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UNIVERSITY OF MINNESOTA
AQUIFER THERMAL ENERGY STORAGE (ATES) PROJECT
REPORT ON THE SECOND LONG-TERM CYCLE

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MASTER

EP

FOREWORD

Seasonal thermal energy storage (STES) involves storing thermal energy, such as winter chill, summer heat, and industrial waste heat, for future use in heating and cooling buildings or for industrial processes. Widespread development and implementation of STES would significantly reduce the need to generate primary energy in the United States. Data indicate that STES is technically suitable for providing 5 to 10% of the nation's energy, with major contributions in the commercial and industrial sectors and in district heating and cooling applications.

Aquifer thermal energy storage (ATES) is predicted to be the most cost-effective technology for seasonal storage of low-grade thermal energy. Approximately 60% of the United States is underlain by aquifers that are potentially suitable for underground energy storage. ATES has the potential to substantially reduce energy consumption and electrical demand. However, the geohydrologic environment that the system will use is a major element in system design and operation, and this environment must be characterized for development of efficient energy recovery.

Under sponsorship of the U.S. Department of Energy (DOE), the Pacific Northwest Laboratory (PNL) manages DOE's STES Program and directs numerical modeling, laboratory studies, and field testing of ATES at several sites. PNL is operated by Battelle Memorial Institute for the U.S. Department of Energy under contract DE-AC06-76RLO 1830.

This report describes the results of the second long-term heat injection/recovery cycle at the St. Paul (Minnesota) field test facility (FTF). Results of four short-term cycles and one long-term cycle have already been published and results of a third long-term cycle will be published at a later date. The St. Paul FTF, operated by the University of Minnesota, is the principal U.S. facility for research on relatively high-temperature ATES. The primary objectives of investigations at the St. Paul FTF are to: 1) evaluate

the technical issues associated with design and operation of a high-temperature ($>100^{\circ}\text{C}$) ATEs system and 2) obtain data on fundamental geotechnical processes to validate laboratory and bench-scale geochemical testing and geohydrothermal modeling.

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ABSTRACT

The technical feasibility of high-temperature [$>100^{\circ}\text{C}$ ($>212^{\circ}\text{F}$)] aquifer thermal energy storage (ATES) in a deep, confined aquifer was tested in a series of experimental cycles at the University of Minnesota's St. Paul field test facility (FTF). This report describes the second long-term cycle (LT2), which was conducted from October 1986 through April 1987. Heat recovery; operational experience; and thermal, chemical, hydrologic, and geologic effects are reported.

Approximately 61% of the 9.21 GWh of energy added to the $9.38 \times 10^4 \text{ m}^3$ of ground water stored during LT2 was recovered. Temperatures of the water stored and recovered averaged 118°C (244°F) and 85°C (185°F), respectively. Results agreed with previous cycles conducted at the FTF. System operation during LT2 was nearly as planned. Operational experience from previous cycles at the FTF was extremely helpful.

Ion-exchange softening of the heated and stored aquifer water prevented scaling in the system heat exchangers and the storage well, and changed the major-ion chemistry of the stored water. Sodium bicarbonate replaced magnesium and calcium bicarbonate as primary ions in the softened water. Water recovered from storage was approximately at equilibrium with respect to dissolved ions. Silica, calcium, and magnesium were significantly higher in recovered water than in injected water. Sodium was significantly lower in water recovered than in water stored.

Temperatures at Ironton-Galesville horizons in storage site monitoring wells reached $\sim 118^{\circ}\text{C}$ ($\sim 244^{\circ}\text{F}$) during LT2. Following heat recovery, temperatures were $\sim 40^{\circ}\text{C}$ ($\sim 104^{\circ}\text{F}$) at the same locations. Slow and slight thermal responses were observed in low permeability zones. No thermal or chemical effects were observed at the remote monitoring site.

SUMMARY

The purpose of the aquifer thermal energy storage (ATES) project at the St. Paul field test facility (FTF) is to conduct high-temperature [$>100^{\circ}\text{C}$ ($>212^{\circ}\text{F}$)] ATES experimental cycles in a deep, confined aquifer to determine the technical feasibility of ATES. Monitoring hydrogeological, hydrogeochemical, and hydrogeothermal effects is an integral, and essential, part of the project. The project, which began in 1980, included designing and constructing the FTF and conducting and modeling four short-term and two long-term ATES cycles. The second long-term cycle (LT2), which lasted 183 days (October 1986 to April 1987), is the subject of this report. Heat recovery; the operational experience of LT2; and thermal, chemical, hydrologic, and geologic effects are reported. Residual heat from cycles completed 18 months previously remained at the site.

The St. Paul FTF was designed to inject and recover heat at a rate of 5 MW (thermal) (1.71×10^7 Btu/hr), using a well doublet 255 m (835 ft) apart, operating at an injection/recovery rate of 18.9 L/sec ($68.1 \text{ m}^3/\text{hr}$, 300 gpm) and at temperatures up to 150°C (302°F). Design delta T (temperature difference across the heat exchanger) is 66°C (119°F). Heat for the experimental ATES cycles was derived from saturated steam supplied to the St. Paul campus by the campus heating plant. Aquifer water for storage was heated by this steam in the condenser and subcooler located at the test site. Heat load for the experimental ATES cycles was simulated by a water-to-air heat exchanger. A field office trailer housed the instrumentation recording equipment. Piping between the storage and source sites was routed through the existing steam tunnel.

LT2 included three phases, each approximately 60-days long: injecting heated water into the Franconia-Ironton-Galesville (FIG) aquifer for storage; storing the heated water; and recovering the stored, heated water from the FIG aquifer. During the heat storage (or injection) phase, water was pumped from the FIG aquifer at the supply well, softened by ion-exchange to prevent scaling in the heat exchangers or the storage well, heated in a shell-and-tube condenser and subcooler, and injected into the FIG aquifer through the storage

well. Following a storage period of approximately 60 days, the heat recovery phase began. During the heat recovery phase, water was pumped from the FIG aquifer at the storage well, the water was cooled by the simulated heating load (a large water-to-air radiator), and returned to the FIG aquifer through the supply well. Temperatures and pressures in the FIG aquifer were monitored at an array of monitoring wells. Major-ion chemistry of the source, softened, injected, and recovered aquifer water was monitored by periodic sampling. Water samples from monitoring wells were also taken.

The following summary includes conclusions drawn from the second long-term cycle (LT2):

1. LT2 lasted 183 days: 59 days of heated-water injection over a 65-day period, 59 days of storage, and 60 days of heated-water recovery.
2. A total of $9.38 \times 10^4 \text{ m}^3$ of water, to which 9.21 GWh of heat was added, was injected and stored; a total of $9.21 \times 10^4 \text{ m}^3$ of water containing 5.54 GWh of heat energy was recovered. Average temperature of the water stored was 118°C (244°F); average temperature of the water recovered was 85°C (185°F).
3. Approximately one-half of the water recovered was warmer than 85°C (185°F), a useful minimum for supplying heat for conventional hot water space heating. All of the recovered water was warmer than 55°C (131°F), useful for supplying domestic hot water, heat pumps, and warming condensate.
4. Energy recovered during this symmetrical ATEs cycle was about 61% of the energy stored, which is consistent with the results from previous cycles conducted and modeled at the site.
5. Ion-exchange water softening of the source water before heating effectively prevented carbonate scaling of the heat exchanger and the storage well. The softener lowered hardness of the source water from 160 mg/L to less than 10 mg/L as calcium carbonate. Sodium concentrations in the source water increased from ~ 44 mg/L to ~ 122 mg/L in the water softener.
6. Ground-water chemistry results from LT2 suggest that the water from the source well was at equilibrium with respect to major ions. Water recovered from storage had reached equilibrium with respect to hardness and silica at the recovered water temperature. Mass balances calculated for different parts of LT2 show effects of ion-exchange softening, changes in equilibrium concentration or water temperature, and mixing.

7. Analyses of water samples collected from the Ironton-Galesville part of the FIG aquifer at one of the monitoring wells 14 m (46 ft) from the injection well during the early part of LT2 indicate that the water injected reached the well less than 2 days after the cycle began. The temperature rose rapidly at the same horizons of the well after 3 days.
8. Modeled results are in close agreement with actual field test results, suggesting that the model adequately describes the aquifer for these ATEs cycles.
9. Temperatures recorded in monitoring wells were consistent with results from the previous test cycles. The layered nature of the aquifer produced an hourglass thermal profile in the 7-m (23 ft) and 14-m (46 ft) distant monitoring wells. Highest temperatures were approximately equal to the average temperature of the water stored [118°C (244°F)]. The monitoring well at a distance of 30.5 m (100 ft) showed a higher temperature in the Ironton-Galesville portion of the aquifer, with only a small temperature rise [to ~45°C (~113°F)] observed in the upper Franconia portion of the aquifer.
10. Leakage between the FIG aquifer and the Mt. Simon aquifer at a storage site monitoring well was detected by higher than ambient sodium concentrations in water samples from the Mt. Simon aquifer collected before LT2. Thermal profiles of monitoring wells revealed that leakage was taking place at well AC1. A packer test suggested that leakage was slow inside the pipe. A thermocouple string and packer were installed before LT2 to determine if there was leakage along the borehole. Results suggest that the leakage rate is slow and may be occurring along the borehole (see Appendix D).

A significant percentage (>60%) of the heat stored on a seasonal basis may be recovered in a confined ATEs system. The performance at the University of Minnesota FTF for both long-term cycles was very consistent. Water softening of hard ground water is one method that can be used successfully to eliminate carbonate scaling during the heat-storing phase.

ACKNOWLEDGMENTS

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REPORT ON THE SECOND LONG-TERM CYCLE

1.0 INTRODUCTION

In May 1980, the University of Minnesota was awarded a contract from Pacific Northwest Laboratory (PNL) as part of the U.S. Department of Energy's Underground Energy Storage Program. The goal was to design and construct an aquifer thermal energy storage (ATES) field test facility (FTF) with a nominal 5-MW thermal input/output capacity using a confined aquifer and, upon completion, perform a series of test cycles. This report describes the second long-term test cycle performed at the University of Minnesota FTF.

The original plan of the project entailed two stages. The first stage was to design and construct a test facility with 5-MW capacity and use it to acquire the basic hydrogeological, hydrogeochemical, and hydrogeothermal data needed to design a 20-MW ATES demonstration system integrated with the University of Minnesota's heating/cooling system. The second stage was to construct and operate the 20-MW system, but program changes resulted in elimination of plans for a 20-MW facility. The operational phase of the project was later modified to a test program comprised of four short-term test cycles (Phase 1) and two long-term cycles (Phase 2) using the 5-MW experimental system.

Final designs for the test facility and monitoring array were prepared after a variance was granted by the Minnesota Pollution Control Agency (MPCA) to allow the injection of water for the short-term cycles, and after appropriate permits were granted by the Minnesota Department of Health (MDH) and Minnesota Department of Natural Resources (DNR). Construction began in September 1980 with the drilling of core holes at the heat-storage and water-supply sites. Construction was completed during winter 1981, and initial isothermal injection testing began in spring 1982. Short-term test cycles were completed in December 1983 (Walton et al. 1991). Preliminary modeling results from four short-term cycles and the first long-term cycle are included

in a series of U.S. Geological Survey publications (Miller 1984, 1985, 1986, 1989; Miller and Voss 1986).

A new variance from the MPCA and new permits from MDH and DNR were required for the two long-term cycles. In August 1984, the permitting aspects were completed. A water softener and a new monitoring well were added to the facility by November 1984; long-term cycle 1 (LT1) was conducted from November 1984 through May 1985. After completion of a draft report and a public meeting to review LT1, final preparations were made for the second long-term cycle (LT2). LT2, the subject of this report, was conducted from October 1986 through April 1987.

The University of Minnesota Physical Plant Operations supervised design and construction of the facility, and continues to provide operations maintenance. The Minnesota Geological Survey (MGS) provided site geologists during well drilling, supervised coring at the site, and continues to coordinate operations at the site. It also oversees data collection and analyses from the experimental test cycles and coordinates water chemistry studies and monitoring being done by the University's Department of Civil and Mineral Engineering, Environmental Engineering Laboratory. The U.S. Geological Survey Water Resources Division, St. Paul, is responsible for data acquisition and aquifer modeling. All cores from the drilling phase are housed at the MGS. Other field studies related to the effects of the heated-water injection were conducted by PNL at the FTF using a field injectivity test stand (FITS).

This report is a summary of the second long-term cycle. A description of the FTF is presented in Section 2. LT2 is described in Section 3. Section 4 summarizes the responses of the aquifer and surrounding rock. Water chemistry analyses are presented in Section 5. Conclusions from the second long-term cycle and associated activities are presented in Section 6. Section 7 contains a review and comparison of LT1 and LT2. Appendixes present tabular data on LT2, operating parameters for the cycle, and a report on investigations at the storage site regarding leakage between the FIG aquifer and the Mt. Simon aquifer. Complete reports on modeling performed in support of LT2 will be published by the U.S. Geological Survey.

2.0 FIELD TEST FACILITY

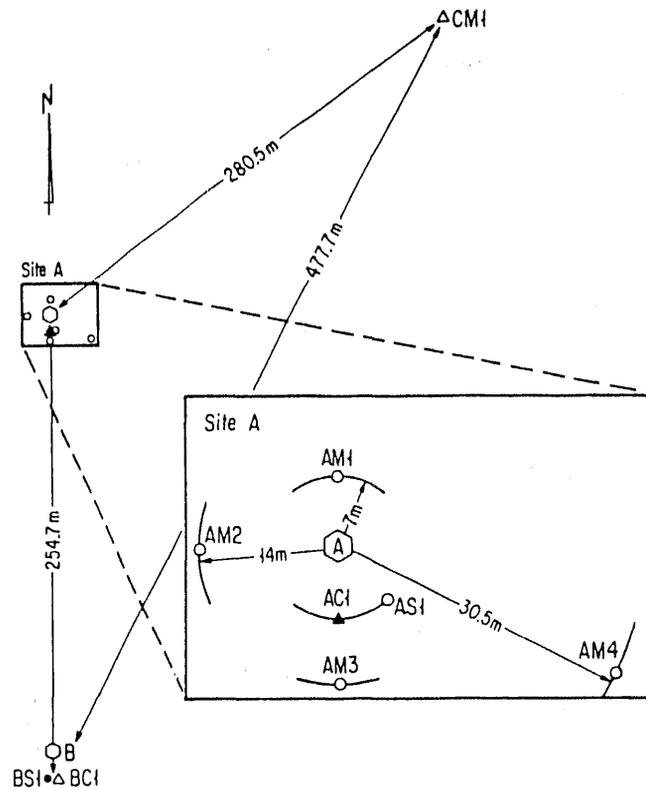
2.1 SITE LOCATION AND DESCRIPTION

The FTF is located on the St. Paul campus of the University of Minnesota (U/M). It is located near the center of the Twin Cities Artesian Basin, a Paleozoic structural and stratigraphic basin subsidiary to the Hollandale Embayment. Beneath the site there is a thickness of approximately 300 m (1000 ft) of almost horizontal Paleozoic sandstone, dolostone, and shale formations. Three major confined aquifers lie beneath the site: the Prairie du Chien-Jordan, the Franconia-Ironton-Galesville (FIG), and the Mt. Simon-Hinckley. These are separated by confining beds. The static water levels differ sufficiently to identify each aquifer by water levels alone. Walton et al. (1991) presents a more detailed account of the geologic and hydrogeologic setting.

