AN EVALUATION OF INJECTION WELL PLUGGING FROM THE OAKES SCHOOL HEAT PUMP/PASSIVE COOLING SYSTEM, DICKEY COUNTY, NORTH DAKOTA

By
Robert B. Shaver

Water Resource Investigation No. 25
North Dakota State Water Commission

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INTRODUCTION

In 1982 the Oakes Public School District constructed a ground-water heat pump system to heat and cool the Oakes Public School. A 12-inch diameter supply well and a 12-inch diameter injection well were constructed on school property by Falk Well Drilling Company, Hankinson, North Dakota in July 1982. In September 1982, two 8-inch diameter injection wells also were constructed on school property by Falk Well Drilling. The 8-inch diameter injection well located near the northeast corner of the tennis court was later abandoned due to well screen failure.

On April 23, 1986, Mr. Nicholos Roster, Oakes School Superintendent, sent a letter to the State Engineer regarding a plan to abandon the two remaining injection wells. The plan proposed continued use of the existing supply well and heat pump with ground water to be discharged into a nearby storm sewer. This plan was conceived because of operation and maintenance problems associated with the injection wells. Apparently, well rehabilitation methods used to mitigate well screen/aquifer plugging and annular leakage were becoming cost prohibitive.

On March 16, 1988, Mr. Gary White, alderman, city of Oakes, sent a letter to the State Engineer requesting that the State Water Commission evaluate the impact on water levels in the Oakes aquifer should the proposed discharge plan be adopted. The city was particularly concerned about the impact on pumping levels in their three municipal wells, all of which are within about 2,000 feet of the supply well used by the school.

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In January 1989, Falk Drilling constructed four, 4-inch diameter injection wells on Oakes school property to be used in conjunction with the original 12-inch diameter injection well and the 8-inch diameter injection well located near the northwest corner of the tennis court. In addition, efforts were made by Falk Well Drilling to rehabilitate the 12-inch and 8-inch diameter injection wells.

In a letter dated December 10, 1991 to Mr. Roster, Mr. Robert Shaver, Hydrologist Manager, Water Appropriation Division, indicated that the State Engineer would not grant approval on the proposed plan to discharge water from the Oakes school heat pump into the storm sewer. Water use for the school heat pump system in 1990 was 349.5 acre-feet which was 209.5 acre-feet in excess of the maximum annual allocation of 150 acre-feet of water available under perfected water permit No. 3526. The increased use reflected operation of the heat pump during the winter and passive cooling during the summer. Throughout 1990, water was returned to the Oakes aquifer using injection wells. Rejection of the plan was based on concern over projected long-term water level declines in the north part of the Oakes aquifer, and the demonstrated need to more than double consumptive use.

In the same letter, Mr. Shaver stated that the State Water Commission could provide support to the Oakes school by defining the extent and cause(s) of injection well plugging. Based on the results of the investigation, the State Water Commission would provide specific recommendations to the school board to mitigate injection well plugging.

On December 8, 1992, Mr. Shaver met with Mr. Art Conklin, Oakes School District Superintendent, and the school board to discuss State Water Commission involvement to evaluate injection well plugging. At that meeting, it was decided that the State Water Commission would develop and submit a proposal and cost estimate for a study to evaluate injection well plugging.

A proposal/cost estimate was developed by the State Water Commission and was approved by the school board. On April 23, 1993 the North Dakota State Water Commission entered into an agreement with the Oakes School District to 1) determine the cause(s) of declining injection well capacities in the Oakes Public School ground-water heat pump system and 2) to provide a basis for designing an injection well remediation plan. The agreement was effective from April 29, 1993 to November 1, 1993.

LOCATION-NUMBERING SYSTEM

The location-numbering system used in this report is based on the public land classification system used by the U.S. Bureau of Land Management. The system is illustrated in figure 1. The first number denotes the township north of a base line, the second number denotes the range west of the fifth principal meridian, and the third number denotes the section in which the well or test hole is located. The letters A, B, C, and D designate, respectively, the northeast, northwest, southwest, and southeast quarter section, quarter-quarter section, and quarter-quarter-quarter section (10-acre tract). For example, well 131-059-28BBA is located in the NE1/4 NW1/4 NW1/4 Section 28, Township 131 North, Range 59 West. Consecutive

one mile

131-059-28BBA
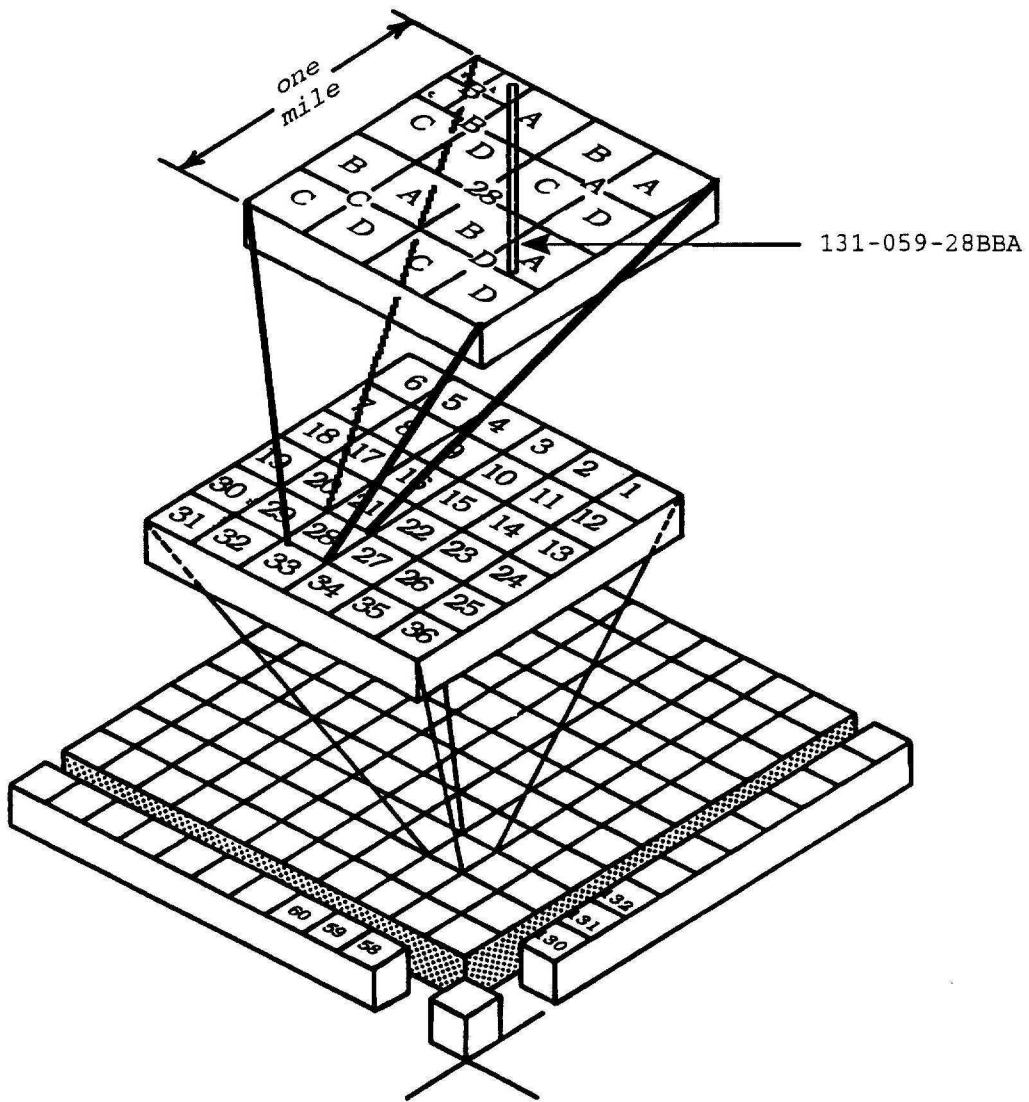
Figure 1.-- Location - numbering system

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terminal numerals are added if more than one well or test hole is located within a 10-acre tract. The locations of the wells in the study area are shown in figure 2.

HYDROGEOLOGIC SETTING

Geology

The Oakes school property is underlain by stratified sand and gravel deposits that form a deltaic complex up to about 70 feet thick. The deltaic complex is part of the Pleistocene Coleharbor Group. These deposits are composed of quartz, shale, lignite, Canadian shield silicates, and carbonates (Shaver and Schuh, 1990).

Occurrence and Movement of Ground Water

The sand and gravel deltaic complex comprises the north part of the Oakes aquifer (Shaver and Schuh, 1990). In the study area, the Oakes aquifer is unconfined (fig. 3). The bottom of the aquifer is about 70 feet below land surface and the static water level measured in June 1993 is about 20 feet below land surface. The direction of regional ground-water flow in the Oakes area is west toward the James River.

Hydraulic Properties

During August 1982, the North Dakota State Water Commission conducted an aquifer test using the Oakes school heat-pump supply well located at 131-059-28BBA1 (fig. 2). After pumping the supply well at a constant rate of 845 gallons per minute for 4,200 minutes,
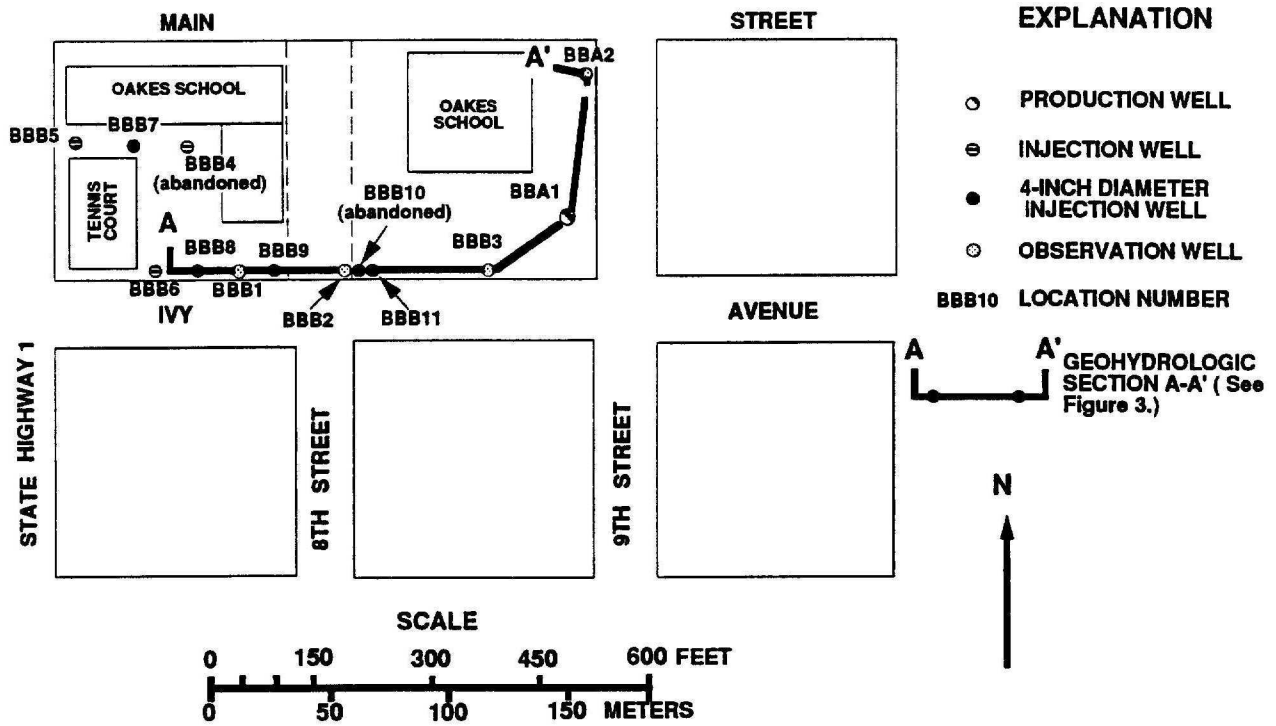
Figure 2 .-- Location of production well, injection wells, and observation wells at the Oakes school
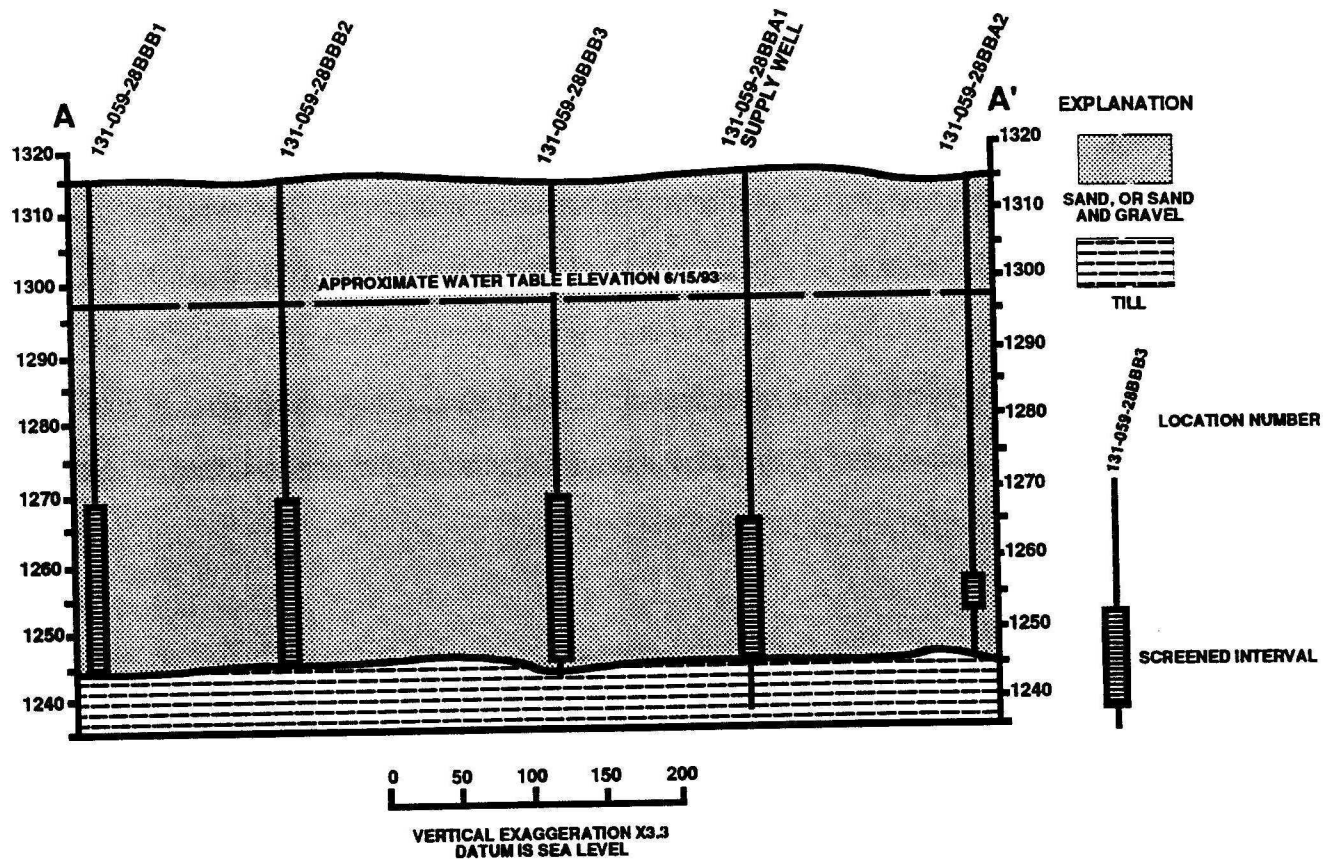
Figure 3 .— Geohydrologic section A-A' showing the Oakes aquifer at the Oakes school

the specific capacity (well discharge rate divided by water-level drawdown in the well) was calculated at 26.6 gallons per minute per foot of drawdown.

