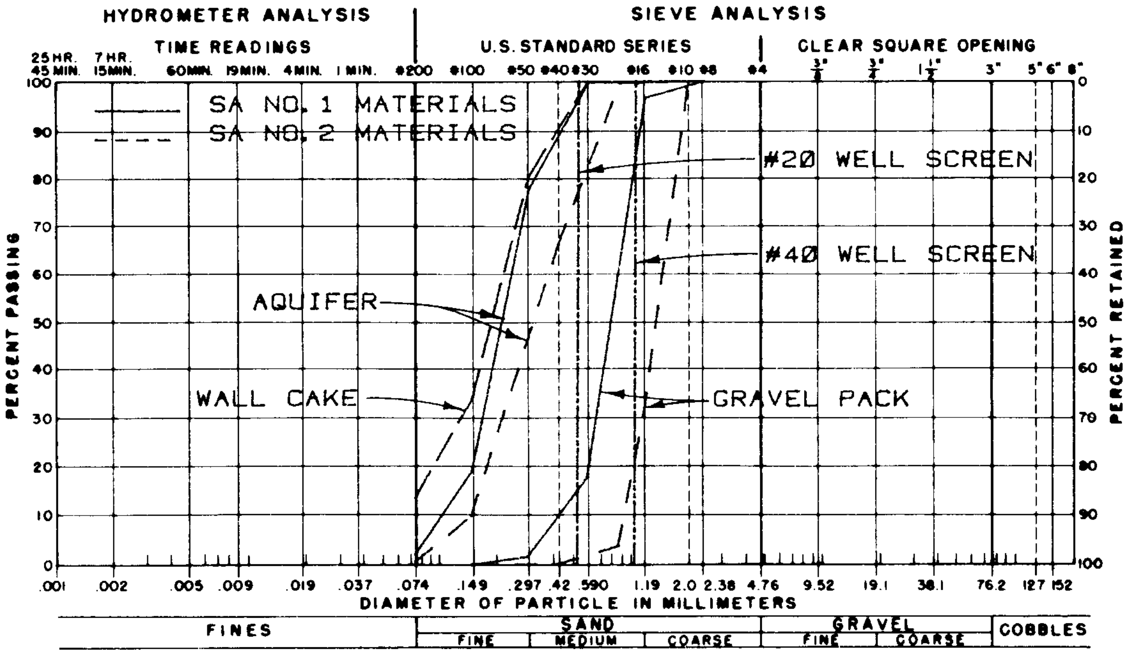


Figure 9. – Well screen slot widths vs. standard sieve analysis for SA No. 1 and SA No. 2 materials.

Table 3. – Summary of principal parameters* for soil and well-screen materials.

Formation parameter	SA No. 1		SA No. 2		SA No. 1 and SA No. 2
	Aquifer	Gravel pack	Aquifer	Gravel pack	Wall cake
D_{50}, mm	0.22	0.80	0.32	1.29	0.22
D_{60}, mm	.25	.85	.38	1.33	.26
D_{10}, mm	.10	.45	.15	0.96	.04
P/A	N/A	3.6	N/A	4.0	N/A
C_u	2.50	1.89	2.53	1.39	6.5
d (before)	100.6	-	-	-	-
d (after)	100.6	-	-	-	-

	Well-screen materials		
Well-screen type	Stainless steel wire-wound-cage	Stainless steel wire-wound-cage	PVC slotted
Slot width	0.020 in (0.51 mm)	0.040 in (1.02 mm)	0.040 in (1.02 mm)
Intake area	59 in²/ft (38 064 mm²/0.3 m)	100 in²/ft (64 516 mm²/0.3 mm)	32.784 in²/ft (21 151 mm²/0.3 m)

*Symbols:
D = Particle size diameter at percent passing designation.
P/A = Ratio of gravel pack to aquifer at D_{50} particle size.
C_u = Uniformity coefficient, D_{60}/D_{10}.
d (before) = Dry density before jetting.
d (after) = Dry density after jetting.
N/A = Not applicable.

through 4, but was included for test runs No. 5 and 6. The wall cake extended the full height of the gravel pack and was capped at the 4.33-foot (1.3-m) level. The use of the concrete blocks, placed on top of the aquifer at the 5.8-foot (1.8-m) level, for a surcharge began with test run No. 5.

The jet nozzle velocity remained constant for each jet tool pass during the first four test runs at 70, 90, 120, and 150 ft/s (21.3, 27.4, 36.6, and 45.7 m/s), respectively. The jet nozzles were raised to the 4-foot (1.3-m) level at a constant speed of 1 ft/min (0.3 m/min) for each jet tool pass. The penetration distance of the jet into the gravel pack increased as the jet nozzle was raised to the 4-foot (1.3-m) level [fig 10(a)]. Apparently, the aquifer and gravel pack began to liquefy, particularly at about the 2-foot (0.6-m) level.

After jetting the first 9 inches (229 mm) from the bottom of the well, larger cavities above the whirling motion of the jet began to form. Figure 10(b) shows a typical cavity formation at the window of the well sectional model. There are three reasons why the cavities above the jet develop:

1. Gravel pack material is displaced as the whirling motion of the return flow washes the finer particles through the well screen slots into the well. Even though some of the material is picked up by the high-velocity jet flow and is forced back through the well screen slots into the gravel pack, the net volume of the gravel pack decreases.

2. The outward thrust of the jet flow whirling motion mixes the gravel pack with the aquifer material when the penetration distance is greater than the gravel pack thickness. The gravel pack expands and additional finer material from the aquifer is added to the gravel pack. At the same time, the gravel pack mixture is being consolidated. The combined effect causes the net volume of the gravel pack to decrease.

3. The depleted gravel pack material is replaced by the material above the jet. However, the material from above does not sink or slump into the cavity fast enough to fill the cavity as it develops to maintain the same relative density; i.e., the porosity of the material above the jet momentarily increases significantly.

It is very important that some of the material from the gravel pack be removed and washed back into the well screen so that the cavity (or the high porosity) will form above the jet. Without the cavity, the whirling motion of the materials caused by the energy from the jet will not develop [4]. However, when the cavity develops, the jet has less resistance and therefore penetrates farther. As the jet nozzles were raised in the well sectional model, the cavities became larger, causing deeper penetration when the jet nozzle velocity remained constant, as illustrated on figure 10(a). The funnel-shaped limit of penetration shown on figure 10(a) was measured on the window, but it extended symmetrically around the perimeter of the half-circle well screen.

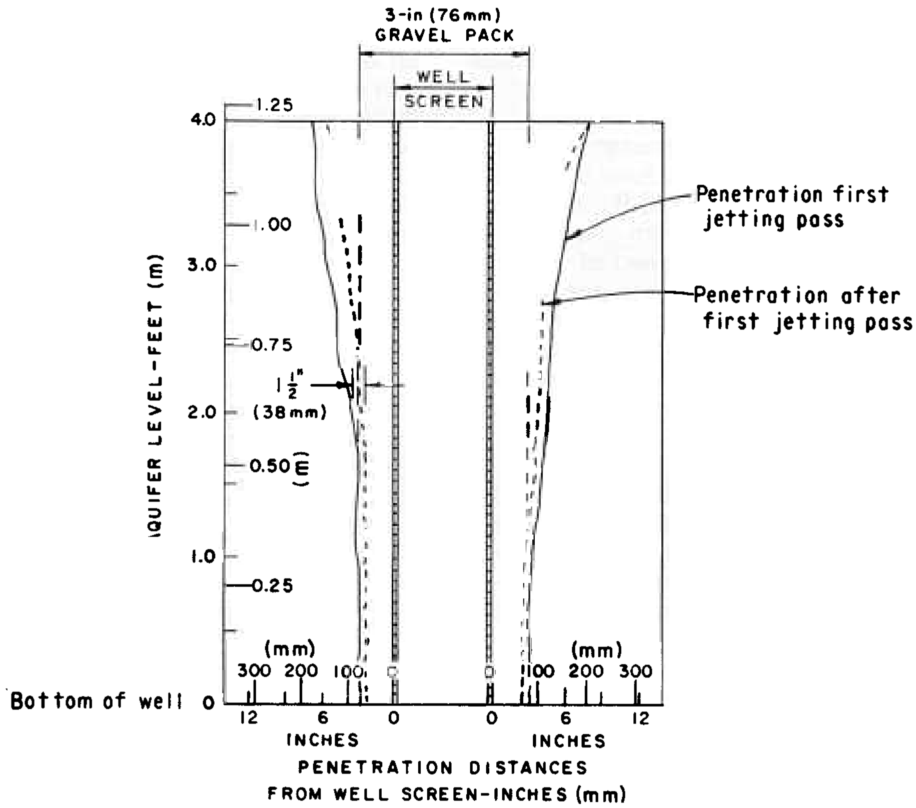
Three important conclusions were made at this point in the study:

1. High velocity water jetting must proceed from the bottom to the top of the well so that the cavities formed above the jet can be replaced by material from above. When the jetting stops, the material from above slowly slumps into the remaining cavity, filling it up to 90 percent, with a few small cavities remaining. However, a complete breach between the aquifer and well screen never develops.

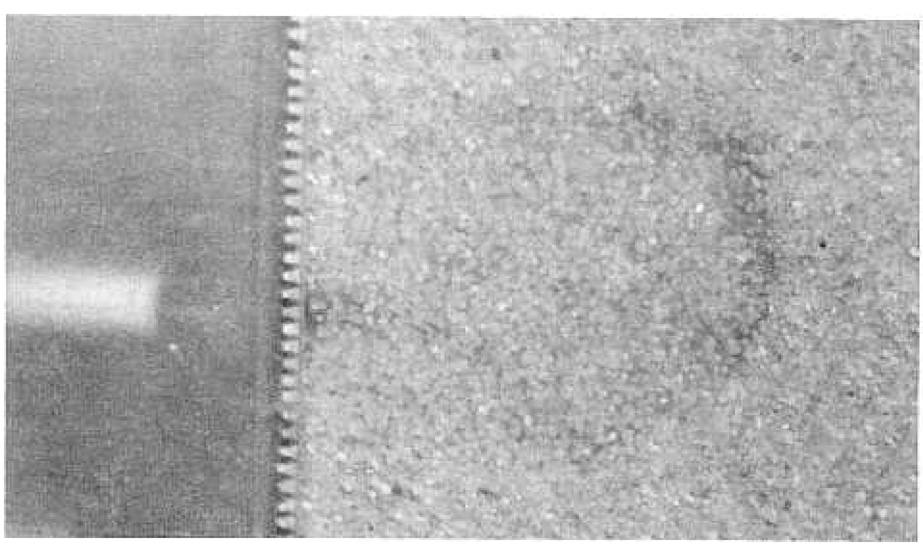
2. The penetration distance of the jet increases significantly once the cavity is formed. However, it takes only a few seconds of jetting for the cavity to develop; at which time, the whirling motion begins.

3. The whirling motion of the jet appears to consolidate the gravel pack material during the first jet tool pass. The consolidated material causes a greater resistance to the whirling motion, which, in turn, decreases the jet penetration distance for the same jet nozzle velocity for the subsequent jet tool passes by about 13 percent, as illustrated on figure 10(a). The whirling motion is dependent upon the porosity of the material and is, therefore, also affected by the gradation of the material [4].

Another indication that the permeability of the gravel pack material has decreased, after the first jet pass, is demonstrated on figure 11, using test run No. 3 as an example. The specific capacity of the well decreased 12 percent, from 2.25 to 1.98 gal/min per foot (0.142 to 0.125 L/s per 0.3 m) drawdown, after three jet tool passes were completed on the first day of the test run. Most of the decrease appeared to be caused by air bubbles from the high-velocity jet trapped in the pores of the gravel pack material. Notice that the specific capacity, after the fourth jet tool pass, increased 15 percent to 2.28 gal/min per foot (0.144 L/s per 0.3 m) drawdown. The fourth jet tool pass was completed on the first day of testing. However, the steady-state scan to obtain the specific capacity was not conducted until the next morning. It is postulated that the trapped air bubbles dissolved into the water overnight, providing more passages or total area for the water to flow into



(a) Funnel-shaped limits of water jet penetration at constant velocity.



(b) Water jet cavity formation.

Figure 10. – Typical views of preliminary test runs. P801-D-80975

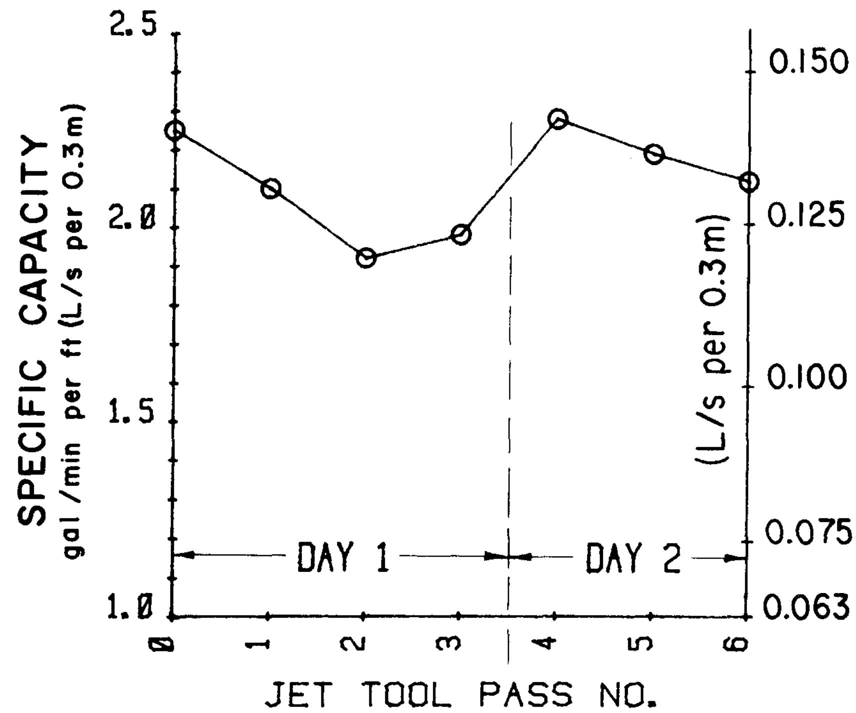


Figure 11. – Specific capacity vs. jet tool pass number for test run No. 3, without the wall cake formation.

the well and increase the permeability. Air bubbles trapped in the voids of the sand materials apparently act as grains of sand blocking the flow passages. This characteristic was observed throughout the test program. After the first jet tool pass was completed on the second day of testing (jet tool pass No. 5, fig. 11), the specific capacity decreased, indicating that air from the jet flow was again being trapped in the pores of the pack material, decreasing the permeability.

Density measurements of the gravel pack were not made during the preliminary test runs. However, measurements made during the special test run without the wall cake indicate that the density of the gravel pack increased about 1.3 percent after one jet tool pass was completed (see table 14), the small increase in the gravel pack density indicates that the permeability of the pack material decreased slightly. The gravel pack has its greatest permeability when it is poured into its water-filled annular space, and the sand grains are allowed to settle by gravity. It is concluded that well development methods that disturb the pack material, such as jetting, should not be applied when there is no wall cake between the aquifer and the gravel pack.

However, the wall cake formation usually exists because of the drilling methods used in the construction of the well. A ⅜-inch (9.5-mm) thick wall cake was hand placed to simulate the prototype well conditions after drilling and before well development, as explained previously, beginning with runs No. 5 and 6.

With the simulated wall cake formation in place the initial specific capacity of the well for test run No. 5 (fig. 12) was less than that for test run No. 3 without the wall cake (fig. 11). In test run No. 5, the wall cake was erased during the sixth and seventh jet tool pass when the jet nozzle velocity was increased to 120 and 150 ft/s (36.6 and 45.7 m/s), respectively, from the 100 ft/s (30.4 m/s) velocity of jet tool pass No. 5. There was a significant 37-percent increase in the specific capacity from pass No. 5 to No. 7 (fig. 12), 1.39 to 1.90 gal/min per ft (0.088 to 0.12 L/s per 0.3 m) drawdown. Until the whirling action of the jet actually penetrates through the wall cake, the specific capacity of the well can decrease. This was demonstrated by jet tool passes No. 1 through 5 [run at jet velocities of 70 ft/s (21.3 m/s) for pass No. 1 through 4 and 100 ft/s (30.4 m/s) for pass No. 5]. Subsequent jet tool passes, after pass No. 7, continued to show an improvement in the well specific capacity [passes No. 8 through No. 10 run at jet velocities of 100 ft/s (30.4 m/s)]. However, after pass No. 10 was completed, the wall cake on top of the gravel pack sunk 8 inches (203 mm), exposing the aquifer to the upper 4 inches (102 mm) of open slots of the well screen. It is believed that the sinking of the gravel pack allowed more flow into the well screen near the top as aquifer material poured into the well screen during the steady-state flow test.

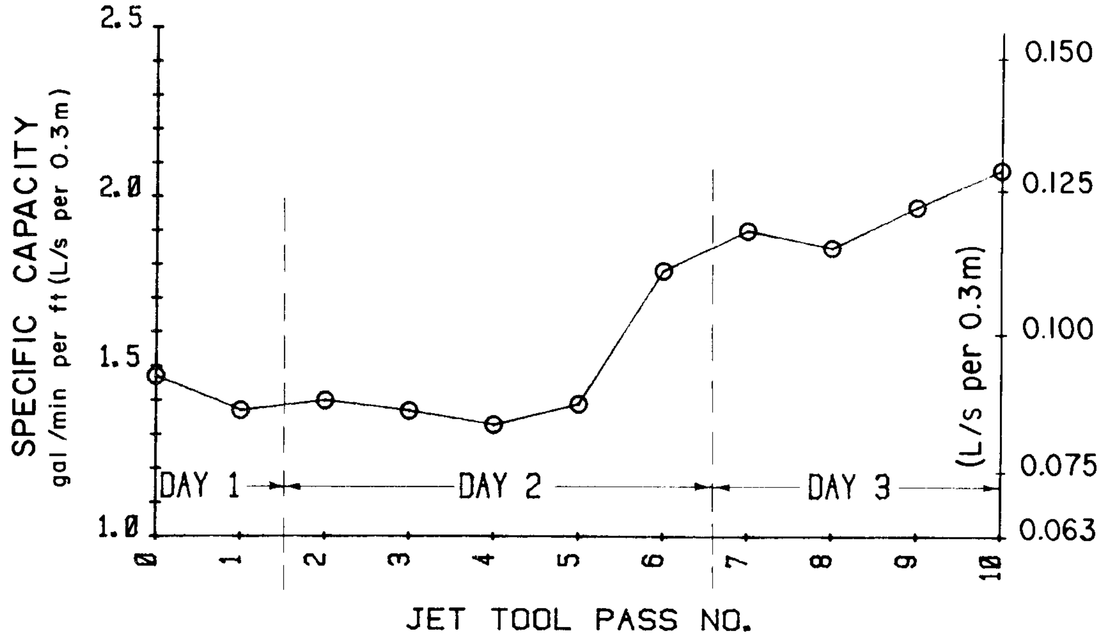


Figure 12. – Specific capacity vs. jet tool pass number for test run No. 5, with the wall cake formation.

Based on the results of run No. 5, it was concluded that the wall cake should be erased by the first jet tool pass. The jet velocity for the first pass should be just sufficient to penetrate through the wall cake. Penetrating too far, however, would mix more fines into the gravel pack and make it more difficult to clean out with subsequent jet tool passes. The subsequent jet tool passes should be run at a jet velocity slightly less than that of the first pass to avoid further mixing of the finer aquifer materials into the gravel pack. This is true even though the jet penetrates less after the first pass because the material has been consolidated. Figure 13 illustrates the results of the specific capacity when the wall cake formation has been penetrated on the first jet tool pass. The specific capacity increased 45 percent, from 1.18 to 1.71 gal/min per ft (0.074 to 0.108 L/s per 0.3 m) drawdown.

Therefore, the high-velocity water jetting well development procedure should be as follows:

1. Penetrate the wall cake formation on the first jet tool pass. The jet penetration of the first pass should be just sufficient to completely destroy the wall cake with a minimum penetration into the aquifer formation.

2. Run about four more jet tool passes at slightly less jet nozzle velocity than the first pass to avoid further penetration. This should achieve the optimum specific capacity of the well.

It is important to realize that the high-velocity water jet inside the well screen loses a very large amount of its energy when it passes through the well screen. There is more head loss through the well screen having the smaller slot width. Also, the whirling motion of the jet varies considerably as the jet nozzle is rotated. The wire-wound-cage type well screen has a V-shaped slot, with the narrow end towards the outside, and vertical rods for structural strength. The water jet stream is deflected, and the angle of the deflection continuously changes as the horizontal water jet passes the vertical rods. The deflected jet stream is also deflected in the vertical direction when it passes through the well screen V-shaped slot. Therefore, the shape, the flow streamlines, and the radial velocity of the jet as it enters into the gravel pack has been greatly modified from that of the jet exiting from the nozzle. This causes the mixing action within the whirling motion area to continuously change. The whirling motion depends on the geometric design of the well screen and on the gradation of the gravel pack material.

The addition of the concrete blocks on top of the aquifer did help reduce the width of the funnel-shaped penetration limit [figure 10(a)] near the top of the well screen, but it did not eliminate this characteristic. Therefore, the following procedure was decided on for future test runs:

1. Tape the well screen above the 2.5-foot (0.8-m) level, cap the gravel pack at the 3.33-foot (1.0-m) level, and limit the jetting to the lower 2 feet (0.6 m) of the well screen to prevent the aquifer from making direct contact with open slots of the well screen when the gravel pack subsides during the jetting.

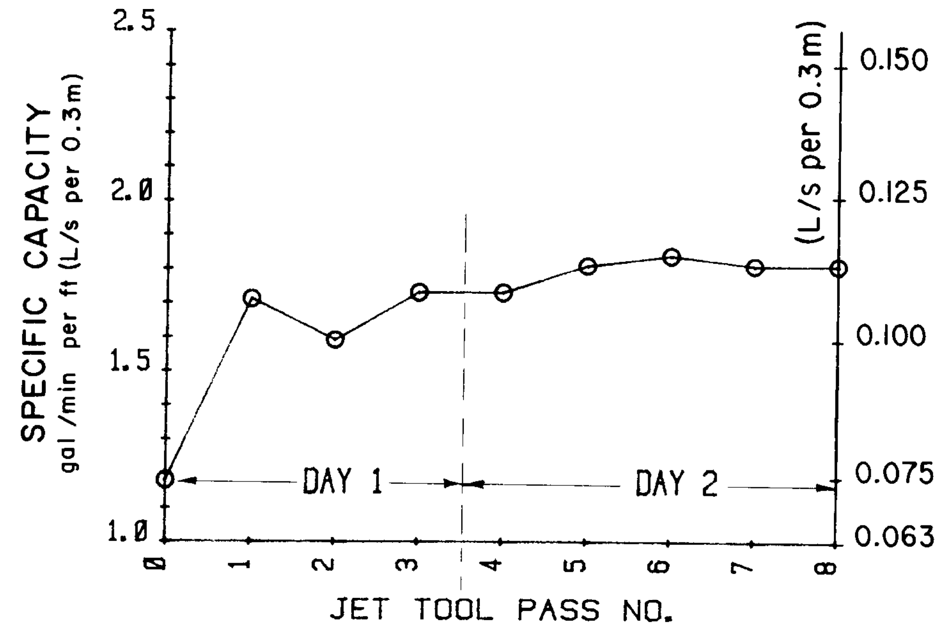


Figure 13. – Specific capacity vs. jet tool pass number for test run No. 6, with the wall cake formation erased on the first pass.

2. Vary the velocity of the jet nozzle as the jet rises to the 2-foot (0.6-m) level to maintain a constant penetration distance.

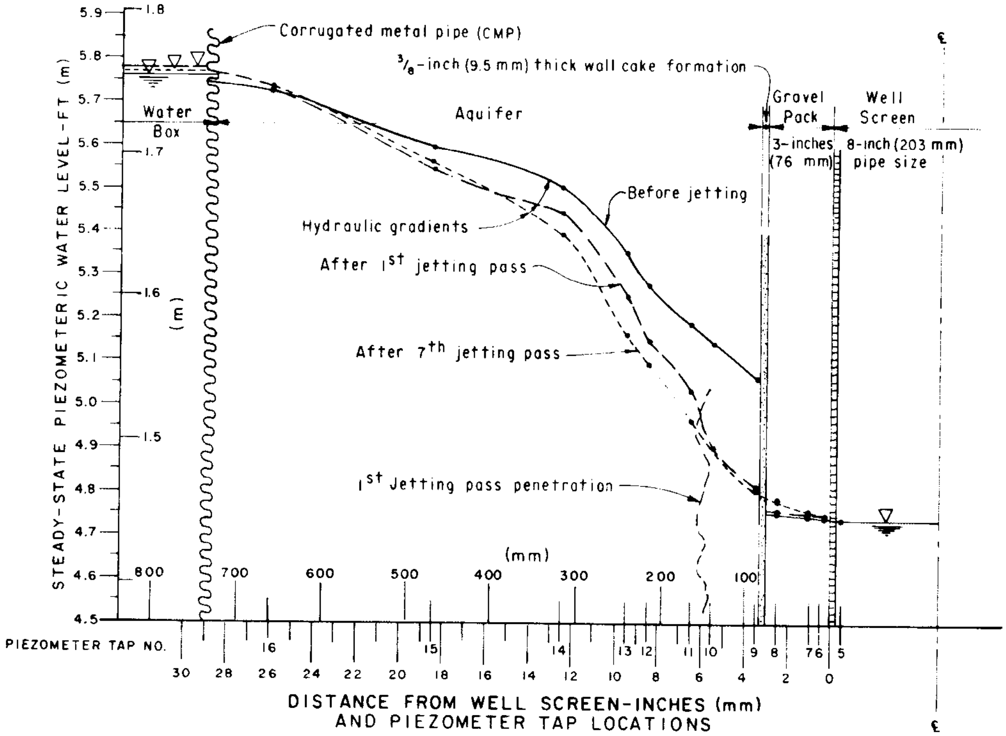
3. Use the 6-inch (152-mm) level of the well sectional model aquifer configuration to represent the prototype well and determine the penetration distance versus jet nozzle velocity measurement.