For the long-term test cycles, the facility consisted of two pumping/injection (source and storage) wells completed in the FIG aquifer; nine monitoring wells in the FIG aquifer, its confining beds, and the Jordan and Mt. Simon aquifers; connecting piping, heat exchangers, and a water softener between the source and storage wells; and piping to supply steam to the heat exchangers (Figures 2.1, 2.2, and 2.3).

The FIG aquifer was chosen for use in the U/M ATEs project because it is the least used aquifer in the immediate area. It has the lowest hydraulic conductivity and transmissivity of the aquifers, and its hydraulic gradient at the site is very low (<0.004). Environmental concerns about possible effects from high temperatures of the ATEs tests made selection of a little-used aquifer with a low hydraulic gradient an important siting factor.

Examination of cores, geophysical logs, packer test results, and ambient temperature measurements confirmed that the FIG aquifer comprises interbedded, highly stratified, fine- to medium-grained sandstone and thin shale beds. The FIG aquifer occurs at a depth of about 181 m (594 ft), and is approximately



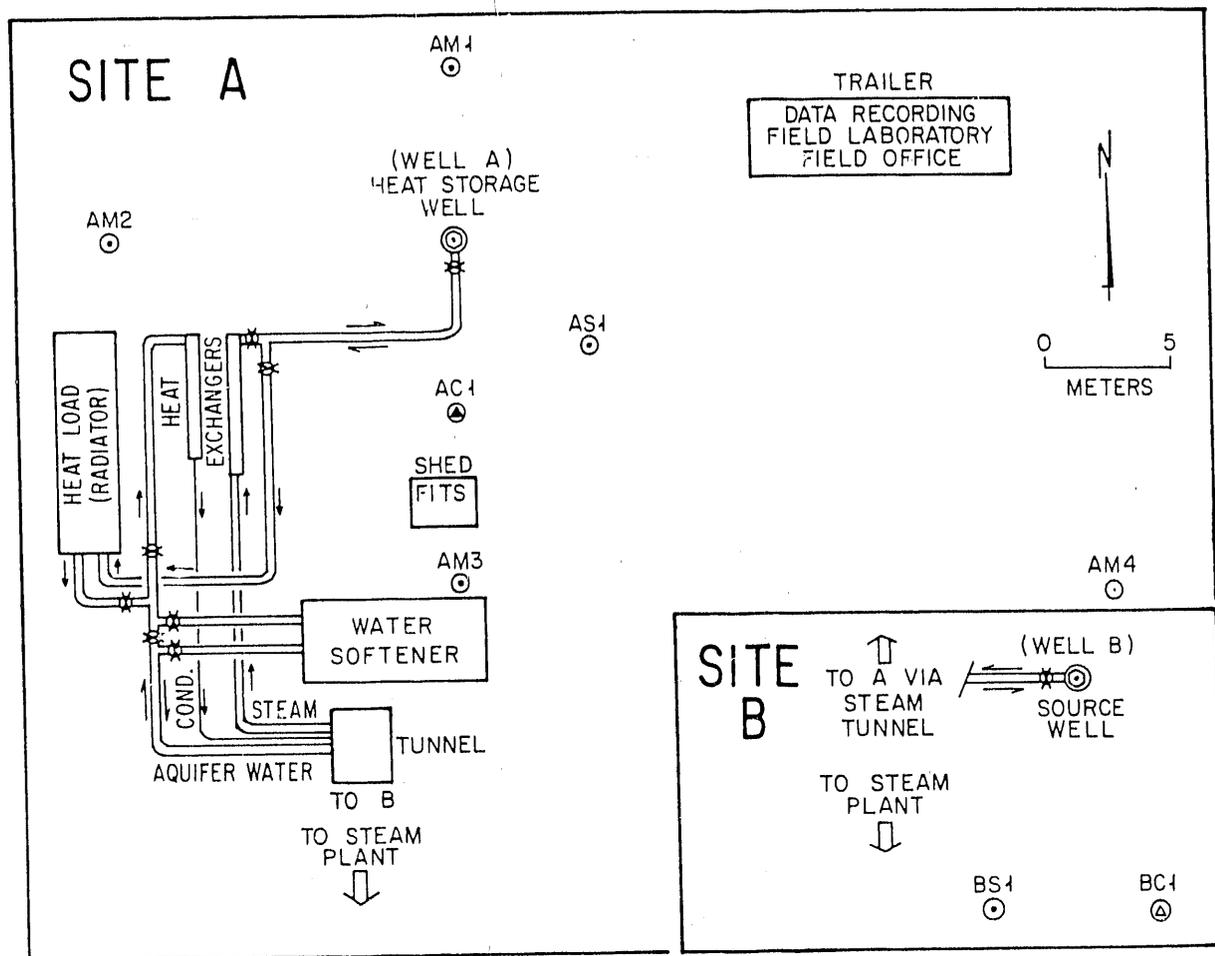
Site A = storage site; A = storage well;
 B = source well; AC1, BC1 = core hole monitoring wells;
 AM1, AM2, AM3, AM4, AS1, BS1, CM2 = monitoring wells.

FIGURE 2.1. Well Plan of University of Minnesota St. Paul Field Test Facility for Long-Term Cycles

61 m (200 ft) thick at the site. Static water levels for the FIG aquifer are at a depth of about 55 m (180 ft). Hydraulic conductivity ranges from about <math><0.01</math> to 1.5 m/day (<math><0.03</math> to 5.0 ft/day); the horizontal-to-vertical conductivity ratio is about 10:1 in permeable horizons and 100:1 in less permeable horizons. The presence of thin strata of low hydraulic conductivity interbedded with beds of high hydraulic conductivity greatly reduces thermal convection and thermal stratification.

2.2 SOURCE AND STORAGE WELLS

The source well (B), and the storage well (A), were each completed with two screened intervals in the FIG aquifer. The head of well A is at an elevation of 287 m (941 ft) above mean sea level (msl); the head of well B is 278 m (912 ft) above msl. The upper 13.7-m (45-ft) section of the 25-slot



Site A = storage site; Site B = source site;
 FITS = field injectivity test stand;
 AC1, AM1, AM2, AM3, AM4, AS1, BC1, BS1 = monitoring wells.

FIGURE 2.2. Sites A and B at the University of Minnesota St. Paul Field Test Facility for the Long-Term Cycles

stainless steel screen is opposite the upper portion of the Franconia formation in the interval between 90 m (296 ft) msl and 104 m (341 ft) msl. The lower 21.3-m (70-ft) section of screen is opposite the entire thickness of the Ironton and Galesville sandstones and small thicknesses of the lowermost Franconia and uppermost Eau Claire formations (Figures 2.3, 2.4). The construction of the wells in the screened interval is diagrammed in Figure 2.4.

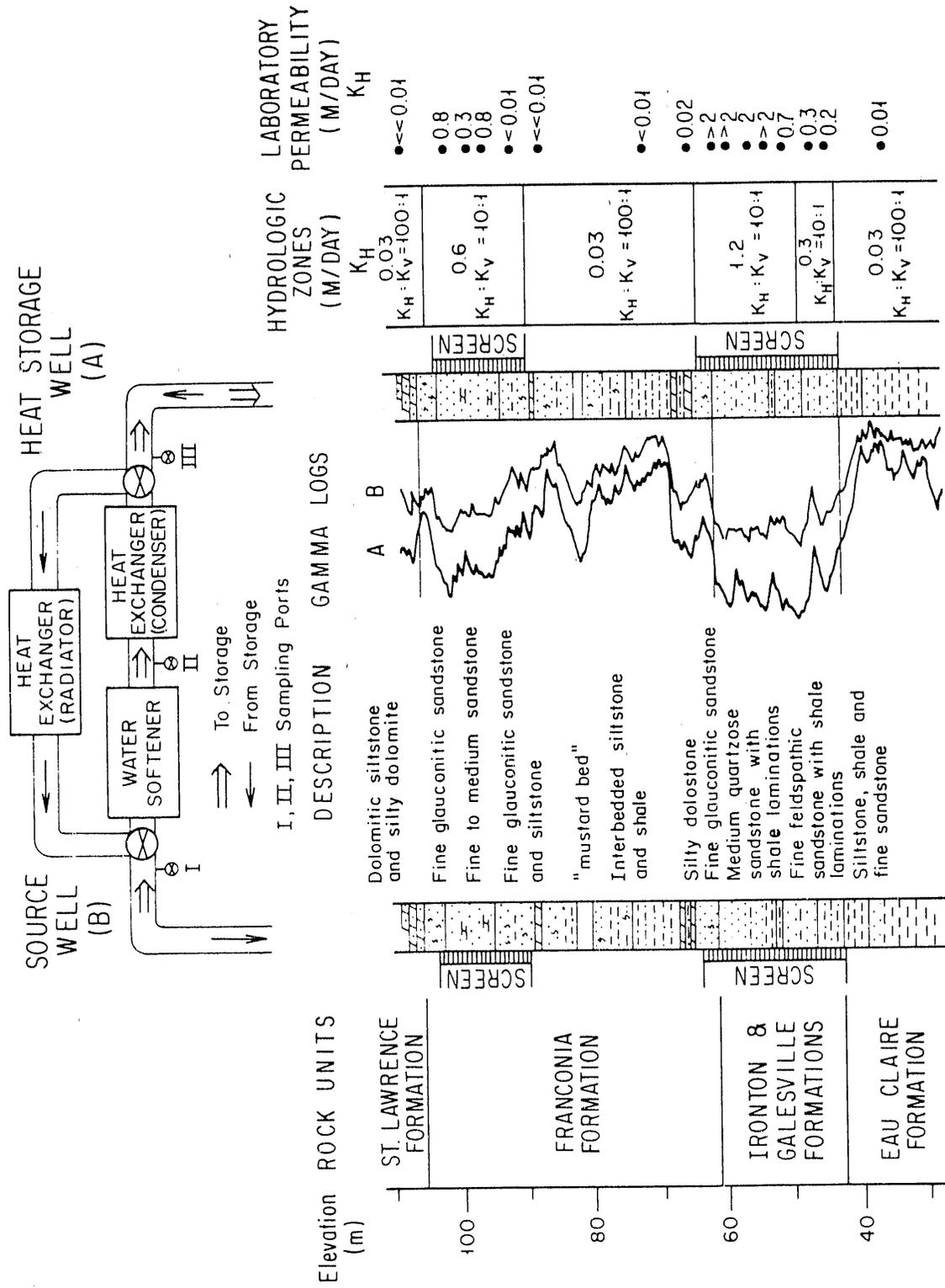


FIGURE 2.3. Stratigraphy and Hydrogeologic Units at the St. Paul ATEs Field Test Facility and Flow Path for the Long-Term Cycles

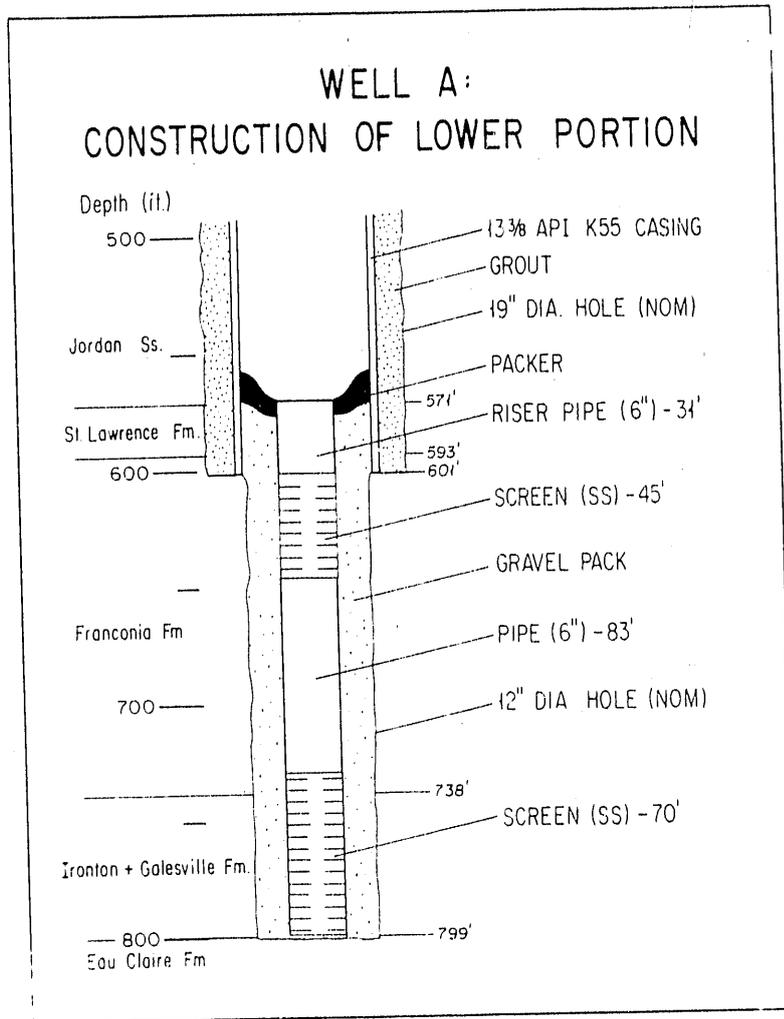


FIGURE 2.4. Diagram of Lower Portion of Well A

The wells were constructed to accommodate thermal expansion in the screened interval and to restrain it in the grouted interval. The turbine pumps in each well are set at a depth of 154 m (505 ft), corresponding to an elevation of 133 m (436 ft) msl in well A and 124 m (406 ft) in well B.

2.3 MONITORING WELLS

Nine monitoring wells provide instrumentation for the full stratigraphic interval affected by the system. Parameters measured at monitoring wells are temperature, pressure (water level), and composition of the ground water. Six

wells are located at the storage site (Site A), two at the source site (Site B), and one at Site C. Site C is located 280.5 m (920 ft) northeast of the storage well at a position expected to be beyond any thermal effects of test cycles (Figure 2.1).