Analysis of the aquifer test data yielded a transmissivity of 11,000 feet squared per day, an apparent storativity of 0.29 and a hydraulic conductivity of 220 feet per day (Shaver and Schuh, 1990).

Water Chemistry

Near the end of the above described aquifer test, a water sample was collected for chemical analysis. The ground water was a calcium-bicarbonate type with a dissolved-solids concentration of 408 mg/L and an iron (Fe^{2+}) concentration of 0.50 mg/L (Appendix II). Field determinations of pH, dissolved oxygen, and iron were not made at the time of sample collection.

WATER SAMPLING METHODS

For this investigation, a gas-squeeze bladder pump connected to a plastic flow-through sampling chamber was used to collect water samples for chemical analysis and measure selected field parameters (fig. 4). Water samples for chemical analysis were also collected inside the school during periods of passive cooling and heating to evaluate potential chemical changes that may affect injection well plugging. For these samples, the flow-through chamber was directly connected to the discharge pipeline inside the school.

Temperature, pH, and dissolved oxygen were measured with probes installed in sealed ports in the top of the sampling chamber.
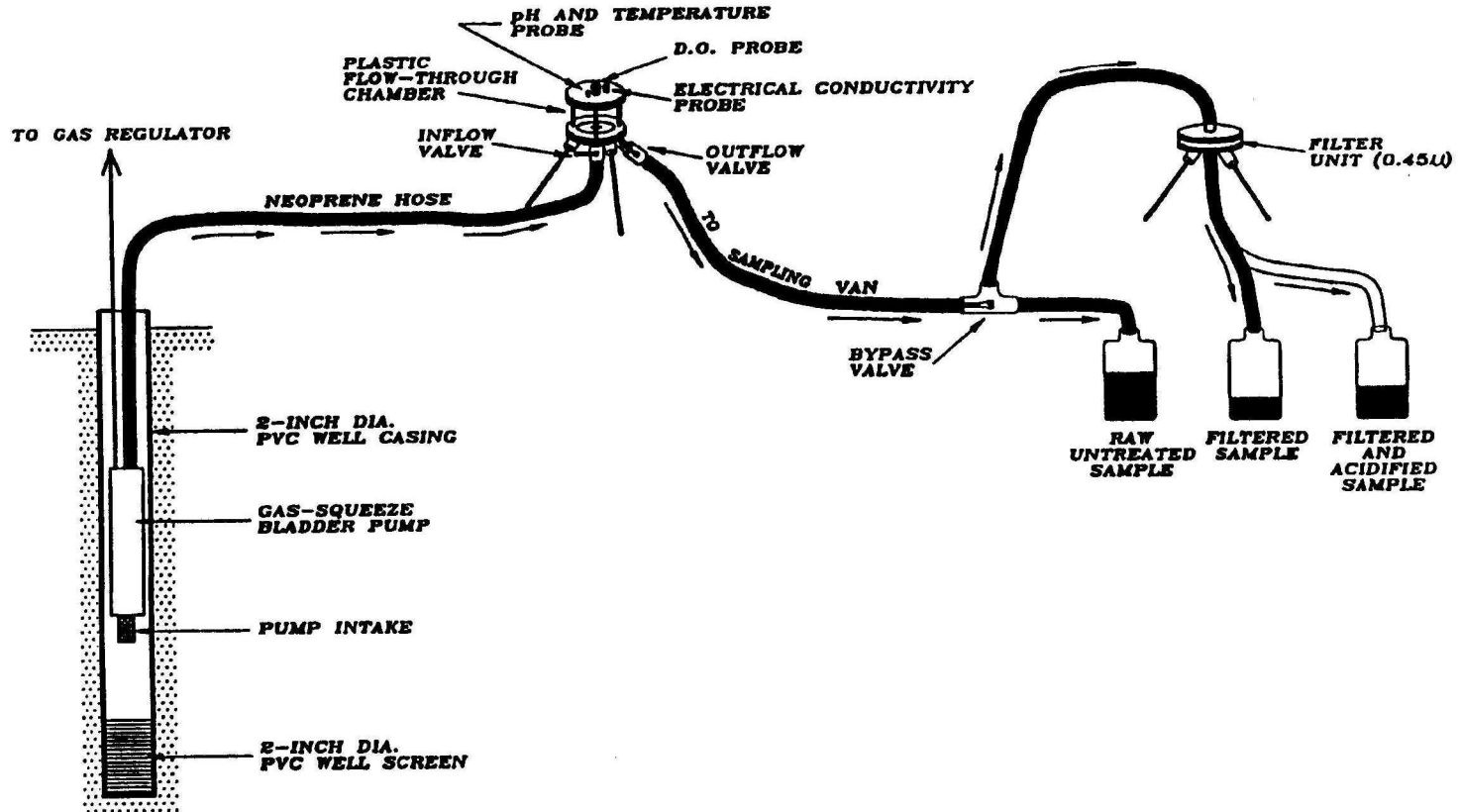
Figure 4.-- Schematic diagram of sampling apparatus

Temperature and pH were measured using a digital pH meter equipped with an automatic temperature compensating probe. Field alkalinity was measured by sulfuric acid titration to an end-point pH of 4.5 (Braun and others, 1970). Field determinations were made for ferrous iron (Fe^{2+}) and total iron using a Hach DR/2000 spectrophometer.

After selected field parameters were measured and recorded, three samples were collected in plastic bottles for analysis in the laboratory.

1) Raw (500 ml)
2) Filtered (500 ml)
3) Filtered and acidified (500 ml)

A two-ml ampule of concentrated nitric acid was added to sample three to prevent precipitation of carbonates and metal oxides. Specific conductance, pH, and concentrations of bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) were measured in the lab using the raw sample. Concentrations of sulfate (SO_4^{2-}), chloride (Cl^-), fluoride (F^-), Boron (B^{3+}), nitrate (NO_3^-), silica (SiO_2), and total-dissolved solids were measured in the lab using the filtered (0.45 micron) sample. Concentrations of calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+), iron (Fe^{2+}) and manganese (Mn^{2+}) were determined using the filtered and acidified sample. Field filtering was accomplished using a pressure regulated nitrogen tank connected to a filter device shown in figure 4. Samples for major cation/anion analysis were chilled during transport to the lab but not during storage in the lab prior to analysis.

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SUPPLY WELL

Construction Data

The supply well (131-059-28BBA1) was installed by Falk Well Drilling on July 15, 1982. The drillers log indicates sand and gravel from land surface to a depth of 70 feet (Appendix I). The well was constructed with 12-inch diameter plastic casing from land surface to a depth of 50 feet and 20 feet of 12-inch pipe size diameter, 60 slot, stainless steel screen from 50 to 70 feet. The well was gravel packed.

Well Hydraulics

Based on the aquifer test conducted on this well in 1982 by the State Water Commission, the specific capacity was 31.7 gallons per minute per foot after 30 minutes of pumping at a rate of 845 gallons per minute. This well was redeveloped by M&W Drilling in July 1993, using high pressure water jetting and pumping techniques. On July 26, 1993, prior to collecting a water sample, a short pumping test was conducted on the well. The specific capacity was 39.0 gallons per minute per foot after 30 minutes of pumping at a constant rate of 69 gallons per minute.

Water Chemistry

After the short-term pumping test was completed on July 26, 1993, a water sample was collected using the gas-squeeze bladder pump. The intake of the pump was set at a depth of about 65 feet. The three water samples (raw, filtered, and filtered/acidified) were collected after 60 minutes of pumping when temperature, pH, and dissolved oxygen became relatively stable (fig. 5). The in-situ ground-water temperature estimated from bailed samples was 10.4°C (50.7°F). The ground-water temperature became relatively stable at about
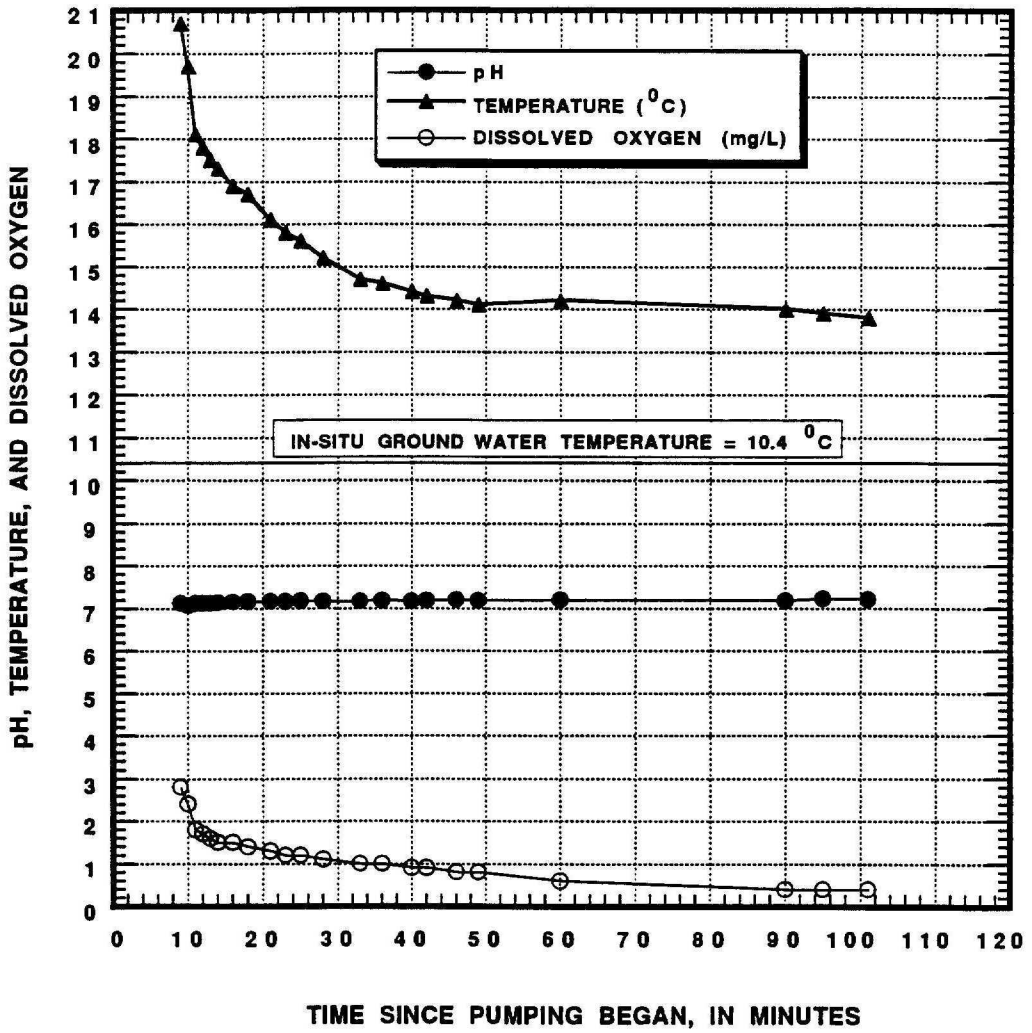
Figure 5.-- Temporal variation in pH, temperature, and dissolved oxygen in ground water from the Oakes school production well (Sampled 7/26/93)

14° C (57.2° F) within the sample chamber. The increased temperature is due to exposure of the pump hoses, tubing, and sampling chamber to the atmosphere. The pH varied from 7.06 to 7.24. Dissolved oxygen decreased from 2.8 mg/L after about nine minutes of pumping to 0.4 mg/L after 150 minutes of pumping. The decline in dissolved oxygen probably is due to air purging from the pump hoses, tubing, and sampling chamber. The small dissolved oxygen concentration (0.4 mg/L) may be caused by leaks and/or diffusion through the sampling apparatus.

Field determinations were also made for total iron and Fe^{2+} using a Hach DR/2000 spectrophotometer. Total iron was 1.08 mg/L and Fe^{2+} was 1.02 mg/L in a raw, unfiltered sample. The Fe^{3+} concentration is estimated at 0.06 mg/L which is the difference between total iron and Fe^{2+}.

The amounts and kinds of dissolved ions or molecules containing iron in the ferrous (Fe^{2+}) and ferric (Fe^{3+}) states are related to the pH (hydrogen ion concentration) and Eh (oxidation-reduction potential) of the water in which they occur (Hem and Cropper, 1959). Fe^{3+} can be present in true solution in amounts greater than 0.01 part per million only at pH levels below about 5.0. In aerated waters with a pH above about 5, Fe^{3+} can be present in excess of 0.01 parts per million only as a suspension of oxide or hydroxide. Therefore, in most ground water, dissolved iron occurs predominantly as Fe^{2+}. When exposed to air, Fe^{2+} is oxidized to Fe^{3+}. This reaction is slow in strong acid, but can be rapid in the normal range of pH for natural water (Hem and Cropper, 1959). The

distribution of iron species in ground water from the supply well conforms to the above theoretical chemical framework.

Laboratory analysis of the sample indicates the ground water is a calcium-bicarbonate-sulfate type with a dissolved-solids concentration of 854 mg/L (computed using field HCO^-_3) (Appendix II).

The geochemical model WATEQ4F (Ball and Nordstrom, 1991) was used to evaluate the potential of mineral precipitation in the heat pump/distribution/injection well system. The calculated saturation index for calcite was 0.257 and the calculated saturation index for ferrihydrite ($Fe_5HO_8 \cdot 4H_2O$) was 2.335. Based on the above, an increase in pH or a significant increase in water temperature could cause calcite (lime) precipitation. In the presence of free oxygen, iron hydroxide precipitation is likely.