Gravel Pack Thickness

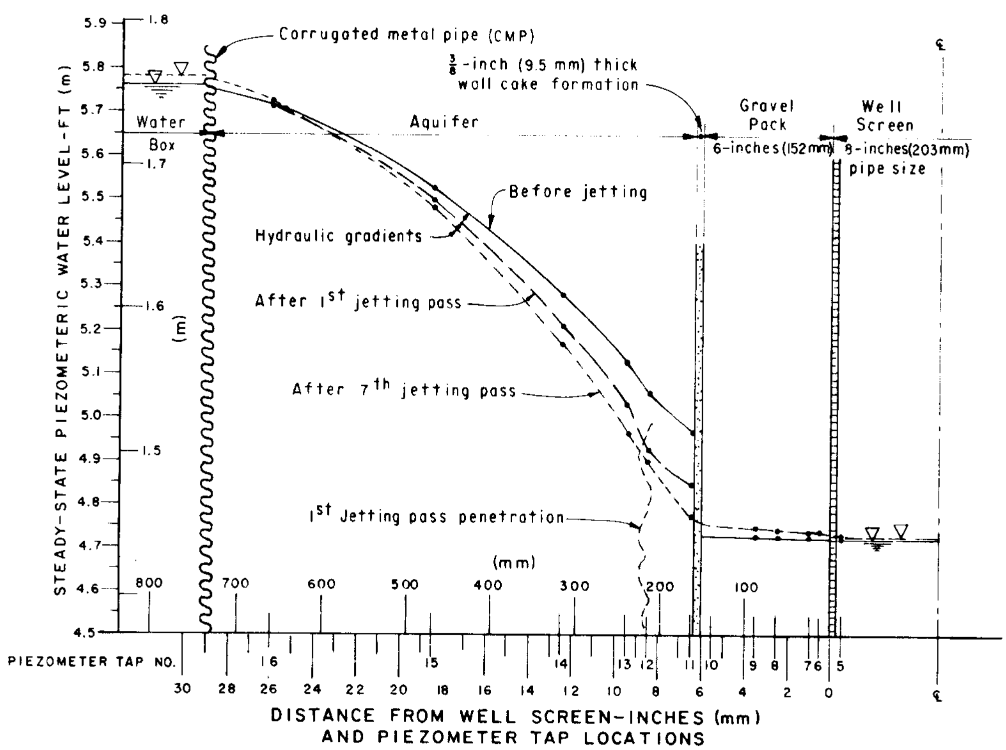
Thirteen test runs were conducted for the purpose of defining the optimum gravel pack thickness. Three gravel pack thicknesses, 3, 6, and 9 inches (76, 152, and 229 mm), were investigated. The 3/8-inch (9.5-mm) thick wall cake formation was hand placed between the aquifer and the gravel pack materials to simulate the prototype drill hole conditions after the drilling operation is completed and before well development begins. High-velocity horizontal water jetting from inside the well screen was used for the well development method. However, the highest jet nozzle velocity [220 ft/s (67 m/s) at a supply pressure of 660 lb/in^2 (4,550 kPa)], the maximum obtainable by the laboratory high-pressure pump, was not sufficient to penetrate through the wire-wound-cage type well screen and the 9-inch (229-mm) gravel pack. Therefore, the two 9-inch (229-mm) gravel pack test runs could not be used in the thickness investigation. Further details of the test procedure used to conduct the test runs are described earlier, in the section on test procedure in this report.

The results of the test runs clearly demonstrate that the wall cake formation has properties similar to those of an impervious core zone used in earth dams. The head loss across the wall cake is significant during steady-state flow conditions. Figures 14(a) and (b) illustrate the significant head loss by use of the 3-inch (76-mm) thick gravel pack in test run No. 19 and the 6-inch (152-mm) thick gravel pack in test run No. 17, respectively, as typical examples. The steady-state flow condition piezometric water levels are plotted for each piezometer tap location distance from the well screen (for details of the piezometric tap installation see fig. 3). The location of the well screen and wall cake are shown schematically for illustration purposes. The head loss across the wall cake and/or gravel pack was determined by taking the differences of the piezometric water levels at the taps located closest to the outward and inward edges, respectively. The solid lines of figures 14(a) and (b) represent the hydraulic gradients before jetting, or the initial conditions before well development began. The 3-inch (76-mm) gravel pack [fig. 14(a)] had an initial head loss across the wall cake of 0.31 ft (0.09 m). For the 6-inch (152-mm) gravel pack, the initial wall cake head loss was 0.24 ft. (0.07 m). The head loss caused by the wall cake was, therefore, considerably greater than the initial head loss across the gravel pack, which was 0.01 foot (0.003 m) for the 3-inch (76-mm) and 0.005 foot (0.002 m) for the 6-inch (152-mm) gravel pack.

The long dashed lines of figures 14(a) and (b) represent the hydraulic gradient steady-state flow conditions after the first jetting pass was completed. The first jet tool pass destroyed the wall cake formation



(a) 3-inch (76-mm) gravel pack – test run No. 19.



(b) 6-inch (152-mm) gravel pack – test run No. 17.

Figure 14. – Typical examples of the steady-state piezometric water levels across the wall cake and gravel pack formations before and after jetting.

and reduced the head loss significantly. However, the head loss across the gravel pack had increased. Even after the seventh jetting pass, shown as the short dashed line, the head loss across the pack material remained higher than the initial conditions (solid line). The gravel pack higher head loss was caused by (1) the addition of aquifer and wall cake fines into the pack material [note the distance of penetration of the water jet for the first jetting pass in figures 14(a) and (b)] and (2) the consolidation of the pack material during the mixing action of the horizontal high-velocity water jets. The before and after jetting conditions are discussed in greater detail in subsequent paragraphs on the jetting evaluation and special test runs.

Figure 15 illustrates the effects of the hydraulic gradient when the wall cake formation was not destroyed during jetting well development. The laboratory high-pressure supply pump did not supply enough energy to the two ¼-inch (6.4-mm) water jet nozzles to penetrate more than about 8 inches (203 mm) into the 9-inch (229-mm) pack material. As a result, the wall cake remained in place. The head loss actually increased after the first and fourth jetting passes (fig. 15, long and short dashed lines, respectively) as compared with the initial conditions before jetting (solid line). The increased head loss across the wall cake may have been the result of the outward movement of the fines within the gravel pack. These fines may have been forced into the pores of the wall cake by the forces of the high-velocity horizontal water jets, thereby decreasing its porosity. The outward inertia of the water jets could also cause the wall cake formation to compact or consolidate, increasing its density and decreasing its porosity further. A decrease in the porosity caused by the plugging of pores with fines or by compaction may have caused the head loss of the wall cake to increase.

The results of the 11 test runs conducted for the 3- and 6-inch (76- and 152-mm) gravel pack thicknesses are summarized in table 4. Table 5 summarizes the two test runs conducted for the 9-inch (229-mm) gravel pack thickness. Both tables identify the material gradation (SA No. 1 or 2), the test run number, and the gravel pack thickness. The steady-state specific capacity gal/min per ft drawdown is listed next for the initial conditions (before jetting) and the value measured after each jetting pass was completed. The jet nozzle velocity (ft/s) used for each jetting pass is listed below the specific capacity in parenthesis. The average specific capacity for the jetting passes is then listed. Listed next is the percent change in the specific capacity, which was determined by comparing the average with the initial value. The measured head losses across the wall cake and gravel pack for the initial and end (before jetting and after the seventh jetting pass, respectively) conditions are then shown. The last item lists the percent of the wall cake formation remaining after the seventh jetting pass, measured at the 6-inch (152-mm) level during the excavation phase of the test run. The steady-state flow conditions made for the test runs listed are included in the appendix as supporting data for tables 4 and 5.

An optimum gravel pack thickness could not be determined from the results of the test runs summarized in table 4. The change in the specific capacity, which ranged from +14.7 to +29.8 percent for an average of +24.3 percent, does not show a distinct advantage for either the 3-inch (76-mm) or the 6-inch (152-mm) gravel pack thickness. Table 6 summarizes the head losses and the specific capacity. In table 6, the head loss before and after was obtained by adding the initial and end conditions, respectively, of both the wall cake and gravel pack head losses listed in table 4. The net reduction of the head loss, in table 6, is the difference between the before and after conditions. The data in table 6 show that there does not appear to be a clear relationship or trend between the 3- and 6-inch (76- and 152-mm) gravel pack thicknesses. However, the results show to some degree that the net reduction in the head loss across the wall cake and gravel pack formations is related to the increase in the specific capacity.

The net reduction in head loss versus the increase in specific capacity for each test run (table 6) is plotted on figure 16. The spread in the data points is wide. However, test runs No. 11, 13, 17, and 19 had the least remaining wall cake observed during the excavation phase of the test run (last column, table 4) combined with the least water jet penetration distance into the aquifer material. These test runs are plotted on figure 16 as the solid data points. The straight line drawn through the solid data points indicates that the specific capacity increases proportionally as the net reduction in head loss across the wall cake and gravel pack increases.

The water jet did not penetrate through the 9-inch (229-mm) gravel pack. Except in run No. 21 (table 5 and fig. 15), the jet splash against the clear plastic window caused the water jet to penetrate about 10 inches (305 mm), but extended into the aquifer and wall cake about 2 inches (51 mm) from the window; this erased about 10 percent of the wall cake. The penetration of the water jet at the window was thought to be caused by the window boundary condition and was, therefore, not representative of the penetration beyond 2 inches (51 mm) from the window, which averaged about 8 inches (203 mm). However, the erasure of the wall cake at the window caused the specific capacity to increase 37.4 percent. In run No. 9 (table 5) the water jet did not penetrate through the wall cake, even at the window

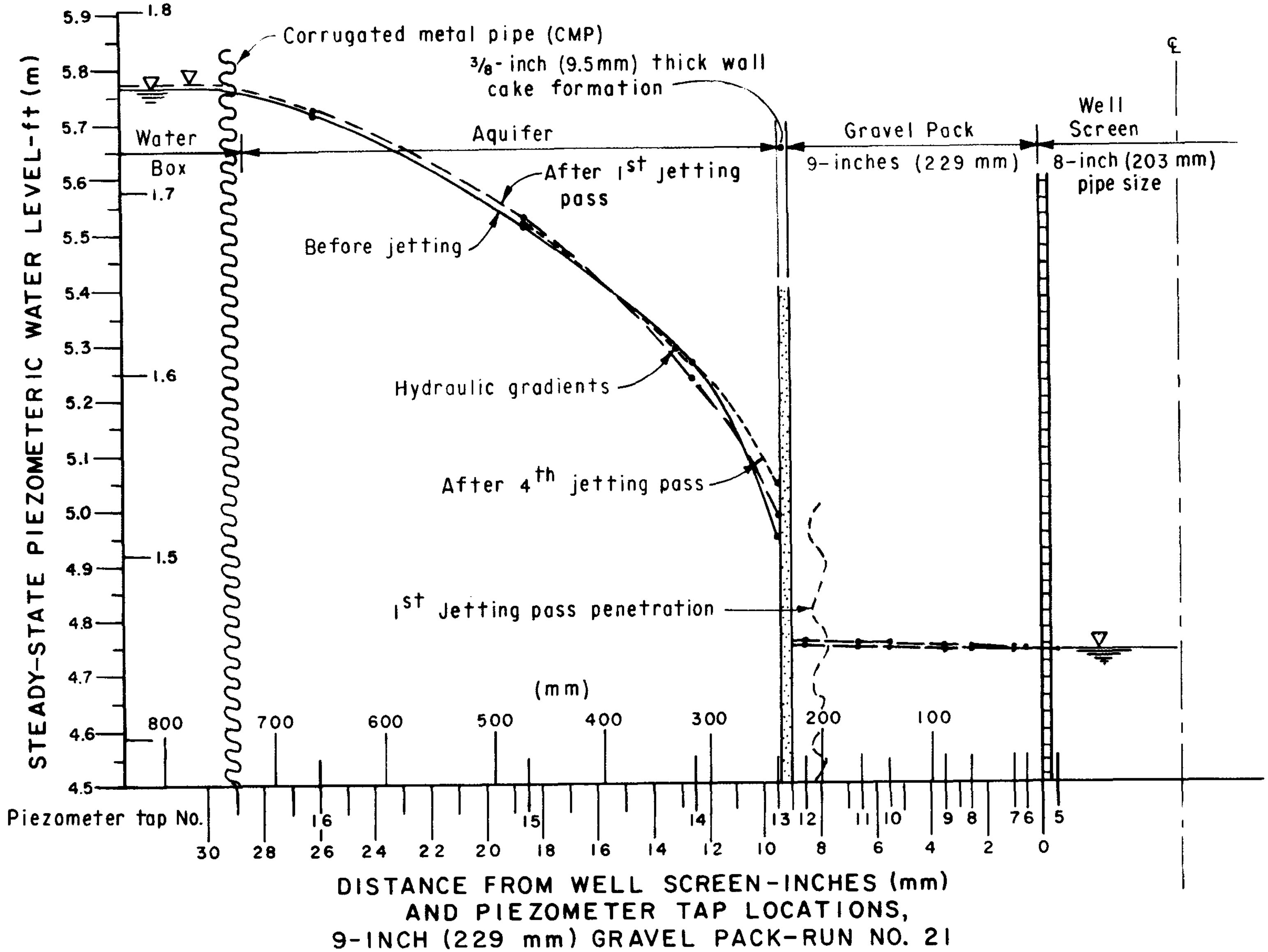


Figure 15. – Typical example of the steady-state piezometric water levels across the wall cake and gravel pack formations when the wall cake is not destroyed.

Table 4. – Summary of test runs for 3- and 6-inch gravel pack thicknesses – wire-wound-cage type well screen and high-velocity water jetting well development method.[1]

Mat. grad.	Run No.	Gravel pack thick-ness in (mm)	Steady-state specific capacity, gal/min per ft drawdown (Jet nozzle velocity at 6-in (152-mm) level ft/s)										Head loss				Wall cake remaining, %
				Jet tool pass No.									Wall cake		Gravel pack		
			Initial 0	1	2	3	4	5	6	7	Avg.	Change, %	Initial, ft	End, ft	Initial, ft	End, ft	
SA No. 1	7	3 (76)	1.11	1.27 (170)	1.35 (160)	1.36 (160)	1.34 (160)	1.39 (160)	1.38 (160)	1.38 (160)	1.35	+21.9	0.24	0.04	0.03	0.08	0
	12	3 (76)	0.82	0.91 (150)	1.02 (142)	0.98 (140)	1.00 (140)	1.00 (140)	1.02 (140)	1.02 (140)	0.99	+21.1	.23	.004	.01	.02	10% at 6-in (152-mm), level
	*13	3 (76)	0.91	1.06 (148)	1.06 (145)	1.08 (145)	1.07 (145)	1.12 (145)	1.09 (145)	1.13 (145)	1.09	+19.5	.16	.03	.004	.01	0
	[2]8	6 (152)	1.01	1.32 (200)	1.39 (190)	1.44 (190)	1.55 (190)	1.46 (190)	1.53 (190)	1.53 (190)	1.46	+44.6	.29	.02	.09	.05	10% at 1-ft (305-mm) level 50% at 6-in (152-mm) level
	10	6 (152)	0.97	1.08 (210)	1.19 (212)	1.13 (200)	1.16 (195)	1.20 (195)	1.24 (195)	1.19 (195)	1.17	+20.6	.27	.01	.08	.05	50% at 6-in (152-mm) level
	*11	6 (152)	1.06	1.24 (195)	1.29 (190)	1.26 (185)	1.29 (185)	1.32 (185)	1.31 (185)	1.32 (185)	1.29	+21.7	.17	.03	.03	.03	25% at 6-in (152-mm) level
SA No. 2	18	3 (76)	1.19	1.38 (150)	1.44 (145)	1.47 (140)	1.49 (140)	1.68 (140)	1.70 (140)	1.65 (140)	1.54	+29.8	.31	.03	.004	.07	0
	*19	3 (76)	1.27	1.60 (130)	1.59 (120)	1.62 (120)	1.60 (120)	1.58 (120)	1.69 (120)	1.66 (120)	1.62	+27.6	.31	.03	.01	.04	0
	20	3 (76)	1.13	1.33 (110)	1.38 (100)	1.35 (100)	1.37 (100)	1.48 (100)	1.43 (100)	1.44 (100)	1.40	+23.6	.30	.01	.005	.02	100% at 6-in (152-mm) level
	16	6 (152)	1.73	1.85 (115)	1.80 (140)	1.94 (155)	1.96 (195)	2.00 (200)	2.16 (195)	2.18 (195)	1.98	+14.7	.27	.10	.003	.03	50% at 1-ft (305-mm) level 100% at 6-in (152-mm) level
	*17	6 (152)	1.77	2.02 (200)	2.04 (200)	2.05 (195)	2.03 (195)	2.32 (195)	2.29 (195)	2.39 (180)	2.16	+22.2	.24	.03	.005	.02	50% at 6-inch (152-mm) level
	Average											+24.3	.254	.030	.024	.038	

[1] All measurements were made in English units. Conversion factors to SI metric units: 1 ft/s = 0.3 m/s; 1 gal/min per ft = 3.78 L/min per 0.3 m = 0.063 L/s per 0.3 m.
[2] A leak into the well casing through the top well screen to well casing seal may have developed during the test run causing the high specific capacity.
* Selected example test runs.

Table 5. – Summary of the test runs for the 9-inch gravel pack thicknesses – wire-wound-cage type well screen and high-velocity water jetting well development method.

Material gradation	Run No.	Gravel pack thick-ness, in (mm)	Steady-state specific capacity, gal/min per ft drawdown (Jet nozzle velocity, at 6-in (152-mm) level ft/s): Initial 0	Jet tool pass No. 1	2	3	4	Avg.	Change, %	Head loss: Wall cake Initial, ft	Wall cake End, ft	Gravel pack Initial, ft	Gravel pack End, ft	Wall cake remaining, %
SA No. 1	9	9 (229)	1.69	1.63 (220)	1.64 (220)	1.62 (220)	1.67 (220)	1.64	– 3.0	0.11	0.14	0.04	0.04	100
SA No. 2	21	9 (229)	1.35	1.84 (220)	1.83 (220)	1.88 (220)	1.87 (220)	1.86	+37.4	0.19	0.39	0.01	0.02	90

[1] All measurements were made in English units. Conversion factors to SI metric units: 1 ft/s = 0.3 m/s; 1 gal/min per ft = 3.78 L/min per 0.3 m = 0.063 L/s per 0.3 m.

Table 6. – Summary of the head loss across the wall cake and gravel pack and the percent change in specific capacity after the seventh jet tool pass.[1]

Mat. grad.	Run No.	Gravel pack thickness, in (mm)	Total head loss measured across wall cake and gravel pack: Before[3], ft(m)	After[3], ft(m)	Net reduction[3], ft(m)	Change in specific capacity, %
SA No. 1	7	3(76)	0.27 (0.08)	0.12 (0.04)	0.15 (0.04)	+21.9
	12	3(76)	.24 (0.07)	.024 (0.01)	.216 (0.07)	+21.1
	*13	3(76)	.164 (0.05)	.04 (0.01)	.124 (0.04)	+19.5
	[2]8	6(152)	.38 (0.12)	.07 (0.02)	.31 (0.09)	+44.6
	10	6(152)	.35 (0.11)	.06 (0.02)	.29 (0.09)	+20.6
	*11	6(152)	.20 (0.06)	.06 (0.02)	.14 (0.04)	+21.7
SA No. 2	18	3(76)	0.314 (0.10)	0.10(0.03)	0.214(0.07)	+29.8
	*19	3(76)	.32 (0.10)	.07 (0.02)	.25 (0.08)	+27.6
	20	3(76)	.305 (0.09)	.03 (0.01)	.275 (0.08)	+23.6
	16	6(152)	.273 (0.08)	.13 (0.04)	.143 (0.05)	+14.7
	*17	6(152)	.245 (0.07)	.05 (0.02)	.195 (0.06)	+22.2

[1] All measurements were made in English units.
[2] A leak into the well casing through the top well screen to well casing seal may have developed during the test run causing the high specific capacity.
[3] Averages: before = 0.278 ft; after = 0.068 ft; net reduction = 75.5%.
* Selected example test runs.

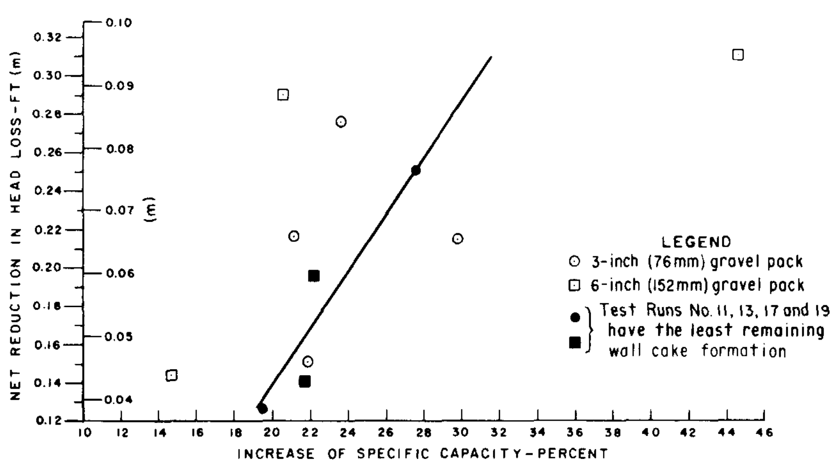


Figure 16. – Net reduction in head loss across the wall cake and gravel pack formations vs. percent increase in specific capacity after seven jet tool passes.

boundary. As a result, the specific capacity decreased 3.0 percent. In both 9-inch (229-mm) test runs, the head loss increased across the wall cake after four jetting passes. The head loss across the gravel pack in test run No. 9 remained the same after the fourth jetting pass even though the pack material was consolidated during the water jet mixing action. In test run No. 21, there was a small increase in the head loss across the gravel pack after the fourth jetting pass. The small increase was probably caused by some fines mixed into the gravel pack material as a result of the penetration of the water jet through the wall cake and into the aquifer at the window boundary. It is concluded that the fines mixed into the gravel pack material cause a proportionally higher head loss than the consolidation of the pack material. Special test runs were conducted to verify this concept and are discussed in detail in subsequent paragraphs.

The effects of the impervious wall cake formation developed during well construction is a major parameter that masks any advantages that may exist for different gravel pack thicknesses. The average head loss that occurred across the wall cake and pack material was 0.278 foot (0.085 m) before jetting for the 11 test runs listed in table 4. After seven jetting passes, the average head loss decreased to 0.068 foot (0.021 m) for an average decrease of 75.5 percent. This 75.5 percent decrease in head loss was caused primarily by the destruction of the wall cake and the expansion of the gravel pack during the first jet tool pass. Comparing the average head loss of the wall cake and gravel pack after seven jetting passes [0.068 ft (0.021 m)] (table 4), with the initial head loss of the gravel pack [0.024 ft (0.007 m)] (table 6), the average head loss increased 183.3 percent. This 183.3 percent increase in head loss was caused primarily by the aquifer fines mixed into the gravel pack during the first water jet tool pass, but not completely cleaned out by subsequent jet tool passes.

The effects of the wall cake formation must be erased completely before the potential specific capacity of the well can be achieved. The efficiency of the well is proportional to the effective elimination of the wall cake impervious characteristics. The special test runs conducted without the wall cake, discussed in subsequent paragraphs, indicate that the specific capacity of test runs No. 19 and 17 (table 4) was recovered to within 3 percent of the ideal conditions. However, the thickness of the gravel pack with the wall cake formation present is limited to a practical dimension when the well development method consists of high-velocity horizontal water jetting from inside the well screen. Thick gravel packs require much higher jet nozzle velocities to penetrate and destroy the wall cake. Thin gravel packs require the opposite, much lower jet nozzle velocities. However, too much penetration into the aquifer could easily occur and the mixing of the finer materials by the water jet could render the filter characteristics of a thin gravel pack ineffective. The aquifer material could then make direct contact with the well screen and cause a well operation failure during the production phase. The gravel pack thickness selected should provide sufficient annular space to ensure that the pack material completely surrounds the well screen during the placement operation, yet allows the easy destruction of the wall cake by the horizontal jetting method of well development. The minimum annular space recommended for successful pack material placement is usually 3 inches (76 mm) [2]. The maximum recommended annular space, with a jet nozzle velocity of 220 ft/s (67 m/s) available, is less than 6 inches (152 mm).