At the storage site, wells are located 7 m (23 ft) (AC1, AM1, AS1), 14 m (46 ft) (AM2, AM3), and 30.5 m (100 ft) (AM4) from the storage well. Downhole gyroscopic surveys were conducted in wells AM1, AM2, AM3, and AM4 to accurately determine their locations with respect to the storage well at the storage horizons for modeling the system (Figure 2.5). All wells were surveyed when drilled. For those surveyed by both the plumb bob method and downhole gyroscopic method, the results were similar. It is believed that the survey results for the plumb bob method are adequate for those wells with insufficient pipe diameters to survey with the gyroscopic tool. Table 2.1

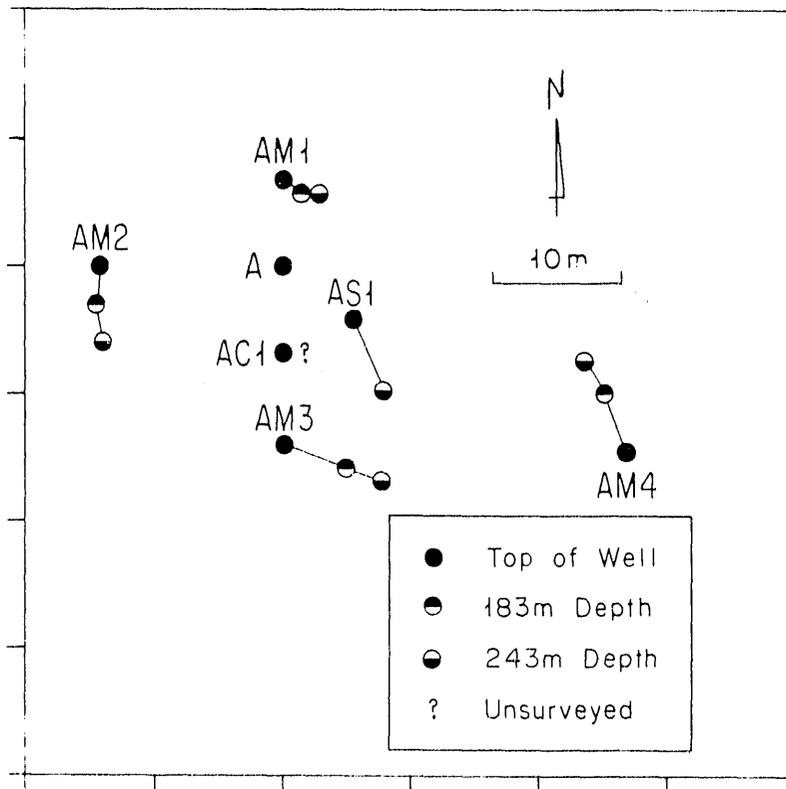


FIGURE 2.5. Plan View of Downhole Gyroscopic Surveyed Locations of Wells AM1, AM2, AM3, and AM4

compares the results of the methods. Well AM4 was drilled by cable-tool and shows a deviation opposite that of all the other surveyed wells, which were drilled by rotary methods.

Wells AM1, AM2, AM3, and AM4 and AS1 at the storage site have multiple-pair thermocouple strings for monitoring temperatures in the FIG aquifer and the immediately overlying and underlying formations (Figure 2.6). These thermocouple strings are in closed-end pipes except in AM1, which was initially constructed with an external thermocouple string attached to the pipe. The AM1 string was replaced before LT1 because several thermocouples failed; the replacement string was installed in the AM1 pipe that is open-ended and extends to the Eau Claire formation. A thermocouple string and packer were installed in AC1 (Figure 2.7) before LT2 to monitor for suspected leakage through the pipe and/or borehole (see Appendix D).

At the source site (B), the monitoring wells, which were not gyroscopically surveyed, are 10 m (33 ft) from the source well. The bottom of well BS1 is known to be immediately adjacent to well B because during the drilling of well B, well BS1 was intersected at a depth of about 206 m (675 ft). Eight different horizons are monitored at the site, from the Jordan to the Mt. Simon aquifers. Each monitored interval has a 0.9-m (3-ft) screen installed at the

TABLE 2.1. Comparison Between Downhole Surveyed Positions of Monitoring Wells at 243 m (797 ft) Depth

Well	Driller's Survey		Gyroscopic Survey		Difference, m
	Displacement, m	Azimuth	Displacement, m	Azimuth	
AM1	- (a)	--	2.51	99°01'	--
AM2	6.49	173°25'	5.99	178°28'	0.74
AM3	8.38	112°22'	8.27	110°39'	0.27
AM4	- (b)	-	7.92	335°03'	--
AS1	6.24	157°20'	- (c)	--	--

- (a) instrument failed
- (b) not surveyed by driller
- (c) pipe too small for tool, unable to survey

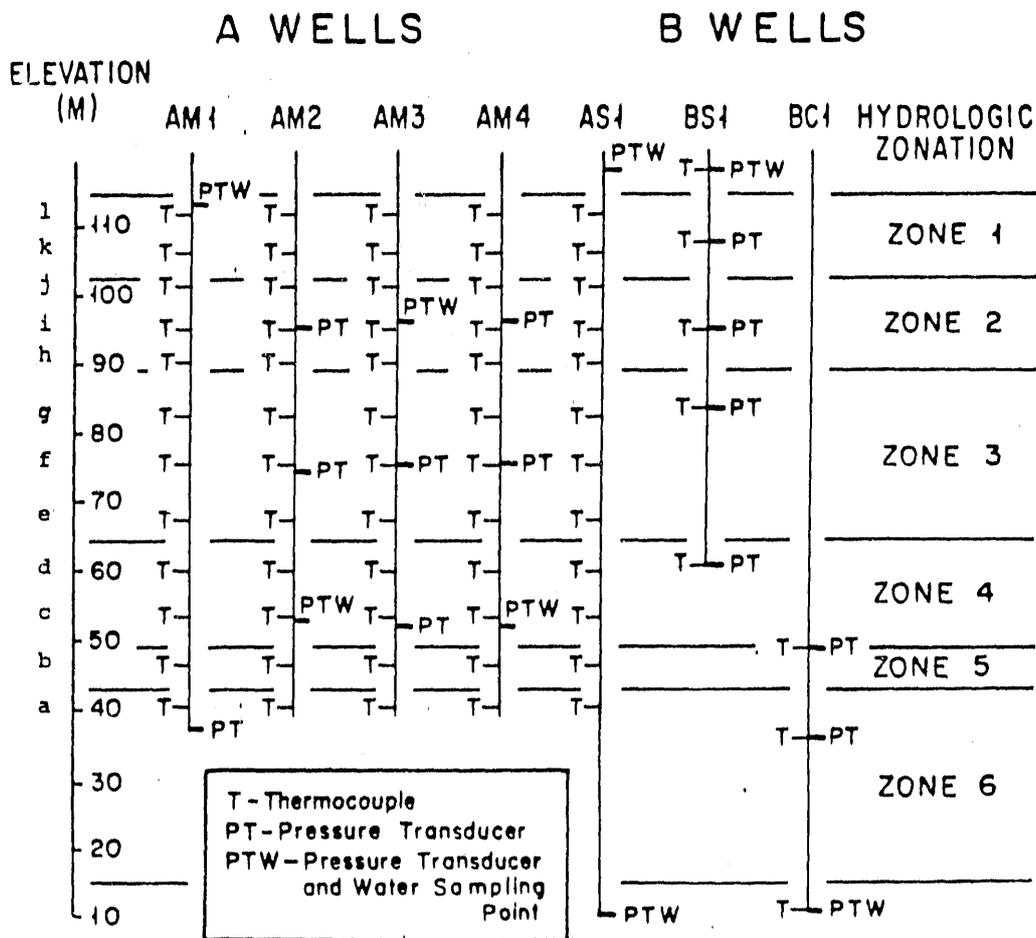


FIGURE 2.6. Monitor Well Instrumentation at Sites A and B

depths indicated in Figure 2.4. The Mt. Simon and Jordan pipes were installed to provide samples for water analyses, as well as for observing pressure (water level) and temperature. The remaining pipes are for monitoring pressure (water level) and temperature only.

Water samples were collected from the Jordan, Mt. Simon, and FIG aquifers at Site A before and after all the tests conducted to date. The 0.03-m (1.25-in.) pipes in monitoring wells AM1, AM2, AS1, BC1, BS1, and CM1 are pipes for sampling and measuring water levels (piezometer). Well AM4 has a 0.05-m (2-in.) pipe for sampling and measuring water levels. The sampling pipe installed in AM3 was plugged, probably with grout during installation.

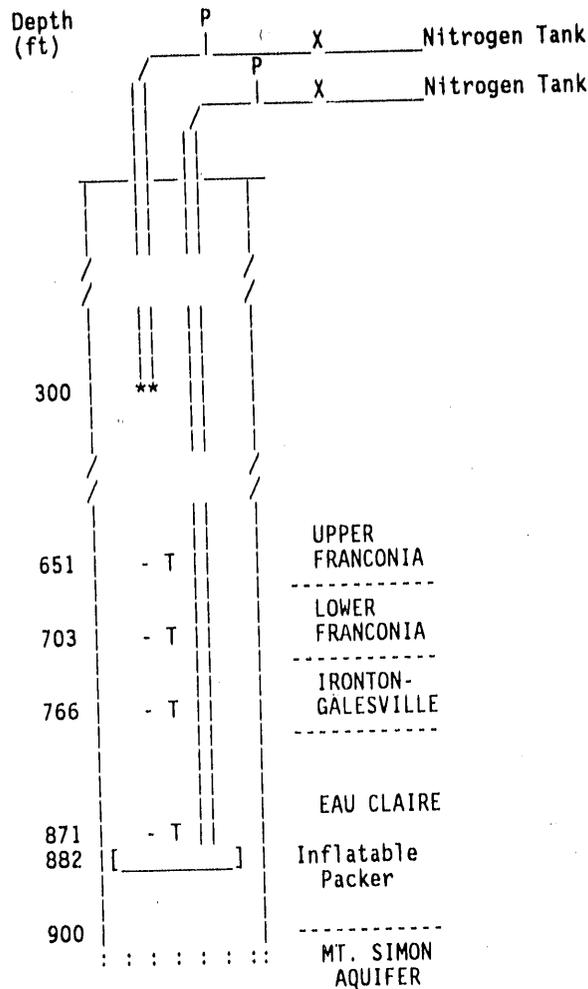


FIGURE 2.7. Well AC1 Instrumentation for Long-Term Cycle 2

The pipe in the upper Franconia in well CM1 was plugged by a pump while attempting to collect water samples.

2.4 CONNECTIVE PIPING, HEAT EXCHANGERS, AND WATER SOFTENER

Physical arrangement of the facilities at the site is described below.

2.4.1 Piping and Heat Exchangers

Piping connecting the storage (Site A) and source (Site B) sites, and from the campus steam plant to Site A, is routed through an existing steam and utilities tunnel that passes under the sites (Figure 2.2). A provision for sending water from the wells to waste via the existing storm sewer was added so that the system could be flushed before beginning injection or recovery and the heated and softened water could be pumped out. The water softener has an

outlet to the sanitary sewer so that brine and final rinse water could be routed to waste. Six-in. diameter lines (Schedule 40 steel with 3-in. Fiberglass insulation) are used for steam and connective piping. The condensate return line is 2-in. in diameter (Schedule 80, 2-in. Fiberglass insulation), and lines to waste are 4-in. in diameter (Schedule 40, uninsulated).

The aquifer water is heated in a tube-and-shell subcooler and a tube-and-shell condenser connected in series. The aquifer water is on the tube side; the 150 psia steam and condensate are on the shell side. Both exchangers are two-pass on the tube side and single-pass on the shell side. Temperature of the aquifer water is regulated during injection by a self-operated valve controlled by a temperature bulb in the aquifer water line downstream of the condenser.

A fan-cooled, water-to-air heat exchanger (radiator) is the simulated heating load during recovery. The radiator is capable of cooling the water by 60°C (119°F). Temperature of the water leaving the radiator controls the operation of the radiator fans when operated in an automatic mode. During LT2, the fans were operated manually to maintain a constant temperature difference. Automatic operation of the control system caused significant temperature fluctuation in return water temperature [5°C to 15°C (41°F to 59°F)] every few minutes.

2.4.2 Water Softener

An ion-exchange water softener was installed for the long-term cycles to allow virtually uninterrupted operation during the injection phase of the cycles. The softener removed the hardness from the ground water before heating by substituting sodium ions for calcium ions. The effect of the softener was to change the ground water from a calcium-magnesium bicarbonate water to a sodium-bicarbonate water. During the injection phase of LT1, the water softener used approximately 684 kg (1500 lb) of solar salt (NaCl) per day. During LT2, only approximately 500 kg (1100 lb) of salt per day were required because the source water was warmer and therefore not as hard.

The water softener consists of three ion-exchange resin tanks filled with Aldex^(a), a brine tank, and a control system. During the injection phase, two tanks were in service at any given time. The third tank was either being regenerated or on standby until the timing cycle for one of the other tanks was completed. Specifications called for each resin tank of the softener to be capable of removing 12 grains (210 mg/L) of hardness from the aquifer water for at least 8 hours at a flow rate of 18.9 L/sec (68.1 m³/hr, 300 gpm).

During LT1 the softener malfunctioned several times, forcing system shutdowns (Hoyer et al. 1991). During LT2, however, the softener worked with only a few malfunctions, none of which required shutting down the system for repair. The operation and effects of the softener are discussed in Sections 3 and 5.

(a) Manufactured by Matt-Son Inc., Streamwood, Illinois.

3.0 LONG-TERM CYCLE 2

Following site preparations, LT2 began at 1500 hours on October 2, 1986, and was completed at 0936 hours on April 4, 1987, 183.8 days later. (Site preparations included installation of a packer and thermocouple string in well AC1, replacement of boards in the data logger, testing pumps in wells A and B, and testing the water softener.) A few problems with the water softener, radiator, and monitoring equipment were encountered at different times during the cycle. However, the cycle was relatively trouble-free. Daily flow and temperature data during the injection and recovery phase are given in Appendix A.

Modeling performed by the U.S. Geological Survey analyzed the thermal and pressure responses at the storage site during LT2. At present, the detailed report on the modeling is unavailable. However, preliminary comparisons between modeled and field test values suggest that responses for LT2 are consistent with the responses of LT1. A detailed report will be published by the U.S. Geological Survey.

Water level and thermal responses observed in the monitoring wells are reported in Section 4. Table 3.1 summarizes significant data from the entire cycle.

TABLE 3.1. Summary of Long-Term Cycle 2

	<u>Duration,</u> <u>days</u>	<u>Average</u> <u>Temperature,</u> <u>°C</u>	<u>Average</u> <u>Flow Rate,</u> <u>L/sec</u>	<u>Volume,</u> <u>10⁴ m³</u>	<u>Energy,</u> <u>GWh</u>
Injection	59.26 ^(a)	117.7	18.3	9.38	9.21
Storage	59.06				
Recovery	59.66 ^(b)	85.1	17.9	9.21	5.54
Energy Recovery Factor					
					(using 33.1°C source water) 0.60
					(using ambient 11.0°C source water) . . . 0.68

(a) Over 64.96 days
(b) Over 59.75 days

3.1 INJECTION PHASE

The injection phase of LT2 was conducted from 1500 hours on October 2, 1986, to 1403 hours on December 6, 1986. A total of 59.26 days of injection were completed during 64.96 days. Mean flow rate was 18.3 L/sec ($65.9 \text{ m}^3/\text{hr}$, 290.5 gpm), mean source water temperature was 33.1°C (91.5°F), mean injected water temperature was 117.7°C (243.8°F), and mean delta T (temperature increase) was 84.6°C (152.3°F). A total of $9.37 \times 10^4 \text{ m}^3$ ($2.48 \times 10^7 \text{ gal}$) of heated water was stored, to which a total of 9.21 GWh ($3.15 \times 10^{10} \text{ Btu}$) of thermal energy was added. A total of 11.62 GWh ($3.97 \times 10^{10} \text{ Btu}$) above ambient conditions was stored in the aquifer.