Redox potential was calculated by WATEQ4F using the Fe^{3+}/Fe^{2+} couple and the Sato (1960) dissolved oxygen method. A redox potential of +0.228 volts was calculated using the Fe^{3+}/Fe^{2+} couple and a redox potential of +0.164 volts was calculated by the Sato method. The positive redox potentials indicate an oxidizing environment.

Iron Bacteria

Smith (1984) lists various environmental parameters cited in the literature that favor iron bacteria growth. These include:

1) temperature - 10°C

2) dissolved Fe^{2+} - > 0.25 mg/L

3) pH - 6 to 8

4) dissolved oxygen - 0.1 to 3.0 mg/L

5) Eh - +0.2 to +0.3 volts

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Parameters measured on July 26, 1993 for water in the supply well are:

1) temperature-10.4°C

2) dissolved Fe^{2+} - 1.02 mg/L

3) pH - 7.06 to 7.24

4) dissolved oxygen - <0.4 mg/L

5) Eh - +0.164 to +0.228 volts

Based on the above, conditions are favorable for iron bacteria growth in the supply well. Gallionella and Leptothrix are two species of iron bacteria that commonly occur in the Eh and pH ranges measured in the supply well (Smith, 1984) (fig. 6).

12-INCH DIAMETER INJECTION WELL

Construction Data

The 12-inch diameter injection well (131-059-28BBB6) was installed by Falk Well Drilling on July 20, 1982 (fig. 2). The driller's log indicates sand and gravel from land surface to a depth of 68 feet, rocks from 68 to 70 feet and shale (clay) from 70 to 71 feet (Appendix I). The well was constructed using 12-inch diameter plastic casing from land surface to a depth of 40 feet and 30 feet of 12-inch pipe size diameter, 60-slot, stainless steel well screen from 40 to 70 feet (fig. 7). The well was gravel packed.

Well Hydraulics

Based on pump test data shown on the completion report submitted by Falk Well Drilling, the specific capacity of this well was

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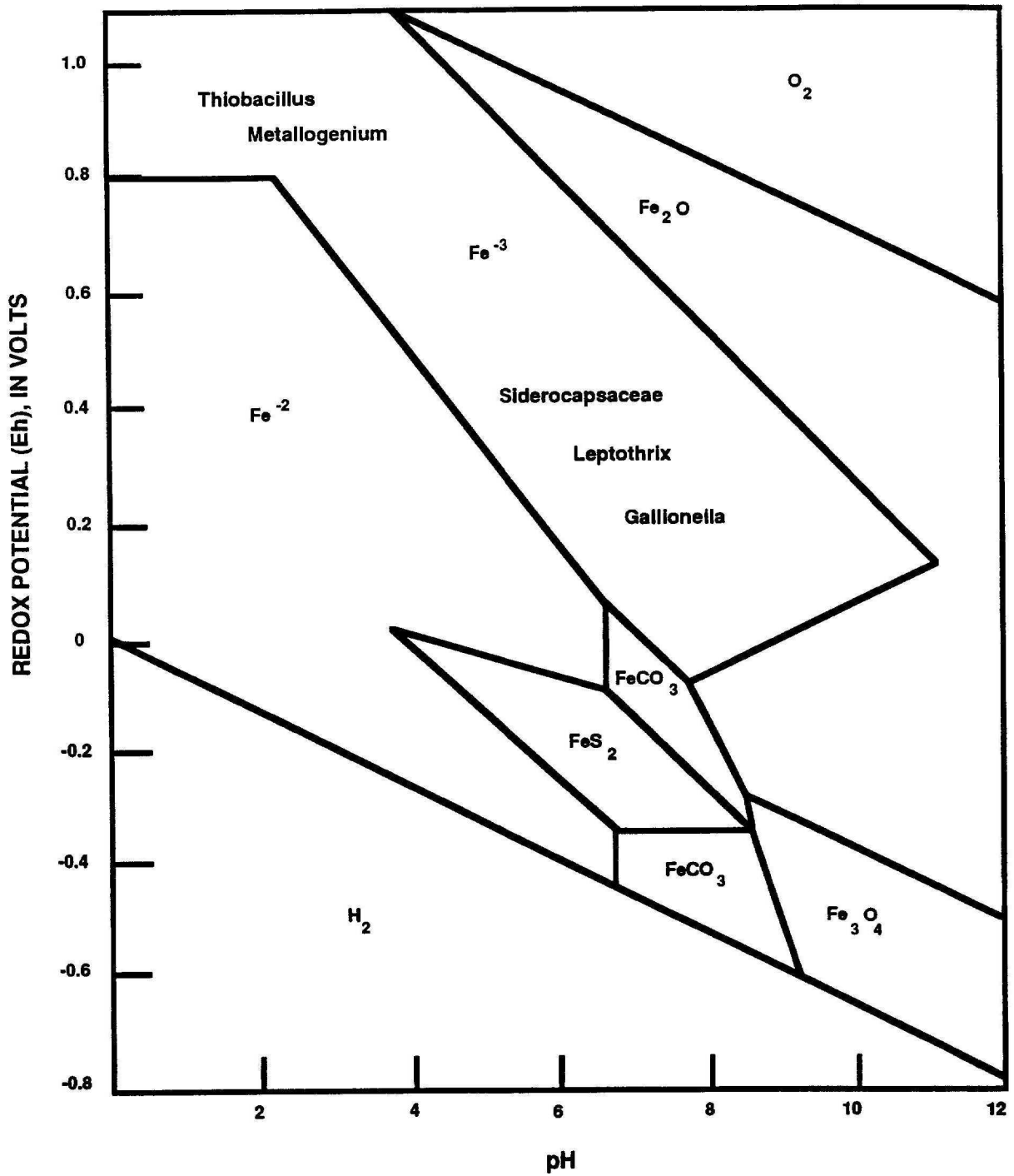
Figure 6.-- Occurrence of iron bacteria in relation to Eh and pH
(from Smith, 1984)

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DEPTH BELOW LAND SURFACE, IN FEET

0 — Land Surface

Pitless Spool

Injection Pipe

10 —

2-inch Diameter PVC Drop Pipe

20 — Static Water Level (Measured 6/15/93)

30 — 12-inch Diameter PVC Well Casing

40 —

12-inch Diameter, 60-Slot
Stainless Steel Well Screen

50 —

60 —

Screen Filled With Sand

Bottom of Aquifer

70 —
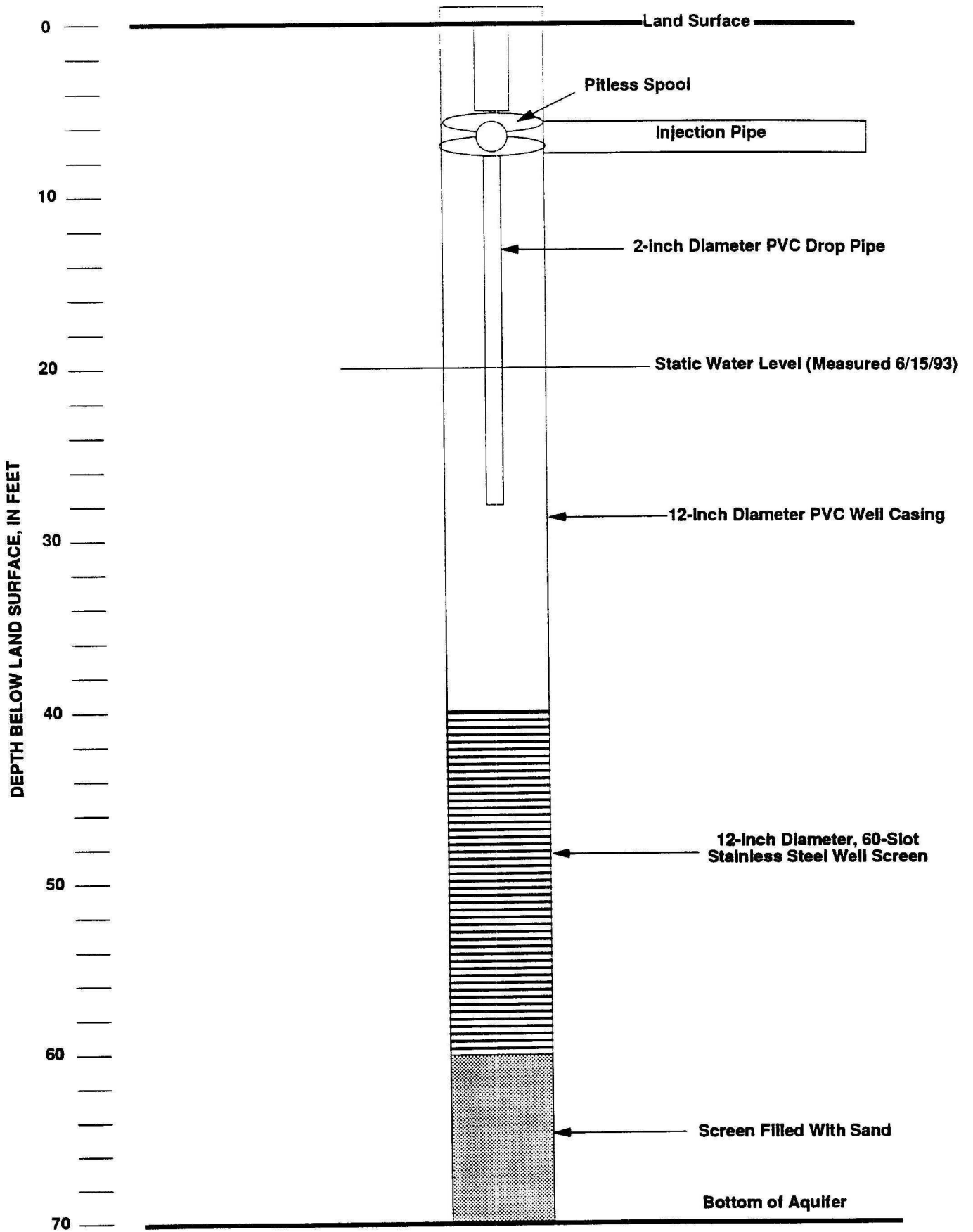
Figure 7.— Schematic diagram of 12-inch diameter injection well

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34.8 gallons per minute per foot after eight hours of pumping at a rate of 700 gallons per minute.

After the pitless unit was removed from the well on June 15, 1993, the total depth of the well was measured at 60 feet. The bottom 10 feet of the screen was filled with an oxidized very fine to medium grained sand. A specific capacity test was conducted prior to evacuating the sand from the well. The well was pumped at a constant discharge rate of 62 gallons per minute for seven minutes using a submersible pump. After seven minutes of pumping, the drawdown was measured at 13.37 feet, and the specific capacity was calculated at 4.6 gallons per minute per foot of drawdown. This specific capacity is only about 13 percent of the original specific capacity reported by Falk Well Drilling in 1982 indicating a significant decline in well efficiency.

After the specific capacity test was completed, the submersible pump was removed from the well and the sand inside the well screen was evacuated by air-lift pumping. A second specific capacity test was conducted and the well was pumped at a constant rate of 65 gallons per minute for 19 minutes. The drawdown measured at the end of the 10-minute pumping period was 9.95 feet and the specific capacity was calculated at 6.5 gallons per minute per foot of drawdown. This specific capacity is only about 19 percent of the original reported specific capacity.

During July 1993, M&W Drilling, Inc., Oakes, ND redeveloped this well using high-pressure water jetting/pumping techniques. The volume of water used during each jetting period was 1,900 gallons (maximum capacity of the drilling contractor's water truck). Water was obtained from the city of Oakes. The discharge rate through the

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jetting tool was 40 gallons per minute. The well was pumped at a rate of 67 gallons per minute during the jetting period to maintain a lower water level in the well in relation to the water level in the aquifer. Maintaining this water level differential enhances removal of fine-grained sediment near the screen/aquifer interface during well development. Each jetting period lasted about 48 minutes. After each jetting period, the well was pumped at a rate of 67 gallons per minute for five minutes to remove fine-grained sediment from the bottom of the well. The submersible pump was then shut off for five minutes to allow the water level in the well to recover. At the end of this five-minute recovery period, the water level in the well was measured and a five-minute specific capacity test was conducted to evaluate the effects of well development on well efficiency.

Ten jetting/specific capacity cycles were completed on this well. The change in specific capacity, with respect to time of development, is shown in figure 8. The initial specific capacity was 6.5 gallons per minute per foot prior to development and 28.2 gallons per minute per foot after 480 minutes (eight hours) of development. Well development regained 81 percent of the specific capacity reported by Falk Well Drilling in 1982. The 31.9 gallon per minute per foot specific capacity measured after 336 minutes of development may be incorrect and the result of a measurement error. After about 384 minutes of development, the change in specific capacity was minor.

M&W Drilling reported that a large amount of sand was removed from the well while jetting. In addition, during the early jetting periods, the discharge water was red-orange-brown in color. During
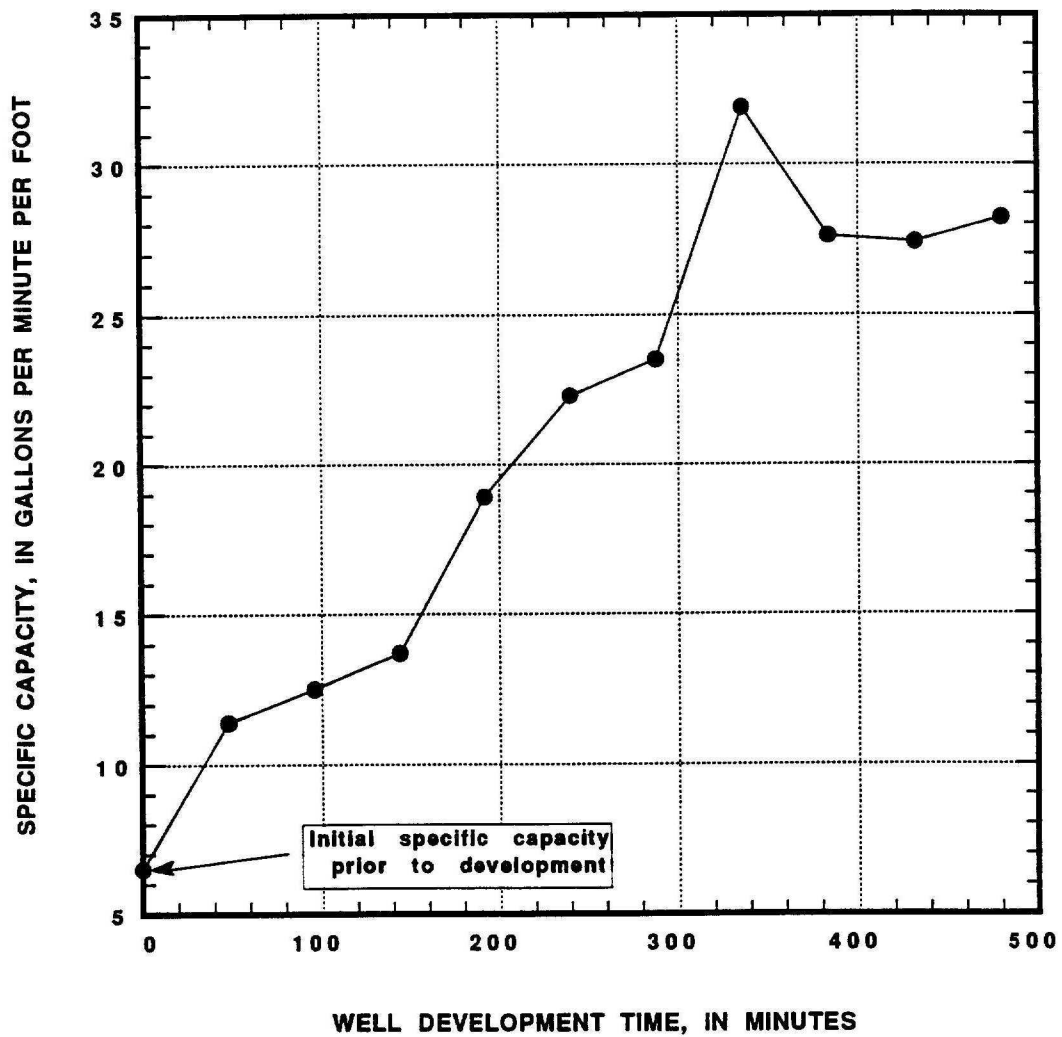
Figure 8. -- Change in specific capacity in relation to well development time for the 12-inch diameter injection well (131-059-28BBB6)

later jetting periods, the volume of sand removed from the well declined and the discharge water remained clear.