Water Jetting Evaluation

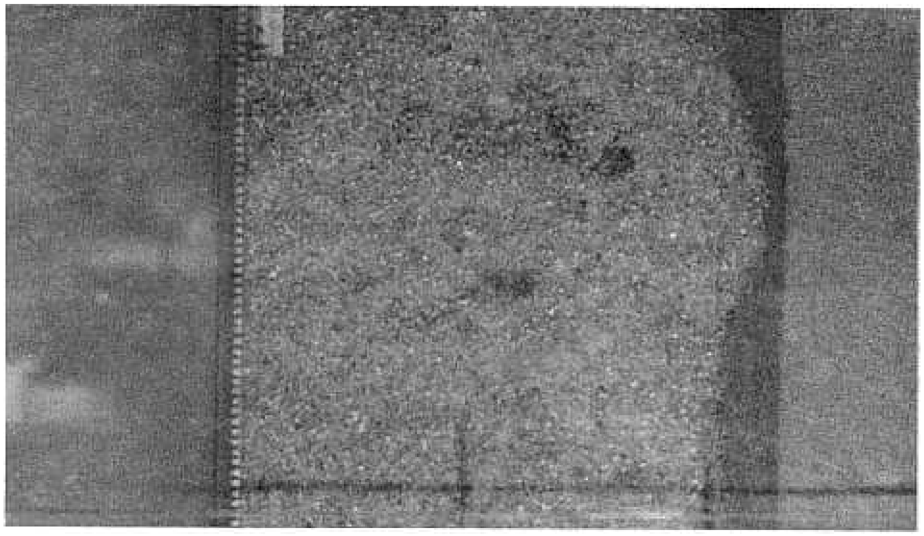
High-velocity horizontal water jetting well development from inside the well screen is an effective technique to completely eliminate the wall cake impervious characteristics. It can physically destroy the wall cake properties, reduce the wall cake head loss by about 75 percent, and increase the well specific capacity by about 24 percent. However, the outward forces and the mixing action of the water jet prevents all of the wall cake effects from being erased.

As discussed previously in the "Preliminary Test Results" section, the development of the cavity above the water jet is necessary before the potential whirling action of the jet can develop. At the same time the cavity develops, there is less resistance to the whirling motion, which allows the jet to penetrate farther. Figure 17 illustrates the cavities that develop and the whirling action of the water jets at the edge of the wall cake formation. Notice the denser ring of gravel pack material surrounding the water jet on figure 17 and, particularly, on figure 10(b). The porosity of the gravel pack material also affects the penetration distance of the water jets. After the first jetting pass, the pack material consolidates and the water jet penetration distance decreases by about 13 percent for the same jet nozzle velocity [see fig. 10(a)].

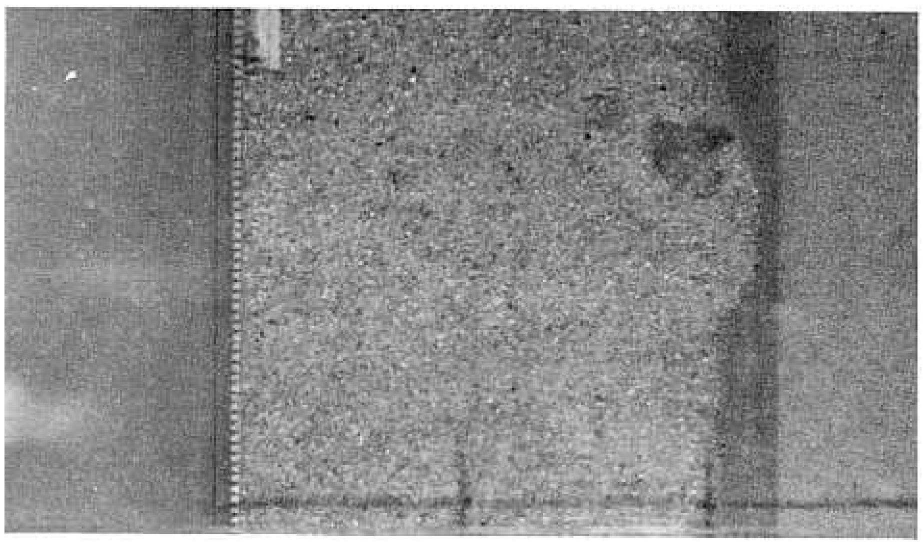
The wall cake formation has a certain amount of rigidity, particularly the hand-placed wall cake formation used in the well sectional model test runs. It is believed the wall cake formed in the prototype well during the drilling operation also has rigid properties compared with the surrounding aquifer and pack materials. Data were not collected from the well model, and field data were not available to evaluate the wall cake structural characteristics. However, because fines are forced into the pores of the aquifer and the outward thrust of the drilling action compacts the forming mud deposits during the drilling operations, it is likely that the wall cake will have a higher density. The hand-placed wall cake formation in the well sectional model was accomplished by (1) adding 30 percent fines [100 percent passing the No. 100 (0.150 mm) sieve] to the SA No. 1 aquifer material, (2) adding 15 percent moisture to the wall cake special blend of dry materials, and (3) hand tamping the special blend with a ¼- by ¾-inch (6.4- by 19.1-mm) metal bar between two sheet metal forms spaced ⅜ inch (9.5 mm) apart.

The penetration distance of the high-velocity horizontal water jets is critical and difficult to predict or control. Most of the high water velocity at the exit of the jet nozzle is expended after passing through the well screen. Therefore, the velocity of the water jet immediately outside the well screen is largely dependent of the type of screen, the slot width, and the total intake area per unit screen area (slot spacing).

If the velocity of the water jets is too low, the destruction of the wall cake will not occur. The high head loss across the wall cake will not be reduced



(a) The formation of the cavity. P801-D-80976



(b) Whirling motion at the inside edge of the wall cake.

Figure 17. – Views of high-velocity horizontal water jetting from inside the wall screen. P801-D-80977

and the well specific capacity will be about 24 percent less than its potential value. If the water jet velocity is just sufficient to reach the wall cake, as shown on figure 17(b), but not sufficient to penetrate through, the erasure of the high head loss characteristic will be incomplete and the full potential of the well specific capacity will not be achieved. Note the flatness of the outward edge of the jet whirling motion on figure 17(b). The flat nose of the whirling motion of the water jet indicates resistance to penetration. Therefore, the wall cake has rigid properties. The velocity of the water jets must be high enough to break up the more rigid wall cake. Once the water jet penetrates through the wall cake formation, it suddenly encounters lower resistance in the aquifer material. This lower resistance causes the water jet to penetrate farther, about 1½ to 3 inches (38 to 76 mm). The extended penetration cannot be avoided; otherwise, the water jet velocity would be insufficient to physically destroy the more rigid wall cake. As a result, fines from the aquifer as well as from the wall cake are mixed into the gravel pack by the whirling action of the water jets. If the jet penetrates too far, a larger proportion of fines are mixed into the pack material. The addition of a larger percentage of fines results in higher head losses across the gravel pack after jetting passes are completed. The horizontal water jetting method does not remove all the fines mixed into the pack annular space.

In summary, the water jet nozzle velocity required to penetrate just far enough to break up the impervious characteristics of the wall cake formation is dependent on:

1. The type of well screen, the slot width, and slot spacing.

2. The gravel pack thickness, gradation, and porosity.

3. The wall cake rigidity, thickness, and gradation.

The well sectional model test runs were not designed to obtain the penetration distance versus the jet nozzle velocity (from inside the well screen) on a quantitative basis. However, the results of the four examples, test runs no. 11, 13, 17, and 19, selected as having the most complete destruction of the wall cake combined with the least water jet penetration distance into the aquifer material are shown on figure 18. The average penetration distance (after the first jetting pass) was measured at the 6-inch (152-mm) level (measured from the bottom of the well) during the excavation phase of the test run. The 6-inch (152 mm) level measurements were used because it is believed this level best represents the prototype well conditions. Figure 19 shows the top views of the measured penetration distances after the first pass, the average penetrations, and the remaining wall cake formation. Additional jet tool passes are required to remove the fine material that was mixed into the gravel pack during the first jet tool pass. The whirling action of the jet washed some of the fine material back into the well screen. Some of the fine material that entered the well screen settled to the bottom, and some was forced back into the gravel pack by the high-velocity water jet. As a result, not all of the fine material could be removed. Also, the jetting well development procedure required that all subsequent jet tool passes made after the first jet tool pass have a slightly lower jet nozzle velocity. The lower jet nozzle velocity avoided mixing more fine material from the aquifer into the gravel pack material. A definite inner circle of penetration was observed during the excavation phase, which occurred after the seventh jet tool pass was completed. The pack material between this inner circle and the outer circle of the first jetting pass penetration distance still contained fine material. The pack material between the well screen and the inner circle was much coarser, but still contained more fines than the initial gravel pack. This is discussed in subsequent paragraphs.

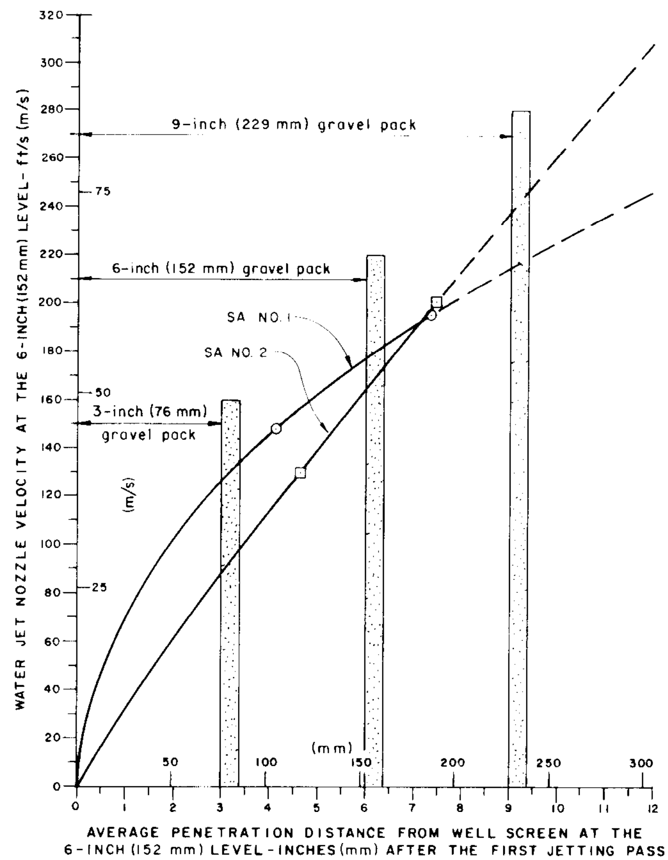


Figure 18. – Average water jet penetration distance from the well screen vs. jet nozzle velocity [after the first jetting pass measured at the 6-inch (152-mm) level] – results from test runs No. 11, 13, 17, and 19.

As shown in table 4, the finer SA No. 1 material [fig. 19(a)] required higher water jet nozzle velocities than the coarser SA No. 2 material [fig. 19(c)] to penetrate the same distance for the 3-inch (76-mm) gravel pack thickness test runs. For the 6-inch (152-mm) gravel pack thicknesses, the average penetration distances and jet nozzle velocities for both SA No. 1 and 2 materials were about the same. However, it should be pointed out that the test runs for the 6-inch (152-mm) gravel packs did not completely erase the wall cake formation (see last column, table 4 and fig. 19). The 6-inch (152-mm) gravel pack test runs should have used higher jet nozzle velocities at the 6-inch (152-mm) level, perhaps up to 220 ft/s (67 m/s). Therefore, the curve extrapolation (fig. 18) probably indicates lower water jet nozzle velocities than those actually needed for the 9-inch (229-mm) gravel pack thickness. The results of the 9-inch (229-mm) gravel pack thickness test runs could not be used on figure 18 because very little of the wall cake was destroyed. A definite penetration distance (outer or inner circle) for the 9-inch (229-mm) gravel pack test runs could not be identified during excavation.

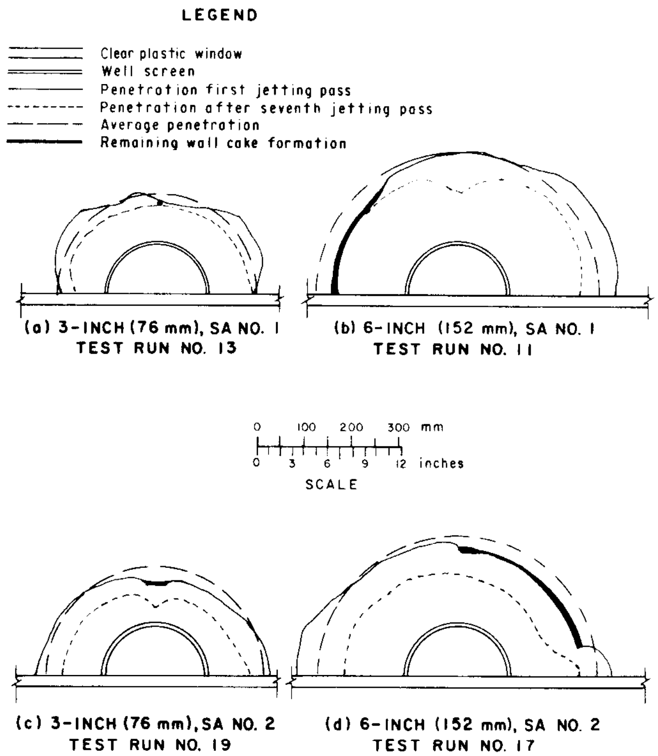


Figure 19. – Top views of water jet penetration distances from the well screen [measured at the 6-inch (152-mm) level].

Standard sieve analyses of the gravel pack material samples taken during the excavation phase of the test run indicate that fines have been mixed into the pack material and have changed its physical properties. A summary of the average particle size, D_{50}, the pack aquifer ratio, P/A, and the uniformity coefficient, C_u, before jetting and after the seventh jetting pass is shown in table 7, using test runs No. 11, 13, 17, and 19 as typical examples. In all examples, the particle sizes at the 50, 60, and 10 percent finer (D_{50}, D_{60}, and D_{10}) levels decreased, particularly at the D_{10} level for the 3-inch (76-mm) gravel pack thickness. The *mixed-in* fines caused the pack aquifer ratio, P/A, to decrease and the uniformity coefficient, C_u, (where $C_u = D_{60}/D_{10}$) to increase substantially. The extended penetration of the water jet beyond the wall cake into the aquifer material was about the same for both the 3- and 6-inch (76- and 152-mm) gravel pack test runs (fig. 19). Therefore, the extended penetration for the 3-inch (76-mm) gravel pack is proportionally greater than the 6-inch (152-mm) gravel pack extended penetration. As a result, a larger percentage of aquifer material was mixed into the smaller 3-inch (76-mm) gravel pack annular space. A higher head loss occurred across the 3-inch (76-mm) than across the 6-inch (152-mm) gravel pack after the seventh jetting pass, as illustrated on figures 14(a) and (b).

The fines mixed into the pack material were not completely washed back into the well screen, even after seven jetting passes. The sieve analysis of the material obtained from the inside of the well screen after each jetting pass (fig. 20) illustrates that fine material was still being removed after the seventh jetting pass. The largest amount of fines is usually removed during the first four jetting passes. The slow removal of the fines indicates that high-velocity horizontal jetting is not an efficient well development method for removing the mixed-in fines that occur during the first jetting pass. A considerable amount of material having a particle size greater than the well screen slot width was found inside the well screen after each jetting pass (fig. 20). Apparently, these larger sized particles slip through the elongated screen slot but did not pass through the square mesh sieve of the same width. Figure 20 also shows the cumulative weight of the material washed into the well screen after each jetting pass. The linear relationship is typical of the jetting well development method experienced in the well sectional model test runs for the gravel pack thickness investigation.

Figures 21(a) through (d) show the standard sieve analyses for the aquifer and gravel pack materials before jetting and after jetting well development is completed. The gravel pack material becomes finer and the aquifer material, within the zone of the extended jet penetration, becomes coarser after jetting is completed. The coarser aquifer material within the extended penetration zone shows the gravel pack expansion caused by the mixing action of the jet. However, the gravel pack physical properties have changed as shown in table 7. The 6-inch (152-mm) gravel pack material remained coarser [figs. 21(b) and (d)] than the 3-inch (76-mm) gravel pack material [figs. 21(a) and (c)]. The smaller percentage of finer material in the 6-inch (152-mm) gravel pack after well development may indicate thicker gravel packs have an advantage over thinner gravel packs from the standpoint of well development using the high-velocity horizontal water jetting method. However, the jet nozzle velocity must also be increased substantially for the thicker gravel packs.

Special Test Runs

High P/A Ratio. – One test run was made to investigate the effectiveness of using a higher pack aquifer ratio, P/A. The pack-aquifer ratio, P/A, is determined by the equation:

$$P/A = \frac{D_{50}\ \text{(pack)}}{D_{50}\ \text{(aquifer)}}$$

where D_{50} represents the median particle size of the pack and the aquifer material; i.e., half (by weight) of the material particle sizes are smaller in diameter.

Table 7. – Examples of gravel pack physical properties before and after jetting.

Material gradation	Physical property	No. 13, 3-inch (76-mm) gravel pack)		No. 11, 6-inch (152-mm) gravel pack	
		Before	After	Before	After
SA No. 1	D_{50}	0.77	0.69	0.78	0.75
	D_{60}	0.83	0.75	0.83	0.80
	D_{10}	0.54	0.26	0.56	0.40
	P/A[1]	3.50	3.14	3.55	3.41
	C_u	1.54	2.88	1.48	2.00

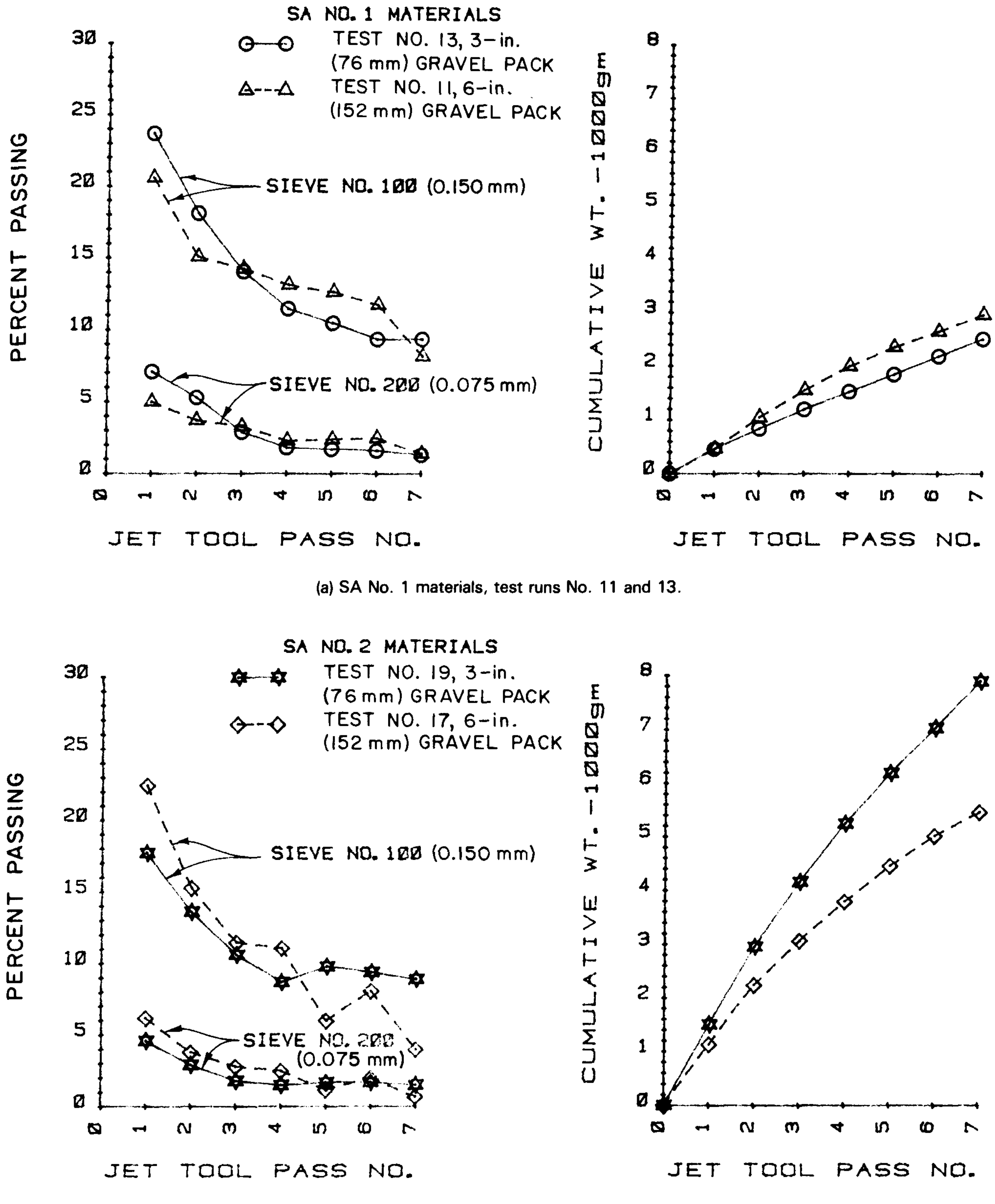
Material gradation	Physical property	No. 19, 3-inch (76-mm) gravel pack		No. 17, 6-inch (152-mm) gravel pack	
		Before	After	Before	After
SA No. 2	D_{50}	1.28	1.12	1.25	1.24
	D_{60}	1.33	1.22	1.30	1.30
	D_{10}	0.95	0.29	0.89	0.43
	P/A[2]	4.00	3.50	3.91	3.88
	C_u	1.40	4.21	1.46	3.02

[1] Aquifer SA No. 1, D_{50} = 0.22 mm, table 3 and figure 9(a).
[2] Aquifer SA No. 2, D_{50} = 0.32 mm, table 3 and figure 9(b).

The purpose of the gravel pack is to prevent fine sand movement into the well screen at high water velocities. The sand movement is controlled by the particle size ratio of the pack and aquifer materials. This is referred to as the *P/A* ratio. A *P/A* ratio of 4, used in the gravel pack thickness test runs, will successfully retain the movement of the aquifer material into the pack, [2, 3, 5]. As the *P/A* ratio increases, the voids within the gravel pack material become larger in comparison with the particle sizes of the aquifer material. Therefore, the potential for the aquifer material to move into the pack increases as the *P/A* ratio increases. However, if the *P/A* ratio is too large, the conditions at the interface of aquifer and the pack could become unstable. The result could be large movement of fines into the well when pumping at high yields, and the well could fail. However, higher *P/A* ratios increase the porosity of the pack material. Therefore, the efficiency in the approach conditions to the well should increase, thereby increasing the well specific capacity. Investigations by the Colorado State University Experiment Station, Fort Collins, Colorado, have determined that the maximum stable *P/A* ratio is 9.5 when uniform gravel packs are used with uniform aquifers [3].

The Colorado State University studies, however, did not include the wall cake formation at the aquifer pack interface. Therefore, the conditions of the gravel pack after jetting well development to destroy the effects of the wall cake were not investigated. Special test run No. 15 was made in this investigation with a *P/A* ratio of 6.18. It included the wall cake formation, and the high-velocity horizontal water jetting was used as the well development method. The SA No. 2 material gradation was used for the gravel pack. The well screen was a wire-wound-cage type having a slot width of 0.040 inch (1.0 mm). The aquifer material had the SA No. 1 gradation. The test run procedure followed the same procedure used for the gravel pack thickness investigation test runs. Five jetting passes were made and the gravel pack thickness was 3 inches (76 mm).

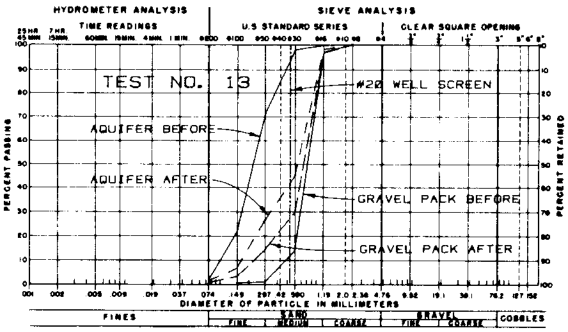
The first jetting pass used a water jet nozzle velocity of 70 ft/s (21 m/s), which appeared to be sufficient to destroy the wall cake formation. However, when the special test run was excavated it was discovered that only about 50 percent of the wall cake was erased. Figure 22 shows the top view of the water jet penetration for special test run No. 15. The wall cake remained in place on the left side (looking into the window from the front). The first jetting pass should have been made with a higher water jet nozzle velocity, perhaps 100 ft/s (30 m/s). The high-velocity water from the jet nozzle on the right side penetrated through the wall cake formation and caused an unbalanced flow condition within the gravel pack material. Apparently, once the more rigid wall cake formation is penetrated, there is less resistance to jet flow in that area. The forces of the opposite jet nozzle are then less effective, particularly when the porosity of the pack material is large, as it would be for high *P/A* ratios. Therefore, the jet nozzle velocity must be sufficiently high to overcome the unbalanced penetration effect. Higher water jet velocities could also cause a zone of penetration into the aquifer greater than that shown on figure 22. A



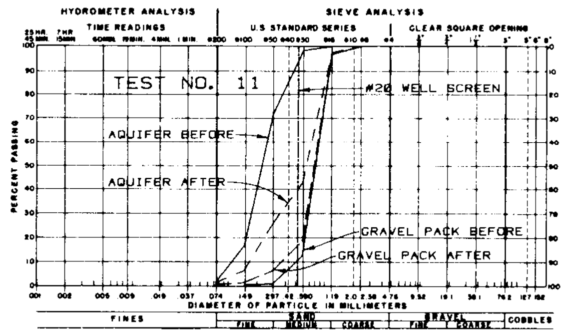
(a) SA No. 1 materials, test runs No. 11 and 13.