During the injection phase, an attempt was made to maintain a relatively constant flow rate and injection temperature. The attempt was not entirely successful. The temperature and flow rate for the first 28 days of injection averaged 119.2°C (246.5°F) and 18.4 l/sec ($66.2 \text{ m}^3/\text{hr}$, 292 gpm), respectively. The final 31 days averaged 116.3°C (241.3°F) and 18.3 L/sec ($65.9 \text{ m}^3/\text{hr}$, 290.5 gpm). The loss of two tubes in a heat exchanger slightly reduced its efficiency resulting in the lower temperatures during the latter half of injection (Figure 3.1). A few interruptions during injection resulted from brief power outages and scheduled shutdowns for system maintenance and repairs. Only one interruption lasted more than 24 hours. No shutdown was required during the few times that the water softener malfunctioned.

The temperature of the stored water fluctuated with the rate of steam delivery, the weather, and with fluctuations in water softener regeneration. Steam flow was a function of incoming steam pressure and valve setting. The steam controller was set to maintain a stored water temperature of approximately 120°C (248°F). The steam system could maintain this temperature as long as the source water temperature and flow required less than 6 MWth ($2.1 \times 10^7 \text{ Btu/hr}$). A lower temperature resulted when the water softener malfunctioned, the outside air was very cold [$\sim -12^\circ\text{C}$ ($\sim 10^\circ\text{F}$)], or the source steam pressure was reduced.

The effect of the final rinse phase of water softener regeneration was evident throughout the injection phase. When aquifer water was diverted

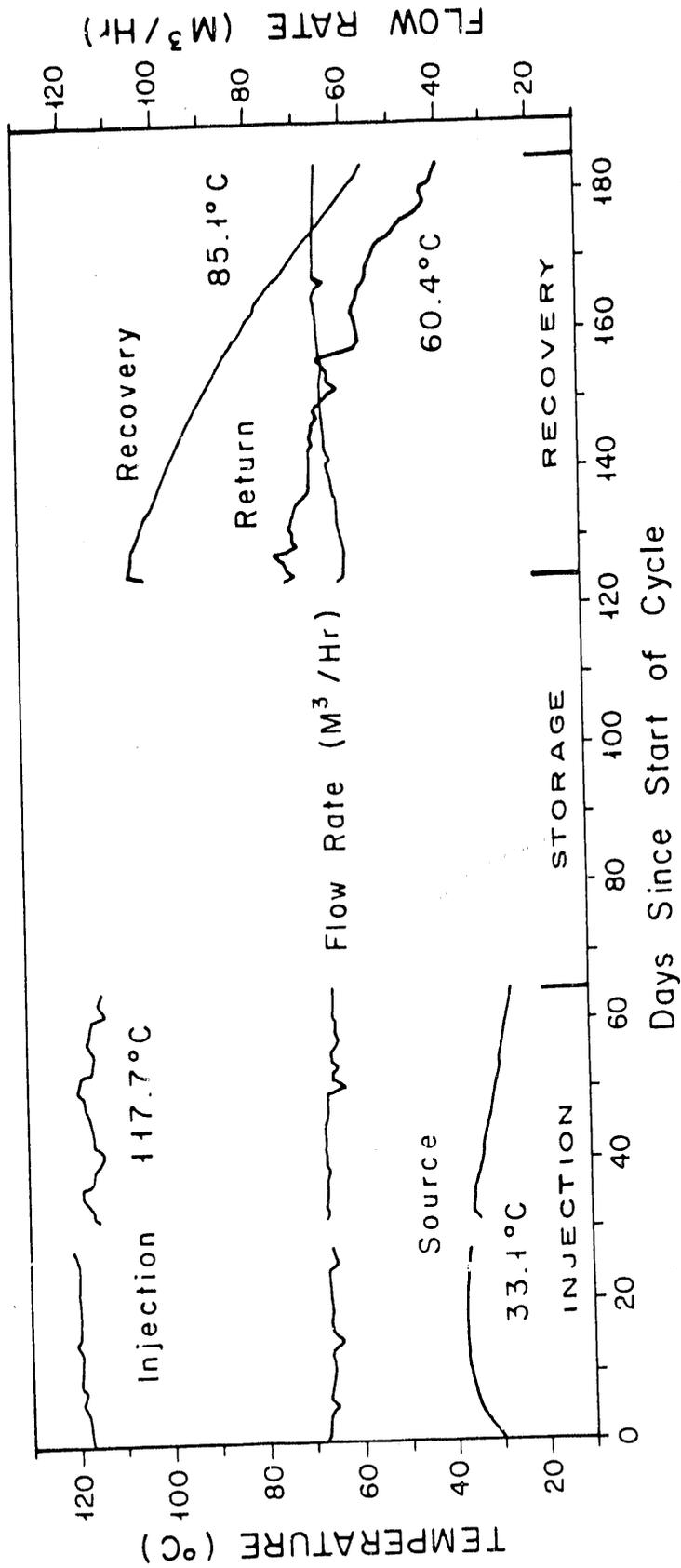


FIGURE 3.1. Flows and Temperatures Plotted Versus Time for LT2

through the regenerating tank to waste, system pressure decreased. The constant speed pump at the source well responded by pumping at a slightly higher rate. However, flow through the heat exchangers was reduced by about 10%. This pattern is reflected in some flow measurements made during a final rinse phase. Temperature of the injected water rose briefly when final rinse began, until the control system adjusted to the reduced flow through the heat exchangers. When normal flow resumed, the control system adjusted the steam flow to the level present before the final rinse. Figure 3.2 shows an example of the chart recording for one such interval.

It was evident that the source waters contained heat remaining from the first long-term cycle. The average temperature of the source water was 33.1°C (91.6°F), compared with normal ambient ground-water temperature of about 11°C (52°F). The source water reached a high temperature of 37.3°C (99.1°F) about 10 days into LT2, after about $1.5 \times 10^4 \text{ m}^3$ had been recovered from the source well. Source water temperature then declined slowly to 26.2°C (79.2°F) by the end of the injection period (see Figure 3.1).

Calcium and magnesium concentrations, as well as alkalinity in the source water, changed with the temperature. Hardness values for the source water indicate calcium carbonate or calcium/magnesium carbonate saturations.

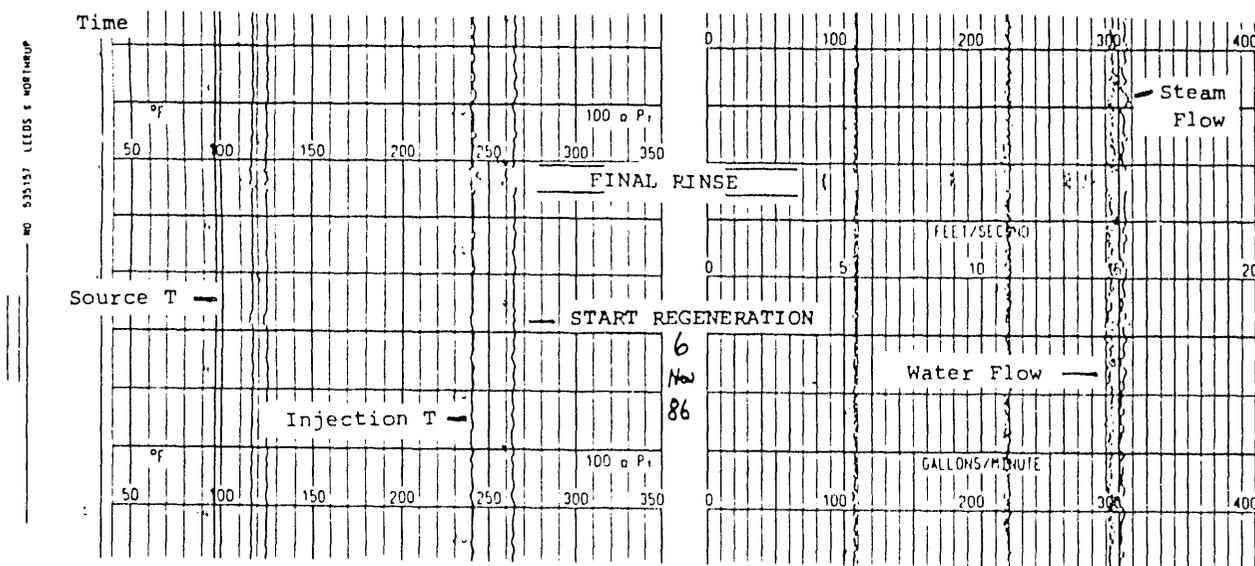


FIGURE 3.2. Portion of Chart Record, November 6, 1986, Showing the Effect of Final Rinse on Flow and Temperature During Injection Phase

The major change in solubility occurred at temperatures higher than that of the source water. Source water for LT2 had a mean hardness of 160 mg/L as CaCO₃. The water softener reduced this to <10 mg/L of hardness when it functioned properly. Sodium levels of the softened water increased from ~44 mg/L to ~122 mg/L. The source water sodium values were somewhat higher than ambient (~10 mg/L) because ground water that had been softened during LT1 was re-used during LT2. Fluctuations in ion concentrations were observed when a recharged softener tank came on-line (see Section 5.2.4). Table 3.2 presents examples of selected parameters of typical water analyses. Details of water sampling, analyses, and chemistry are discussed in Section 5.

3.2 STORAGE PHASE

Storage lasted from 1403 hours on December 4, 1986, to 1536 hours on February 3, 1987, a total of 59.06 days. Temperatures and pressures (water levels) were monitored periodically during this period. Water samples were collected from monitoring wells AM2 and AM4 (see Section 5).

3.3 RECOVERY PHASE

The recovery phase of the test began at 1536 hours on February 3, 1987, and was completed at 0936 hours on April 4, 1987. Return of water to the source well began at 1610 hours on February 3 after 34 min. of pumping to waste to flush the well of turbidity that would reduce the injectivity of the source well.

TABLE 3.2. Typical Water Chemistry of Major Constituents During Long-Term Cycle 2

	<u>Alkalinity,</u> <u>meq/L</u>	<u>Ca,</u> <u>mg/L</u>	<u>Mg,</u> <u>mg/L</u>	<u>Na,</u> <u>mg/L</u>	<u>SiO₂ (as Si),</u> <u>mg/L</u>
Source	4.69	39.84	12.81	44.07	8.12
Softened	4.79	0.80	0.32	119.71	8.12
Injected (a)	4.81	1.04	0.34	119.60	8.03
Recovered	4.96	11.58	3.26	98.01	20.47

(a) Softened and heated

Figure 3.1 shows the flows and temperatures during the recovery phase of LT2 plotted against time. The recovery phase was interrupted only by one brief power outage. Recovery continued for 59.8 days until $9.21 \times 10^4 \text{ m}^3$ (2.43×10^7 gal) of water, which is approximately equal (98%) to the stored volume, was recovered. Temperature of the recovered water reached a high of 106.9°C (224.4°F) during the second day of recovery pumping. The final water temperature was 55.6°C (132.1°F). Mean temperature of the recovered water was 85.1°C (185.2°F). Flow during recovery averaged 17.9 L/sec ($64.3 \text{ m}^3/\text{hr}$, 283 gpm).

Temperatures in the monitoring wells at Site A declined rapidly in strata with relatively high conductivity. Final monitoring well temperatures were in the range of 40°C to 55°C (104°F to 131°F) except at AM4, where temperatures were less than 20°C (68°F) in the upper Franconia, and 30°C to 50°C (86°F to 122°F) in the Ironton-Galesville (see Section 4). Water levels were measured by hand on a daily basis at Site A. Water levels dropped by 7.6 m (25 ft) in the FIG aquifer during heat recovery (see Section 4). Water samples were collected twice per week during the recovery phase (see Section 5).

4.0 THERMAL AND HYDROLOGIC RESPONSES TO LONG-TERM CYCLE 2

Monitoring wells at the storage site recorded the aquifer response to the injection, storage, and recovery of the heated water during the cycle. Observed responses reflected the layered nature of the FIG aquifer. Temperatures within permeable portions of the aquifer rose and fell quite rapidly as the hot water was injected and withdrawn at the storage well. Temperatures within less permeable portions of the aquifer rose and fell quite slowly and by small increments, if at all.

Water level (pressure) changes during LT2 reflected the injection, storage, and recovery phases and seasonal fluctuations during the 6-month cycle.

4.1 THERMAL RESPONSE

Thermal responses were not uniform throughout the aquifer but reflected the hydraulic conductivities and porosities of the hydrologic zones in the aquifer (Figure 2.3) and the injection well construction (Figure 2.4). Temperatures recorded in monitoring wells at Site A increased during the injection phase. The temperature pattern was a relatively rapid increase in the more permeable zones of the FIG aquifer and a slow increase in the less permeable zones and confining beds. The confining beds and low permeability beds of the lower Franconia formation showed a temperature increase throughout the period of storage, and at some wells, throughout the entire cycle. Slow downwell flow occurred at well A from the screened section of the upper Franconia to the Iron-ton-Galesville screened section. This was caused by a head difference between these two parts of the aquifer.