Water Chemistry

On June 15, 1993, prior to evacuating sand in the bottom of the well screen and initiating the well development process, water samples for major cation/anion analysis and iron bacteria were collected from the well using the gas-squeeze bladder pump. The pump intake was set at about 56 feet (about four feet above the top of the sand).

This sample was collected to evaluate the chemistry of relatively stagnant water stored within the well casing. The data provide 1) a basis for determining chemical reactions that may occur within the well when the heat pump is not in operation and, 2) if these chemical reactions contribute to injection-well plugging. Based on a casing storage of 261 gallons, a pumping rate of 0.32 gallons per minute, and an 87-minute pumping period, no more than 11 percent of the casing storage (28 gallons) was removed from the well while sampling.

During the sampling period, the water was pale red-brown and a red-brown sediment accumulated in the bottom of the sampling chamber. The red-brown sediment probably was ferrihydrite.

A water sample was collected after 30 minutes of pumping when field water temperature, pH, and dissolved oxygen stabilized (fig. 9). As previously stated, the ground-water temperature in the aquifer (10.4°C) is less than that measured in the sampling chamber because the sampling chamber, hoses, and tubing are exposed to warmer atmospheric conditions. pH remained relatively constant throughout

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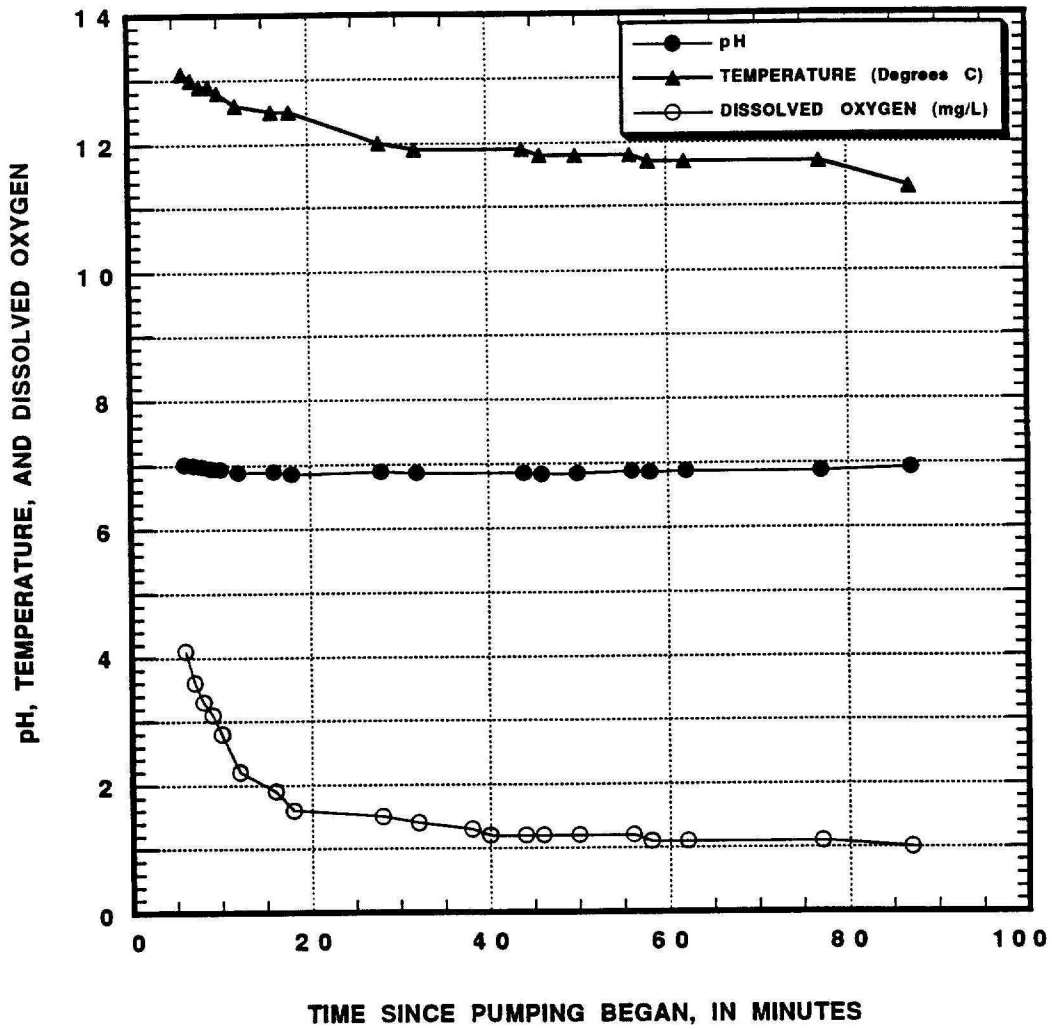
Figure 9. -- Temporal variation in pH, temperature, and dissolved oxygen in ground water from the 12-inch diameter injection well during sampling prior to sand excavation

the sampling period varying, for the most part, between 6.85 and 6.90. Dissolved oxygen decreased from 4.1 mg/L after six minutes of pumping to 1.0 mg/L after 87 minutes of pumping. The rapid decline in dissolved oxygen during the first 20 minutes of pumping probably reflects air purging from the pump hoses, tubing, and sampling chamber.

Field determinations of Fe^{2+} and total iron were made during the sampling period on an unfiltered sample using a Hach DR/2000 spectrophotometer. Total iron was 2.06 mg/L, Fe^{2+} was 0.11 mg/L, and Fe^{3+} was 1.95 mg/L.

Laboratory analysis of the sample indicates the water in casing storage is a calcium-bicarbonate type with a dissolved-solids concentration of 654 mg/L (computed using field HCO_3) (Appendix II).

In the 12-inch diameter supply well, the ground water is clear and iron occurs predominantly as Fe^{2+}, whereas in the 12-inch injection well, the casing storage water is pale red-brown and iron occurs predominantly as Fe^{3+}. The pH of ground water from the supply well is 7.24 (slightly alkaline) and the pH of the casing storage water in the 12-inch diameter injection well varies from between 6.85 and 6.90. It is apparent that Fe^{2+} is unstable in the casing storage water and precipitates to form ferrihydrite that imparts the pale red-brown color. This iron oxide precipitation reaction releases hydrogen ions (H^+), thereby lowering the pH. The slightly acidic pH associated with casing storage water in the injection well supports ferrihydrite precipitation.

The geochemical model WATEQ4F (Ball and Nordstrom, 1991) was used to evaluate the potential of mineral precipitation in the

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casing storage water. The calculated saturation index for calcite was -0.057 and the calculated saturation index for ferrihydrite was 3.661. Based on the above, an increase in pH, or a significant increase in water temperature could cause calcite precipitation in the well. In the presence of free oxygen, ferrihydrite precipitation is likely.

Redox potential was calculated by WATEQ4F using the Fe^{3+}/Fe^{2+} couple and the Sato (1960) dissolved oxygen method. A redox potential of +0.410 volts was calculated using the Fe^{3+}/Fe^{2+} couple and a redox potential of +0.188 volts was calculated by the Sato method. The positive redox potentials indicate an oxidizing environment.

Iron Bacteria Analysis

As with the supply well, the temperature, dissolved Fe^{2+}, pH, dissolved oxygen, and Eh measured in the casing storage of the 12-inch diameter injection well all favor iron bacteria growth. The sample collected on June 15, 1993 for iron bacteria analysis was stored in a 32-ounce, amber glass jar. After collection, the sample was kept chilled in a portable cooler until delivered to the ND State Department of Health and Consolidated Laboratories on June 17, 1993. The sample was examined in the lab on June 21, 1993 and results indicated no detection of iron bacteria (Appendix III - lab report #11396).

EIGHT-INCH DIAMETER INJECTION WELL
Construction Data

The 8-inch diameter injection well (131-059-28BBB5) was installed by Falk Well Drilling on July 20, 1982 (fig.2). The driller's

log indicates sand and gravel from land surface to a depth of 68 feet, rocks from 68 to 70 feet, and shale (clay from 70 to 72 feet). The well was constructed using eight-inch diameter plastic casing from land surface to a depth of 40 feet and 30 feet of 8-inch pipe-size diameter, 60-slot, stainless steel well screen from 40 to 70 feet (fig. 10). A gravel pack was placed around the well screen.

Well Hydraulics

On June 16, 1993, the pitless unit was removed from the 8-inch diameter injection well. The static water level was measured at 20.30 feet below land surface. The well depth was measured at 53.4 feet below land surface. The bottom part of the screen from 53.4 to 70 feet was filled with a very fine to medium oxidized sand.

In July 1993, M&W Drilling used the same well development techniques described for the 12-inch injection well to improve the efficiency of the 8-inch injection well. Because of the smaller well diameter, high pressure water jetting was conducted without simultaneous pumping. After each jetting period (about 48 minutes) the jetting tool was removed from inside the casing and a submersible pump was set near the bottom of the well to remove accumulations of sediment. During the early stages of well development, a large amount of oxidized sand was pumped out of the well. The amount of sand pumped from the well decreased as development time progressed. In addition, the water pumped from the well during early stages of development was red-orange-brown in color. During later stages of development, the water remained clear. Six jetting/specific capacity cycles were completed on this well. The change in specific capacity
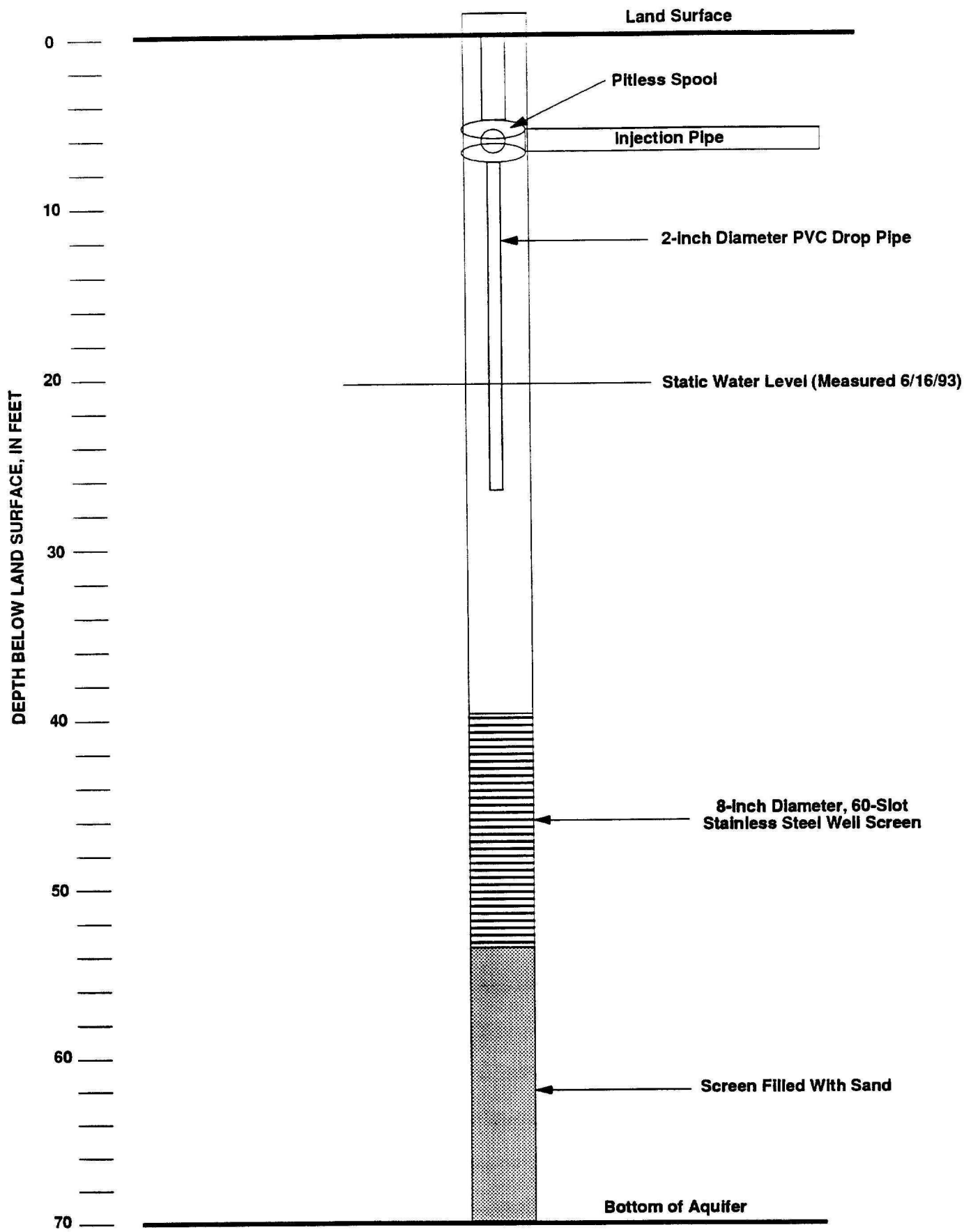
Figure 10.-- Schematic diagram of 8-inch diameter injection well

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versus well development time is shown in figure 11. The initial specific capacity prior to well development (after sand was evacuated from the well) was 2.71 gallons per minute per foot. The change in specific capacity was relatively small after about 240 minutes of development time. The final specific capacity was 18.1 gallons per minute after 288 minutes of development. Specific capacity was not reported by the driller when the well was completed. As a result, a comparison of renovated specific capacity with original specific capacity is not possible.