(b) SA No. 2 materials, test runs No. 17 and 19.

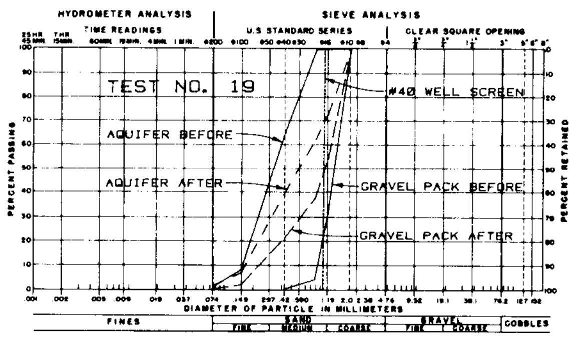
Figure 20. – Sieve analysis and the cumulative weight of material from inside the well screen after each jetting pass.



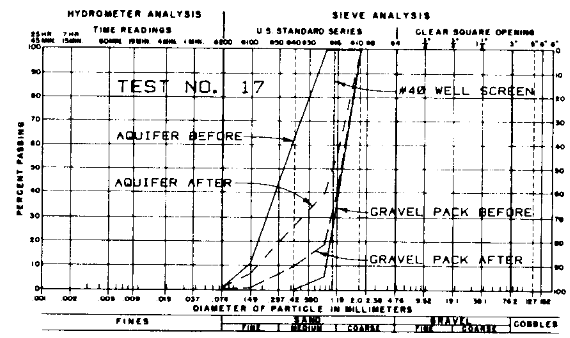
(a) Test run No. 13.



(b) Test run No. 11.



(c) Test run No. 19.



(d) Test run No. 17.

Figure 21. – Standard sieve analysis of the aquifer, extended penetration zone, and gravel pack materials before and after water jetting.

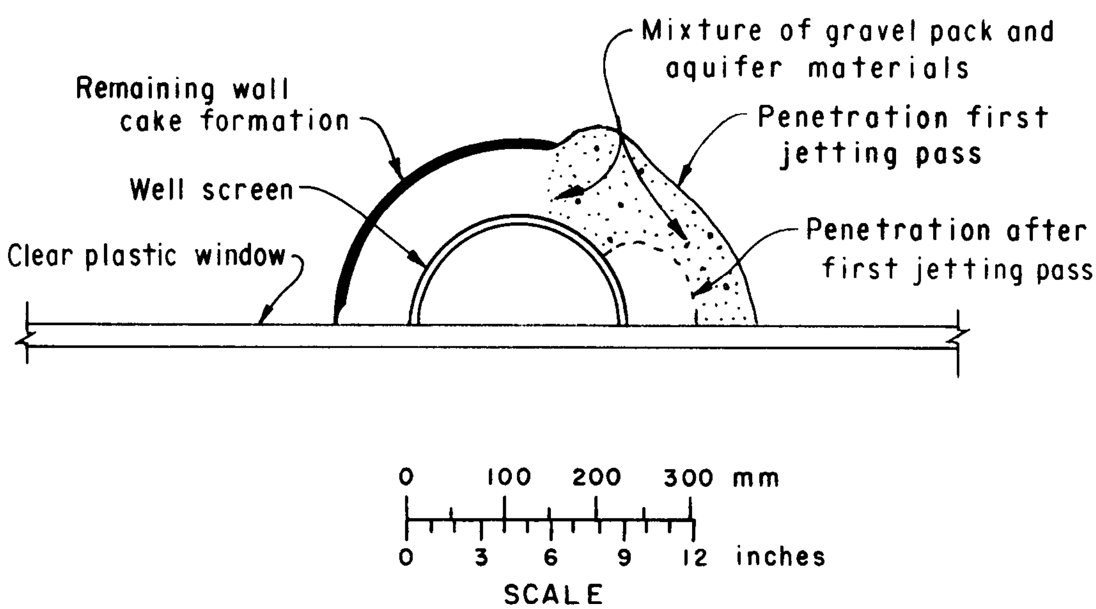


Figure 22. – Top view of water jet penetration for special test run No. 15 for the high P/A ratio [measured at the 6-inch (172-mm) level].

larger percentage of fines would then mix into the relatively porous gravel pack and could render the high *P/A* ratio design ineffective.

The physical properties of the gravel pack before and after five jetting passes (including the aquifer) are shown in table 8.

Table 8. – Physical properties of aquifer and of gravel pack before and after five jetting passes. High *P/A* ratio, special test run No. 15.

Physical property	Gravel pack		Aquifer
	Before	After	
D_{50}	1.36	1.20	0.22
D_{60}	1.45	1.32	.28
D_{10}	0.87	0.22	.13
P/A	6.18	5.45	N/A
C_u	1.67	6.00	2.15

The physical properties for the pack material after five jetting passes changed: particularly the particle size at D_{10}, which decreased significantly, causing the pack material uniformity coefficient, C_u, to increase from 1.67 to 6.00. The pack material became non-uniform and the pack aquifer ratio, *P/A*, decreased from 6.18 to 5.45.

The steady-state flow conditions measured before jetting and after each of the five jetting passes are summarized in table 9.

Only about 61 percent of the total head loss was erased for special test run No. 15. However, as shown on figure 22, only about 50 percent of the wall cake was destroyed. As a result, the specific capacity only increased about 2 percent.

Figure 23 is the standard sieve analysis of the aquifer, the extended zone of penetration, and the gravel pack material before and after water jetting well development. The soil samples were taken on the right side of the well screen (see fig. 22). Figure 23 illustrates that the aquifer material in the extended zone of jet penetration has become coarser. The gravel pack material has become finer and is nearly the same as the extended zone material. Comparing the results of the high *P/A* ratio special test run No. 15 (fig. 23) with figures 21(a) and (c) (test run Nos. 13 and 19 for the 3-inch (76-mm) gravel pack thicknesses) indicates that the after conditions of the gravel pack material appears to have similar physical characteristics.

Based on the results of special test run No. 15 having a high *P/A* ratio, the following conclusions can be made:

1. The high *P/A* ratio permits more aquifer fines to mix into the coarser gravel pack when the water jet penetrates into the aquifer formation.

2. The after conditions of the high *P/A* ratio gravel pack has physical properties similar to those of the after conditions of the low *P/A* ratio test runs.

3. The high-velocity horizontal water jetting method of well development must compensate for unbalanced penetration; i.e., higher jet nozzle velocities on the opposite jets nozzles must overcome unbalanced flow within the gravel pack annular space. However, it appears the maximum jet nozzle velocity needed to penetrate through a coarser gravel pack is lower.

4. High-velocity horizontal water jetting is not an efficient method for cleaning fines from the gravel pack after the wall cake has been physically destroyed.

Jetting from Outside Well Screen. – Special test run No. 14 was conducted to evaluate an alternative unconventional method of well development. Low-velocity horizontal water jetting from outside the well screen was tested. The test run was considered as a preliminary test for investigating alternative well development methods planned for the future. The ongoing research program for ground-water well design criteria will, in the future, emphasize the investigation of alternative well development methods, including those in use today, and the development of new and unconventional methods. Perhaps an unconventional method, such as jetting from outside the well screen or destroying the wall cake as the gravel pack material is being placed, could be developed that would (1) completely eliminate the impervious characteristics of the wall cake formation, (2) optimize the specific capacity of the well, and (3) simplify the well development procedure.

The jetting tool used in special test run No. 14 consisted of four concentric rings (half-circle) of ½-inch (13-mm) diameter copper tubing, as shown on figure 24. The concentric half circles were spaced 1⅜ inches (35 mm) apart. The four half-circle tubes were connected with 1-inch (25-mm) diameter copper tubing at the two 45° lines from the clear plastic window. These tubes were connected to two 1-inch (25-mm) vertical galvanized pipes. The two vertical pipes were then teed into the 1½-inch (38-mm) diameter water supply line. Holes, spaced 1 inch (25 mm) apart and 3/32 inch (2.4 mm) in diameter were drilled through the outer ring in a horizontal plane at the centerline of the ½-inch (13-mm) copper tubing for the water jets. The jetting of water for the outer ring was both in the outward direction into the wall cake formation and inward towards the well screen. The outer edge

Table 9. – Summary of steady-state flow conditions measured before jetting and after each of five jetting passes. High *P/A* ratio, special test run No. 15.

		Jetting pass No.						Change, %
	Initial	1	2	3	4	5	Avg.	
Specific capacity, gal/min per ft (L/s per 0.3 m) drawdown	1.22 (0.08)	1.27 (0.08)	1.23 (0.08)	1.20 (0.08)	1.28 (0.08)	1.25 (0.08)	1.25 (0.08)	+2.1
Jet nozzle velocity, ft/s (m/s) at 6-in level	–	70 (21.3)	65 (19.8)	60 (18.3)	60 (18.3)	60 (18.3)	– –	– –
Head loss across wall cake, ft (m)	0.29 (0.09)	0.07 (0.02)	0.07 (0.02)	0.12 (0.04)	0.11 (0.04)	0.06 (0.02)	0.09 (0.03)	−69.0
Head loss across pack, ft (m)	.02 (0.01)	.000 (0.000)	.005 (0.001)	.06 (0.02)	.06 (0.02)	.01 (0.00)	.03 (0.01)	+50.0
Head loss totals	0.31(0.09)						0.12	

$$\text{Reduction in head loss} = \frac{[0.31\ (\text{initial}) - 0.12\ (\text{after})]}{0.31\ (\text{initial})} \times 100 = 61.3\%$$

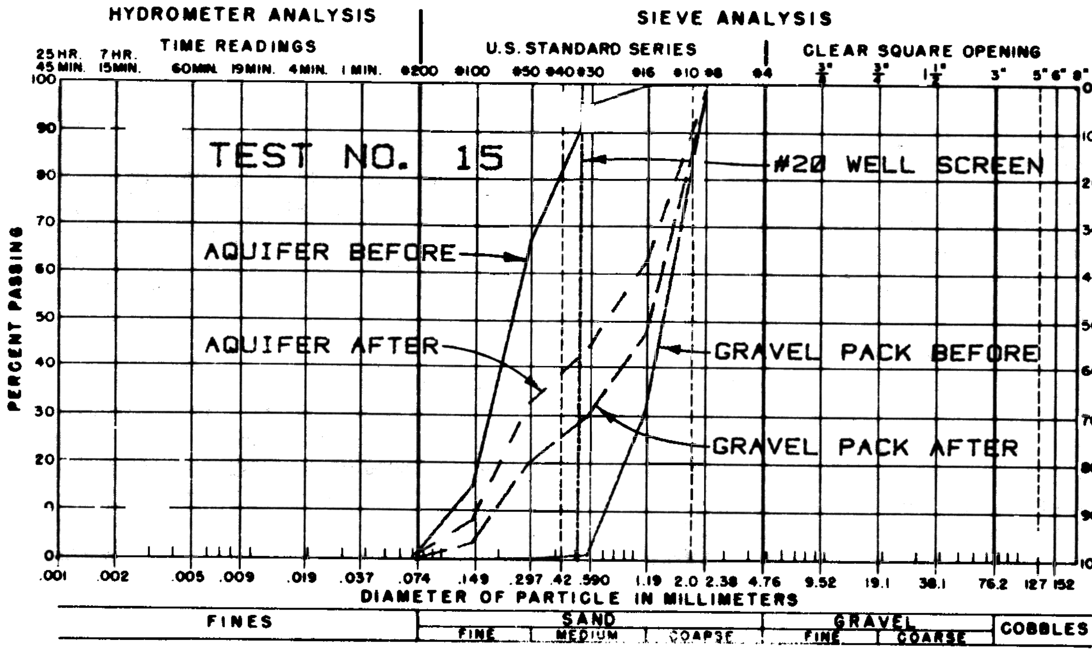


Figure 23. – Standard sieve analysis of the aquifer, extended penetration zone, and gravel pack materials before and after water jetting for special test run No. 15 having a high P/A ratio.

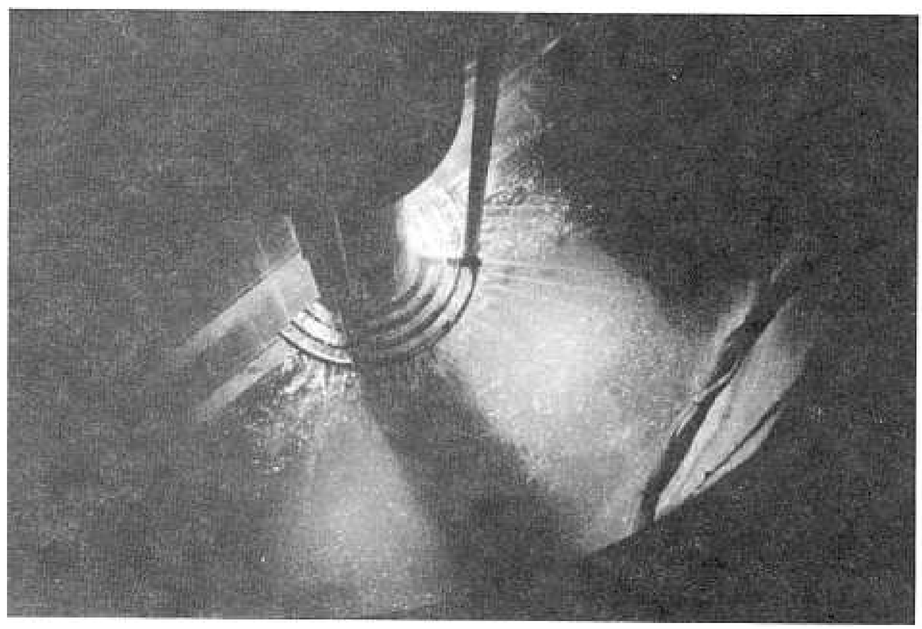


Figure 24. – Jetting tool used in special test run No. 14, low-velocity horizontal water jetting well development from outside the well screen. P801-D-80978

of the outer half-circle tubing was ¾ inch (19 mm) from the inside edge of the wall cake formation for the 6-inch (152-mm) gravel pack thickness. The water jet 3/32-inch (2.4-mm) diameter holes for the three inner rings were drilled only on the inside perimeter of the ½-inch (13-mm) copper tubing. Therefore, the water jetting for the three inside tubes was only directed inward towards the well screen. A total of 133 jet holes were drilled in the four concentric half circle tubes, which were capped at the ends next to the clear plastic window. A ½-inch (13-mm) square No. 30 (0.6 mm) mesh screen was placed over each jet hole and soldered at the four corners to diffuse the water jet stream. The inside edge of the inner ring was ½ inch (13 mm) from the outside edge of the 8.651-inch (220-mm) o.d. wire-wound-cage well screen.

The unconventional jetting tool was placed at the bottom of the well of the sectional model, inside the annular space for a 6-inch (152-mm) gravel pack. The construction of the aquifer, wall cake, and placement of the gravel pack using SA No. 1 materials then proceeded in the same manner used for the gravel pack thickness test runs.

It was postulated that the whirling action of the water jets would destroy the wall cake formation and direct a highly concentrated flow of water inward toward the well screen. The whirling action of the jets would suspend the sand particles and move the finer material towards and into the well screen. The test began by pumping water from the well casing, lowering the water column inside the screen about 1 foot (0.3 m) below the static water level outside the aquifer. The water supply line to the jetting tool was then opened slowly until the whirling action of the jets began. The water column inside the well screen was maintained at 1-foot (0.3-m) drawdown as flow from the special jetting tool into the well increased. Then the jetting tool was slowly raised by an overhead electric hoist. It was thought the whirling action of the jets would fluidize the gravel pack material above the four half-circle rings. The fluidic state of the gravel pack was expected to offer little resistance to the upward lift of the jet rings. The main resistance to the upward lift was supposed to be the friction of sand material against the two vertical supply lines on the 45° lines from the window; this friction was estimated to be insignificant. However, the fluidic state did not completely form for the full circumference of the jet rings.

The fluidic state did not develop evenly because of the characteristics of the flow in the jetting rings. The fluidic state occurred at the jet holes nearest the two vertical supply pipes, and very little, if any, occurred at the ends of the rings at the window and halfway between the two vertical supply pipes (90° from the window). Figure 25 shows a typical top view of the jet penetration distance from the well screen. The extended zone of penetration at the 45° lines was considerable; it reached 5 to 6 inches (127 to 152 mm) beyond the 6-inch (152-mm) gravel pack. There was a lot of resistance to the upward lift of the jet tool because of the unbalanced fluidic state above the water jet rings.

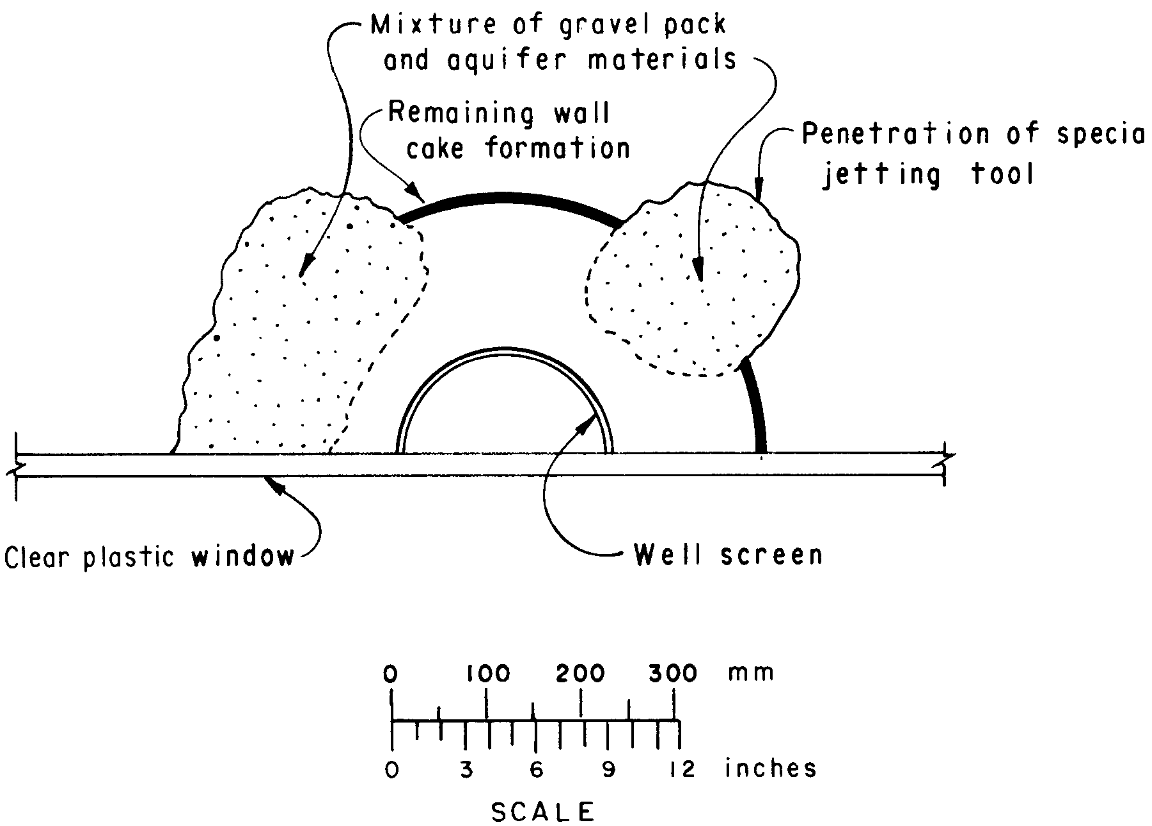


Figure 25. – Typical top view of the jet penetration distance from the well screen for special test run No. 14, low-velocity horizontal water jetting well development from outside the well screen.

Therefore, the special test run to evaluate the low-velocity horizontal water jetting from outside the well screen was not completely successful. Balanced jet nozzle velocity and, thus, uniform penetration around the perimeter of the wall cake formation was not accomplished. However, it was estimated that 50 percent of the wall cake was destroyed.

The physical properties of the aquifer and of the gravel pack before and after the one special jetting tool pass are shown in table 10.

Table 10. – Physical properties of aquifer and of gravel pack before and after special jetting tool pass from outside the well screen (special test run No. 14).

Physical property	Gravel pack Before	Gravel pack After	Aquifer
D_{50}	0.77	0.67	0.22
D_{60}	.81	.72	.26
D_{10}	.54	.19	.125
P/A	3.50	3.05	N/A
C_u	1.50	3.79	2.08

Comparing the results in table 10 with those for test run No. 11 in table 7 indicates that the jetting from outside the well screen was not as clean as the jetting from inside the well screen. More fines were mixed into the gravel pack in the special test run mainly because of the large extended zone of penetration. The intent of the low-velocity jetting from the outside of the well was to just penetrate through the wall cake and break up the impervious characteristics. Only a small percentage of fines should have been mixed into the pack material.

The steady-state flow conditions before and after the one special jetting tool pass are summarized in table 11.

Only about 43 percent of the total head loss was erased for special run No. 14. However, as shown on figure 25, only about 50 percent of the wall cake was destroyed. The specific capacity did increase by 25 percent, which was about the average increase experienced for the gravel pack thickness test runs. The average velocity of the jets was only 22 ft/s (7 m/s), which required a supply pressure of 23 lb/in^2 (159 kPa). The fluidic state occurred nearest the supply pipe; this indicated that a higher than average velocity would occur at this location.

Figure 26 is the standard sieve analysis of the aquifer in the extended zone of penetration and of the gravel pack before and after the special jetting from outside the well screen. Comparing the after conditions of the gravel pack with test run No. 11 [fig. 21(b)], the aquifer extended zone of penetration was coarser and the gravel pack was finer. Therefore, a larger percentage of the aquifer material was mixed into the pack material and the gravel pack was expanded considerably more than in test run No. 11. The gravel pack material properties, after the special jetting from outside the well screen test, had characteristics similar to those of the test runs for jetting from inside the screen. There was a large amount of fines mixed in and not enough washed out; this decreased the efficiency of flow through the gravel pack.

However, jetting from outside the well screen:

1. Has a great potential as a simple and efficient well development method if it could be accomplished correctly.

2. Requires modifications of test equipment and of procedure and additional tests to verify the potential of the unconventional low-velocity horizontal water jetting from outside the well screen as a practical well development method.

Without Wall Cake Formation. – Special test runs were made without the wall cake formation to establish the performance of the well sectional model for an ideal condition. The ideal condition assumes that either the wall cake did not develop during the well drilling operation or the wall cake was erased

Table 11. – Summary of steady-state flow conditions measured before and after the special jetting tool pass from outside the well screen.

	Before	After	Change, %
Specific capacity, gal/min per ft (L/s per 0.3 m) drawdown	1.28 (0.08)	1.60 (0.10)	+25.0
Jet nozzle velocity, ft/s (m/s)	22 (6.7)	–	
Head loss across wall cake, ft (m)	0.27 (0.08)	0.11 (0.03)	−59.3
Head loss across gravel pack, ft (m)	0.03 (0.01)	0.06 (0.02)	+100.0
Head loss totals	0.30 (0.09)	0.17 (0.05)	

$$\text{Reduction in head loss} = \frac{[0.30\ (\text{before}) - 0.17\ (\text{after})]}{0.30\ (\text{before})} \times 100 = 43.3\%$$

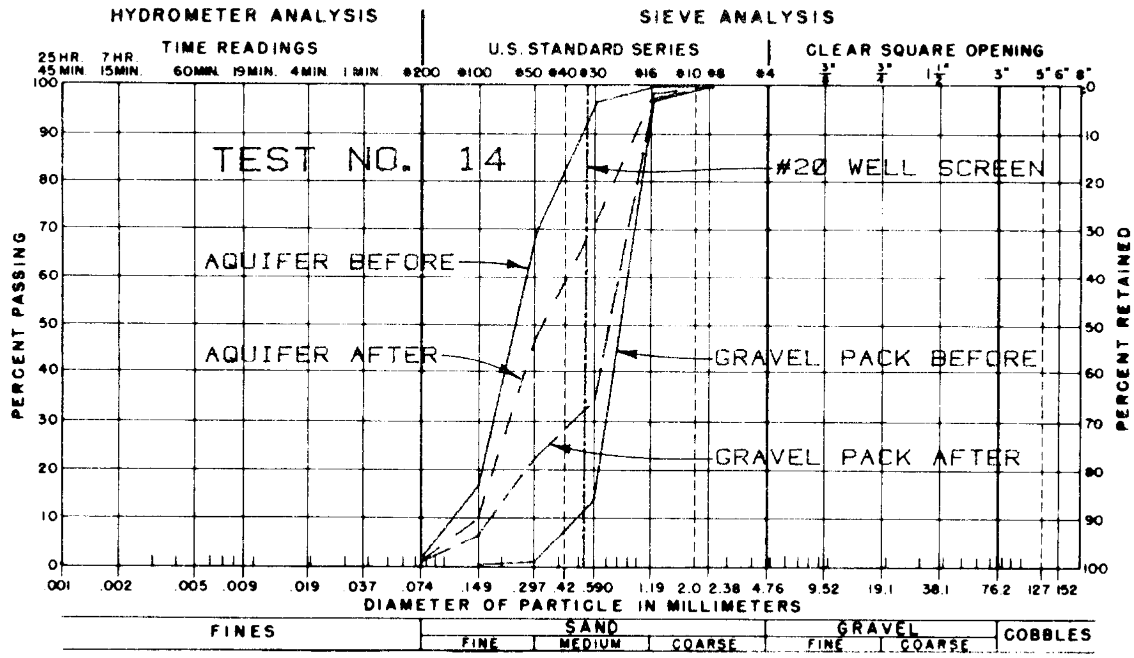


Figure 26. – Standard sieve analysis of the aquifer, extended penetration zone, and gravel pack materials before and after jetting from outside the well, special test run No. 14.

perfectly, during the well development phase. The performance data for the ideal condition are used to further evaluate the success of the high-velocity horizontal water jetting method of well development and the effects of thicker gravel packs.