Hot water (>80°C) reached all storage site (Site A) monitoring wells at the Iron-ton-Galesville part of the aquifer, the most permeable zone (Figures 4.1 through 4.10). Hot water reached the wells 7 m (23 ft) and 14 m (46 ft) from the storage well at the upper Franconia part of the aquifer, the second most permeable zone (Figures 4.1 through 4.3, 4.5 through 4.8, and 4.10). Warm water (~40°C) reached the 30.5-m (100-ft) well at the upper Franconia level (Figures 4.4, 4.9). The lower Franconia part of the aquifer, which is

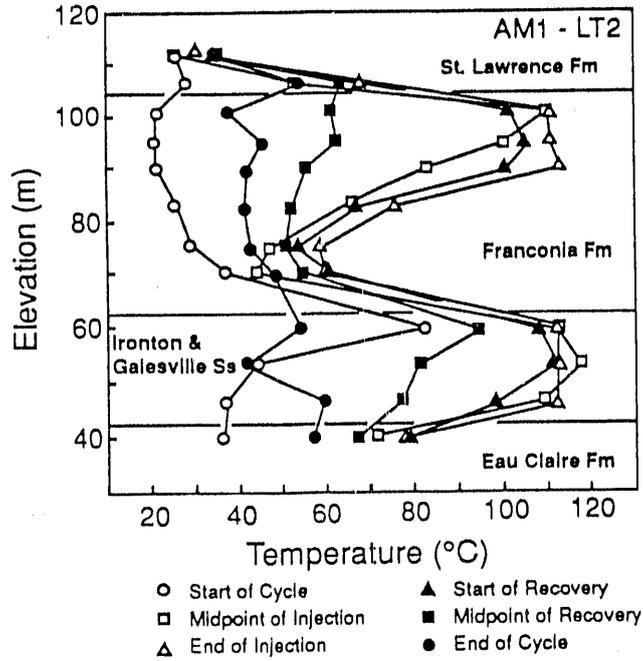


FIGURE 4.1. Temperature Profiles in Well AM1 During Long-Term Cycle 2

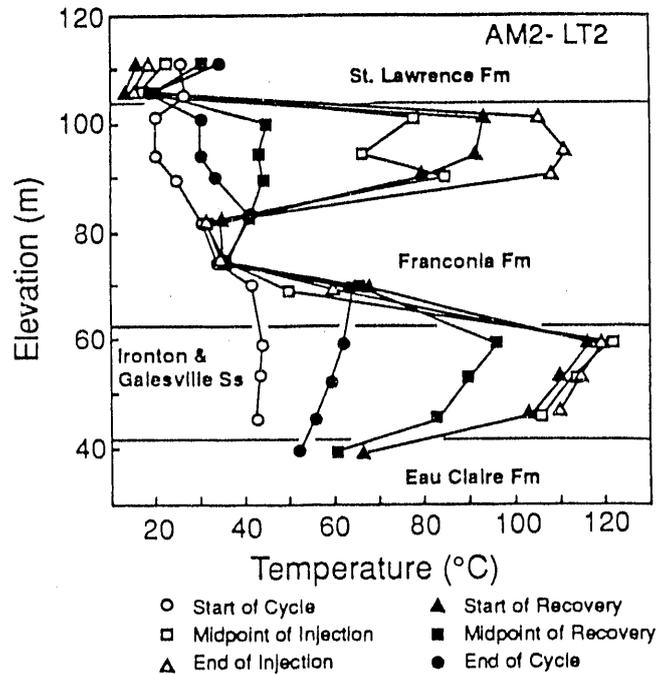


FIGURE 4.2. Temperature Profiles in Well AM2 During Long-Term Cycle 2. Thermocouple in middle of Ironton-Galesville unit failed; value plotted at that horizon is average of the thermocouple readings above and below it.

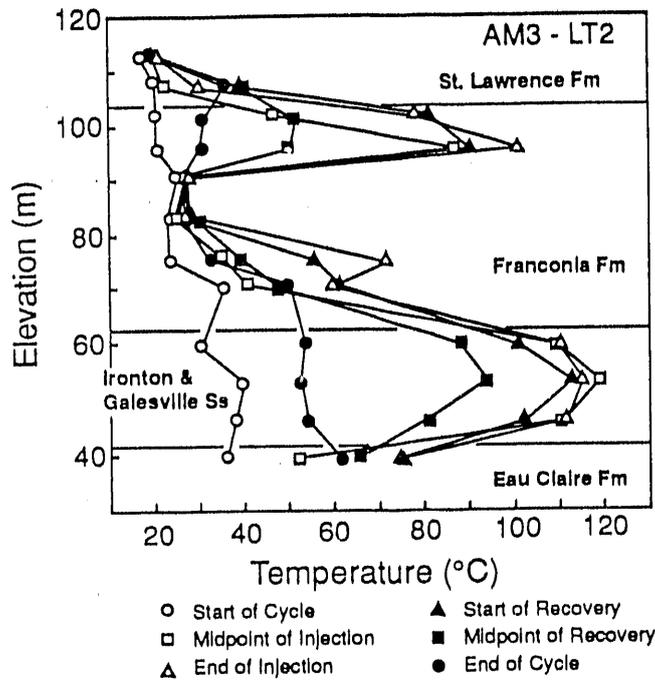


FIGURE 4.3. Temperature Profiles in Well AM3 During Long-Term Cycle 2

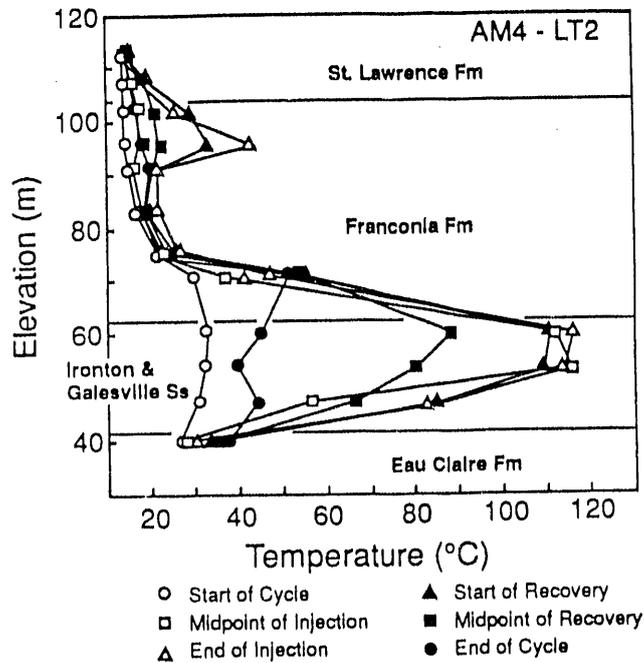


FIGURE 4.4. Temperature Profiles in Well AM4 During Long-Term Cycle 2

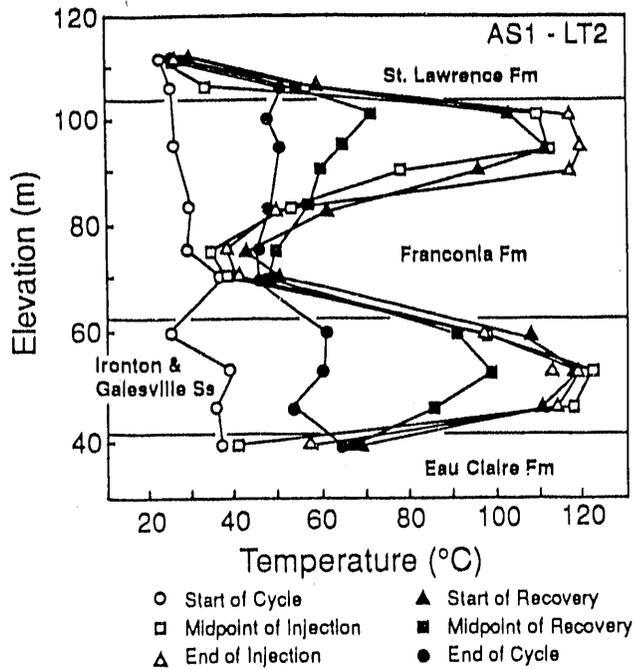


FIGURE 4.5. Temperature Profiles in Well AS1 During Long-Term Cycle 2

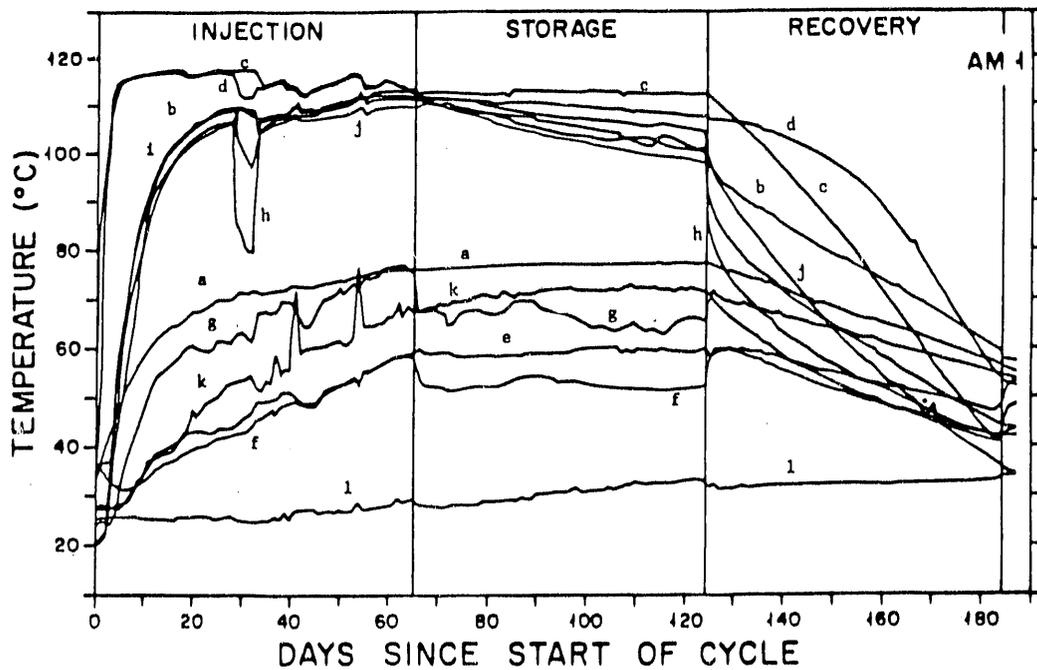


FIGURE 4.6. Temperatures in Well AM1 During Long-Term Cycle 2. Thermocouple locations shown in Figure 2.6.

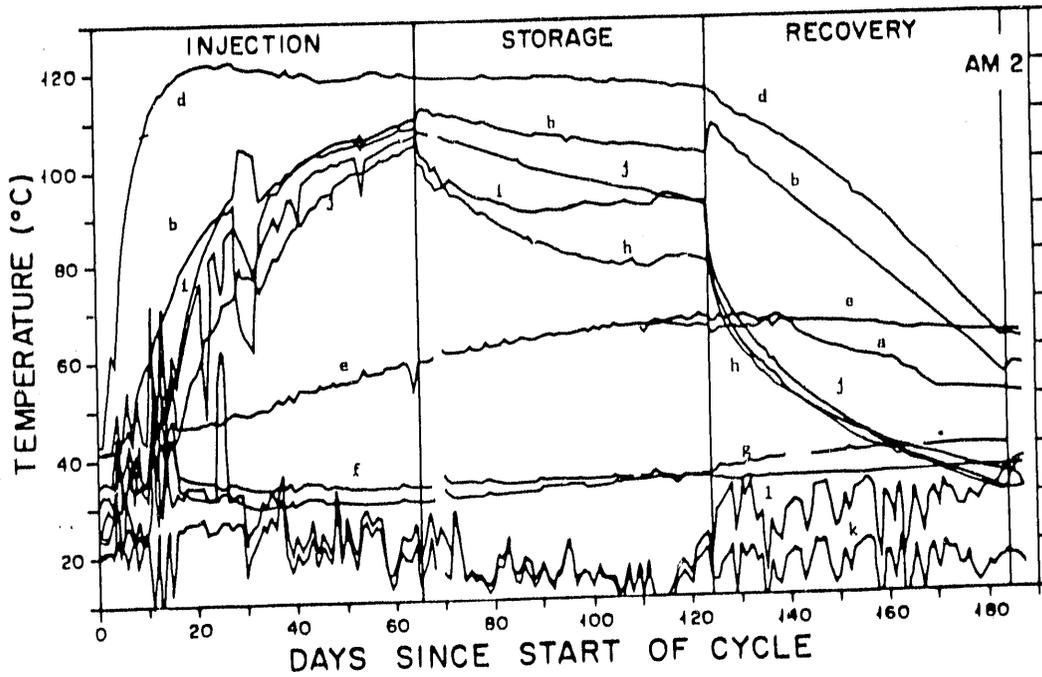


FIGURE 4.7. Temperatures in Well AM2 During Long-Term Cycle 2. Thermocouple locations shown in Figure 2.6.

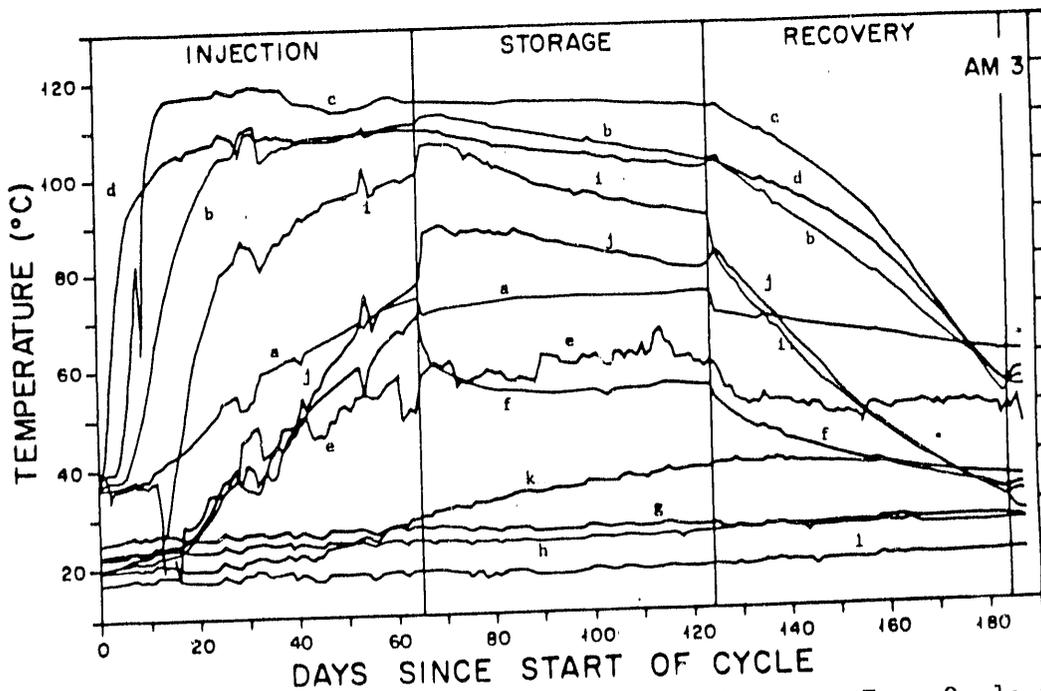


FIGURE 4.8. Temperatures in Well AM3 During Long-Term Cycle 2. Thermocouple locations shown in Figure 2.6.