Water Chemistry

On June 16, 1993, prior to evacuating sand in the bottom of the well screen and initiating the well development process, water samples for major cation/anion analysis and iron bacteria were collected from the well using the gas-squeeze bladder pump. The intake of the gas-squeeze bladder pump was set at about five feet above the top of sand inside the well screen.

As with the 12-inch injection well, a sample was collected from the 8-inch injection well to evaluate the chemistry of relatively stagnant water stored within the well casing. Based on a casing storage of 120 gallons, a pumping rate of 0.32 gallons per minute, and a 67-minute pumping period, no more than 17.5 percent of the casing storage volume (21 gallons) was removed from the well while sampling.

Unlike the 12-inch injection well, pH steadily decreased through the sampling period from 7.44 after 10 minutes of pumping to 6.90 after 67 minutes of pumping (fig. 12). The change in pH with
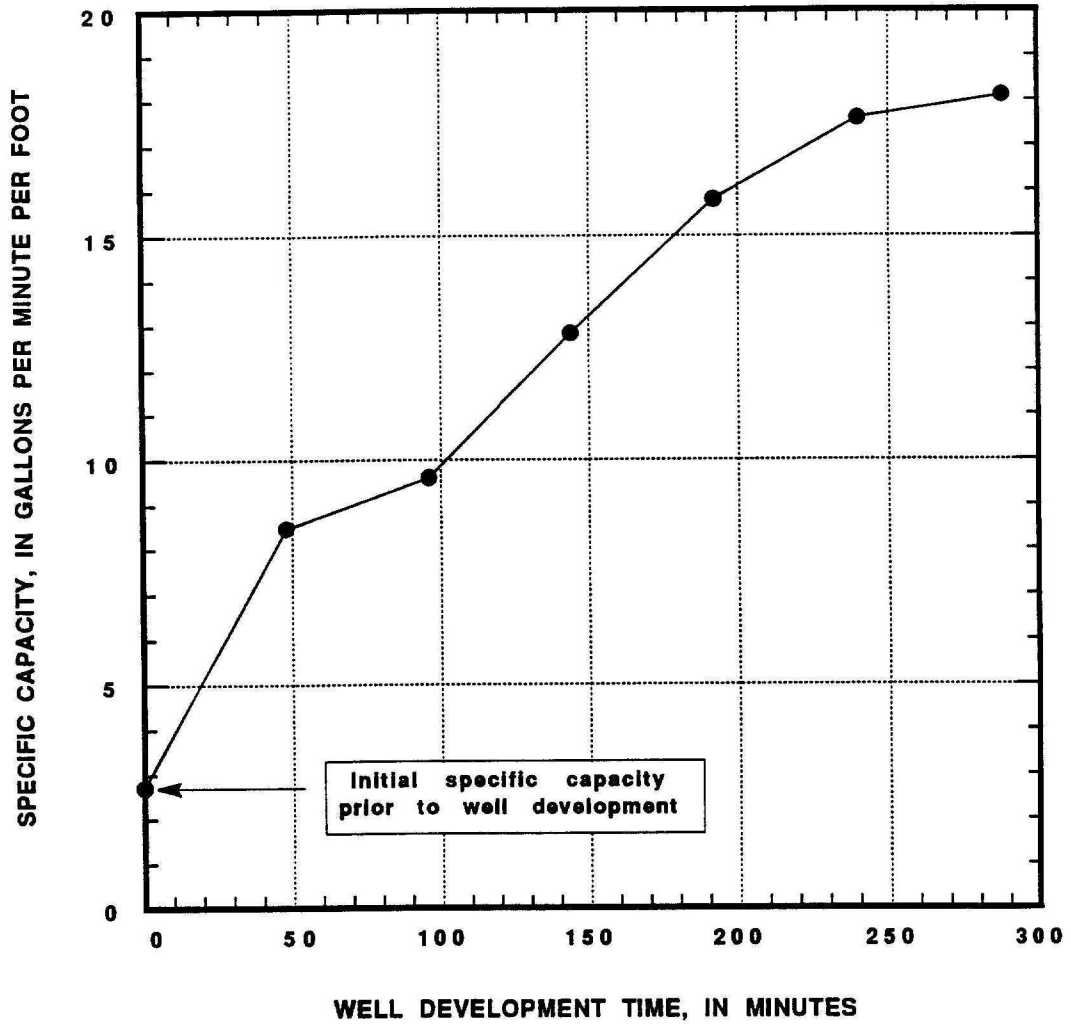
Figure 11. -- Change in specific capacity in relation to well development time for the 8-inch diameter injection well (131-059-28BBB5)
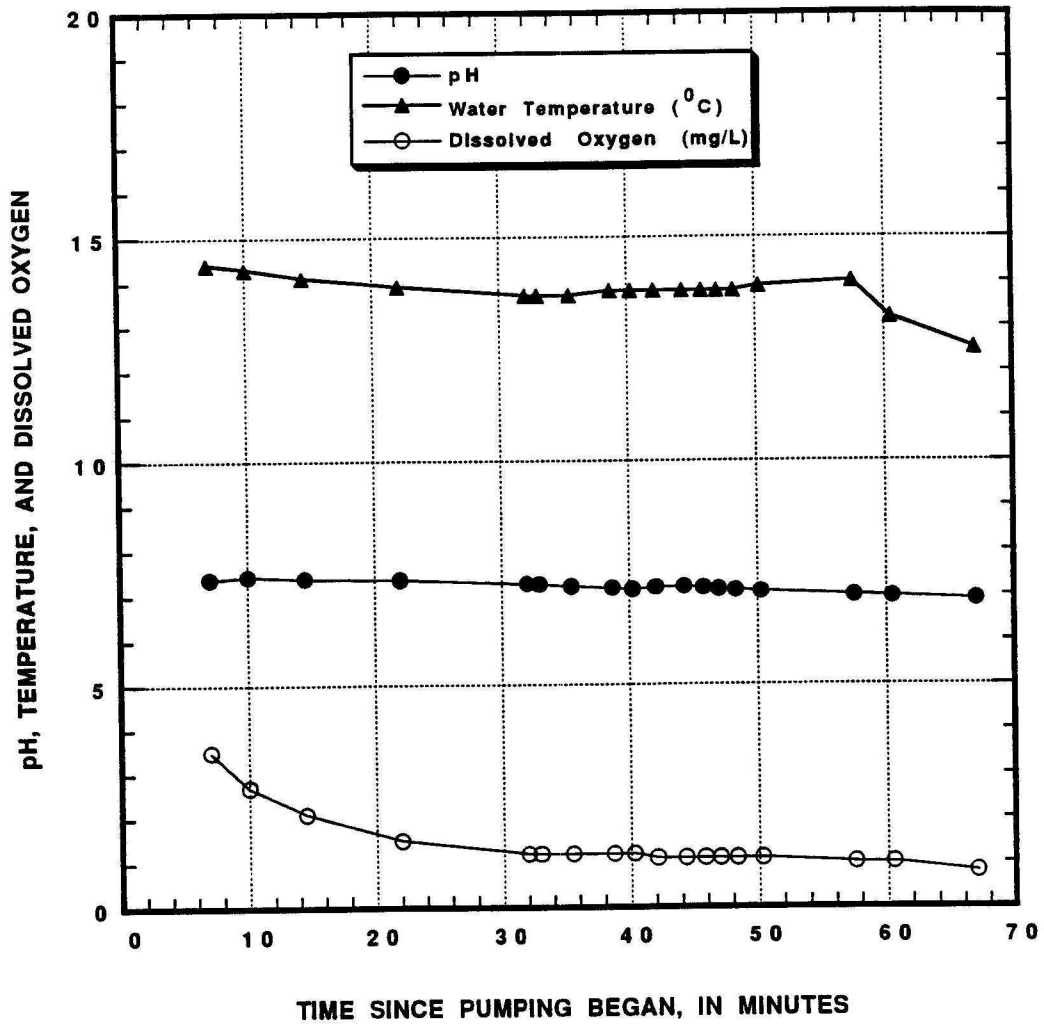
Figure 12. -- Temporal variation in pH, temperature, and dissolved oxygen in ground water from the 8-inch diameter injection well during sampling prior to development

pumping time may reflect capture of water stored above the well screen in the well casing or capture of some water from the aquifer near the well screen. The water temperature remained relatively constant for about the first 60 minutes of pumping. After 60 minutes, the temperature decreased because the pumping rate was increased to collect the three samples for laboratory analysis. The ground-water temperature in the aquifer (10.4°C) is less than that measured in the sampling chamber because the sampling chamber, pump, hoses, and tubing are exposed to warmer atmospheric conditions. Dissolved oxygen decreased from 3.5 mg/L after seven minutes of pumping to 0.8 mg/L after 67 minutes of pumping. The rapid decline in dissolved oxygen during the first 20 minutes of pumping probably reflects air purging from the pump hoses, tubing, and sampling chamber.

Field determinations of Fe^{2+} and total iron were made during the sampling period on an unfiltered sample using a Hach PR/2000 spectrophotometer. Total iron was greater than 3 mg/L (maximum limit of detection) and Fe^{2+} was 0.86 mg/L. Fe^{3+} was calculated at greater than 2.14 mg/L.

After 60 minutes of pumping, three samples were collected for major cation and anion analysis. Analysis indicates the water in the casing storage is a calcium-bicarbonate type with a dissolved-solid concentration of 703 mg/L (computed using field HCO^-_3) (Appendix II.)

During the sampling period, the water was pale yellow-brown and a red-brown precipitate accumulated in the bottom of the sampling chamber. The red-brown precipitate probably was ferrihydrite.

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As with the 12-inch diameter injection well, casing storage water in the 8-inch diameter injection well is characterized by a slightly acidic pH with iron occurring predominantly as Fe^{3+}. It is apparent that Fe^{2+} is unstable in the casing storage water and precipitates to form ferrihydrite. This iron oxide precipitation reaction releases hydrogen ions (H^+) thereby lowering pH. The slightly acidic pH associated with casing storage water in the injection well supports ferrihydrite precipitation.

The geochemical model WATEQ4F (Ball and Nordstrom, 1991) was used to evaluate the potential for mineral precipitation in the casing storage water. The calculated saturation index for calcite was 0.048 and the calculated saturation index for ferrihydrite was 3.728. Based on the above, an increase in pH, or a significant increase in water temperature could cause calcite precipitation in the well. In the presence of free oxygen, ferrihydrite precipitation is likely.

Redox potential was calculated by WATEQ4F using the Fe^{3+}/Fe^{2+} couple and the Sato (1960) dissolved oxygen method. Fe^{3+} was estimated assuming a total iron concentration of 3.0 mg/L. A redox potential of +0.358 volts was calculated using the Fe^{3+}/Fe^{2+} couple and a redox potential of +0.186 volts was calculated by the Sato method. The positive redox potentials indicate an oxidizing environment.

Iron Bacteria Analysis

As with the supply well and 12-inch diameter injection well, the temperature, dissolved Fe^{2+}, pH, dissolved oxygen, and Eh measured in the casing storage of the 8-inch diameter injection well all favor iron bacteria growth. The sample collected on June 16, 1993 for iron

bacteria analysis was stored in a 32-ounce amber glass jar (Lab I.D.#11397) (Appendix III). On June 17, 1993, another 32-ounce water sample was collected for iron bacteria analysis by inserting a two-foot long, 2-inch diameter brass tube about five feet beneath the top of the sand inside the well screen (Lab I.D. #11398) (Appendix III). The sample consisted of predominantly oxidized sand with a small amount of orange-red water. Both samples were chilled immediately upon collection and dropped off at the ND State Department of Health and Consolidated Laboratories on June 17, 1993. The samples were examined for iron bacteria on June 21, 1993 and results indicated no detection of iron bacteria.

FOUR-INCH DIAMETER INJECTION WELLS

Construction Data

In January 1989, Falk Well Drilling installed four, 4-inch diameter injection wells to be used in conjunction with the 12-inch and 8-inch diameter injection wells originally installed in 1982. These four additional wells were installed to reduce the frequency of remediation applications due to plugging. Completion reports for these four wells were not submitted to the Board of Water Well Contractors. Based on a telephone conversation with Jim Falk, Falk Well Drilling, the four injection wells are constructed with 4-inch diameter PVC casing to a depth of 30 feet, and 40 feet of either 30- or 40-slot plastic screen to a depth of 70 feet. The wells were gravel packed. No record exists regarding the measurement of specific capacity at the time of well construction.

In August 1993, M&W Drilling installed a replacement injection well (131-059-28BBB11) for injection well 131-059-28BBB10 (fig. 2). The completion report indicates sand and gravel to a depth of 64 feet. The well was completed with 4-inch plastic casing to a depth of 34 feet and 30 feet of 4-inch pipe size, 60-slot PVC screen from 34 to 64 feet.

Well Hydraulics

During July 1993, M&W Drilling removed the pitless units and developed the four wells installed by Falk Well Drilling using high pressure water-jetting techniques. The development procedure was as previously described for the 8-inch diameter injection well.

After pitless units were removed from the wells, total depths were measured. Well 131-059-28BBB7 was filled with oxidized sand to a depth of 57 feet, wells 131-059-28BBB8 and BBB9 were filled with oxidized sand to a depth of 58 feet, and well 131-059-28BBB10 was filled with oxidized sand to a depth of 36.9 feet. Prior to and after evacuating the sand from each well, the pump broke suction at a pumping rate of five gallons per minute during each specific capacity test. Based on the above, the initial (pre-development) specific capacity measured at each well was less than about 0.5 gallons per minute per foot. During the development process, large amounts of oxidized sand and red-orange-brown colored water were removed from all four wells.

The specific capacity at well 131-059-28BBB10 was not improved to an acceptable level during development. As a result, this well was abandoned and a replacement well (131-059-28BBB11) was completed 10 feet east of well BBB10. Maximum specific capacities of

the 4-inch diameter injection wells after development are summarized in Table 1.