Three special test runs, Nos. 22, 23, and 24, were conducted without the wall cake formation for the 9-, 6-, and 3-inch (229-, 152-, and 76-mm) gravel pack thicknesses, respectively. The results of these special test runs are compared with test runs No. 21, 17, and 19, respectively. These earlier test runs included the wall cake formation, which was erased using the high-velocity horizontal water jetting (from inside the well screen) method.

The construction of the well sectional model aquifer configuration (using the SA No. 1 materials) without the wall cake formation and the measurement of the steady-state flow conditions followed the exact same procedures for each of these special test runs. The placement of materials into the well sectional model began on a Monday; on that day the fill was completed to the 2-foot (0.6-m) level. The placement of the sand materials followed the "Test Procedure-Preparation" described previously. However, the wall cake formation was not included in the lower 2 feet (0.6 m). The second day, the aquifer configuration was completed to the 6-foot (1.8-m) level, the top of the well box. Above the 2-foot (0.6-m) level, the wall cake formation was placed in the same exact manner used in test runs No. 21, 17, and 19, so that comparable results, with and without the wall cake, could be obtained. In test runs No. 21, 17, and 19, water jetting to erase the wall cake ended at the 2-foot (0.6-m) level. An example of the completed aquifer configuration without the wall cake below the 2-foot (0.6-m) level can be observed on figure 1, which shows test run No. 23 for the 6-inch (152-mm) gravel pack thickness.

On the third day, the water jetting rig and the concrete blocks were installed. The piezometer taps were purged of air and preparations for conducting the steady-state flow condition test run scans were completed. Four steady-state flow conditions were measured on the fourth day and again on the fifth day. Eight steady-state flow conditions were measured to obtain an average specific capacity of the aquifer configuration without the wall cake formation.

On the sixth day (the following Monday), one water jetting pass was made, with care taken to keep the water jet from penetrating into the aquifer material. After the jetting pass was completed, four more steady-state flow conditions were measured. The purpose of the sixth day activities was to determine whether the specific capacity of the aquifer configuration would change after the gravel pack was subjected to one jetting pass. One special test run without the wall cake formation completed the activities of the sixth day.

The results of the special test runs without the wall cake are compared with those for the test runs that included the wall cake before and after water jetting on figure 27.

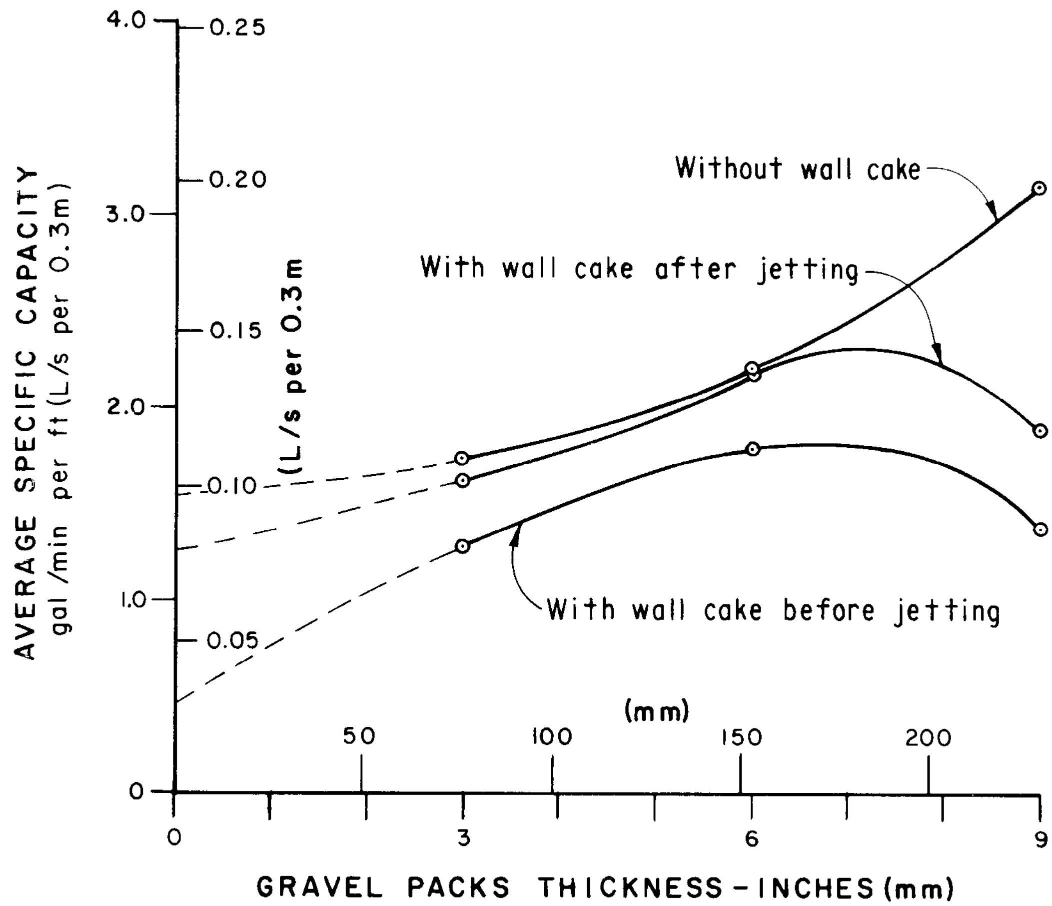


Figure 27. – Specific capacity vs. gravel pack thickness for test runs without wall cake and with wall cake before and after water jetting.

The upper curve of figure 27 demonstrates that the well specific capacity for the ideal conditions, i.e., without the wall cake, increases for the thicker gravel packs. The data in column (4) of table 12 show that the average increase was about 27 percent for 3-inch (76-mm) incremental increases in the gravel pack thicknesses; this represents the measured increase from the special test run data. The theoretical increase of discharge into a well constructed in a water table aquifer for steady-state flow conditions can be determined from the following equation [2]:

$$Q = \frac{P\,(H^2 - h^2)}{1055 \log \frac{R}{r}}$$

where:

Q = well yield or pumping rate, gal/min,
P = permeability of the aquifer material, gal/d per ft^2,
H = height of the water table, ft,
h = water height in the well while pumping, ft,
R = cone of depression radius, ft, and
r = radius of the well, ft.

The theoretical change in the well yield, $\triangle Q$, for the same aquifer formation and well water level drawdown conditions (i.e., the values of H, h, P, and R remain constant) becomes a function of the well radius, r. Based on the above equation and assumptions, the change in the well yield, $\triangle Q$, can be expressed as:

$$\triangle Q = f \left(\frac{1}{\log \frac{R}{r_1}} - \frac{1}{\log \frac{R}{r_2}} \right)$$

This equation can be applied to the well sectional model with R as the radius of the CMP (fig. 2) and r as the well screen outside radius plus the gravel pack thickness. The theoretical percent change in the specific capacity can be calculated as listed in table 12, column (8). Theoretically, the average specific capacity increases about 31 percent for 3-inch (76-mm) incremental increases in the gravel pack thickness. The theoretical increase is slightly greater than the measured specific capacity increase, table 12, columns (8) and (4). The comparison generally confirms that thicker gravel packs can increase the effective

Table 12. – Increase in specific capacity without the wall cake formation compared with the theoretical increase vs. gravel pack thickness.

Gravel pack thickness	Measured: Test run No.	Measured: Specific capacity gal/m per ft (L/s per 0.3 m)	Measured: Change, %	Theoretical: r,[1] in (mm)	Theoretical: R, in (mm)	Theoretical: $\frac{1}{\log \frac{R}{r}}$	Theoretical: Change, %
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
0		[2]1.55		4.31	33	1.13	
		(0.10)	+11.0	(109.5)	(838.2)		+35.4
3 in (76 mm)	24	1.72		7.31	33	1.53	
		(0.11)	+26.7	(185.7)	(838.2)		+29.4
6 in (152 mm)	23	2.18		10.31	33	1.98	
		(0.14)	+43.1	(261.9)	(838.2)		+28.3
9 in (229 mm)	22	3.12		13.31	33	2.54	
		(0.20)		(338.1)	(838.2)		
Average			+26.9				+31.0

[1] r is determined by adding the gravel pack thickness to the outside radius of the well screen, which is equal to 4.31 inches (109.5 mm) (o.d. = 8.625 in (219.1 mm), see table 14).
[2] Value determined from figure 27 by the extended dashed line to the 0 gravel pack thickness for the ideal conditions.

diameter of the well and, thus, increase the specific capacity.

The lower curve of figure 27 demonstrates the effects of the wall cake formation before its erasure by the water jetting. The lower curve is a plot of the specific capacity of test runs No. 19, 17, and 21 (which included the wall cake) before the first jetting pass. The comparison indicates that the wall cake, before its erasure, can cause an average reduction of the well specific capacity of about 34 percent less than the ideal condition, as shown in table 13, column (5).

After seven passes with the jetting tool, almost all of the reduction in the specific capacity caused by the wall cake can be recovered, as demonstrated by the middle curve on figure 7. All but about 3 percent [average of the 3- and 6-inch (76- and 152-mm) gravel pack thickness test runs] can be recovered, as shown in table 13, column (6). The recovery after jetting, an average of about 3 percent less than the ideal condition, indicates that the method of horizontal jetting at high velocities from inside the well screen can effectively eliminate the wall cake impervious characteristics. However, the results are somewhat misleading. To successfully erase the wall cake, the water jet must penetrate farther into the aquifer formation, as discussed previously. The extended penetration beyond the wall cake formation causes the gravel pack to expand. The expanded gravel pack after jetting increases its thickness and effectively increases the specific capacity of the well, as discussed above. Therefore, the recovery appears to be related mostly to the gravel pack expansion and not so much to the physical destruction and removal of the wall cake fines.

The 9-inch (229-mm) gravel pack thickness, test run No. 21, results after jetting were not included in the average 3 percent reduction, column (6), table 13. The water jets for test run No. 21 did not have sufficient velocity to successfully penetrate the wall cake. However, the data demonstrate that if a high percentage of recovery to the ideal condition is to be achieved, the wall cake must be physically destroyed.

The activities of the sixth day of the special test runs without the wall cake formation were designed to determine whether water jetting consolidates the gravel pack material and affects the well specific capacity. When the gravel pack is poured into its annular space, the sand grains settle by gravity. The settlement by gravity should cause the gravel pack to have its greatest permeability, if left undisturbed. The whirling motion of the water jet (fig. 17) appears to have the tendency of consolidating the sand grains, thus decreasing the permeability and decreasing the well specific capacity. It was, therefore, of interest to determine the magnitude of the gravel pack consolidation and the change from ideal conditions in the well specific capacity caused by water jetting.

Table 14 summarizes the results of the special test runs without wall cake, before and after one water jetting pass. The specific capacity used for the before

Table 13. – Summary of special test runs without wall cake compared with test runs with wall cake before and after jetting.

Gravel pack thickness	Without wall cake, ideal: Test run No.	Without wall cake, ideal: Specific capacity, gal/m per ft (L/s per 0.3 m)	With wall cake after jetting: Test run No.	With wall cake after jetting: Specific capacity, gal/m per ft (L/s per 0.3 m)	With wall cake before jetting: Test run No.	With wall cake before jetting: Specific capacity, gal/m per ft (L/s per 0.3 m)	Difference: Before vs. ideal, [2]%	Difference: After vs. ideal, [3]%
(1)		(2)		(3)		(4)	(5)	(6)
3 in (76 mm)	24	1.72 (0.11)	19	1.62 (0.10)	19	1.27 (0.08)	−26.2	−5.8
6 in (152 mm)	23	2.18 (0.14)	17	2.16 (0.14)	17	1.77 (0.11)	−18.8	−0.9
9 in (229 mm)	22	3.12 (0.20)	21	1.86 (0.12)	21	1.35 (0.09)	−56.7	−40.4
Average							−33.9	[4]−3.4

[1] Note: All measurements were made in English units and, therefore, only the English units are shown. It is the responsibility of the reader to convert to SI metric, if desired.

[2] $\frac{(4) - (2)}{(2)} \times 100$

[3] $\frac{(3) - (2)}{(2)} \times 100$

[4] The 9-in (229-mm) gravel pack percent difference (after vs. ideal) is not included in the average.

Table 14. – Summary of special test runs without wall cake before and after one water jetting pass.

Gravel pack thickness	Test run No.	Specific capacity, gal/min per ft (L/s per 0.3 m): Before[1] jetting[1]	Specific capacity: After one jetting pass	Specific capacity: Difference,[2] %	Dry density, lbs/ft^3, (kg/m^3): Before jetting	Dry density: After one jetting pass	Dry density: Difference,[3] %
(1)		(2)	(3)	(4)	(5)	(6)	(7)
3 in (76 mm)	24	1.86 (0.12)	1.91 (0.12)	+2.7	92.73 (1483.7)	96.47 (1543.5)	+4.0
6 in (152 mm)	23	2.34 (0.15)	2.34 (0.15)	0.0	91.75 (1468.0)	93.49 (1495.8)	+1.9
9 in (229 mm)	22	3.34 (0.21)	3.31 (0.21)	−0.9	94.17 (1506.7)	92.35 (1477.6)	−1.9
Average				+0.6			+1.3

[1] The specific capacity Before jetting is the value measured just prior to jetting.

[2] $\frac{(3) - (2)}{(2)} \times 100$

[3] $\frac{(6) - (5)}{(5)} \times 100$

conditions, column (2), was measured just prior to the one jetting pass. The before specific capacity is slightly greater than the average shown in table 13, column (2), as a result of the aquifer configuration being undisturbed over the weekend. As discussed previously, the specific capacity often increased from one day to the next. It is believed that small air bubbles, trapped between particles of sand, dissolve into the water, increasing the permeability of the aquifer material and, thus, increasing the specific capacity. The specific capacity after one jetting pass, column (3), is the average of four steady-state flow conditions measured after the one jetting pass was completed. The average percent difference of +0.6, column (4), indicates that the specific capacity actually increased slightly after jetting. However, the dry density of the gravel pack material from samples obtained during the excavation of the well sectional model [columns (5) and (6), respectively] increased slightly, averaging +1.3 percent, column (7), table 14. This slight increase in the density indicates that the gravel pack material had consolidated and should have caused a slight decrease in the specific capacity. The two measurements of specific capacity and density give contradictory results. However, the differences are small and probably within the accuracy of measurement for the well sectional model. Therefore, it can be concluded that water jetting does not significantly change the performance of the gravel pack.

Figure 28 shows the comparison between the cones of depression of the steady-state flow hydraulic gradients for the ideal conditions without the wall cake, and the before and after jetting conditions with the wall cake. The cones of depression for the ideal conditions are the measured hydraulic gradients for the 3- and 6-inch (76- and 152-mm) gravel pack thicknesses, test runs No. 24 and 23, respectively. Figure 14(a) is used to represent the before and after jetting condition with the wall cake for the 3-inch (76-mm) gravel pack thickness, test run No. 19. The ideal condition is significantly better than the before jetting condition for the 3-inch (76-mm) gravel pack test runs. The ideal condition is not as good as the after jetting condition. After making seven jetting passes to erase the wall cake formation, the gravel pack expanded from the initial 3-inch (76-mm) thickness to approximately 6 inches (152 mm). As a result, the performance of the well improved compared with the ideal condition of the 3-inch (76-mm) gravel pack. The performance, however, of the after conditions of the gravel pack expanded to 6 inches (172 mm) was not as good as the ideal conditions of the 6-inch (172-mm) gravel pack thickness. Therefore, after the wall cake formation is physically destroyed by the high-velocity horizontal water jetting method of well development, the specific capacity of the well can increase above that for the ideal condition; i.e., when the wall cake is not present, jetting is not performed, and the initial (as-constructed) gravel pack thickness is the same.

The special test runs without the wall cake determined the difference in the piezometric water levels between the taps on each side of the aquifer and gravel pack interface for the 3-, 6-, and 9-inch (76-, 152-, and 229-mm) gravel pack thicknesses. Figure 3 and table 1 give the details of these piezometer tap locations. The water level drawdown for the special test run steady-state flow conditions averaged 1.034 feet (0.315 m) and ranged from 0.990 foot (0.302 m) to 1.054 feet (0.321 m). The decrease in the hydraulic gradient ½ inch (13 mm) from the inside edge of the aquifer material to ½ inch (13 mm) from the outside edge of the gravel pack material averaged 0.145 foot (0.044 m) and ranged from 0.12 foot (0.037 m) to 0.19 foot (0.058 m). The 0.145-foot (0.044-m) average head loss without the wall cake was less than the initial head loss with the wall cake, which averaged 0.254 foot (0.077 m), as shown in table 4. This indicates that the wall cake caused a 75-percent increase in the head loss across the adjacent piezometric taps. After jetting, the head loss decreased to an average of 0.030 foot (0.009 m). Therefore, the erasure of the wall cake and the expansion of the gravel pack by water jetting reduced the head loss across the same piezometric taps by about 79 percent more than the ideal condition.

The head loss across the gravel packs for the ideal condition averaged 0.004 foot (0.0012 m) for the 3 inch (76 mm), 0.014 foot (0.0043 m) for the 6 inch (152 mm), and 0.020 foot (0.0061 m) for the 9 inch (229 m). The average head loss for the three gravel packs was 0.013 foot (0.0040 m), considerably less than that measured after jetting, 0.038 foot (0.0116 m) (table 4, "End" gravel pack head loss).

The water jetting method of well development, when the wall cake formation is present, has the following characteristics compared with the ideal conditions:

1. The wall cake increases the head loss at the interface of the aquifer-gravel pack ideal condition by about 75 percent.

2. When the wall cake is physically destroyed by water jetting, the head loss at the aquifer-gravel pack interface decreases by about 79 percent of the ideal condition.

3. Successful water jetting causes the gravel pack to expand about 3 inches (76 mm) from the interface.

4. After jetting, the head loss across the initial gravel pack thickness increases about 195 percent.

5. After jetting, the specific capacity of the well recovers to within about 3 percent of the ideal condition.

Conclusions based on the results of the special test runs without the wall cake compared with the test runs with the wall cake present are summarized as follows:

1. Under ideal conditions, thicker gravel packs increase the effective diameter of the well and increase the specific capacity to near the theoretical increase.

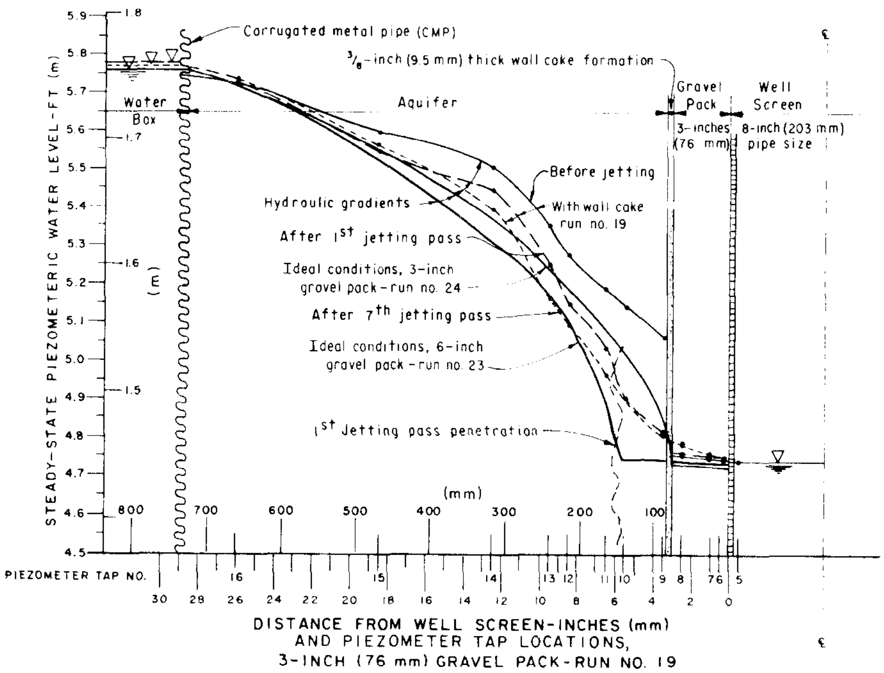


Figure 28. – Comparison of cones of depression for ideal conditions without wall cake and those with wall cake before and after water jetting.

2. High-velocity horizontal water jetting is an effective well development method. The wall cake is destroyed and, in the process, the gravel pack expands, and the specific capacity of the well recovers to within 3 percent of its ideal condition.

3. Water jetting does not significantly consolidate the gravel pack material or cause a reduction in the well specific capacity.

PVC Well Screen. – The objective of the special test runs with the PVC-type slotted well screen was to determine whether the high-velocity horizontal water jetting method of well development from inside the well screen would be different from that with the wire-wound-cage screen. The slot shape of the PVC well screen is considerably different from the wire-wound-cage screen, as shown on figure 29. The shape of the intake opening and the design of the well screen affects the diffusion of the high-velocity horizontal water jet as it passes through the screen into the gravel pack material. The physical dimensions of the PVC and the wire-wound-cage well screens [6] are listed in table 15.

The PVC well screen slots are cut from the outside with gangs of small circular saws; each of which has a thickness equal to the slot width, 0.040 inch (1.0 mm). The circular saw leaves a rectangular opening on the inside of the well screen about 2 inches (51 mm) long with eight saw cuts per circumference. The rectangular opening expands to about 2⅞ inches (73.0 mm) in length on the outside of the well screen, which has a wall thickness of about 0.423 inch (10.7 mm).

The wire-wound-cage well screen design has a teardrop-shaped wire wrapped around and spot welded to each of the 44 vertical 0.175-inch (4.4-mm) diameter rods forming a continuous V-shaped slot. The narrowest part of the V-shaped intake opening, equal to the slot width of 0.040 inch (1.0 mm), is on the outside and expands to about 3/32 inch (2.4 mm) on the inside of the well screen, which has a wall thickness of about 9/64 inch (3.6 mm) excluding the vertical rod supports.

The PVC well screen intake area of 12.1 percent is considerably smaller than the 29.4 percent intake area of the wire-wound-cage type well screen (table 15). It appears that the thick rectangular slot design of the PVC well screen is less efficient for the water jet passing through it than the narrow V-shaped slot design of the wire-wound-cage well screen. Therefore, it was assumed the velocity of the water jet nozzle from inside the PVC well screen must be greater to penetrate the same distance outside the well screen because of the smaller intake area.