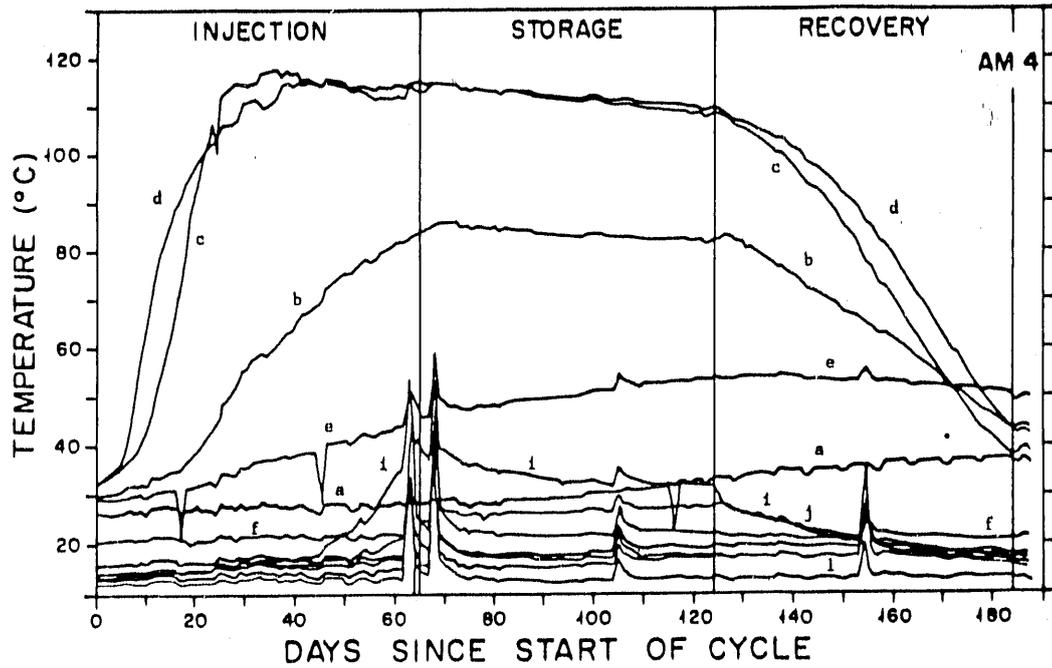


FIGURE 4.9. Temperatures in Well AM4 During Long-Term Cycle 2. Thermocouple locations shown in Figure 2.6.

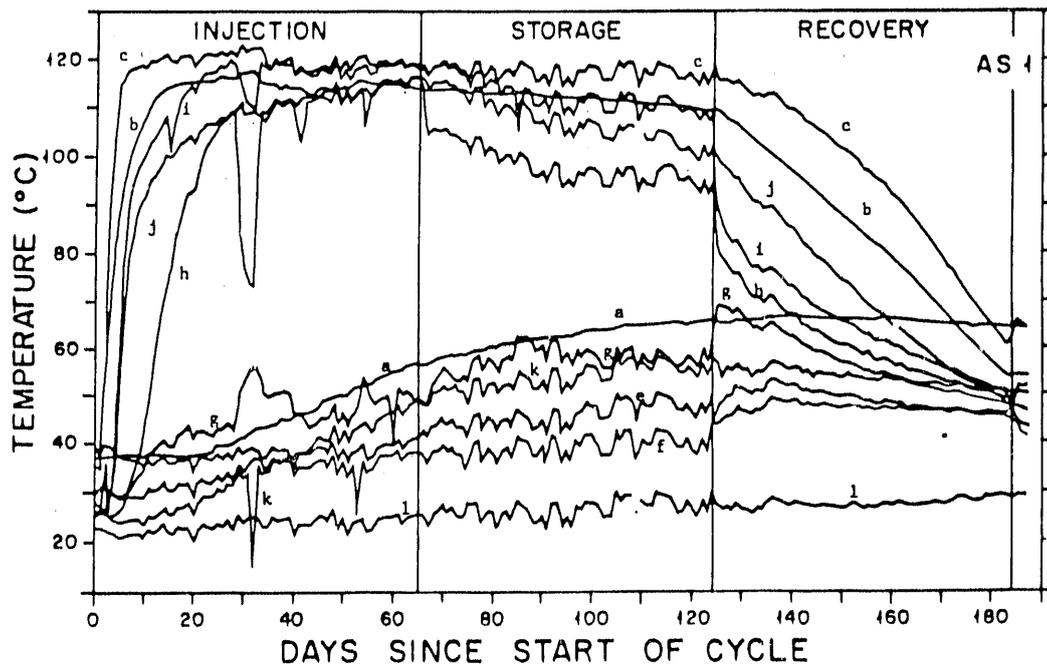


FIGURE 4.10. Temperatures in Well AS1 During Long-Term Cycle 2. Thermocouple locations shown in Figure 2.6.

the least permeable part of the aquifer, and the vertically adjacent confining beds showed only slow and slight temperature changes throughout the cycle (Figures 4.1 through 4.10).

Initial temperatures, which were higher than ambient [11°C (52°F)] at all Site A monitoring wells in the FIG aquifer and immediately adjacent confining beds, ranged from 10°C to 40°C (50°F to 104°F). Temperatures in the Franconia part of the aquifer at well AM4 were all less than 20°C (68°F). The higher temperatures were caused by the residual heat remaining from the previous cycles, particularly LT1, which had been completed 18 months previously.

Thermal profiles of monitoring wells at Site A immediately before, during, and immediately after LT2 (Figures 4.1 through 4.5) show the hourglass-shape of the temperature profiles. This reflects the high conductivity of the upper and lower permeable zones, which were screened, in contrast to the middle zone of low permeability. Temperatures of the upper Eau Claire and lower St. Lawrence formations increased slowly at Site A during LT2. The upper Franconia and Iron-ton-Galesville parts of the aquifer increased and decreased in temperature (ΔT) by as much as 80°C (144°F) during the cycle.

As during the previous cycles (Hoyer et al. 1985, 1991; Walton et al. 1991), heat arrived at thermocouples in permeable zones after less than 2 days of injection in monitoring wells located 7 m (23 ft) and 14 m (46 ft) from the storage well. Thermal responses were not uniform throughout the aquifer, but reflected the hydraulic conductivities and porosities of the zones of the aquifer being monitored. Figures 4.6 through 4.10 show daily temperatures in wells AM1, AM2, AM3, AM4, and AS1 during LT2. The heat arrival was not uniform and the response to pump shutoff varied with location in the aquifer.

Highest temperatures in the permeable parts of the Iron-ton-Galesville portion of the FIG aquifer were reached in well AM1 after about 2 days of injection. The temperature then followed the same trend as the injected water temperature (Figures 4.6, 3.1).

When injection was interrupted, temperatures at some horizons dropped while others increased. Where shales predominated, temperatures increased throughout the storage phase so that several horizons were warmer at the end of the storage phase than at the beginning. This reflects heat conduction from adjacent permeable beds to low permeability beds.

Temperatures in the porous and permeable portions of the aquifer declined during recovery (for example, see Figures 4.1 through 4.10). The shapes of the recovery curves in the Ironton-Galesville and upper Franconia portions of the aquifer are not the same: Ironton-Galesville is convex up (curves b, c, and d), and upper Franconia is concave up (h, i, and j). The recovered water temperature curve most nearly matches the Ironton-Galesville curves, which indicates that the Ironton-Galesville part of the aquifer received and supplied most of the heated water during LT2.

The Ironton-Galesville part of the aquifer, which has many thin interbedded shale layers, has the highest hydraulic conductivity. High-temperature water reached all of the Site A wells at these horizons. A slight amount of convective tilting of the thermocline and the interface between injected and ambient water occurred in these layers. However, large-scale convection was inhibited by the many thin interbeds of shale.

The upper Franconia part of the aquifer, which has few interbeds of shale, has the second highest hydraulic conductivity. High-temperature water reached all the 7-m (23-ft) and 14-m (46-ft) wells (Figures 4.1 through 4.3, 4.5 through 4.8, 4.10), but the temperature in well AM4 reached only 40°C (104°F) (Figure 4.4, 4.9). Downwell flow in well A accounts for some of the temperature decline in the upper Franconia portion of the aquifer during storage. The upper Franconia also gives evidence of thermal convection, with temperatures in the uppermost part increasing and temperatures in lower portion decreasing, as illustrated in Figure 4.6 (AM1) and Figure 4.7 (AM2). The lower Franconia part of the aquifer is essentially a confining bed effectively dividing the FIG aquifer into two aquifers. Strata in this zone showed a slow increase or constant temperature during LT2, comparable to the thermal response in the overlying and underlying confining beds.

The consistent thermal behavior during both long-term cycles suggests that no detectable changes took place in the hydraulic or thermal characteristics of the aquifer. This was not clear from data taken during the short-term cycles, which were not as consistent. However, during the short-term cycles, the rapid changes in flow rate and temperature, and the short duration of injection periods (<48 hours each), served to make interpretation of these differences difficult and uncertain.

A few thermocouples failed during LT2. These were identified by recorded temperatures well beyond the range of possible temperatures [$<10^{\circ}\text{C}$ to $>125^{\circ}\text{C}$ ($<50^{\circ}\text{F}$ to $>257^{\circ}\text{F}$)], or a sudden shift of the recorded temperatures to unreasonable values. The temperature curves show spikes, some of which are real, but others were caused by bad scans resulting from electronic noise on the data logger. Some thermocouples have more of these than others, such as AM2 (Figure 4.7) and AM4 (Figure 4.9).

Figure 4.11 presents temperatures recorded at well CM1 located 280 m (920 ft) from the storage site. As expected, no thermal effects reached the remote site.

4.2 HYDROLOGIC RESPONSE

Hydrologic response to injection and recovery was monitored by measuring water levels with a steel tape. The repeated failure of pressure transducers during earlier operations resulted in the decision to measure the water levels

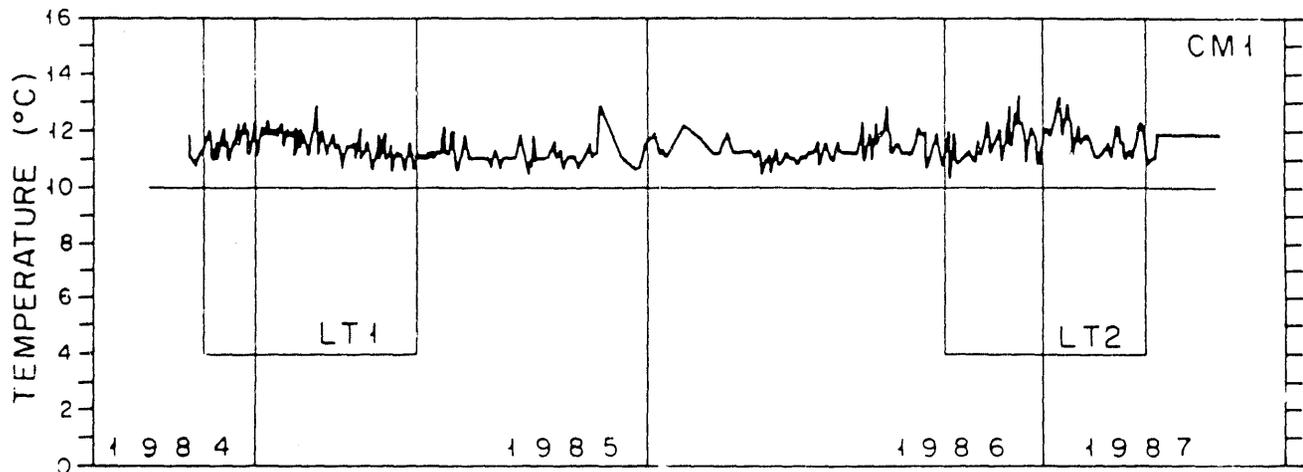


FIGURE 4.11. Temperatures Recorded at Well CM1

periodically by hand. Measurements in monitoring wells at the storage site were made daily during injection and recovery, and twice per week during storage. Wells BC1MS and CM1 were measured at least weekly during the cycle. Figures 4.12 through 4.16 present the water levels measured at the storage site.

The seasonal trends of the piezometric surfaces of the aquifers at the site near the center of the Twin Cities Basin are for a gradual rise in late fall through early spring, and for a decline in late spring through early fall. FIG aquifer static water levels measured during storage and at the end of the cycle were somewhat higher than static levels at the beginning of the cycle (Figures 4.12 through 4.15), showing the seasonal trends. The overlying Jordan and underlying Mt. Simon aquifers' water levels show just the seasonal trends throughout the entire cycle (Figure 4.16).

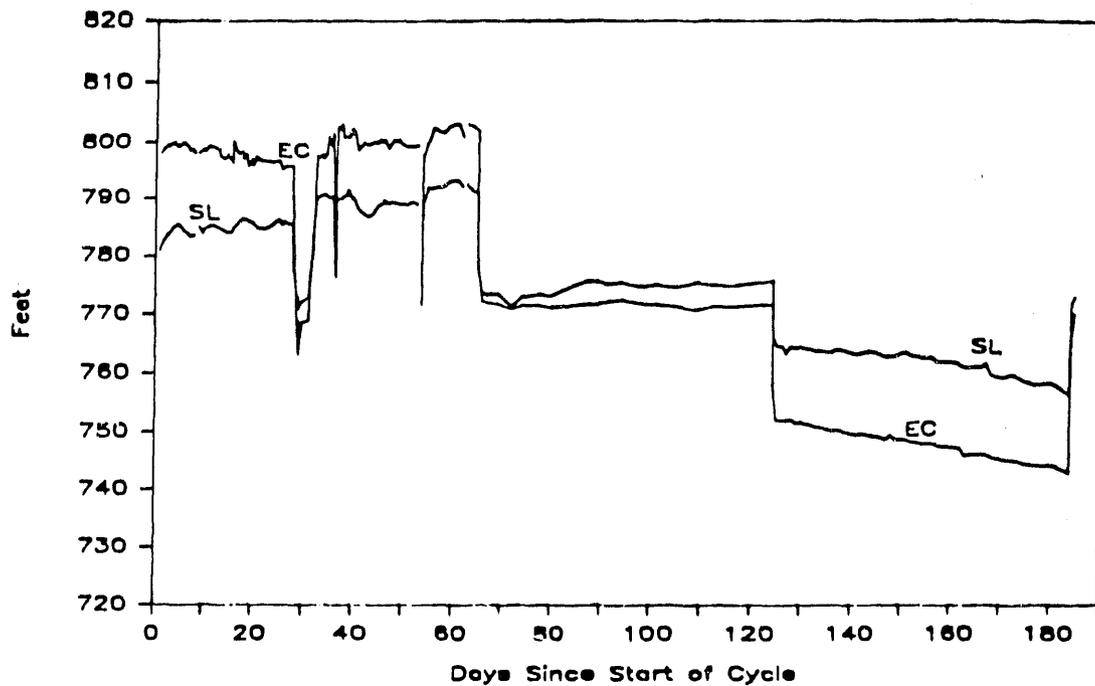


FIGURE 4.12. Water Levels in Well AM1 During Long-Term Cycle 2.
SL = St. Lawrence, EC = Eau Claire