Table 1. -- Specific capacities of 4-inch diameter injection wells

Well Location	Pumping Rate (gallons per minute)	Duraton of Test (hours)	Specific Capacity (gallons per minute per foot)
131-059-28BBB7	67.1	0.5	13.8
131-059-28BBB8	67.1	1.0	14.6
131-059-28BBB9	67.1	1.0	16.4
131-059-28-BBB11	67.1	2.0	23.7

Samples for iron bacteria and water chemistry analysis were not collected from these wells. Data of this type from the supply well and 12- and 8-inch injection wells were deemed sufficient to evaluate the cause(s) of injection well plugging.

WATER CHEMISTRY EVALUATION DURING CIRCULATION THROUGH THE SCHOOL (HEAT PUMP/PASSIVE COOLING NOT OPERATING)

During the afternoon of June 16, 1993, all pitless units were removed from the 12-, 8-, and four, 4-inch diameter injection wells. Prior to developing the injection wells, the production (supply) well was pumped at a rate of about 650 gallons per minute for one hour. Water was circulated through the school without engaging the heat pump. Because the injection wells were plugged, water discharged through the tops of the injection wells at land surface. For about the first 45 minutes of pumping, a large amount of red-orange-brown sediment was observed in the discharge water. The sediment consisted of very soft, fluffy solid masses up to about two-inches square and about one-fourth inch thick. This sediment (probably ferrihydrite)

originated in the school plumbing facilities and possibly the discharge pipe line.

During the morning of June 17, the production well was again turned on to obtain a water sample for chemical analysis. Water from the production well was again circulated through the system without engaging the heat pump. Discharge from the top of injection well 131-059-28BBB10 contained a lot of air bubbles. No air bubbles were observed in discharge from the top of injection well 131-059-28BBB9. As a result, a water sample was collected for chemical analysis from the top of this well using the gas-squeeze pump.

After about 20 minutes of pumping until the end of the sampling period (58 minutes), the pH remained relatively constant varying between 7.37 and 7.40 (fig. 13). During the first 45 minutes of pumping the water temperature varied from 11.3 to 11.4° C. At the end of the sampling period, the water temperature dropped to 11.1° C reflecting cooling of the pump hoses, tubing, and sampling chamber. As with other samples, the measured water temperature is above the aquifer water temperature because the pump hose, tubing, and sampling chamber are exposed to the atmosphere. Dissolved oxygen also remained relatively constant varying between 6.4 and 7.0 mg/L. The source of the dissolved oxygen was from air purging in the heat-pump plumbing and conveyance facilities. Pipe-full conditions were not maintained in the supply and discharge parts of the heat-pump conveyance facilities when the system was not operating.

Field determinations of Fe^{2+} and total iron were made during the sampling period on an unfiltered sample using a Hach DR/2000 spectrophotometer. Total iron was 0.86 mg/L, Fe^{2+} was 0.41 mg/L,

Figure 13.-- Temporal variation in pH, temperature, and dissolved oxygen in ground water from the Oakes school production well (Sampled 6/17/93 - Sampling point at 4-inch injection well)

and Fe^{3+} was calculated at 0.45 mg/L. The large Fe^{3+} concentration probably reflects suspended ferrihydrite originally precipitated in the heat-pump plumbing facilities and pipelines when the system was not operating.

After 50 minutes of pumping, three water samples were collected for major cation and anion analysis. Analysis indicates the water is a calcium-bicarbonate type with a dissolved-solids concentration of 681 mg/L (computed using field HCO^-_3)(Appendix II).

During the sampling period, a very fine red-brown sediment accumulated in the bottom of the sampling chamber. The red-brown sediment was probably ferrihydrite.

The geochemical model WATEQ4F (Ball and Nordstrom, 1991) was used to evaluate the potential for mineral precipitation and associated injection well plugging. The calculated saturation index for calcite was 0.344 and the calculated saturation index for ferrihydrite was 3.270. Based on the above, an increase in pH, or a significant increase in water temperature could cause calcite precipitation. In the presence of free oxygen, ferrihydrite precipitation is likely.

Redox potential was calculated by WATEQ4F using the Fe^{3+}/Fe^{2+} couple and the Sato (1960) dissolved oxygen method. A redox potential of +0.280 volts was calculated using the Fe^{3+}/Fe^{2+} couple and a redox potential of +0.174 volts was calculated by the Sato method. The positive redox potentials indicate an oxidizing environment.

WATER CHEMISTRY EVALUATION DURING CIRCULATION THROUGH THE PASSIVE COOLING SYSTEM

On September 1, 1993, a water sample was collected for chemical analysis inside the school to evaluate the impact on water

chemistry as water from the supply well is circulated through the passive cooling system. Passive cooling is accomplished by fans blowing air across radiator-like pipe configurations and into duct work to circulate cool air throughout the building. Ground-water is circulated through the radiator-like pipe configurations and discharged into the injection wells with an increase in temperature of less than about three degrees centigrade depending on atmospheric temperature. The templifier unit is by-passed during periods of passive cooling.

The water sample for chemical analysis was collected at a small petcock installed in the discharge line after water circulated through the passive cooling system. During the 130-minute sampling period, no red-brown sediment accumulated in the sample chamber. In addition, the water was clear and air bubbles were not visible. Prior to sampling, the supply well had been pumping continuously for about 24 hours.

During the first 45 minutes of the monitoring period, ground water was not circulated through the passive cooling system. After 45 minutes during the monitoring period, water was circulated through the passive cooling system until the end of the 130-minute monitoring period. The increase in water temperature after 45 minutes reflects the effect of passive cooling on the discharge water (fig. 14). pH varied between 7.31 and 7.39 during the 130-minute monitoring period. Initially, dissolved oxygen was measured at 1.0 mg/L and after about 45 minutes decreased to 0.2 mg/L. The decreasing dissolved oxygen with time probably reflects air purging from the sample chamber and associated tubing. Field determinations for iron on a raw
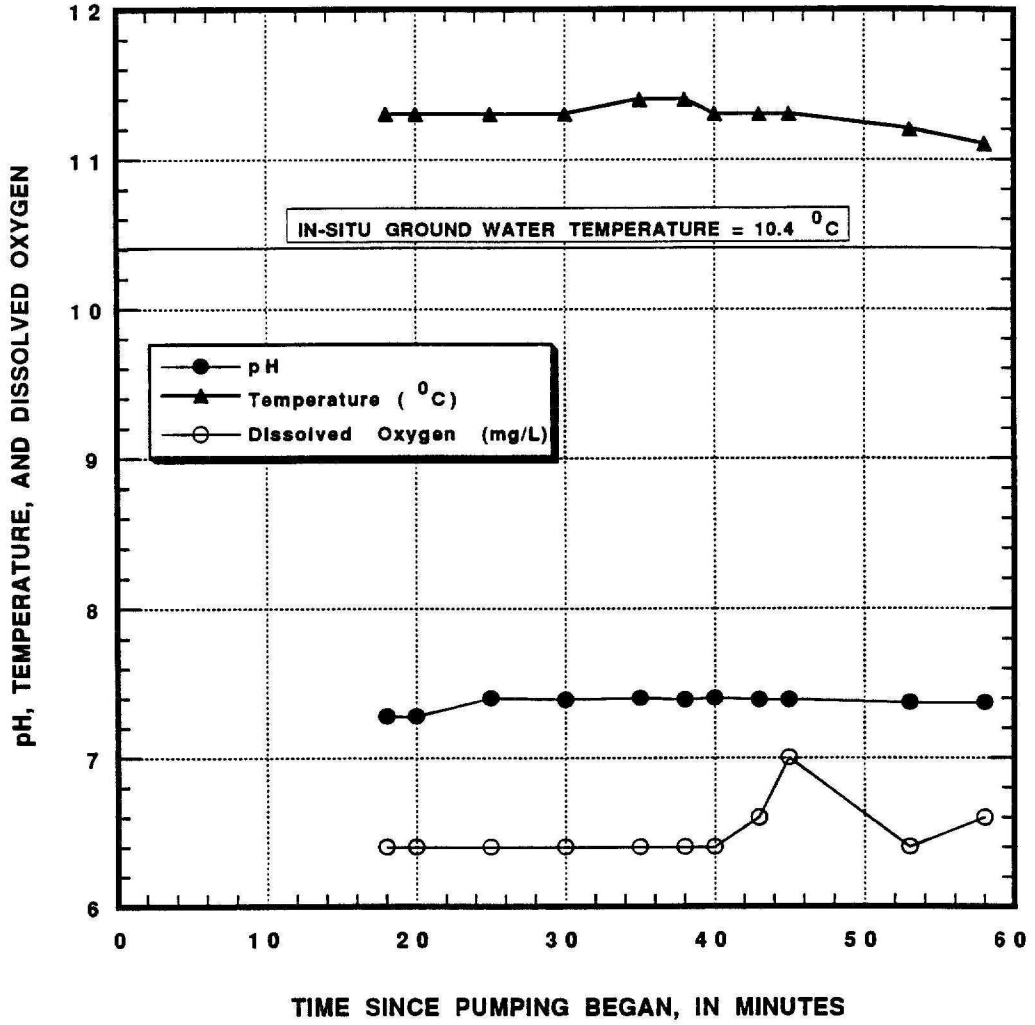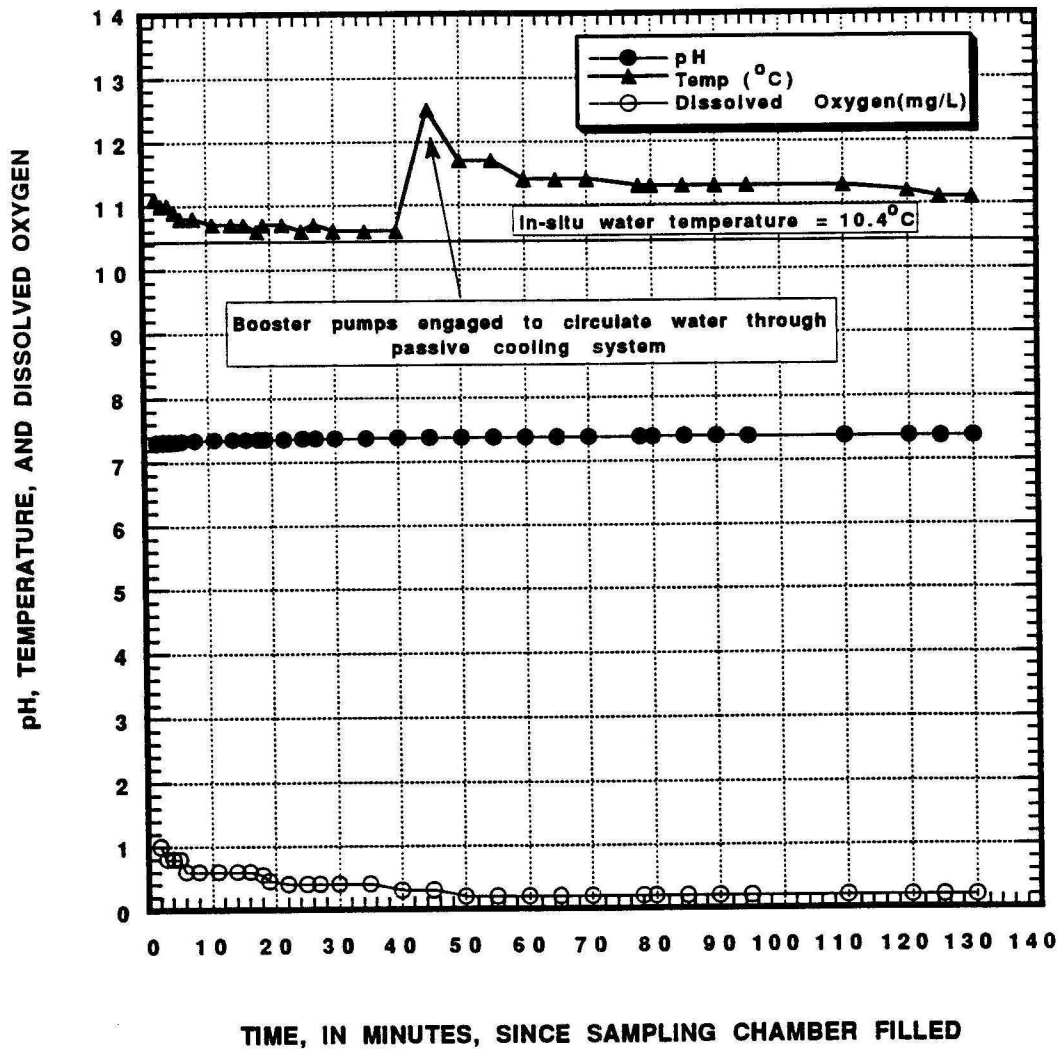
Figure 14.-- Temporal variation in pH, temperature, and dissolved oxygen in ground water from the Oakes School production well (sampled 9/1/93 - Sampled inside school prior to injection)

sample indicate an Fe^{2+} concentration of 0.83 mg/L, an Fe^{3+} concentration of 0.01 mg/L, and a total iron concentration of 0.84 mg/L.

After 120 minutes of monitoring, three water samples were collected for major cation and anion analysis. Analysis indicates the water is a calcium-bicarbonate type with a dissolved-solids concentration of 634 mg/L (computed using field HCO_3^-) (Appendix II).

The geochemical model WATEQ4F (Ball and Nordstrom, 1991) was used to evaluate the potential for mineral precipitation and associated injection well plugging. The calculated saturation index for calcite was 0.355 and the calculated saturation index for ferrihydrite was 1.569. Based on the above, an increase in pH or a significant increase in water temperature could cause calcite precipitation. In the presence of free oxygen, ferrihydrite precipitation is likely.

Redox potential was calculated by WATEQ4F using the Fe^{3+}/Fe^{2+} couple and the Sato (1960) dissolved oxygen method. A redox potential of +0.164 volts was calculated using the Fe^{3+}/Fe^{2+} couple and a redox potential of +0.153 volts was calculated by the Sato method. The positive redox potentials indicate an oxidizing environment.

Effects of Passive Cooling on Ground-Water Chemistry

The sample collected from the 12-inch diameter supply well (131-059-28BAA1) after 70 hours of pumping during the aquifer test in 1982 indicates a calcium-bicarbonate type water with a dissolved-solids concentration of 408 mg/L. Iron (Fe^{2+}) concentration was 0.50 mg/L.

The sample collected on July 26, 1993 from 131-059-28BAA1 after one hour of pumping indicates a calcium-bicarbonate-sulfate type water with a dissolved-solids concentration of 854 mg/L. Fe^{2+} was 1.02 mg/L, Fe^{3+} was 0.06 mg/L, and total iron was 1.08 mg/L. Field pH and dissolved oxygen were 7.24 and 0.4 mg/L, respectively.

The sample collected on September 1, 1993 from 131-059-28BAA1 after 26 hours of pumping and after circulating through the passive cooling system indicates a calcium-bicarbonate type water with a dissolved solids concentration of 634 mg/L. Fe^{2+} was 0.83 mg/L, Fe^{3+} was 0.01 mg/L, and total iron was 0.84 mg/L. Field pH and dissolved oxygen were 7.38 and 0.2 mg/L, respectively.