Two special test runs, No. 25 and 26, with the wall cake formation in place and the PVC slotted well screen installed, were conducted for the 3- and 6-inch (76- and 152-mm) gravel pack thicknesses, respectively. Unfortunately, neither special test run

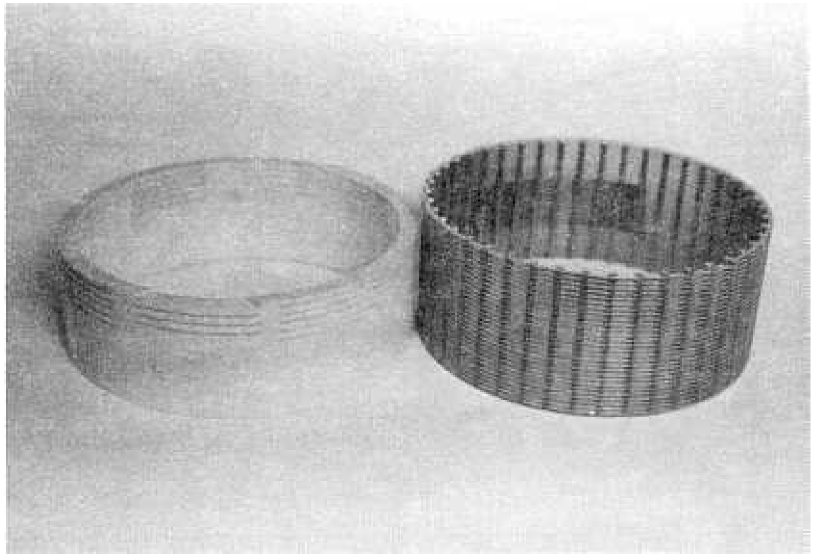


Figure 29. – Slot design of the PVC slotted (left) and the wire-wound-cage type (right) well screens. P801-D-80979

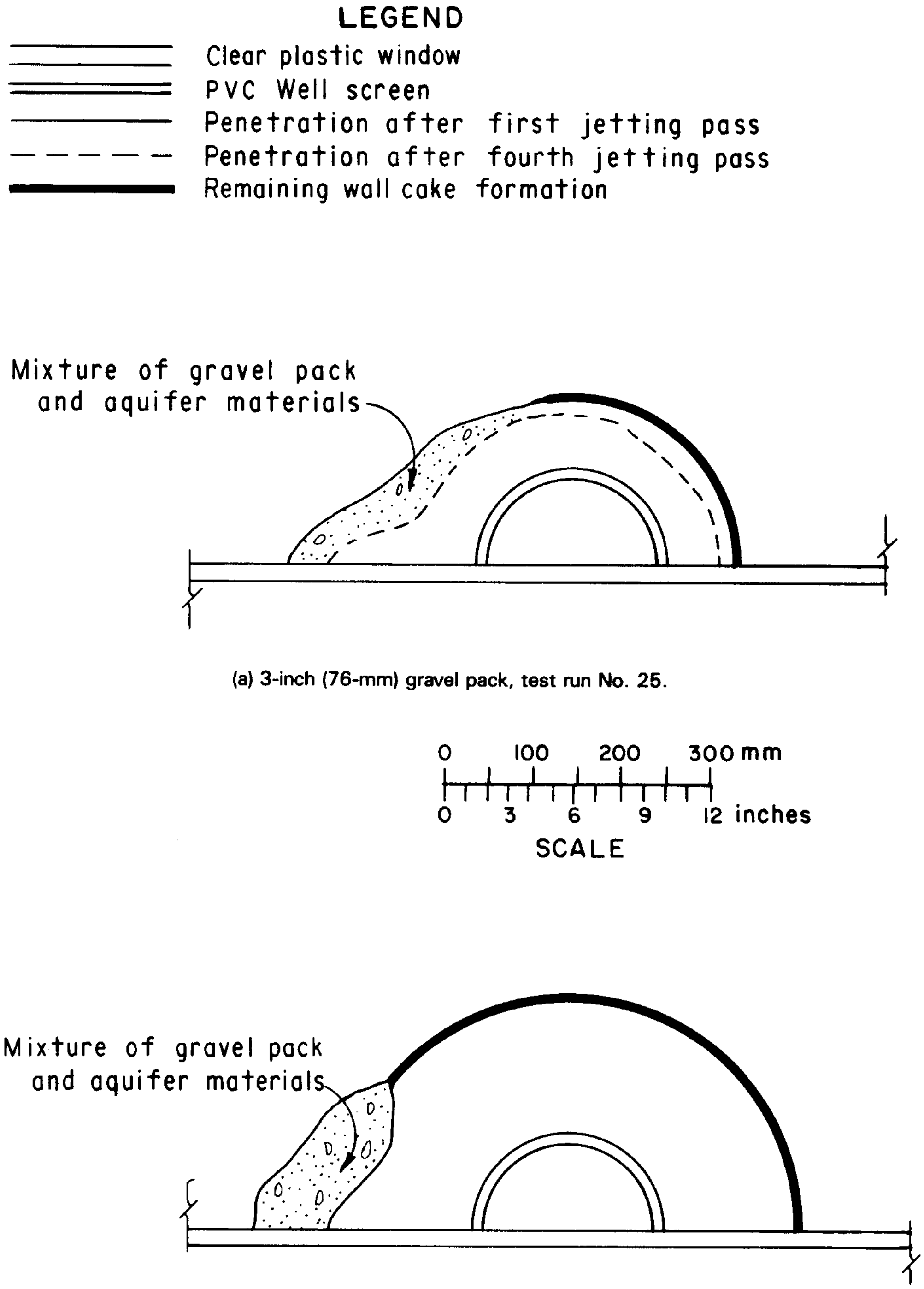
Table 15. – Physical dimensions of the PVC and wire-wound-cage type well screens each having a 0.040-inch (1-mm) slot width and 8-inch (203-mm) pipe diameter.

Physical dimensions	PVC Class 200	Wire-wound-cage
Screen i.d., D_i, inches (mm)	7.805 (198.2)	8.378 (212.8)
Screen o.d., D_o, inches (mm)	8.651 (219.7)	8.625 (219.1)
Slots per lin. ft (per lin. m), G_n	53.31 (174.9)	92.0 (301.8)
Average slot width, W_s, inches (mm)	0.04242 (1.0)	0.03837 (0.97)
Average slot length, L_s, inches (mm)	1.972 (50.1)	27.096 (688.2)
Slots per circumference, S_n	8.0	1.0
Average intake area, A_o, in²/ft (mm²/0.3 m)	[1]35.68 (23 019.3)	[2]95.65 (61 709.6)
Average intake area, A_o, %	12.1	29.4
Slot width standard deviation, σ, inches (mm)	0.00236 (0.06)	0.00131 (0.033)

[1] Inside diameter controls intake area.
[2] Outside diameter controls intake area.

was completely successful. Severe piping developed along the clear plastic window boundary on the left side (looking at the front of the window) caused by the high-velocity water jet. Figure 30 shows the top views of the 3- and 6-inch (76- and 152-mm) gravel packs and the penetration of the water jet on the left side. There are two reasons why the severe piping on the left occurred: (1) the entrance of the left jet nozzle has become more efficient from the many high-velocity jet tool passes made during the course of this investigation, and (2) the left jet nozzle was swung too far, and the main thrust of the water jet splashed directly on the window boundary. The penetration on the left through the wall cake at the beginning of the jet tool pass resulted in operating the jet tool at a pressure lower than required. The jet velocity was then insufficient to penetrate and destroy the wall cake at the interior of the aquifer formation. As discussed previously, once the wall cake formation is penetrated, unbalanced flow conditions develop within the annular space of the gravel pack. It then requires an even higher jet velocity of the opposite jet nozzle to penetrate the required distance.

Of the two special test runs, test run No. 25 for the 3-inch (76-mm) gravel pack thickness was the most successful. About 62 percent of the wall cake surrounding the 3-inch (76-mm) gravel pack was erased. The highest jet nozzle velocity was 150 ft/s (45.7 m/s), which is about 15 percent greater than that for the comparable test run No. 19 (table 4) with the wire-wound-cage well screen. About 13 percent of



(a) 3-inch (76-mm) gravel pack, test run No. 25.

(b) 6-inch (152-mm) gravel pack, test run No. 26.

Figure 30. – Top views of the water jet penetration at the 1.0-foot (0.3-m) level for special test runs.

the wall cake surrounding the 6-inch (152-mm) gravel pack, test run No. 26, was erased. The jet nozzle velocity was the maximum available, 220 ft/s (67 m/s), that the well sectional model high-pressure pump could supply. Comparing the results of the special test run No. 26 with the comparable test run No. 17 (table 4) having the wire-wound-cage well screen: (1) the PVC well screen jet nozzle velocity was about 10 percent higher, but (2) only 13 percent of the wall cake for the PVC well screen test, compared with about 50 percent for the wire-wound-cage well screen, was erased. The PVC well screen requires a higher jet velocity (greater than 15 percent) than the wire-wound-cage well screen to penetrate an equal distance. The erasure of the wall cake for PVC well screen special test runs No. 25 and 26 (fig. 30) can be compared with wire-wound-cage screen test runs No. 19 and 17 [figs. 19(c) and (d)] respectively, for the same aquifer conditions.

The mixing action of the water jet outside the PVC well screen appeared to be more efficient than that observed for the wire-wound-cage screen. The physical properties of the gravel packs, before and after water jetting, listed in table 16 can be compared with the results shown in table 7 for test runs No. 19 and 17. The samples for sieve analysis for the after conditions of the PVC well screen tests were taken within the mixed area of the gravel packs (fig. 30) in the manner shown on figure 7; except that the angle from the window was 30 degrees instead of 45 degrees. Comparing the results shown in table 16 with those in table 7, the average of both PVC well screen tests for the pack-aquifer ratio, *P/A*, was slightly higher, and the uniformity coefficient, C_u, was slightly lower. The gravel packs, after water jetting through the PVC well screen, remained slightly coarser. This indicated that (1) the mixing of the aquifer material was concentrated toward the outside edge of the expanded gravel pack as shown on figure 30 and (2) more fines were washed back into the well screen.

The sieve analysis of the sample taken from the material removed from inside the PVC well screen after each jet tool pass for test runs No. 25 and 26 are shown on figure 31. The results indicate more fines were removed in four jet tool passes than for the wire-wound-cage tests shown on figures 20(c) and (d) for the respective aquifer configurations. However, the accumulative weight of the samples from inside the PVC well screen was considerably less, mainly because a smaller percentage of wall cake was destroyed during the PVC well screen tests. The small percentage of wall cake destruction could also bias these results.

The standard sieve analysis of the gravel packs, after jetting through the PVC well screen, also indicated that the gravel packs remained coarser than those for wire-wound-cage screen test runs No. 19 and 17. This is shown in table 17.

Therefore, the condition of the gravel packs after jetting through the PVC well screen appear to be cleaner, indicating that the mixing action of the water jet is more efficient. The main difference in the mixing action for the two types of well screen could be caused by the number of vertical supports. The PVC well screen has eight solid sections between the eight slots per circumference. However, the wire-wound-cage well screen has 44 vertical support rods that are 0.175 inch (4.4 mm) in diameter (fig. 29). As the high-velocity horizontal water jet passes the vertical supports, the jet is deflected sideways. The angle of the jet deflection continuously changes as the jet nozzle rotates back and forth. It is believed the sideways deflection of the jet reduces the efficiency of the jet swirling motion required to wash material back into the well screen. Because the PVC well screen has fewer vertical supports than the wire-wound type, it has less interference to the back wash motion of the water jet swirl. This permits more of the finer materials to enter the well screen.

It was believed the high-velocity horizontal water jetting would cause severe clogging of sand grains in the slots of the relatively thick-walled, 0.423-inch (10.7-mm) PVC slotted well screen. However, this clogging did not occur. Figure 32 illustrates the conditions of the well screen slots for the PVC and the wire-wound-cage screens after water jetting. The well screens were cleaned by simply brushing with the hand over the outside surface. The number of sand grain particles in the slots for both types of well

Table 16. – Gravel pack physical properties before and after water jetting with the PVC-type slotted well screen.

Physical Property	SA No. 2 gravel pack, before[1]	Test run No. 25 3-inch (76-mm) gravel pack, after	Test run No. 26 6-inch (152-mm) gravel pack, after
D_{50}	1.26	1.20	1.30
D_{60}	1.32	1.28	1.35
D_{10}	0.92	0.29	0.62
P/A[2]	3.96	3.75	4.06
C_u	1.43	4.41	2.18

[1] The before physical properties of the gravel pack are the averages of test runs No. 19 and 17 (table 7).
[2] Aquifer SA No. 2, D_{50} = 0.32 mm (table 3 and fig. 9).

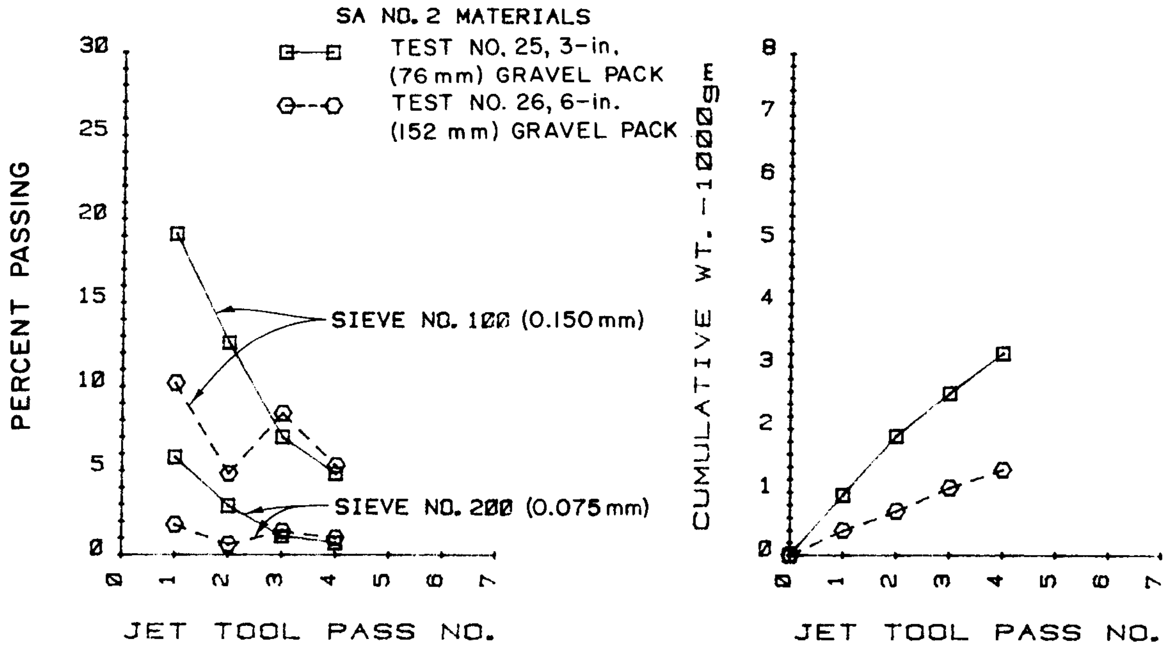


Figure 31. – Sieve analysis and cumulative weight of the material obtained from inside the PVC slotted well screen after each jetting pass [for 3-inch (76-mm) test run No. 25, and 6-inch (152-mm) test run No. 26].

Table 17. – Comparison of standard sieve analysis data (avg. percent passing) for wire-wound-cage and PVC well screens.

	Wire-wound-cage		PVC slotted	
	Test No. 19	Test No. 17	Test No. 25	Test No. 26
Sieve No.	3-inch (76-mm) gravel pack	6-inch (152-mm) gravel pack	3-inch (76-mm) gravel pack	6-inch (152-mm) gravel pack
10 (2.00 mm)	100.0	99.8	99.8	99.8
16 (1.18 mm)	54.2	41.1	47.0	28.8
20 (0.85 mm)	38.0	19.0	33.1	12.5
40 (0.425 mm)	21.2	9.7	21.2	7.3
100 (0.150 mm)	1.7	0.8	1.4	0.5
200 (0.075 mm)	0.1	0.1	0.1	0.05

screens appeared to be about the same. About 1 in 10 particles had to be pried out with a knife for both types of screens. It was therefore concluded that the degree of clogging of the slots by the high-velocity horizontal water jetting method of well development for both the PVC and the wire-wound-cage well screens was about the same magnitude.

The steady-state flow conditions measured before and after water jetting through the PVC well screen are compared with those for the wire-wound-cage screen for the respective aquifer configurations in table 18.

The specific capacity of the PVC well screen tests before jetting was nearly the same as that of the wire-wound-cage screen test. The after jetting specific capacity was about the same for the 3-inch (76-mm) gravel pack thicknesses even though only 62 percent of the wall cake was erased. However, the after jetting specific capacity for the 6-inch (152-mm) test run was considerably less for the PVC well screen test because only about 13 percent of the wall cake was erased. The comparisons of the head losses across the wall cake and gravel pack for the PVC and wire-wound-cage well screens before and after jetting follow the same comparative analyses made for the specific capacity.

Conclusions based on the results of the special test runs with the PVC well screen installed compared

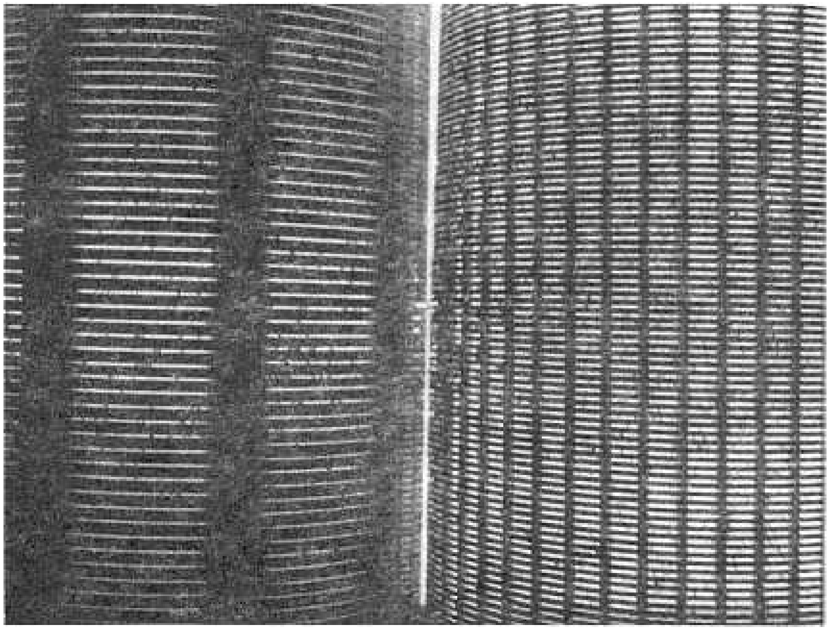


Figure 32. – Clogging of the PVC slotted well screen (left) and the wire-wound-cage type well screen (right) after water jetting. P801-D-80980

Table 18. – Comparison of steady-state flow conditions for wire-wound-cage and PVC slotted well screens.

	Wire-wound-cage		PVC slotted	
	Test No. 19	Test No. 17	Test No. 25	Test No. 26
	3-inch (76-mm) gravel pack	6-inch (152-mm) gravel pack		
Specific capacity, gal/m per ft (L/s per 0.3 m)				
before	1.27 (0.08)	1.77 (0.11)	1.28 (0.08)	1.72 (0.11)
after	1.62 (0.10)	2.16 (0.14)	1.68 (0.11)	1.85 (0.12)
Head loss across, ft:				
Wall cake:				
before	0.31 (0.09)	0.24 (0.08)	0.27 (0.09)	0.23 (0.08)
after	.03 (0.01)	.03 (0.01)	.05 (0.02)	0.20 (0.07)
Gravel pack:				
before	0.01 (0.003)	0.005 (0.002)	0.002 (0.001)	0.01 (0.003)
after	.04 (0.01)	.02 (0.006)	.02 (0.006)	.01 (0.003)

with the respective test runs on the wire-wound-cage type well screen are summarized as follows:

1. The PVC slotted well screen requires a higher water jet velocity, greater than 15 percent, to erase the wall cake formation when using the high-velocity horizontal water jetting method of well development.

2. The mixing action of the water jet outside the PVC well screen is slightly more efficient in cleaning out the fines; this leaves the gravel pack material slightly coarser.

3. The more efficient jet mixing action appears to be the result of the PVC well screen having fewer vertical supports and longer slots, even though the total intake area is smaller.

4. The degree of clogging of the slots by the high-velocity horizontal water jetting method of well development for both the PVC and the wire-

wound-cage well screens is about the same magnitude.

5. The high-velocity horizontal water jetting method of well development with the PVC slotted well screen installed was not significantly different from the water jetting with the wire-wound-cage well screen.

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APPENDIX

WELL SECTIONAL MODEL TEST DATA (TEST RUNS NO. 3 AND NOS. 5 THROUGH 26)

GLOSSARY OF TERMS

PASS NO. = The number of the jetting tool pass; No. 0 is the initial steady state conditions before the first pass was made.

DATE and TIME = The calendar date and time of day the jet tool pass and steady state scan was made.

DRAW = The drawdown of the hydraulic gradient between piezometer tap No. 3 and 5 (in ft).

YIELD = The volumetric flow measurement of the suction pump during the steady-state scan (in gal/min).

SP. CAP. = The specific capacity of the well sectional model (in gal/min per ft drawdown).

PTAP = The number of the piezometric tap and the measured hydraulic gradient (in ft).

Note: All measurements were made in English units; therefore, only the English units are shown. It is the responsibility of the reader to convert to SI metric if desired.

TEST RUN NO.= 3 GRAVEL PACK THICKNESS= 3.0-INCHES
SCREEN TYPE= WIRE-WOUND, SLOT=0.020-INCHES
AQUIFER AND GRAVEL PACK GRADATION=SA NO.1

PASS NO=	0	1	2	3	4	5	6
DATE =	18AUG83	18AUG83	18AUG83	18AUG83	19AUG83	19AUG83	19AUG83
TIME =	0828	1010	1333	1438	0754	0902	1015
DRAW =	1.0761	1.0856	1.2344	1.2698	1.1148	1.1451	1.2166
YEILD =	2.4261	2.2798	2.3748	2.5095	2.5395	2.5093	2.5824
SP.CAP.=	2.2546	2.1001	1.9238	1.9762	2.2780	2.1914	2.1227
PTAP = 3	6.0262	6.0923	6.1651	6.1426	6.0077	6.0797	6.1356
4	4.9515	5.0075	4.9335	4.8731	4.8922	4.9356	4.9155
5	4.9501	5.0067	4.9307	4.8728	4.8929	4.9346	4.9190
6	4.9501	5.0257	4.9670	4.9021	4.9142	4.9554	4.9285
7	4.9578	5.0350	4.9717	4.9099	4.9193	4.9588	4.9420
8	4.9704	5.0422	4.9831	4.9181	4.9294	4.9731	4.9511
9	5.0188	5.0736	5.0157	4.9564	4.9636	5.0070	4.9879
10	5.1763	5.2170	5.1826	5.1428	5.1543	5.1539	5.1541
11	5.2357	5.2759	5.2534	5.2108	5.1877	5.2356	5.2284
12	5.3393	5.3833	5.3875	5.3415	5.2999	5.3577	5.3605
13	5.4073	5.4607	5.4484	5.4119	5.3549	5.4185	5.4260
14	5.5230	5.5855	5.6151	5.5835	5.5021	5.5707	5.5908
15	5.7379	5.8178	5.8660	5.8317	5.7302	5.8024	5.8406
16	5.9569	6.0306	6.1027	6.0699	5.9416	6.0170	6.0661

TEST RUN NO.= 5 GRAVEL PACK THICKNESS= 3.0-INCHES
SCREEN TYPE= WIRE-WOUND, SLOT=0.020-INCHES
AQUIFER AND GRAVEL PACK GRADATION=SA NO.1

PASS NO=	0	1	2	3	4	5	6	7
DATE =	26SEP83	26SEP83	27SEP83	27SEP83	27SEP83	27SEP83	27SEP83	28SEP83
TIME =	1244	1406	0735	0900	1041	1238	1356	0750
DRAW =	1.0395	0.9965	1.0114	0.9815	1.0035	1.0221	1.0658	1.0168
YEILD =	1.5301	1.3660	1.4178	1.3430	1.3316	1.4178	1.8963	1.9284
SP.CAP.=	1.4719	1.3708	1.4018	1.3683	1.3270	1.3871	1.7792	1.8966
PTAP = 3	5.7875	5.7679	5.7824	5.7778	5.7859	5.7928	5.7813	5.7769
4	4.7495	4.7751	4.7722	4.7924	4.7785	4.7742	4.7102	4.7620
5	4.7480	4.7714	4.7710	4.7963	4.7824	4.7707	4.7155	4.7601
6	4.7512	4.7766	4.7789	4.7934	4.7808	4.7659	4.7329	4.7855
7	4.7555	4.7777	4.7735	4.7942	4.7833	4.7772	4.7260	4.7909
8	4.7633	4.7856	4.7835	4.8025	4.7913	4.7835	4.7459	4.8113
9	5.2139	5.1924	5.1612	5.1461	5.1418	5.1411	4.9188	4.8299
10	5.2122	5.2675	5.2119	5.2443	5.2663	5.1933	4.9946	4.9406
11	5.2563	5.2928	5.2589	5.2829	5.2965	5.2381	5.0431	4.9974
12	5.3275	5.3633	5.3391	5.3572	5.3713	5.3204	5.1661	5.1242
13	5.3647	5.3945	5.3733	5.3900	5.3981	5.3580	5.2105	5.1730
14	5.4045	5.4678	5.4727	5.4797	5.4837	5.4817	5.4267	5.3635
15	5.6050	5.6074	5.6056	5.6100	5.6167	5.5977	5.5293	5.5142
16	5.7394	5.7276	5.7357	5.7288	5.7375	5.7408	5.7142	5.7051

PASS NO=	8	9	10
DATE =	28SEP83	28SEP83	28SEP83
TIME =	1059	1306	1423
DRAW =	1.0091	0.9588	1.0022
YEILD =	1.8700	1.8897	2.0897
SP.CAP.=	1.8531	1.9709	2.0850
PTAP = 3	5.7777	5.7594	5.7898
4	4.8197	4.7902	4.7876
5	4.7686	4.8006	4.7876
6	4.8020	4.8011	4.7976
7	4.7889	4.8117	4.8004
8	4.7964	4.8076	4.8075
9	4.8281	4.8435	4.8400
10	4.9478	4.9687	4.9525
11	4.9909	5.0207	5.0140
12	5.1224	5.1216	5.1330
13	5.1927	5.1758	5.1840
14	5.2493	5.3608	5.3639
15	5.5271	5.5135	5.5282
16	5.7113	5.6962	5.7174