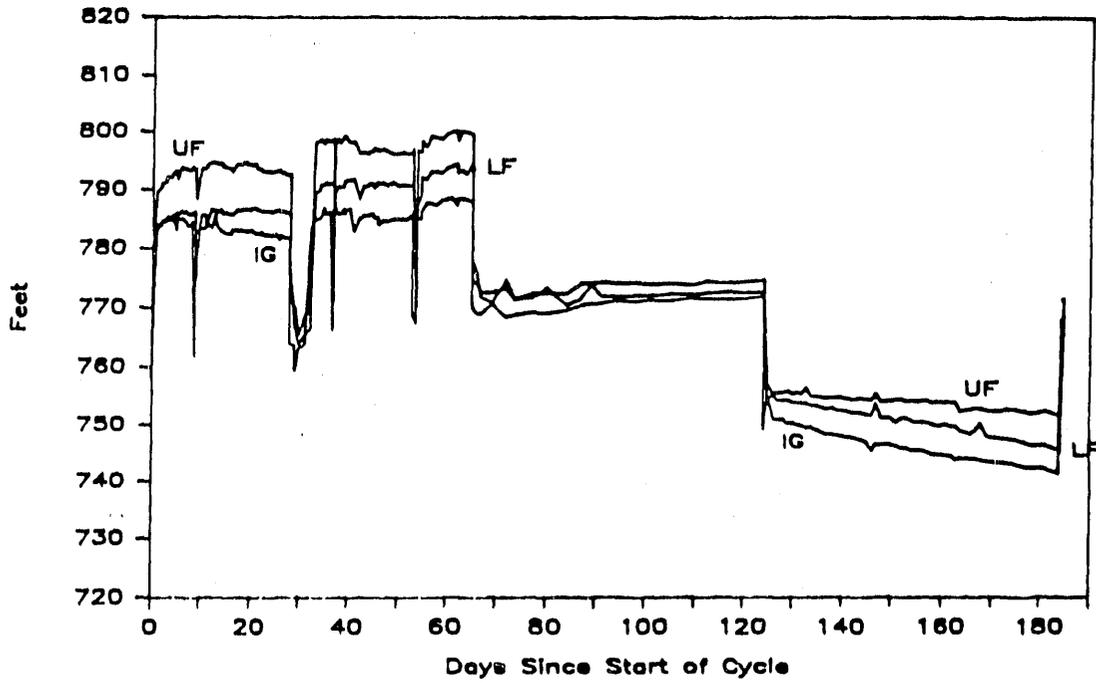


FIGURE 4.13. Water Levels in Well AM2 During Long-Term Cycle 2.
 UF = upper Franconia, LF = lower Franconia;
 IG = Ironton-Galesville

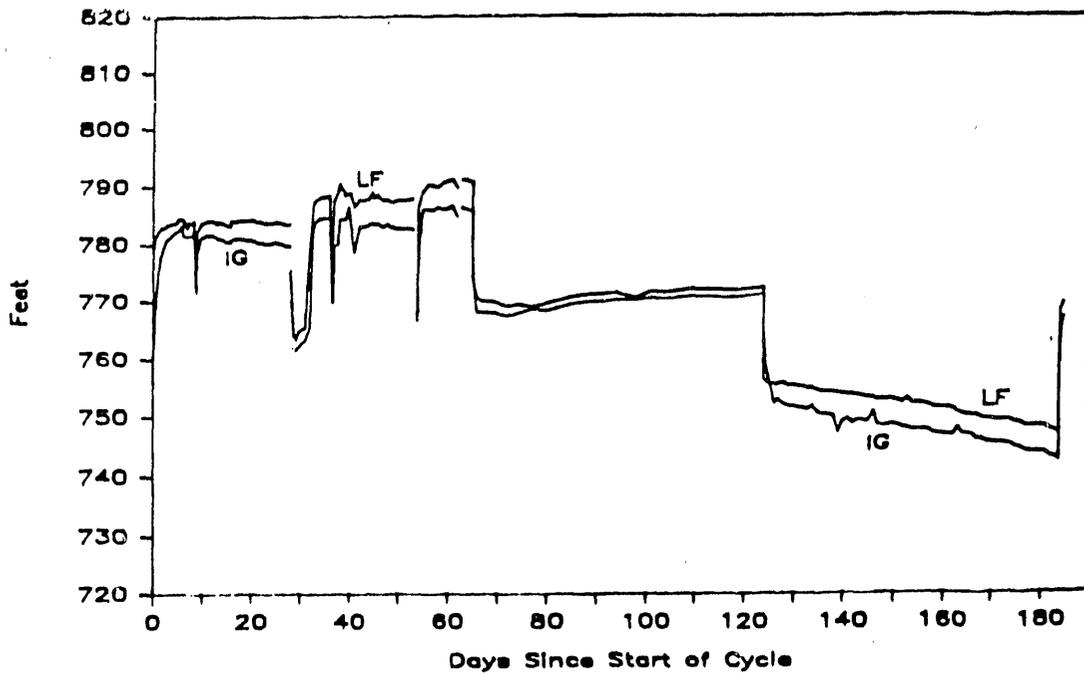


FIGURE 4.14. Water Levels in Well AM3 During Long-Term Cycle 2.
 UF = upper Franconia, LF = lower Franconia,
 IG = Ironton-Galesville

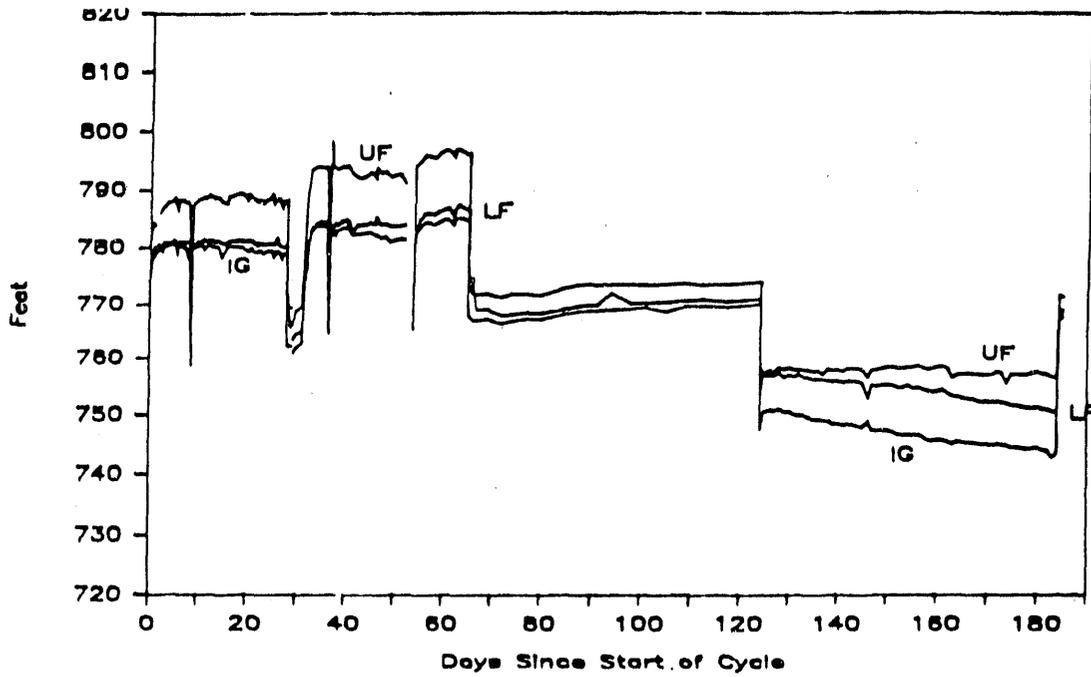


FIGURE 4.15. Water Levels in Well AM4 During Long-Term Cycle 2.
 UF = upper Franconia, LF = lower Franconia,
 IG = Ironton-Galesville

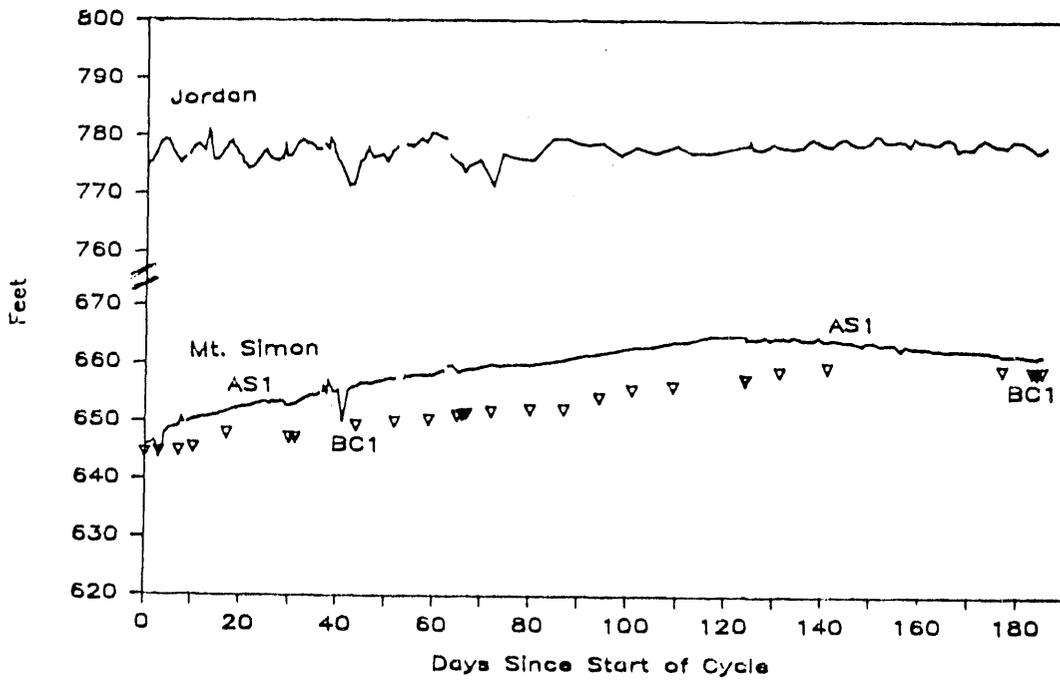


FIGURE 4.16. Water Levels in Well AS1 During Long-Term Cycle 2

Static water levels in the FIG aquifer were about 232 m (760 ft) above sea level (asl) prior to the start of LT2. During the injection phase, the water levels rose rapidly at the storage site by less than 9 m (30 ft). This change in water levels represents a pressure difference of ~90 kPa (~13 psi). Following injection, FIG water levels quickly declined during storage to a static level of about 235 m (770 ft) asl. During recovery, the FIG water levels at the storage site dropped by 7.6 m (25 ft) as pumping from the storage site progressed. This change in water level represents pressure differences of 75 kPa (11 psi). Following LT2, the FIG water levels returned to 235 m (770 ft) asl. Static water levels measured during storage and at the end of the cycle were somewhat higher than static levels at the beginning of the cycle, reflecting the normal seasonal trend.

Responses of the upper Franconia (UF), lower Franconia (LF), and Iron-ton-Galesville piezometers were not uniform, reflecting the different hydrologic properties of the different zones in the FIG aquifer. The LF portion of the FIG aquifer, the least permeable part (Figure 3.3), shows the slowest response to injection or pumping from the aquifer at the site. The UF portion of the aquifer, of intermediate permeability (opposite upper screen, Figure 3.3), shows an intermediate response rate to the cycle. The IG portion of the FIG aquifer, of highest permeability (opposite lower screen, Figure 3.3), responds most rapidly to the injection or pumping from the aquifer. These response rates parallel the thermal responses at the monitoring wells.

Water levels in the Jordan and Mt. Simon aquifers at the site were essentially unaffected by the injection and recovery phases of the cycle (Figure 4.16). The Jordan water levels follow both a weekly cycle (caused by weekly pumping elsewhere in the basin) and the seasonal trend. The Mt. Simon water levels show primarily the seasonal upward trend. Figure 4.17 presents the differences in water levels from the beginning of the cycle at well AM2 for the FIG completions, and for both the Jordan and Mt. Simon completions of well AS1 (and the Mt. Simon completion of BC1) during all of LT2.

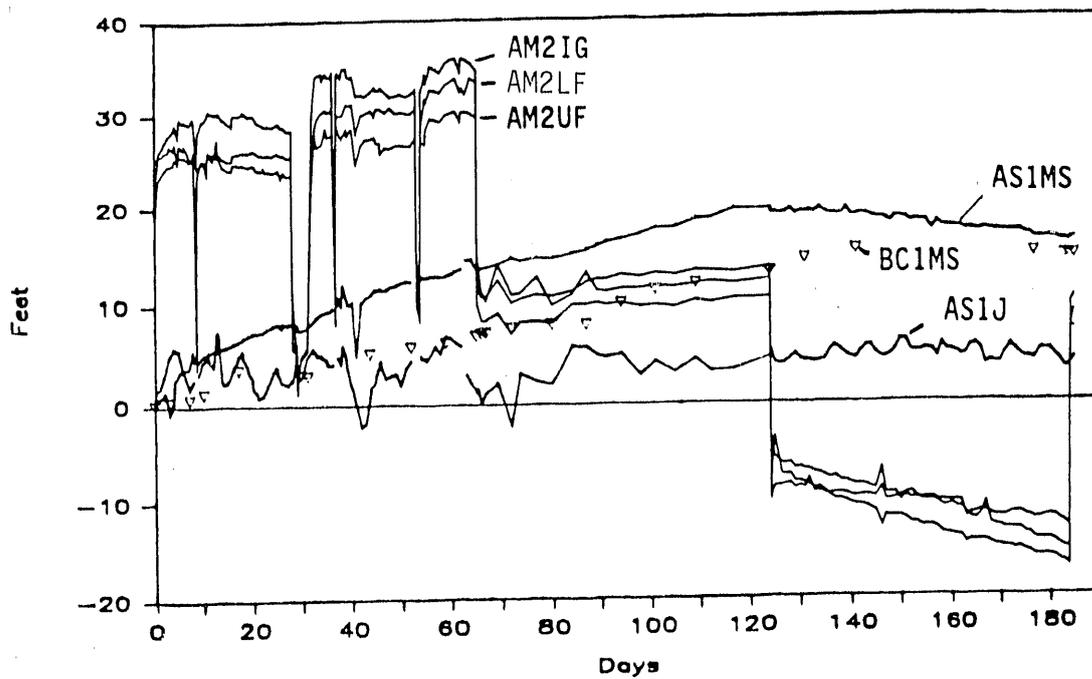


FIGURE 4.17. Water Level Differences During Long-Term Cycle 2 at Wells AM2 (FIG), AS1 (Mt. Simon and Jordan), and BC1 (Mt. Simon)

5.0 WATER CHEMISTRY

The geochemistry of water at the ATEs FTF has been a part of the monitoring and experimental plan since initiation of the project. Water samples have been collected during the four short-term tests and the two long-term tests and analyzed for major ions. The geochemical results of the short-term and first long-term test cycles have been reported in Holm et al. (1987) and Perlinger et al. (1987). Complete analytical results of previous cycles are included in Walton et al. (1991) and Hoyer et al. (1991).

This section presents a summary of LT2 water chemistry. The methods used in collecting and analyzing water samples are described first. The results of water analyses are then presented, followed by characterization of ambient ground water. Concentrations, concentration trends, and mass balances of dissolved chemicals from LT2 are presented and finally compared with results from LT1. Analytical results from LT2 and monitoring well samples are presented in Appendix B.