Based on the above analyses, there is a significant amount of natural variation in water chemistry from well 131-059-28BAA1. Water chemistry varies from a calcium-bicarbonate type to a calcium-bicarbonate-sulfate type with dissolved solids ranging from 408 to 854 mg/L. The water chemistry of the sample collected during passive cooling is about intermediate between the August 1982 and July 1993 samples. Most of the differences in dissolved-solids concentrations are due to differences in calcium, bicarbonate, and sulfate. Chemical variations of this type and magnitude occur in the Oakes aquifer over relatively short distances from net recharge to net discharge areas. However, net discharge areas characterized by high calcium and sulfate concentrations do not occur near the Oakes school study area.

Based on the fact that the ground-water supply is slightly oversaturated with respect to calcite, calcite precipitation could occur in the plumbing facilities or injection wells if during passive cooling the pH and/or water temperature increases significantly. The

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increase in pH from 7.24 (July 26 sample) to 7.38 (September 1 sample) may be a natural variation or the result of CO_2 degassing caused by a decrease in pressure in the pump impeller. Regardless of the cause, the change in pH is small and, as a result, will have a negligible effect on calcite precipitation. In addition, the increase in water temperature (up to about $3^\circ C$ during passive cooling) is also insignificant with respect to initiating calcite precipitation.

As previously stated, in the presence of free oxygen, ferrihydrite precipitation is likely. Dissolved oxygen ranged from 0.4 mg/L in the supply well (7/26/93 sample) to 0.2 mg/L (9/1/93 sample - after passive cooling circulation). These small values may be caused by leaks in and/or diffusion through the sampling apparatus. Free oxygen is not being introduced in any significant quantity into the discharge water during passive cooling and, as a result, ferrihydrite precipitation and associated injection well plugging are not considered likely.

Iron bacteria were not detected in stagnant water/sediment samples collected from the 12- and 8-inch diameter injection wells. This suggests that injection well plugging is not caused by iron bacteria masses and associated ferrihydrite precipitation. However, filamentous iron bacteria are sessile, that is, they fix themselves to solid surfaces such as well screen, casing, and drop pipes. As a result, detection can be difficult because iron bacteria may not readily occur in the water sample. In addition, bacteria filaments in sludge taken from injection wells may only be dead remnants passing from the supply well (Smith, 1984). Injection well culturing techniques may be required to determine the existence of iron bacteria. In-line, flow-cell assemblies can also be used to collect biofilm samples on glass slides

in an effort to monitor iron producing bacteria in wells (Tuhela and others, 1993).

WATER CHEMISTRY EVALUATION DURING CIRCULATION THROUGH THE HEAT PUMP SYSTEM

On December 27, 1993, a water sample was collected for chemical analysis inside the school to evaluate the impact on water chemistry as water from the supply well is circulated through the heat pump system. The water sample for chemical analysis was collected at a small petcock installed in the discharge line after water circulated through the heat pump system. During the 76-minute sampling period, no red-brown sediment accumulated in the sample chamber. In addition, the water was clear and air bubbles were not visible. Prior to sampling, the supply well had been pumping almost continuously since November 23, 1993.

The water temperature ranged from 12.9°C when the sample chamber was initially filled to 11.4°C after monitoring for 43 minutes (fig. 15). Water temperature stabilized between 11.4°C and 11.5°C after 43 minutes of monitoring to the end of the 76-minute monitoring period. pH decreased rather steadily from 6.72 to about 6.67 at the end of the 76-minute monitoring period. Initially, dissolved oxygen was measured at 1.0 mg/L and after about 30 minutes of monitoring, decreased to 0.45 mg/L. The decreasing dissolved oxygen with time probably reflects air purging from the sample chamber and associated tubing. Field determinations for iron on the raw sample indicate an Fe^{2+} concentration of 0.75 mg/L, an Fe^{3+} concentration of 0.01 mg/L, and a total iron concentration of 0.76 mg/L.

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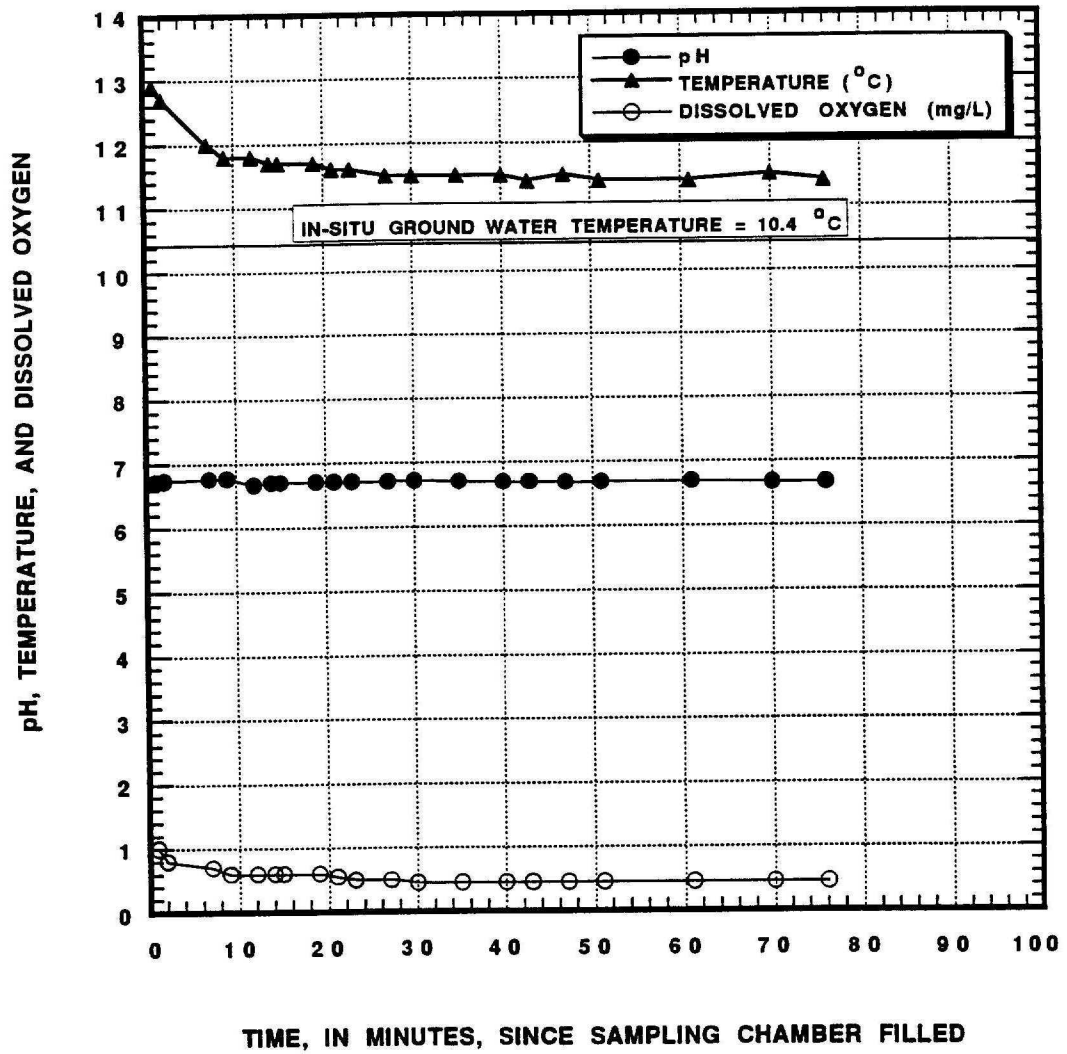
Figure 15.-- Temporal variation in pH, temperature, and dissolved oxygen in ground water from the Oakes School production well (sampled 12/27/93 - Sampled inside school prior to injection)

After 60 minutes of monitoring, three water samples were collected for major cation and anion analysis, analysis indicates the water is a calcium-bicarbonate type with a dissolved-solids concentration of 625 mg/L (computed using field HCO^-_3) (Appendix II).

The geochemical model WATEQ4F (Ball and Nordstrom, 1991) was used to evaluate the potential for mineral precipitation and associated injection well plugging. The calculated saturation index for calcite was -0.371 and the calculated saturation index for ferrihydrite was +1.154. Calcite precipitation is not considered likely and in the presence of free oxygen, ferrihydrite precipitation is likely.

Redox potential was calculated by WATEQ4F using the Fe^{3+}/Fe^{2+} couple and the Sato (1960) dissolved oxygen method. A redox potential of +0.259 was calculated using the Fe^{3+}/Fe^{2+} couple and a redox potential of +0.197 was calculated by the Sato method. The positive redox potentials indicate an oxidizing environment.

Effects of Heat Pump Circulation on Ground-Water Chemistry

The sample collected on December 27, 1993 after circulation through the heat pump system is very similar to the analysis collected on September 1, 1993 during passive cooling. A major difference is the decrease in pH from 7.38 (9/1/93) to 6.69 (12/27/93). It was not determined if the decrease in pH is caused by natural variation in the Oakes aquifer or by circulation through the heat pump. Regardless of the cause, the decreased pH reduces the potential for calcite (lime) precipitation and associated injection well plugging. In addition, more acidic conditions increase the solubility of Fe^{3+}. However, in the

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presence of free oxygen, with a pH of 6.67, ferrihydrite precipitation is still likely.

The lowest temperature measured in the sample chamber during the December 27, 1993 monitoring period was 11.4°C (fig. 15) During the previous summer, the in-situ temperature of ground water in the supply well was measured at 10.4°C. It was anticipated that after circulation through the heat pump, the discharge water temperature would be between 2 to 4°C below the in-situ water temperature. The higher temperature (11.4°C) measured in the sample chamber probably reflects warming due to ambient temperature in the utility room where discharge was monitored. A 4°C decrease in temperature below the in-situ temperature (10.4°C) would have a minor effect on calcite solubility. The effect would be to increase calcite solubility, thereby reducing the potential for calcite precipitation and associated injection well plugging.

CAUSES OF INJECTION WELL PLUGGING

Based on injection well inspection and evaluation water chemistry analyses, injection well plugging was primarily caused by entrainment of fine-grained sediment in the well screen/aquifer interface and ferrihydrite precipitation. Biofouling due to iron bacteria growth was not indicated.

During July 1993, when the pump was removed from the supply well, it was determined that the back-flow prevention valve was improperly installed and would not fully close when the pump was shut off. This allowed water in some of the heat-pump plumbing facilities inside the school and in the supply pipeline to drain back

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through the well. Back flushing caused rearrangement of the aquifer matrix adjacent to the well screen. When the pump was restarted, some rearranged fine-grained sediment moved through the well screen into the heat pump distribution system and ultimately accumulated in the injection wells.

Each time the pump was shut off, pipe-full conditions were not maintained and air entered the supply part of the plumbing facilities. In the presence of free oxygen, ferrihydrite precipitation occurred in the static water remaining in the plumbing facilities. When pumping began in the supply well, the ferrihydrite precipitate was flushed through the heat pump system and into the injection wells. In addition, until the plumbing facilities were entirely air purged, the injection water was aerated causing ferrihydrite precipitation. The rate of this precipitation reaction is rapid at near neutral pH (Hem, 1985). Data compiled by Sung and Morgan (1980, in Hem, 1985), and determined from their own investigations, suggest that ferrihydrite precipitation has a half-time of about 18 minutes in aerated solutions with ionic strengths of 0.02 or less at 25°C, and pH 6.84 in the presence of about 550 mg/L HCO^-_3. This suggests that ferrihydrite precipitation also may have occurred further out into the aquifer.

The drop pipes in the injection wells are not equipped with back-pressure valves. During the initial periods of heat pump operation, when injection capacities of the wells are greatest, pipe-full conditions may not be met in the discharge pipeline. This may cause aeration of the discharge water and subsequent ferrihydrite precipitation in the aquifer. In addition, without back pressure valves on the drop pipes, pipe-full conditions were not maintained in the

discharge part of the heat pump system when the supply well was not operational. This caused ferrihydrite to precipitate in static water remaining in the plumbing facilities which was later flushed into the injection wells when the supply well pump was restarted. Until the plumbing facilities were entirely air purged, the injection water was aerated which may have caused ferrihydrite to precipitate in the aquifer.

REMEDIAL ACTIONS

During August 1993, a new back-flow prevention valve was properly installed in the pump column of the supply well. This action coupled with the previously described well development process should all but eliminate sand pumping and subsequent entrainment in the injection wells. In addition, the back-flow prevention valve will maintain pipe-full conditions in the supply part of the heat pump system, thereby greatly reducing ferrihydrite precipitation in the plumbing facilities.

In September 1993, a solenoid activated valve was installed in the discharge pipeline inside the school. This valve will close just prior to supply well shut down. The purpose of this valve is to maintain pipe-full conditions within the plumbing facilities throughout the school. This should reduce the potential for ferrihydrite precipitation and subsequent flushing into the injection wells.

Back-pressure valves were installed on all injection well drop pipes at the water table (about 20 feet below land surface). About seven to eight feet of additional drop pipe was attached to the bottom of each back-pressure valve so that the drop pipe/valve assembly

extended below the water table. Two-inch diameter back-pressure valves and two-inch diameter drop pipes were installed in the four, 4-inch diameter injection wells. Three, 2-inch diameter back-pressure valves and three 2-inch diameter drop pipes were installed in the 8-inch diameter injection well. One, 4-inch diameter back-pressure valve and a 4-inch diameter drop pipe was installed in the 12-inch diameter injection well. All valves are rated at 6.5 pounds per square inch cracking pressure and 16.5 pounds per square inch full-open pressure.

Manual valves were installed at each injection well in the discharge pipeline near the inlet to each pitless unit. When each valve is closed, discharge is routed to a nearby storm sewer. These valves were installed to enable flushing of the heat pump/distribution system after prolonged periods of non-use that commonly occur during the spring and fall.

CONCLUSIONS

Results of this investigation indicate that injection well plugging was caused by entrainment of fine-grained sediment in the well screen/aquifer interface and ferrihydrite precipitation. An improperly installed back-flow prevention valve on the pump column assembly in the supply well was the major cause of sand mobilization and subsequent deposition in the injection wells.

Water chemistry analyses indicated in the presence of free oxygen, Fe^{2+} was unstable and ferrihydrite precipitation was likely. Large amounts of ferrihydrite were flushed from the plumbing facilities and removed from the injection wells during development.