TEST RUN NO.= 6 GRAVEL PACK THICKNESS= 3.0-INCHES
SCREEN TYPE= WIRE-WOUND, SLOT=0.020-INCHES
AQUIFER AND GRAVEL PACK GRADATION=SA NO.1

PASS NO=	0	1	2	3	4	5	6	7
DATE =	20OCT83	20OCT83	20OCT83	20OCT83	21OCT83	21OCT83	21OCT83	21OCT83
TIME =	0755	0920	1129	1348	0758	0910	1036	1250
DRAW =	0.9927	1.0101	1.0072	1.0227	1.0128	1.0084	1.0189	1.0458
YEILD =	1.1679	1.7265	1.6013	1.7737	1.7536	1.8259	1.8708	1.8935
SP.CAP.=	1.1765	1.7093	1.5899	1.7342	1.7314	1.8107	1.8360	1.8106
PTAP = 3	5.7711	5.7637	5.7456	5.7769	5.7748	5.7426	5.7744	5.7962
4	4.7804	4.7715	4.7385	4.7531	4.7629	4.7319	4.7501	4.7522
5	4.7784	4.7736	4.7384	4.7542	4.7620	4.7342	4.7555	4.7504
6	4.7817	4.8701	4.7837	4.7821	4.7873	4.7574	4.7740	4.7655
7	4.7804	4.8722	4.7885	4.7824	4.7900	4.7637	4.7801	4.7721
8	4.7890	4.9019	4.8004	4.7976	4.7969	4.7724	4.7888	4.7906
9	5.1179	4.9119	4.8112	4.8186	4.8050	4.7807	4.7970	4.7966
10	5.1864	5.0583	4.9062	4.9287	4.9177	4.9037	4.9381	4.9102
11	5.2704	5.0585	4.9837	4.9855	4.9861	4.9539	4.9750	4.9770
12	5.3429	5.1424	5.0763	5.1207	5.1003	5.0714	5.0953	5.1001
13	5.4305	5.1994	5.1417	5.1636	5.1681	5.1241	5.1819	5.1940
14	5.4738	5.3247	5.3107	5.3081	5.2996	5.2637	5.2905	5.3002
15	5.6139	5.5462	5.5204	5.5346	5.5341	5.5009	5.5332	5.5426
16	5.7250	5.7210	5.6918	5.7175	5.7138	5.6776	5.7099	5.7277

PASS NO=	8
DATE =	21OCT83
TIME =	1335
DRAW =	1.0270
YEILD =	1.8580
SP.CAP.=	1.8091
PTAP = 3	5.7796
4	4.7592
5	4.7526
6	4.7653
7	4.7712
8	4.7836
9	4.7904
10	4.9133
11	4.9737
12	5.0979
13	5.1581
14	5.2920
15	5.5317
16	5.7152

TEST RUN NO.= 7 GRAVEL PACK THICKNESS= 3.0-INCHES
SCREEN TYPE= WIRE-WOUND, SLOT=0.020-INCHES
AQUIFER AND GRAVEL PACK GRADATION=SA NO.1

PASS NO=	0	1	2	3	4	5	6	7
DATE =	1NOV83	1NOV83	1NOV83	1NOV83	1NOV83	2NOV83	2NOV83	2NOV83
TIME =	0733	0916	1037	1236	1406	0726	0916	1042
DRAW =	1.0183	1.0229	1.0199	1.0411	1.0131	1.0181	1.0394	1.0102
YEILD =	1.1297	1.2954	1.3807	1.4116	1.3537	1.4157	1.4375	1.3954
SP.CAP.=	1.1094	1.2663	1.3538	1.3558	1.3362	1.3905	1.3830	1.3814
PTAP = 3	5.7884	5.7911	5.7678	5.7899	5.7723	5.7689	5.7781	5.7473
4	4.7705	4.7743	4.7471	4.7498	4.7586	4.7491	4.7435	4.7340
5	4.7701	4.7682	4.7479	4.7488	4.7592	4.7508	4.7388	4.7371
6	4.7727	4.7779	4.7845	4.7994	4.7849	4.7786	4.7639	4.7714
7	4.7735	4.7931	4.7917	4.8145	4.7892	4.7820	4.7635	4.7715
8	4.8015	4.8502	4.8223	4.8104	4.8270	4.8067	4.7956	4.8131
9	5.0397	4.9317	4.8387	4.8390	4.8322	4.8382	4.8442	4.8559
10	5.2210	5.0258	4.9061	4.9406	4.9202	4.8963	4.9315	4.9379
11	5.3014	5.1225	4.9941	4.9961	5.0043	4.9862	4.9825	4.9883
12	5.3251	5.2025	5.1326	5.1544	5.1484	5.1311	5.1307	5.1231
13	5.3655	5.2565	5.1908	5.2134	5.2074	5.1905	5.1895	5.1792
14	5.4664	5.3893	5.3377	5.3527	5.3486	5.3342	5.3346	5.3189
15	5.6132	5.5861	5.5495	5.5707	5.5582	5.5468	5.5569	5.5390
16	5.7425	5.7402	5.7194	5.7415	5.7206	5.7140	5.7236	5.7020

TEST RUN NO.= 8 GRAVEL PACK THICKNESS= 6.0-INCHES
SCREEN TYPE= WIRE-WOUND, SLOT=0.020-INCHES
AQUIFER AND GRAVEL PACK GRADATION=SA NO.1

PASS NO=	0	1	2	3	4	5	6	7
DATE =	5DEC83	5DEC83	5DEC83	5DEC83	6DEC83	6DEC83	6DEC83	6DEC83
TIME =	0835	1007	1118	1322	0728	0831	0925	1026
DRAW =	1.0329	1.0086	1.0271	1.0150	1.0194	1.0260	1.0124	1.0218
YEILD =	1.0458	1.3359	1.4260	1.4660	1.5810	1.5009	1.5498	1.5651
SP.CAP.=	1.0126	1.3246	1.3884	1.4443	1.5510	1.4629	1.5309	1.5317
PTAP = 3	5.7885	5.7862	5.7748	5.7578	5.7719	5.7714	5.7505	5.7797
4	4.7568	4.7766	4.7500	4.7412	4.7510	4.7438	4.7391	4.7595
5	4.7557	4.7777	4.7477	4.7428	4.7525	4.7454	4.7381	4.7579
6	4.7575	4.7915	4.7649	4.7570	4.7700	4.7600	4.7544	4.7755
7	4.7617	4.7991	4.7708	4.7613	4.7746	4.7680	4.7597	4.7789
8	4.7654	4.8111	4.7803	4.7743	4.7811	4.7744	4.7621	4.7870
9	4.7731	4.8150	4.7993	4.7788	4.8026	4.7963	4.7703	4.7918
10	4.8436	4.8402	4.8030	4.7884	4.7985	4.7953	4.7736	4.8100
11	5.1367	4.9093	4.8183	4.8034	4.8195	4.8070	4.7985	4.8292
12	5.2501	5.0606	4.9633	4.9210	4.9367	4.9378	4.9313	4.9563
13	5.2921	5.1298	5.0596	5.0246	5.0365	5.0395	5.0324	5.0574
14	5.4096	5.2841	5.2494	5.2240	5.2309	5.2313	5.2179	5.2457
15	5.6021	5.5403	5.5147	5.4964	5.5022	5.4959	5.4831	5.5096
16	5.7532	5.7352	5.7219	5.7037	5.7140	5.7123	5.6900	5.7175

TEST RUN NO.= 9 GRAVEL PACK THICKNESS= 9.0-INCHES
SCREEN TYPE= WIRE-WOUND, SLOT=0.020-INCHES
AQUIFER AND GRAVEL PACK GRADATION=SA NO.1

PASS NO=	0	1	2	3	4
DATE =	6FEB84	6FEB84	6FEB84	6FEB84	6FEB84
TIME =	0841	1000	1128	1331	1433
DRAW =	1.0092	1.0016	1.0315	1.0172	1.0290
YEILD =	1.7085	1.6346	1.6972	1.6494	1.7208
SP.CAP.=	1.6928	1.6320	1.6454	1.6215	1.6723
PTAP = 3	5.7473	5.7506	5.7699	5.7619	5.7745
4	4.7349	4.7479	4.7370	4.7444	4.7459
5	4.7380	4.7490	4.7385	4.7447	4.7456
6	4.7413	4.7612	4.7486	4.7539	4.7582
7	4.7447	4.7576	4.7512	4.7589	4.7620
8	4.7562	4.7690	4.7574	4.7660	4.7676
9	4.7599	4.7686	4.7666	4.7712	4.7732
10	4.7689	4.7798	4.7678	4.7745	4.7803
11	4.7711	4.7831	4.7713	4.7774	4.7806
12	4.7789	4.7845	4.7795	4.7837	4.7881
13	4.8852	4.9282	4.9280	4.9212	4.9255
14	5.0684	5.1044	5.1345	5.0995	5.1947
15	5.4549	5.4643	5.4650	5.4795	5.4688
16	5.6722	5.6829	5.7046	5.6891	5.7025

TEST RUN NO.= 10 GRAVEL PACK THICKNESS= 6.0-INCHES
SCREEN TYPE= WIRE-WOUND, SLOT=0.020-INCHES
AQUIFER AND GRAVEL PACK GRADATION=SA NO.1

PASS NO=	0	1	2	3	4	5	6	7
DATE =	7MAR84	7MAR84	7MAR84	7MAR84	7MAR84	8MAR84	8MAR84	8MAR84
TIME =	0742	0844	1009	1131	1357	0816	1028	1141
DRAW =	1.0194	1.0226	1.0149	1.0548	1.0367	1.0216	1.0261	1.0183
YEILD =	0.9843	1.1080	1.2095	1.1957	1.2077	1.2212	1.2688	1.2157
SP.CAP.=	0.9655	1.0834	1.1918	1.1335	1.1650	1.1955	1.2365	1.1939
PTAP = 3	5.7598	5.7605	5.7481	5.7792	5.7624	5.7770	5.7650	5.7467
4	4.7512	4.7504	4.7293	4.7252	4.7252	4.7541	4.7356	4.7202
5	4.7404	4.7379	4.7332	4.7244	4.7257	4.7555	4.7389	4.7284
6	4.7495	4.7813	4.7802	4.7524	4.7513	4.7753	4.7576	4.7411
7	4.7564	4.7629	4.7801	4.7604	4.7372	4.7785	4.7575	4.7357
8	4.7867	4.7821	4.7730	4.7559	4.7583	4.7819	4.7590	4.7469
9	4.7673	4.7812	4.7754	4.7707	4.7739	4.7856	4.7739	4.7474
10	4.8296	4.8091	4.8010	4.8075	4.7682	4.8021	4.7824	4.7721
11	5.0991	4.9640	4.8522	4.8308	4.8061	4.8223	4.8020	4.7855
12	5.2275	5.1117	4.8116	4.9281	4.9244	4.9326	4.8952	4.8726
13	5.2636	5.2165	4.9921	4.9936	5.0084	5.0055	4.9814	4.9635
14	5.4495	5.3567	5.1566	5.1387	5.1983	5.1957	5.2973	5.2908
15	5.5377	5.4848	5.4541	5.4720	5.4449	5.4795	5.4669	5.4486
16	5.6987	5.6843	5.6680	5.7013	5.6844	5.6985	5.6865	5.6620

TEST RUN NO.= 11   GRAVEL PACK THICKNESS= 6.0-INCHES
SCREEN TYPE= WIRE-WOUND,   SLOT=0.020-INCHES
AQUIFER AND GRAVEL PACK GRADATION=SA NO.1

PASS NO=	0	1	2	3	4	5	6	7
DATE =	19MAR84	19MAR84	19MAR84	19MAR84	19MAR84	20MAR84	20MAR84	20MAR84
TIME =	0735	0848	1007	1111	1312	0828	1002	1058
DRAW =	1.0058	1.0034	0.9890	1.0043	1.0157	1.0323	1.0331	1.0262
YEILD =	1.0617	1.2489	1.2744	1.2644	1.3108	1.3575	1.3560	1.3495
SP.CAP.=	1.0556	1.2447	1.2886	1.2590	1.2905	1.3150	1.3125	1.3151
PTAP = 3	5.7418	5.7428	5.7569	5.7390	5.7652	5.7877	5.7872	5.7785
4	4.7355	4.7391	4.7703	4.7351	4.7524	4.7562	4.7547	4.7532
5	4.7359	4.7394	4.7678	4.7347	4.7495	4.7554	4.7541	4.7524
6	4.7383	4.7483	4.7790	4.7452	4.7666	4.7561	4.7603	4.7687
7	4.7419	4.7508	4.7845	4.7489	4.7660	4.7673	4.7652	4.7636
8	4.7516	4.7610	4.7910	4.7550	4.7717	4.7734	4.7703	4.7690
9	4.7502	4.7654	4.7946	4.7560	4.7736	4.7772	4.7725	4.7697
10	4.7655	4.8174	4.7930	4.7648	4.7816	4.7845	4.7846	4.7794
11	4.9315	4.8460	4.8500	4.7895	4.8021	4.8089	4.8080	4.8075
12	5.0577	4.9552	4.9711	4.9330	4.9543	4.9544	4.9545	4.9536
13	5.1161	5.0265	5.0410	5.0068	5.0270	5.0302	5.0283	5.0256
14	5.2586	5.1906	5.2069	5.1763	5.2006	5.2000	5.2007	5.1959
15	5.4750	5.4554	5.4671	5.4351	5.4569	5.4688	5.4637	5.4581
16	5.6777	5.6720	5.6831	5.6613	5.6831	5.6933	5.6860	5.6774

TEST RUN NO.= 12   GRAVEL PACK THICKNESS= 3.0-INCHES
SCREEN TYPE= WIRE-WOUND,   SLOT=0.020-INCHES
AQUIFER AND GRAVEL PACK GRADATION=SA NO.1

PASS NO=	0	1	2	3	4	5	6	7
DATE =	29MAR84	29MAR84	29MAR84	29MAR84	29MAR84	30MAR84	30MAR84	30MAR84
TIME =	0757	0900	1052	1229	1358	0820	0922	1058
DRAW =	1.0271	1.0428	1.0091	1.0315	1.0131	1.0283	1.0130	1.0243
YEILD =	0.8428	0.9488	1.0319	1.0129	1.0096	1.0265	1.0379	1.0483
SP.CAP.=	0.8206	0.9098	1.0226	0.9819	0.9965	0.9983	1.0247	1.0234
PTAP = 3	5.7845	5.7809	5.7623	5.7782	5.7545	5.7778	5.7578	5.7771
4	4.7586	4.7391	4.7479	4.7473	4.7410	4.7461	4.7440	4.7495
5	4.7575	4.7381	4.7532	4.7467	4.7414	4.7495	4.7449	4.7528
6	4.7599	4.7518	4.7613	4.7619	4.7566	4.7648	4.7541	4.7581
7	4.7650	4.7516	4.7637	4.7602	4.7548	4.7610	4.7569	4.7581
8	4.7674	4.7583	4.7738	4.7653	4.7568	4.7688	4.7579	4.7678
9	4.9984	4.8692	4.7915	4.7729	4.7695	4.7713	4.7655	4.7717
10	5.1475	5.0369	4.9666	4.9663	4.9603	4.9657	4.9533	4.9647
11	5.1956	5.0866	5.0237	5.0219	5.0167	5.0173	5.0097	5.0191
12	5.2731	5.1922	5.1390	5.1364	5.1276	5.1330	5.1221	5.1359
13	5.3061	5.2342	5.1836	5.1895	5.1656	5.1814	5.1677	5.1832
14	5.4179	5.3468	5.3075	5.3114	5.2985	5.3115	5.2958	5.3082
15	5.5932	5.5578	5.5252	5.5347	5.5171	5.5317	5.5168	5.5347
16	5.7445	5.7205	5.7046	5.7104	5.6924	5.7128	5.6910	5.7024

TEST RUN NO.= 13 GRAVEL PACK THICKNESS= 3.0-INCHES
SCREEN TYPE= WIRE-WOUND, SLOT=0.020-INCHES
AQUIFER AND GRAVEL PACK GRADATION=SA NO.1

PASS NO=	0	1	2	3	4	5	6	7
DATE =	9APR84	9APR84	9APR84	9APR84	9APR84	10APR84	10APR84	10APR84
TIME =	0742	0844	1007	1105	1315	0824	0956	1111
DRAW =	1.0282	1.0220	1.0176	1.0376	1.0144	1.0203	1.0419	0.9914
YEILD =	0.9335	1.0797	1.0797	1.1224	1.0811	1.1390	1.1404	1.1178
SP.CAP.=	0.9079	1.0565	1.0611	1.0818	1.0657	1.1163	1.0945	1.1275
PTAP = 3	5.7790	5.7812	5.7649	5.7766	5.7381	5.7616	5.7762	5.7558
4	4.7560	4.7585	4.7440	4.7301	4.7266	4.7419	4.7359	4.7642
5	4.7509	4.7592	4.7474	4.7391	4.7237	4.7412	4.7343	4.7644
6	4.7480	4.7693	4.7525	4.7489	4.7352	4.7538	4.7499	4.7771
7	4.7459	4.7712	4.7511	4.7535	4.7356	4.7486	4.7422	4.7767
8	4.7551	4.7741	4.7624	4.7479	4.7449	4.7559	4.7569	4.7753
9	4.9145	4.8341	4.7835	4.7738	4.7644	4.7791	4.7678	4.8040
10	5.0568	4.9792	4.9415	4.9371	4.9253	4.9413	4.9391	4.9612
11	5.0958	5.0314	4.9940	4.9855	4.9754	4.9797	4.9911	5.0075
12	5.1905	5.1495	5.1226	5.1164	5.0956	5.1091	5.1153	5.1270
13	5.2353	5.2230	5.2112	5.1711	5.1521	5.1667	5.1658	5.1820
14	5.3515	5.3405	5.2998	5.3015	5.2959	5.2970	5.2978	5.3003
15	5.5626	5.5523	5.5284	5.5308	5.5047	5.5309	5.5322	5.5265
16	5.7313	5.7315	5.7077	5.7204	5.6814	5.7112	5.7117	5.6984

TEST RUN NO.= 14 GRAVEL PACK THICKNESS= 6.0-INCHES
SCREEN TYPE= WIRE-WOUND, SLOT=0.020-INCHES
AQUIFER AND GRAVEL PACK GRADATION=SA NO.1

PASS NO=	0	1
DATE =	26APR84	26APR84
TIME =	0739	1034
DRAW =	1.0106	1.0432
YEILD =	1.2898	1.6735
SP.CAP.=	1.2763	1.6041
PTAP = 3	5.7500	5.7801
4	4.7410	4.7370
5	4.7395	4.7368
6	4.7456	4.7493
7	4.7482	4.7485
8	4.7538	4.7826
9	4.7597	4.7914
10	4.7645	4.7961
11	5.0324	4.9029
12	5.1844	4.9952
13	5.2588	5.0924
14	5.3880	5.2987
15	5.5570	5.5316
16	5.7053	5.7221

TEST RUN NO.= 15 GRAVEL PACK THICKNESS= 3.0-INCHES
SCREEN TYPE= WIRE-WOUND, SLOT=0.020-INCHES
AQUIFER AND GRAVEL PACK GRADATION=SA NO.1 1/

PASS NO=	0	1	2	3	4	5
DATE =	8MAY84	8MAY84	8MAY84	8MAY84	8MAY84	8MAY84
TIME =	0754	0909	1038	1135	1322	1431
DRAW =	1.0296	0.9866	1.0360	1.0220	1.0426	0.9989
YEILD =	1.2556	1.2543	1.2721	1.2210	1.3351	1.2510
SP.CAP.=	1.2195	1.2714	1.2279	1.1948	1.2805	1.2524
PTAP = 3	5.7513	5.7185	5.7676	5.7685	5.7772	5.7447
4	4.7233	4.7329	4.7346	4.7442	4.7384	4.7517
5	4.7216	4.7320	4.7316	4.7466	4.7346	4.7458
6	4.7223	4.7338	4.7379	4.7489	4.7406	4.7520
7	4.7216	4.7334	4.7396	4.7505	4.7424	4.7542
8	4.7411	4.7324	4.7364	4.7527	4.7454	4.7596
9	5.0345	4.8069	4.8100	4.8110	4.7994	4.8153
10	5.1160	4.9431	4.9071	4.9281	4.9093	4.9640
11	5.1670	5.0152	5.0269	5.0404	5.0323	5.0306
12	5.2512	5.1423	5.1672	5.1691	5.1680	5.1581
13	5.2802	5.2070	5.2247	5.2192	5.2320	5.2115
14	5.3998	5.3205	5.3512	5.3562	5.3589	5.3417
15	5.5574	5.5077	5.5494	5.5517	5.5544	5.5325
16	5.7146	5.6768	5.7257	5.7241	5.7331	5.7002

1/ Gravel pack gradation equivalent to SA No. 2 materials. Refer to text - Special Test Runs.

TEST RUN NO.= 16 GRAVEL PACK THICKNESS= 6.0-INCHES
SCREEN TYPE= WIRE-WOUND, SLOT=0.040-INCHES
AQUIFER AND GRAVEL PACK GRADATION=SA NO.2

PASS NO=	0	1	2	3	4	5	6	7
DATE =	22MAY84	22MAY84	22MAY84	22MAY84	22MAY84	22MAY84	22MAY84	22MAY84
TIME =	0843	0948	1050	1237	1357	0824	1000	1057
DRAW =	0.9912	1.0627	1.0326	1.0310	1.0269	1.0824	1.0355	1.0212
YEILD =	1.7119	1.9650	1.8580	1.9987	2.0117	2.1648	2.2368	2.2283
SP.CAP.=	1.7271	1.8490	1.7993	1.9386	1.9589	1.9999	2.1601	2.1821
PTAP = 3	5.7369	5.7998	5.7785	5.7833	5.7721	5.8284	5.7516	5.7715
4	4.7411	4.7365	4.7410	4.7584	4.7339	4.7533	4.7423	4.7454
5	4.7457	4.7371	4.7459	4.7523	4.7452	4.7459	4.7160	4.7503
6	4.7356	4.7332	4.7503	4.7499	4.7590	4.7646	4.7373	4.7557
7	4.7269	4.7450	4.7453	4.7529	4.7250	4.7617	4.7537	4.7699
8	4.7488	4.7429	4.7507	4.7533	4.7612	4.7623	4.7515	4.7672
9	4.7436	4.7562	4.7552	4.7555	4.7606	4.7781	4.7515	4.7574
10	4.7486	4.7407	4.7523	4.7852	4.7638	4.7889	4.7759	4.7746
11	5.0141	4.9951	4.9932	5.0179	4.9498	4.8987	4.8667	4.8750
12	5.1031	5.1027	5.1052	5.1315	5.0898	5.0752	5.0421	5.0426
13	5.1759	5.1749	5.1755	5.1758	5.1445	5.1325	5.0948	5.1015
14	5.3267	5.3276	5.3292	5.3341	5.2873	5.2701	5.2509	5.2509
15	5.5400	5.5649	5.5764	5.5780	5.5514	5.5662	5.5374	5.5421
16	5.6932	5.7330	5.7412	5.7336	5.7210	5.7315	5.7290	5.7182

TEST RUN NO.= 17 GRAVEL PACK THICKNESS= 6.0-INCHES
SCREEN TYPE= WIRE-WOUND, SLOT=0.040-INCHES
AQUIFER AND GRAVEL PACK GRADATION=SA NO.2

PASS NO=	0	1	2	3	4	5	6	7
DATE =	6JUN84	6JUN84	6JUN84	6JUN84	6JUN84	4JUN84	4JUN84	4JUN84
TIME =	0740	0907	1040	1139	1349	0847	1006	1106
DRAW =	1.0360	1.0328	1.0428	1.0340	1.0276	1.0072	1.0620	1.0505
YEILD =	1.8368	2.0832	2.1323	2.1175	2.0831	2.3411	2.4341	2.5066
SP.CAP.=	1.7730	2.0171	2.0448	2.0479	2.0271	2.3244	2.2919	2.3861
PTAP = 3	5.7619	5.7632	5.7760	5.7693	5.7578	5.7384	5.7802	5.7820
4	4.7248	4.7234	4.7319	4.7389	4.7291	4.7283	4.7167	4.7294
5	4.7259	4.7304	4.7332	4.7354	4.7301	4.7313	4.7182	4.7315
6	4.7359	4.7401	4.7415	4.7473	4.7429	4.7366	4.7310	4.7366
7	4.7232	4.7374	4.7439	4.7464	4.7368	4.7382	4.7306	4.7402
8	4.7265	4.7433	4.7458	4.7543	4.7441	4.7427	4.7292	4.7403
9	4.7293	4.7480	4.7642	4.7562	4.7477	4.7456	4.7331	4.7454
10	5.7243	5.6520	5.6250	5.5629	5.4542	5.4534	5.5476	5.4884
11	4.9681	4.8475	4.7919	4.7918	4.7832	4.7765	4.7725	4.7738
12	5.0557	4.9289	4.9179	4.9229	4.9072	4.9012	4.8972	4.8986
13	5.1241	5.0305	5.0062	5.0020	4.9788	4.9681	4.9705	4.9652
14	5.2827	5.2100	5.2119	5.1944	5.1842	5.1641	5.1685	5.1693
15	5.5237	5.4997	5.5055	5.4989	5.4860	5.4620	5.4925	5.4839
16	5.7196	5.7196	5.7335	5.7227	5.7100	5.6868	5.7231	5.7222