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The improperly installed back-flow prevention valve on the supply well, and the lack of back-pressure valves at the base of the drop pipes in each injection well did not maintain pipe-full conditions in plumbing facilities when the system was not operating. As a result, ferrihydrite precipitation occurred in the static water remaining in the plumbing facilities. When the supply well pump was re-started after each cooling and heating cycle, ferrihydrite precipitate was flushed into the injection wells thereby gradually plugging the well screens.

In August 1993, a back-flow prevention valve was properly installed in the supply well and a solenoid-type valve was installed in the discharge line inside the school. In addition, drop-pipes in each of the six injection wells were equipped with back-pressure valves. These actions were taken to maintain pipe-full conditions in the plumbing facilities when the system is not operating. Pipe-full conditions reduce exposure to free oxygen and, therefore, reduce ferrihydrite precipitation and subsequent injection well-screen plugging.

Manual valves were also installed at each injection well in the discharge pipeline near the inlet to each pitless unit. When each valve is closed, discharge is routed to a nearby storm sewer. These valves were installed to enable flushing of the heat pump/distribution system after prolonged periods of non-use that commonly occur during the spring and fall.

During heating and passive cooling cycles, no significant changes in temperature and dissolved oxygen were measured. pH decreased from 7.38 (passive cooling) to 6.67 (heating). It was not determined if

the decrease in pH was caused by natural variations in the Oakes aquifer or by circulation through the heat pump. Regardless of the cause, the decreased pH reduces the potential for calcite (lime) precipitation and associated injection well plugging. The small dissolved oxygen concentrations measured during passive cooling and heating suggest that ferrihydrite precipitation will be minor. Although water temperature, dissolved Fe^{2+} and oxygen, pH and Eh favor iron bacteria growth, biofouling of the injection wells due to iron bacteria growth was not indicated.

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APPENDIX I. - Lithologic logs of wells

131-059-28BBA1
OAKES PUBLIC SCHOOL DISTRICT

Date Completed:	7/15/82	Purpose:	Supply Well
L.S. Elevation (ft):	1315	Well Type:	12" PVC
Depth Drilled (ft):	75	Aquifer:	Oakes
Screened Interval (ft):	50-70	Source:	Falk Bros.

Lithologic Log

Unit	Description	Depth (ft)
GRAVEL	yellow	0-30
SAND		30-68
ROCK		68-70
CLAY		70-75

131-059-28BBA2
OAKES PUBLIC SCHOOL DISTRICT

Date Completed:	Unknown	Purpose:	Observation Well
L.S. Elevation (ft):	1315	Well Type:	2" PVC
Depth Drilled (ft):	72	Aquifer:	Oakes
Screened Interval (ft):	59-62	Source:	M&W Drilling

Lithologic Log

Unit	Description	Depth (ft)
GRAVEL		0-1
TOPSOIL		1-2
SAND	medium, brown	2-22
SAND	medium	22-35
SAND	fine, lignitic	35-40
SAND	coarse	40-59
SAND & GRAVEL	coarse sand to fine gravel	59-64
GRAVEL	fine to medium	64-67
GRAVEL	medium	67-69

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TILL   gray   69-72

131-059-28BBB1

OAKES PUBLIC SCHOOL DISTRICT

Date Completed:	8/16/82	Purpose:	Observation Well
L.S. Elevation (ft):	1315	Well Type:	2" PVC
Depth Drilled (ft):	70	Aquifer:	Oakes
Screened Interval (ft):	48-68	Source:	SWC

Lithologic Log

Unit	Description	Depth (ft)
TOPSOIL		0-4
SAND	fine to medium	4-25
SAND & GRAVEL	medium sand to granule gravel, moderately well sorted	25-30
SAND	medium to coarse, subrounded, well sorted	30-55
SAND	medium to very coarse, boulders	55-70

131-059-28BBB2

OAKES PUBLIC SCHOOL DISTRICT

Date Completed:	8/16/82	Purpose:	Observation Well
L.S. Elevation (ft):	1315	Well Type:	2" PVC
Depth Drilled (ft):	69	Aquifer:	Oakes
Screened Interval (ft):	47-67	Source:	SWC

Lithologic Log

Unit	Description	Depth (ft)
TOPSOIL		0-2
SAND	fine to medium, subrounded, moderately well sorted	2-15
SAND	medium to coarse, subrounded, moderately well sorted	15-28
SAND	fine to medium, well sorted	28-50
SAND & GRAVEL	medium to very coarse sand, 20% gravel, boulders at 69 feet	50-69

131-059-28BBB3
OAKES PUBLIC SCHOOL DISTRICT

Date Completed:	8/18/82	Purpose:	Observation Well
L.S. Elevation (ft):	1315	Well Type:	2" PVC
Depth Drilled (ft):	69	Aquifer:	Oakes
Screened Interval (ft):	49-69	Source:	SWC

Lithologic Log

Unit	Description	Depth (ft)
TOPSOIL	sandy, black	0-3
SAND	fine to very coarse, predom. medium to coarse	3-25
SAND & GRAVEL	coarse sand to granule gravel, subrounded, moderately well sorted	25-35
SAND	medium to very coarse, subrounded	35-50
SAND & GRAVEL	medium sand to fine gravel, subangular, moderately well sorted	50-69

131-059-28BBB4
OAKES PUBLIC SCHOOL DISTRICT

Date Completed:	9/21/82	Purpose:	Injection well (aband)
L.S. Elevation (ft):	1315	Well Type:	8" PVC
Depth Drilled (ft):	72	Aquifer:	Oakes
Screened Interval (ft):	40-70	Source:	Falk Bros.

Lithologic Log

Unit	Description	Depth (ft)
GRAVEL	yellow	0-30
SAND		30-68
BOULDERS		68-70
CLAY		70-72

131-059-28BBB5

OAKES PUBLIC SCHOOL DISTRICT

Date Completed:	9/23/82	Purpose:	Injection Well
L.S. Elevation (ft):	1315	Well Type:	8" PVC
Depth Drilled (ft):	70	Aquifer:	Oakes
Screened Interval (ft):	40-70	Source:	Falk Bros.

Lithologic Log

Unit	Description	Depth (ft)
GRAVEL	yellow	0-30
SAND		30-68
ROCK		68-70
CLAY		70-72

131-059-28BBB6

OAKES PUBLIC SCHOOL DISTRICT

Date Completed:	7/20/82	Purpose:	Injection Well
L.S. Elevation (ft):	1315	Well Type:	12" PVC
Depth Drilled (ft):	70	Aquifer:	Oakes
Screened Interval (ft):	40-70	Source:	Falk Bros.

Lithologic Log

Unit	Description	Depth (ft)
GRAVEL	yellow	0-30
SAND		30-68
ROCK		68-70
CLAY		70-72

131-059-28BBB7

OAKES PUBLIC SCHOOL DISTRICT

Date Completed:	1/89	Purpose:	Injection Well
L.S. Elevation (ft):	1315	Well Type:	4" PVC
Depth Drilled (ft):	Unknown	Aquifer:	Oakes
Screened Interval (ft):	30-70	Source:Completion report not filed

Lithologic Log

**** COMPLETION REPORT NOT FILED ****

131-059-28BBB8

OAKES PUBLIC SCHOOL DISTRICT

Date Completed:	00/00/00	Purpose:	Industrial Well
L.S. Elevation (ft):	1315	Well Type:	4" PVC
Depth Drilled (ft):	Unknown	Aquifer:	Oakes
Screened Interval (ft):	30-70	Source:	Completion report not filed

Lithologic Log

**** COMPLETION REPORT NOT FILED ****

131-059-28BBB9

OAKES PUBLIC SCHOOL DISTRICT

Date Completed:	00/00/00	Purpose:	Industrial Well
L.S. Elevation (ft):	1315	Well Type:	4" PVC
Depth Drilled (ft):	0	Aquifer:	Oakes
Screened Interval (ft):	30-70	Source:	Completion report not filed

Lithologic Log

**** COMPLETION REPORT NOT FILED ****

131-059-28BBB10

OAKES PUBLIC SCHOOL DISTRICT

Date Completed:	1/89	Purpose:	Industrial Well
L.S. Elevation (ft):	1315	Well Type:	4" PVC
Depth Drilled (ft):	Unknown	Aquifer:	Oakes
Screened Interval (ft):	30-70	Source:	Completion report not filed

Lithologic Log

**** COMPLETION REPORT NOT FILED ****

131-059-28BBB11

OAKES PUBLIC SCHOOL DISTRICT

Date Completed:	8/1993	Purpose:	Industrial Well
L.S. Elevation (ft):	1315	Well Type:	4" PVC
Depth Drilled (ft):	64	Aquifer:	Oakes
Screened Interval (ft):	34-64	Source:	M&W Drilling

Lithologic Log

Unit	Description	Depth (ft)
TOPSOIL		0-1
SAND	brown	1-18
SAND	medium, gray	18-32
SAND & GRAVEL	medium to coarse sand, 10% fine gravel	32-64

APPENDIX II. -- Water chemistry analyses

Appendix II. -- Water chemistry analyses

Location	Screened Interval (ft)	Date Sampled	SiO$_2$	Fe	Mn	Ca	Mg	Na	K	HCO$_3$	CO$_3$	SO$_4$	Cl	F	NO$_3$	B	TDS	Hardness as CaCO$_3$	as NCH	% Na	SAR	Spec Cond (µmho)	Temp (oC)	pH
131-059-28BBA1	50-70	08/23/82	29	0.5	0.66	92	24	27	7.3	320	0	70	12	0.4	0.5	0.18	422	330	66	15	0.6		11	
131-059-28BBA1	50-70	06/17/93	29	0.55	0.81	140	38	36	6.8	419	0	190	32	0.2	0	0.15	713	510	110	13	0.7	1014	11.1	7.37
131-059-28BBA1	50-70	07/26/93	29	0.89	0.85	170	42	46	9.3	417	0	320	30	0.2	0	0.2	845	600	270	14	0.8	1220	13.8	7.24
131-059-28BBA1	50-70	09/01/93	29	0.63	0.79	130	36	35	7.3	425	0	150	33	0.3	2.3	0.25	635	470	120	14	0.7	929	11.3	7.38
131-059-28BBA1	50-70	12/27/93	30	0.52	0.82	120	37	34	7.4	418	0	160	28	0.3	1.4	0.17	628	450	110	14	0.7	883	11.4	6.69
131-059-28BBB5	40-70	06/16/93	21	0.88	1.1	140	40	37	7.2	544	0	160	27	0.3	0	0.15	672	510	120	13	0.7	1045	13.2	6.96
131-059-28BBB6	40-70	06/15/93	23	0.22	0.95	140	38	36	7.2	460	0	160	28	0.2	0.2	0.17	656	510	140	13	0.7	1022	11.3	6.92

** Water temperatures shown were measured in sampling chamber and as a result do not represent in-situ values **

APPENDIX III. -- Iron bacteria analyses

———————————————————— Antimicrobial Susceptibility and Organism Identification Report ————————————   ** FINAL **

Name : SHAVER,OAKES PUBLIC SCH
ID# : 11395

                                             Room : DW

Service : IRON BACTERIA

Institution : .

Specimen Number : 00011395
Specimen Source : SPECIAL WATER

                          Collected : 06/16/93   8:30
                          Received : 06/17/93   16:19

Miscellaneous Tests and Comments

IRON BACTERIA NOT FOUND

Comments :   131-059-28-BBB 6 ISC

Organisms Identified

Iso/Result	Identity	Tested	Comments
* 01	.	06/21/93	STATE WATER COMMISSION ATTN BOB SHAVER 900 E BLVD BISMARCK ND 58505

———

*   Susceptibilities, if performed, appear on the following page(s).

Tech : _____
Report Date : 06/21/93 13:23   Source   : SPECIAL WATER   Name : SHAVER,OAKES PUBLIC SCH   ** FINAL
                              Collected : 06/16/93   8:30   ID # : 11395

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——————————————————————— Antimicrobial Susceptibility and Organism Identification Report ——————— ** FINAL **

Name : SHAVER,OAKES PUBLIC SCH
ID# : 11396

Room : DW

Service : IRON BACTERIA

Institution : .

Specimen Number : 00011396
Specimen Source : SPECIAL WATER

Collected : 06/15/93 16:00
Received : 06/17/93 16:19

Miscellaneous Tests and Comments

IRON BACTERIA NOT FOUND

Comments : 131-059-28 BBB 6PD

Organisms Identified

Iso/Result	Identity	Tested	Comments
* 01	.	06/21/93	STATE WATER COMMISSION ATTN BOB SHAVER 900 E BLVD BISMARCK ND 58505

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* Susceptibilities, if performed, appear on the following page(s).

Tech : _____
Report Date : 06/21/93 13:23

Source   : SPECIAL WATER
Collected : 06/15/93 16:00

Name : SHAVER,OAKES PUBLIC SCH
ID # : 11396

** FINAL **

———————————————————— Antimicrobial Susceptibility and Organism Identification Report ———————   ** FINAL **

Name : SHAVER,OAKES PUBLIC SCH
ID# : 11397

                                          Room : DW

Service : IRON BACTERIA

Institution : .

Specimen Number : 00011397
Specimen Source : SPECIAL WATER

                     Collected : **/**/**   **:**
                     Received : 06/17/93   16:20

Miscellaneous Tests and Comments

IRON BACTERIA NOT FOUND

Comments :   131-059-28BBB5 PD2

Organisms Identified

Iso/Result	Identity	Tested	Comments
* 01	.	06/21/93	STATE WATER COMMISSION ATTN BOB SHAVER 900 E BLVD BISMARCK ND 58505

* Susceptibilities, if performed, appear on the following page(s).

Tech :   _pw_   Source   : SPECIAL WATER   Name : SHAVER,OAKES PUBLIC SCH   ** FINAL
Report Date : 06/21/93   13:23   Collected : **/**/**   **:**   ID # : 11397

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—————————————————— Antimicrobial Susceptibility and Organism Identification Report —————————— ** FINAL **

Name : SHAVER,OAKES PUBLIC SCH   Room : DW
ID# : 11398
                        Service : IRON BACTERIA

                        Institution : .

         Specimen Number   : 00011398
         Specimen Source   : SPECIAL WATER   Collected : 06/17/93 **:**
                                           Received : 06/17/93 16:20

Miscellaneous Tests and Comments

     IRON BACTERIA NOT FOUND

    Comments :   131-059-28 BBB SW

Organisms Identified

Iso/Result	Identity	Tested	Comments
* 01	.	06/21/93	STATE WATER COMMISSION ATTN BOB SHAVER 900 E BLVD BISMARCK ND 58505

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*   Susceptibilities, if performed, appear on the following page(s).

Tech :
Report Date : 06/21/93 13:24   Source   : SPECIAL WATER   Name : SHAVER,OAKES PUBLIC SCH   ** FINAL **
                              Collected : 06/17/93 **:**   ID # : 11398

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