TEST RUN NO.= 18 GRAVEL PACK THICKNESS= 3.0-INCHES
SCREEN TYPE= WIRE-WOUND, SLOT=0.040-INCHES
AQUIFER AND GRAVEL PACK GRADATION=SA NO.2

PASS NO=	0	1	2	3	4	5	6	7
DATE =	15JUN84	15JUN84	15JUN84	15JUN84	15JUN84	18JUN84	18JUN84	18JUN84
TIME =	0740	0908	1049	1235	1343	0856	1041	1138
DRAW =	1.0212	1.0407	1.0542	1.0477	1.0492	1.0576	1.0546	1.0362
YEILD =	1.2190	1.4361	1.5214	1.5410	1.5589	1.7778	1.7877	1.7062
SP.CAP.=	1.1937	1.3799	1.4433	1.4709	1.4858	1.6809	1.6952	1.6466
PTAP = 3	5.7361	5.7775	5.7795	5.7768	5.7784	5.7819	5.7787	5.7713
4	4.7164	4.7354	4.7415	4.7310	4.7314	4.7275	4.7315	4.7336
5	4.7149	4.7368	4.7254	4.7292	4.7291	4.7242	4.7241	4.7351
6	4.7157	4.7409	4.7449	4.7403	4.7428	4.7453	4.7450	4.7499
7	4.7172	4.7476	4.7573	4.7424	4.7443	4.7343	4.7572	4.7561
8	4.7203	4.7463	4.7579	4.7634	4.7681	4.7649	4.7831	4.8019
9	5.0282	4.8782	4.7979	4.8302	4.7866	4.7980	4.8080	4.8285
10	5.1425	4.8938	4.8864	4.9181	4.8526	4.8931	4.9096	4.9195
11	5.1826	4.9840	4.9192	4.9433	4.9425	4.9411	4.9493	4.9600
12	5.2519	5.1077	5.0713	5.0854	5.0795	5.0664	5.0847	5.0904
13	5.2925	5.1635	5.1404	5.1628	5.1521	5.1392	5.1446	5.1557
14	5.3973	5.3125	5.3040	5.3087	5.3074	5.2987	5.2981	5.3142
15	5.5694	5.5624	5.5487	5.5534	5.5556	5.5524	5.5538	5.5556
16	5.7006	5.7313	5.7255	5.7319	5.7274	5.7310	5.7290	5.7143

TEST RUN NO.= 19 GRAVEL PACK THICKNESS= 3.0-INCHES
SCREEN TYPE= WIRE-WOUND, SLOT=0.040-INCHES
AQUIFER AND GRAVEL PACK GRADATION=SA NO.2

PASS NO=	0	1	2	3	4	5	6	7
DATE =	26JUL84	26JUL84	26JUL84	26JUL84	26JUL84	27JUL84	27JUL84	27JUL84
TIME =	0739	0834	1024	1133	1326	0827	0949	1057
DRAW =	1.0186	1.0417	1.0311	1.0334	1.0398	1.0305	1.0418	1.0403
YEILD =	1.2932	1.6629	1.6431	1.6796	1.6636	1.6296	1.7654	1.7325
SP.CAP.=	1.2696	1.5964	1.5935	1.6252	1.6000	1.5814	1.6946	1.6654
PTAP = 3	5.7591	5.7804	5.7675	5.7757	5.7726	5.7758	5.7814	5.7780
4	4.7431	4.7387	4.7382	4.7410	4.7320	4.7469	4.7346	4.7413
5	4.7405	4.7388	4.7364	4.7423	4.7328	4.7454	4.7396	4.7377
6	4.7430	4.7493	4.7404	4.7522	4.7518	4.7579	4.7473	4.7519
7	4.7450	4.7580	4.7471	4.7560	4.7507	4.7596	4.7460	4.7603
8	4.7540	4.7609	4.7660	4.7825	4.7798	4.7971	4.7807	4.7820
9	5.0619	4.8179	4.8315	4.8260	4.8045	4.8062	4.7968	4.8076
10	5.1458	4.9000	4.9014	4.9012	4.8876	4.8983	4.8992	4.9058
11	5.1894	5.0364	4.9612	4.9575	4.9666	4.9525	4.9493	4.9659
12	5.2769	5.1501	5.0896	5.1040	5.0851	5.0882	5.0778	5.0967
13	5.3530	5.2514	5.1779	5.1664	5.1608	5.1541	5.1569	5.1623
14	5.5088	5.4540	5.3498	5.3656	5.3837	5.3616	5.3953	5.3965
15	5.5951	5.5455	5.5481	5.5564	5.5589	5.5531	5.5589	5.5613
16	5.7217	5.7331	5.7234	5.7305	5.7351	5.7277	5.7277	5.7329

TEST RUN NO.= 20 GRAVEL PACK THICKNESS= 3.0-INCHES
SCREEN TYPE= WIRE-WOUND, SLOT=0.040-INCHES
AQUIFER AND GRAVEL PACK GRADATION=SA NO.2

PASS NO=	0	1	2	3	4	5	6	7
DATE =	7AUG84	7AUG84	7AUG84	7AUG84	7AUG84	8AUG84	8AUG84	8AUG84
TIME =	0734	0835	0953	1101	1332	0829	1006	1057
DRAW =	1.0192	1.0355	1.0342	1.0443	1.0348	1.0435	1.0169	1.0215
YEILD =	1.1511	1.3761	1.4268	1.4076	1.4213	1.5395	1.4542	1.4697
SP.CAP.=	1.1294	1.3289	1.3797	1.3478	1.3735	1.4754	1.4300	1.4387
PTAP = 3	5.7505	5.7673	5.7707	5.7699	5.7643	5.7805	5.7528	5.7698
4	4.7323	4.7333	4.7356	4.7292	4.7320	4.7389	4.7372	4.7463
5	4.7313	4.7318	4.7365	4.7256	4.7295	4.7370	4.7359	4.7483
6	4.7336	4.7341	4.7476	4.7375	4.7398	4.7422	4.7486	4.7524
7	4.7338	4.7420	4.7446	4.7463	4.7431	4.7481	4.7402	4.7558
8	4.7374	4.7481	4.7615	4.7510	4.7496	4.7559	4.7493	4.7634
9	5.0328	4.8764	4.8025	4.7762	4.7633	4.7591	4.7699	4.7715
10	5.1491	4.9735	4.9793	4.9697	4.9642	4.9492	4.9470	4.9546
11	5.1849	5.0535	5.0148	5.0267	5.0159	5.0070	5.0025	5.0151
12	5.2725	5.1895	5.1609	5.1641	5.1605	5.1443	5.1433	5.1558
13	5.3333	5.2416	5.2210	5.2229	5.2192	5.2158	5.2160	5.2206
14	5.4234	5.3538	5.3367	5.3425	5.3390	5.3431	5.3294	5.3460
15	5.5904	5.5592	5.5629	5.5487	5.5607	5.5596	5.5372	5.5546
16	5.7188	5.7271	5.7296	5.7256	5.7240	5.7383	5.7088	5.7321

TEST RUN NO.= 21 GRAVEL PACK THICKNESS= 9.0-INCHES
SCREEN TYPE= WIRE-WOUND, SLOT=0.040-INCHES
AQUIFER AND GRAVEL PACK GRADATION=SA NO.2

PASS NO=	0	1	2	3	4	5 1/
DATE =	20AUG84	20AUG84	20AUG84	20AUG84	20AUG84	21AUG84
TIME =	0733	0837	0954	1100	1332	0731
DRAW =	1.0309	1.0417	1.0134	1.0329	1.0183	1.0253
YEILD =	1.3888	1.9154	1.8542	1.9452	1.9063	1.9722
SP.CAP.=	1.3472	1.8387	1.8297	1.8833	1.8720	1.9234
PTAP = 3	5.7694	5.7761	5.7474	5.7809	5.7690	5.7630
4	4.7391	4.7320	4.7358	4.7302	4.7408	4.7304
5	4.7385	4.7344	4.7340	4.7480	4.7507	4.7377
6	4.7414	4.7433	4.7342	4.7445	4.7454	4.7328
7	4.7395	4.7450	4.7502	4.7393	4.7458	4.7348
8	4.7403	4.7441	4.7390	4.7409	4.7492	4.7363
9	4.7402	4.7452	4.7405	4.7440	4.7473	4.7363
10	4.7439	4.7554	4.7475	4.7464	4.7525	4.7403
11	4.7459	4.7557	4.7474	4.7491	4.7518	4.7414
12	4.7482	4.7548	4.7524	4.7549	4.7567	4.7453
13	4.9363	4.9841	4.9815	5.0115	5.0434	5.0327
14	5.2648	5.2348	5.2347	5.2564	5.2768	5.2686
15	5.5131	5.5262	5.5113	5.5266	5.5256	5.5265
16	5.7204	5.7234	5.6979	5.7231	5.7148	5.7090

1/ Jet tool pass was not made - steady state scan only.

TEST RUN NO.= 22 GRAVEL PACK THICKNESS= 9.0-INCHES
SCREEN TYPE= WIRE-WOUND, SLOT=0.040-INCHES
AQUIFER AND GRAVEL PACK GRADATION=SA NO.2

PASS NO=	0	1	2	3	4	5	6	7
DATE =	8NOV84	8NOV84	8NOV84	8NOV84	9NOV84	9NOV84	9NOV84	9NOV84
TIME =	0832	1042	1242	1359	0743	1035	1231	1403
DRAW =	1.0050	1.0373	1.0150	1.0299	1.0239	1.0396	1.0536	1.0499
YEILD =	3.1070	3.1690	3.1289	3.1453	3.2185	3.3021	3.3193	3.3339
SP.CAP.=	3.0915	3.0552	3.0826	3.0541	3.1433	3.1763	3.1504	3.1755
PTAP = 3	5.7355	5.7672	5.7501	5.7584	5.7549	5.7666	5.7835	5.7784
4	4.7245	4.7283	4.7308	4.7315	4.7289	4.7254	4.7298	4.7267
5	4.7305	4.7299	4.7350	4.7285	4.7309	4.7270	4.7298	4.7286
6	4.7309	4.7282	4.7294	4.7309	4.7283	4.7294	4.7323	4.7282
7	4.7319	4.7332	4.7294	4.7323	4.7318	4.7294	4.7308	4.7317
8	4.7359	4.7360	4.7381	4.7375	4.7393	4.7352	4.7396	4.7375
9	4.7382	4.7383	4.7406	4.7385	4.7381	4.7384	4.7364	4.7406
10	4.7432	4.7416	4.7431	4.7439	4.7379	4.7446	4.7401	4.7411
11	4.7488	4.7429	4.7424	4.7418	4.7514	4.7445	4.7436	4.7463
12	4.7509	4.7480	4.7515	4.7493	4.7532	4.7497	4.7480	4.7463
13	4.8695	4.8958	4.8818	4.8808	4.8687	4.8732	4.8742	4.8699
14	5.0971	5.1618	5.1077	5.1217	5.1020	5.1081	5.1104	5.1092
15	5.4057	5.4286	5.4155	5.4230	5.4117	5.4318	5.4348	5.4283
16	5.6554	5.6903	5.6741	5.6791	5.6656	5.6979	5.6982	5.6907

PASS NO=	8	9 1/	10	11	12
DATE =	13NOV84	13NOV84	13NOV84	13NOV84	13NOV84
TIME =	0740	1004	1122	1253	1400
DRAW =	1.0392	1.0480	1.0303	1.0575	1.0594
YEILD =	3.4672	3.5336	3.4760	3.3803	3.4734
SP.CAP.=	3.3364	3.3716	3.3739	3.1966	3.2787
PTAP = 3	5.7684	5.7746	5.7687	5.7713	5.7812
4	4.7213	4.7355	4.7377	4.7117	4.7339
5	4.7292	4.7266	4.7384	4.7138	4.7218
6	4.7248	4.7415	4.7514	4.7283	4.7288
7	4.7275	4.7453	4.7356	4.7337	4.7360
8	4.7346	4.7363	4.7508	4.7394	4.7406
9	4.7404	4.7364	4.7426	4.7388	4.7463
10	4.7414	4.7406	4.7545	4.7436	4.7467
11	4.7446	4.7446	4.7414	4.7413	4.7463
12	4.7449	4.7499	4.7323	4.7520	4.7508
13	4.8740	4.8568	4.8558	4.8634	4.8604
14	5.0724	5.0784	5.0839	5.0702	5.0878
15	5.4039	5.4075	5.4039	5.4004	5.3993
16	5.6802	5.6886	5.6682	5.6661	5.6712

1/ Jet tool pass was made between No. 8 and No. 9. All other pass Nos. are steady state scans only. Refer to text - Special Test Runs.

TEST RUN NO.= 23 GRAVEL PACK THICKNESS= 6.0-INCHES
SCREEN TYPE= WIRE-WOUND, SLOT=0.040-INCHES
AQUIFER AND GRAVEL PACK GRADATION=SA NO.2

PASS NO=	0	1	2	3	4	5	6	7
DATE =	29NOV84	29NOV84	29NOV84	29NOV84	30NOV84	30NOV84	30NOV84	30NOV84
TIME =	0716	1051	1242	1403	0746	1008	1235	1408
DRAW =	1.0485	1.0409	0.9898	1.0213	1.0205	1.0468	1.0254	1.0504
YEILD =	2.3481	2.2977	2.1681	2.1702	2.2103	2.2859	2.2383	2.2677
SP.CAP.=	2.2393	2.2074	2.1904	2.1249	2.1658	2.1837	2.1829	2.1588
PTAP = 3	5.7777	5.7756	5.7350	5.7544	5.7552	5.7752	5.7601	5.7787
4	4.7272	4.7267	4.7349	4.7319	4.7244	4.7272	4.7332	4.7279
5	4.7291	4.7347	4.7452	4.7331	4.7347	4.7283	4.7348	4.7283
6	4.7277	4.7262	4.7260	4.7389	4.7297	4.7307	4.7317	4.7329
7	4.7243	4.7309	4.7373	4.7309	4.7270	4.7335	4.7375	4.7339
8	4.7252	4.7444	4.7379	4.7439	4.7340	4.7367	4.7359	4.7379
9	4.7280	4.7365	4.7453	4.7397	4.7442	4.7378	4.7359	4.7377
10	4.7420	4.7459	4.7505	4.7499	4.7499	4.7487	4.7426	4.7440
11	4.9175	4.9305	4.9276	4.9301	4.9391	4.9275	4.9266	4.9291
12	5.0955	5.1190	5.1104	5.1095	5.1058	5.1156	5.1013	5.1255
13	5.1609	5.1783	5.1752	5.1700	5.1623	5.1751	5.1541	5.1816
14	5.2822	5.3027	5.2775	5.2990	5.2942	5.3126	5.3063	5.3175
15	5.4925	5.5088	5.4832	5.5077	5.5087	5.5229	5.5110	5.5291
16	5.7014	5.7111	5.6855	5.6943	5.6967	5.7100	5.6893	5.7190

PASS NO=	8	9 1/	10	11	12
DATE =	3DEC84	3DEC84	3DEC84	3DEC84	3DEC84
TIME =	0740	0908	1108	1236	1406
DRAW =	1.0517	1.0192	1.0559	1.0441	1.0484
YEILD =	2.4650	2.4717	2.4797	2.4162	2.3990
SP.CAP.=	2.3438	2.4252	2.3485	2.3141	2.2882
PTAP = 3	5.7860	5.7717	5.7813	5.7663	5.7727
4	4.7297	4.7455	4.7317	4.7316	4.7294
5	4.7343	4.7525	4.7254	4.7222	4.7243
6	4.7272	4.7363	4.7308	4.7302	4.7308
7	4.7382	4.7459	4.7266	4.7359	4.7252
8	4.7435	4.7480	4.7343	4.7348	4.7365
9	4.7416	4.7428	4.7304	4.7361	4.7274
10	4.7480	4.7513	4.7452	4.7530	4.7361
11	4.9191	4.9200	4.9174	4.9149	4.9162
12	5.0894	5.0831	5.0788	5.0823	5.0842
13	5.1518	5.1512	5.1540	5.1451	5.1532
14	5.2911	5.2795	5.2901	5.2829	5.2819
15	5.5137	5.5084	5.5183	5.5060	5.5204
16	5.7038	5.7013	5.7136	5.7024	5.7070

1/ Jet tool pass was made between No. 8 and No. 9. All other pass Nos. are steady state scans only. Refer to text - Special Test Runs.

TEST RUN NO.= 24 GRAVEL PACK THICKNESS= 3.0-INCHES
SCREEN TYPE= WIRE-WOUND, SLOT=0.040-INCHES
AQUIFER AND GRAVEL PACK GRADATION=SA NO.2

PASS NO=	0	1	2	3	4	5	6
DATE =	13DEC84	13DEC84	13DEC84	13DEC84	14DEC84	14DEC84	14DEC84
TIME =	0736	1017	1230	1400	0720	1005	1232
DRAW =	1.0339	1.0364	1.0543	1.0368	1.0511	1.0270	1.0449
YEILD =	1.7822	1.7946	1.7924	1.7246	1.8386	1.7986	1.8269
SP.CAP.=	1.7238	1.7315	1.7001	1.6635	1.7492	1.7513	1.7483
PTAP = 3	5.7650	5.7674	5.7802	5.7625	5.7743	5.7657	5.7726
4	4.7290	4.7226	4.7243	4.7268	4.7310	4.7287	4.7313
5	4.7311	4.7310	4.7259	4.7258	4.7232	4.7386	4.7277
6	4.7287	4.7240	4.7249	4.7266	4.7255	4.7294	4.7317
7	4.7315	4.7314	4.7295	4.7280	4.7199	4.7306	4.7364
8	4.7372	4.7315	4.7253	4.7298	4.7321	4.7404	4.7356
9	4.8660	4.8636	4.8644	4.8577	4.8565	4.8550	4.8570
10	5.0250	5.0257	5.0202	5.0168	5.0260	5.0242	5.0283
11	5.0753	5.0816	5.0832	5.0770	5.0786	5.0732	5.0806
12	5.1771	5.1853	5.1802	5.1772	5.1736	5.1745	5.1833
13	5.2278	5.2300	5.2325	5.2341	5.2365	5.2353	5.2472
14	5.3791	5.3635	5.3631	5.3517	5.3596	5.3622	5.3849
15	5.5402	5.5531	5.5478	5.5448	5.5567	5.5463	5.5594
16	5.7046	5.7225	5.7247	5.7119	5.7274	5.7071	5.7168

2/ TEST RUN NO.= 24 GRAVEL PACK THICKNESS= 3.0-INCHES
SCREEN TYPE= WIRE-WOUND, SLOT=0.040-INCHES
AQUIFER AND GRAVEL PACK GRADATION=SA NO.2

PASS NO=	7	8	9 1/	10	11	12
DATE =	14DEC84	17DEC84	17DEC84	17DEC84	17DEC84	17DEC84
TIME =	1419	0754	0859	1111	1231	1352
DRAW =	1.0358	1.0438	1.0515	1.0205	1.0464	1.0202
YEILD =	1.7809	1.9428	1.9716	1.9579	1.9977	1.9648
SP.CAP.=	1.7194	1.8614	1.8751	1.9186	1.9092	1.9258
PTAP = 3	5.7612	5.7774	5.7742	5.7536	5.7790	5.7488
4	4.7217	4.7291	4.7243	4.7348	4.7338	4.7220
5	4.7255	4.7337	4.7227	4.7332	4.7327	4.7285
6	4.7227	4.7258	4.7331	4.7387	4.7396	4.7301
7	4.7283	4.7320	4.7369	4.7347	4.7401	4.7418
8	4.7300	4.7259	4.7403	4.7525	4.7422	4.7353
9	4.8622	4.8355	4.8312	4.8451	4.8385	4.8402
10	5.0244	5.0113	4.9585	4.9566	4.9661	4.9504
11	5.0825	5.0720	5.0105	5.0153	5.0248	5.0141
12	5.1848	5.1798	5.1413	5.1382	5.1443	5.1391
13	5.2416	5.2345	5.2056	5.1924	5.2073	5.1993
14	5.3722	5.3884	5.3705	5.3337	5.3360	5.3297
15	5.5469	5.5403	5.5298	5.5180	5.5420	5.5204
16	5.7072	5.7218	5.7151	5.6910	5.7110	5.6893

1/ Jet tool pass was made between No. 8 and No. 9. All other pass Nos. are steady state scans only. Refer to text - Special Test Runs.
2/ Note duplicate heading for test run No. = 24.

TEST RUN NO.= 25 GRAVEL PACK THICKNESS= 3.0-INCHES
SCREEN TYPE= PVC-SLOTTED, SLOT=0.040-INCHES
AQUIFER AND GRAVEL PACK GRADATION=SA NO.2

PASS NO=		0	1	2	3	4
DATE	=	1JAN85	1JAN85	1JAN85	1JAN85	1JAN85
TIME	=	0815	0948	1111	1315	1413
DRAW	=	1.0444	1.0398	1.0443	1.0413	1.0483
YEILD	=	1.3373	1.7421	1.7714	1.7301	1.7606
SP.CAP.=		1.2805	1.6754	1.6964	1.6615	1.6795
PTAP =	3	5.7712	5.7679	5.7745	5.7710	5.7759
	4	4.7277	4.7276	4.7343	4.7312	4.7231
	5	4.7269	4.7281	4.7302	4.7297	4.7276
	6	4.7328	4.7360	4.7360	4.7366	4.7277
	7	4.7290	4.7360	4.7444	4.7410	4.7331
	8	4.7289	4.7429	4.7594	4.7496	4.7376
	9	5.0989	4.8044	4.7999	4.7866	4.8007
	10	5.2037	4.9752	4.9656	4.9698	4.9732
	11	5.2456	5.0408	5.0203	5.0225	5.0400
	12	5.3143	5.1532	5.1470	5.1478	5.1521
	13	5.3527	5.2056	5.1960	5.1965	5.2006
	14	5.4417	5.3321	5.3285	5.3230	5.3308
	15	5.5946	5.5419	5.5391	5.5334	5.5363
	16	5.7199	5.7064	5.7019	5.7002	5.7024

TEST RUN NO.= 26 GRAVEL PACK THICKNESS= 6.0-INCHES
SCREEN TYPE= PVC-SLOTTED, SLOT=0.040-INCHES
AQUIFER AND GRAVEL PACK GRADATION=SA NO.2

PASS NO=		0	1	2	3	4
DATE	=	31JAN85	31JAN85	31JAN85	31JAN85	31JAN85
TIME	=	0751	0902	1045	1225	1341
DRAW	=	1.0516	1.0554	1.0534	1.0433	1.0499
YEILD	=	1.8044	1.9116	1.9797	1.9579	1.9326
SP.CAP.=		1.7159	1.8112	1.8793	1.8767	1.8406
PTAP =	3	5.7686	5.7724	5.7743	5.7687	5.7741
	4	4.7208	4.7198	4.7250	4.7271	4.7272
	5	4.7170	4.7170	4.7209	4.7254	4.7242
	6	4.7191	4.7184	4.7255	4.7286	4.7266
	7	4.7216	4.7185	4.7295	4.7300	4.7293
	8	4.7238	4.7219	4.7328	4.7290	4.7330
	9	4.7242	4.7287	4.7348	4.7326	4.7357
	10	4.7289	4.7295	4.7390	4.7358	4.7420
	11	4.9552	4.9383	4.9355	4.9239	4.9229
	12	5.0767	5.0449	5.0019	5.0108	5.0433
	13	5.1366	5.1104	5.1072	5.1062	5.1049
	14	5.2629	5.2454	5.2457	5.2440	5.2394
	15	5.4970	5.4895	5.4910	5.4879	5.4864
	16	5.6999	5.7006	5.7008	5.6946	5.6946

GPO 851-403

Mission of the Bureau of Reclamation

The Bureau of Reclamation of the U.S. Department of the Interior is responsible for the development and conservation of the Nation's water resources in the Western United States.

The Bureau's original purpose "to provide for the reclamation of arid and semiarid lands in the West" today covers a wide range of interrelated functions. These include providing municipal and industrial water supplies; hydroelectric power generation; irrigation water for agriculture; water quality improvement; flood control; river navigation; river regulation and control; fish and wildlife enhancement; outdoor recreation; and research on water-related design, construction, materials, atmospheric management, and wind and solar power.

Bureau programs most frequently are the result of close cooperation with the U.S. Congress, other Federal agencies, States, local governments, academic institutions, water-user organizations, and other concerned groups.

A free pamphlet is available from the Bureau entitled "Publications for Sale." It describes some of the technical publications currently available, their cost, and how to order them. The pamphlet can be obtained upon request from the Bureau of Reclamation, Attn D-822A, P O Box 25007, Denver Federal Center, Denver CO 80225-0007.