5.1 METHODS

5.1.1 Sampling During Long-Term Cycle 2

Samples of the pumped water were taken three times per week (Monday, Wednesday, Friday) throughout the injection phase. On each sampling day, ground water was collected from each of three ports on the system (Figure 5.1). Port I yielded source water before it was softened. Port II yielded water passed through the softening units before it was heated. Port III yielded the heated water before it was injected into the ground at the injection well. During the recovery phase, samples were collected from Port III every other day for the first 3 weeks and twice per week (on Tuesdays and Thursdays) for the remaining time. Port III samples are representative of the water recovered from storage and returned to the source well. Samples from monitoring wells AM2 and AM4 were taken during the first 3 weeks of injection and during storage and recovery (see Section 5.1.2). Sampling methods for AM2 and AM4 are presented in Section 5.1.2.

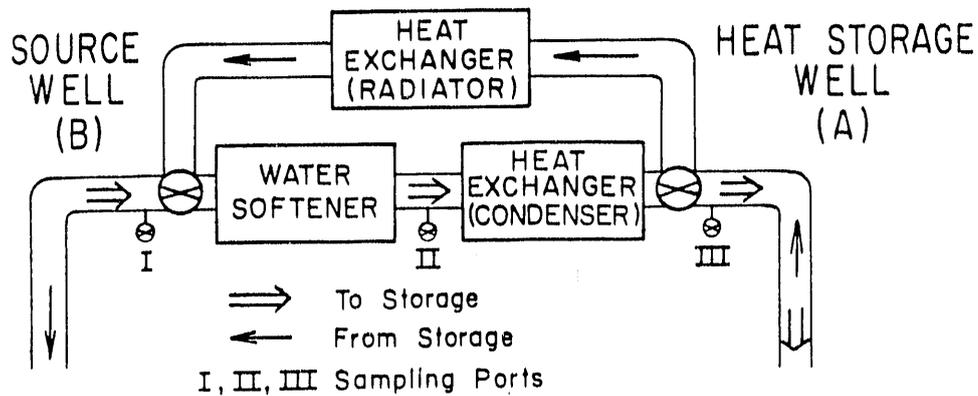


FIGURE 5.1. Schematic of the ATES System Piping

For each sample, dissolved oxygen was analyzed directly at the port using a field kit. An unfiltered sample was collected and taken inside the field trailer for pH and conductivity readings. The exception to this procedure was at Port III, where an in-line pH cell was used with a temperature-resistant pH probe to provide an accurate pH reading at near the actual injection temperature. Because pressurization of the system allowed the injection temperature of the water to be greater than 100°C (212°F), Port III samples were passed through a cooling coil prior to sampling, lowering the temperature into the 90°C to 95°C (194°F to 203°F) range. Filtered samples for use in laboratory analyses were collected directly at each port using a 0.45- μm Millipore membrane filter.

Filtered samples from each port were placed in two polyethylene bottles, a 250-mL bottle (full, not acid washed) for anion, silica, dissolved inorganic carbon (DIC) and alkalinity analyses; and a 1000-mL bottle (half-full, acid washed) for cation analyses. The 250-mL samples were taken by placing the filling hose in the bottom of the bottle and allowing the water to overflow three to four volumes before collecting the final sample. This procedure was used to minimize possible addition of CO₂ to the sample from the initial filling of the bottle. The cation sample was acidified in the field to about 2% by volume with HCl to lower the sample pH to below 2. The anion sample was refrigerated upon arrival in the laboratory (within 1 to 3 hours). Field blanks were collected each sampling day by passing deionized water through the

filter apparatus into separate bottles for anion and cation analyses. The blanks were then processed as samples.

5.1.2 Sampling Monitoring Wells

Monitoring wells were sampled quarterly, except when the ATES system was in operation. (Note: Wells AM2 and AM4 were sampled during LT2 by the methods described below.) For each well, an air hose was lowered about 60 m (197 ft) below the water level, and the well was purged of about three well volumes by air-lifting. Samples collected in this way were slightly altered in dissolved oxygen and CO₂ content. The dissolved oxygen for the monitoring well samples, which were air-lifted, ranged from 6 to 8 mg/L; this compared to less than 1 mg/L for the injected and recovered water.

At each well an unfiltered sample was immediately analyzed for oxygen content, pH, and specific conductance. A 1-L bottle was filled at the well site and then taken back to the field trailer where the water was filtered through a 0.45- μ m Millipore membrane filter using a hand-pressurized system. Blanks and filtered samples were treated in the same manner as water samples taken from the ports during LT2. Well AM4 was sampled using the standard air-lift flushing method; however, its larger diameter reduced flushing efficiency.

5.1.3 Analysis

As mentioned above, dissolved oxygen was quantified in the field with a kit from CHEMetrics, Inc., Calverton, Virginia. All pH readings were obtained on a Beckman Model Phi-21 meter with an automatic temperature compensating (ATC) probe and an Orion Ross combination pH probe. The pH probe and meter was calibrated using a two-point standardization (pH = 7.00 and 4.00) at room temperature. The ATC probe allowed samples at different temperatures to be analyzed without additional calibration. Specific conductance was measured using a Yellow Springs Instrument Model 33 field meter. The cell constant supplied by the manufacturer was used without modification, and all reported values have been corrected to 25°C (77°F).

Alkalinity was determined via a Gran-method titration on a 25-mL sample using 0.02 N H₂SO₄ (Stumm and Morgan 1981). Soluble reactive silica was

measured colorimetrically using a reduced silicomolybdic acid method (Strickland and Parsons 1972). Anion analysis was performed by ion chromatography (O'dell et al. 1984; ASTM 1984) on a Dionex Model 10 instrument. The six anions determined were fluoride, chloride, nitrate, nitrite, phosphate, and sulfate. However, only fluoride, chloride, and sulfate were observed regularly. Dissolved inorganic carbon was determined using a Dohrman Model DC-80 carbon analyzer. Cations were quantified using atomic absorption flame spectrophotometry (Varian AA175) and included calcium, magnesium, sodium, potassium, total iron, and manganese. Hardness was calculated directly as the sum of calcium and magnesium.

5.1.4 Quality Control

To ensure quality control, a system of field replicates, laboratory replicates, field blanks, field spikes, and U.S. Environmental Protection Agency (EPA) quality assurance samples was established. During the cycle, each Port III sample was collected in replicate; i.e., over 10% of all samples collected represented field replicates. One field replicate was collected each time the monitoring wells were sampled, usually from well AM2 or AM4. For each analysis, laboratory replicates were run. These laboratory replicates comprise over 10% of the analyses. Standard deviations for sample values were calculated for each of the field and laboratory replicate data sets. These values are reported in Table 5.1 for each parameter.

The percentage errors of the injection and recovery laboratory replicates are all below 6%, with most less than 3%. The percentage error is greater for both the injection and recovery field replicates than for the laboratory replicates because replicate samples were taken sequentially as the water flowed, rather than from a single well-mixed volume. Short-term fluctuations are discussed in Section 5.2.2. The percentage error for the injection field replicates of 2% to 3% is higher than the recovery samples of 1% to 2% because of short-term fluctuations caused by the water softener.

Field blanks showed no identifiable contamination of the samples from sampling and filtering techniques. Any chemical species found in the field

TABLE 5.1. Concentration Ranges and Standard Deviations of Laboratory and Field Replicates During Long-Term Cycle 2

Injection	Laboratory Replicates		Field Replicates	
	Range	Std. Dev.	Range	Std. Dev.
Alk (meq/L)	4.56-5.42	0.013	4.45-5.45	0.12
SiO ₂ (mmol/L) as Si	0.25-0.33	0.0017	0.00-0.37	0.033
DIC ² (mmol/L) as C	4.48-5.38	0.043	4.78-5.43	0.081
SO ₄ (mmol/L) as S	0.00-0.17	0.0038	0.00-0.15	0.014
Cl ⁻ (mmol/L)	0.10-0.49	0.019	0.04-0.90	0.063
F (mmol/L)	0.00-0.04	0.0022	0.00-0.04	0.0026
Ca (mmol/L)	0.00-0.04	0.00020	0.00-0.30	0.010
Mg (mmol/L)	0.00-0.03	0.00030	0.00-0.11	0.0036
Na (mmol/L)	4.44-6.51	0.038	4.34-7.24	0.085
K (mmol/L)	0.02-0.12	0.00059	0.02-0.16	0.0017
<u>Recovery</u>				
Alk (meq/L)	4.70-5.24	0.016	4.75-5.44	0.13
SiO ₂ (mmol/L) as Si	0.39-1.04	0.0016	0.40-0.96	0.0070
DIC ² (mmol/L) as C	4.04-5.45	0.019	3.97-5.64	0.096
SO ₄ (mmol/L) as S	0.00-0.12	0.013	0.05-0.12	0.0031
Cl ⁻ (mmol/L)	0.00-0.64	0.081	0.36-0.65	0.014
F (mmol/L)	0.00-0.05	0.0047	0.02-0.04	0.0012
Ca (mmol/L)	0.04-0.74	0.073	0.04-0.73	0.011
Mg (mmol/L)	0.02-0.37	0.0017	0.02-0.37	0.0034
Na (mmol/L)	2.50-5.16	0.0080	2.47-5.33	0.018
K (mmol/L)	0.12-0.29	0.0025	0.12-0.29	0.0074

blanks were at or below the detection limits for those compounds. Spikes of anions and cations were added to the appropriate bottles of an extra sample replicate to test any effect the sample matrix had upon the recovery of various ions. During LT2, this extra sample was collected weekly from Port III; during sampling of monitoring wells, the extra sample was taken from either well AM4 or AM2. Recoveries of added ions were regularly between 75% and 129%, indicating that the sample matrix had no significant effect. To check the accuracy of the laboratory techniques, a series of EPA quality assurance samples was run with every sample batch during routine laboratory analysis. In general, results agreed with concentration values supplied by the EPA (Table 5.2).

TABLE 5.2. Analysis of EPA Quality Assurance Standards

<u>Parameter</u>	<u>% Error</u>	<u>% Standard Deviation</u>	<u>No. of Samples</u>
Alkalinity	4.1	3.5	4
Sulfate	4.8	4.8	5
Chloride	2.3	1.4	3
Fluoride	1.0	1.2	3
Calcium	5.0	6.3	24
Magnesium	3.1	5.5	39
Sodium	2.3	2.3	17
Potassium	6.0	4.8	27
Iron	11.1	5.1	8

A further check on the overall analyses was the calculation of an ion balance for each sample analyzed. The ion balance is calculated as follows:

$$\text{Ion balance} = \frac{[(\Sigma \text{ meq cations}) - (\Sigma \text{ meq anions})] \times 100}{(\Sigma \text{ meq cations}) + (\Sigma \text{ meq anions})} \quad (1)$$

A positive imbalance indicates an excess of cations; a negative imbalance indicates an excess of anions. Samples clustered tightly in the +7% to -7% range (Figure 5.2). Samples with an imbalance greater than about 10% indicate a problem in analysis or sampling.

5.2 RESULTS

Source ground water from the start of LT2 is compared to cold (ambient) ground-water analyses performed before the thermal testing began (Section 5.2.1). Trends in chemical concentrations during LT2 are described in Section 5.2.2. The effects of softening, heating, and storage are quantified through the mass balance method in Section 5.2.3. Section 5.2.4 discusses the short-term fluctuations in chemical discharge from the water softener. Finally, Section 5.2.5 compares water chemistry in LT1 and LT2 by examining water temperatures, alkalinity, and elemental concentrations.

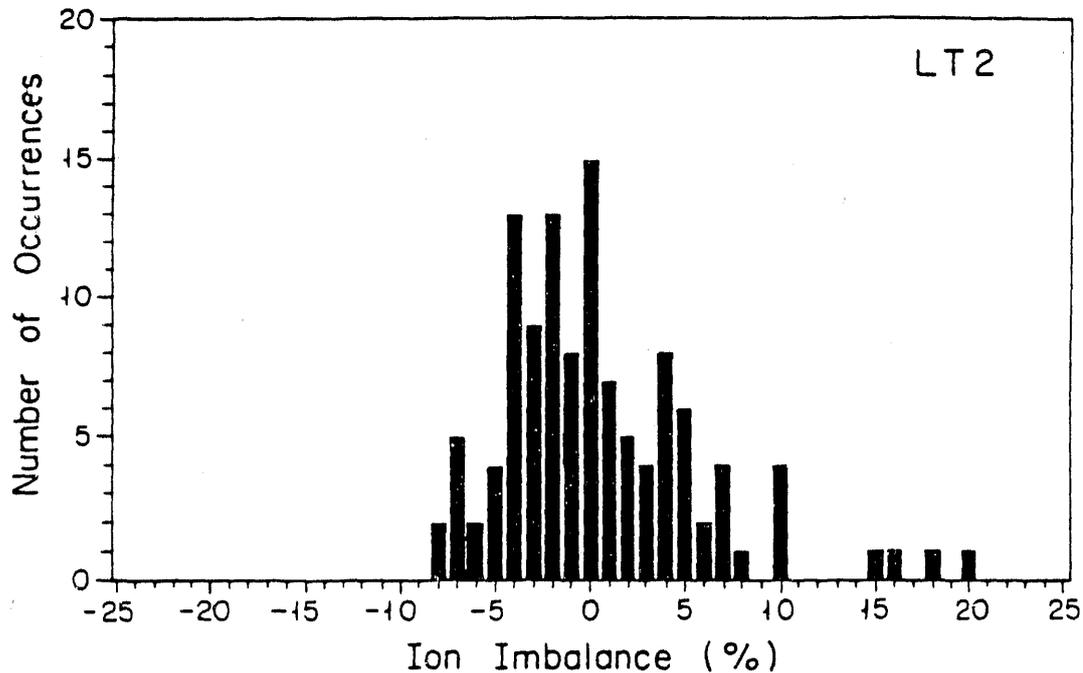


FIGURE 5.2. Frequency Histogram of Percent Ion Imbalance

5.2.1 Ambient Ground-Water Characteristics

Ambient ground-water composition is difficult to characterize because well construction itself disturbs the aquifer at that location. It is seldom known with certainty that the chemistry of the samples collected is not an artifact of the presence in the well of some of the parameters (e.g., dissolved oxygen). Thus, the samples best called "ambient" are those collected after a long period of continuous pumping, which has flushed out the well to such a degree that the chemistry of the water approaches a constant value.

Early in 1982, the system was run with cold (ambient temperature) water to test the pumping and piping systems. Water collected at that time may be considered ambient for most parameters (Table 5.3), the exception being an anomalous high value for potassium. Analysis of subsequent samples collected near the end of the injection phase of LT1, after more than 90,000 m³ had been pumped through the system, suggests a better potassium value of 0.19 mmol/L. In general, the water from the FIG aquifer was a calcium and magnesium bicarbonate water in equilibrium with calcite and quartz at 11°C to 12°C (51°F to 53°F) (Holm et al. 1987).

TABLE 5.3. Comparison of FIG Water Chemistry from Well B Collected Before Thermal Cycles (1982) and Early in Long-Term Cycle 2 (1986)

Parameter	Cold Water Test, 1982	Long-Term Cycle 2, 1986
Temperature	12°C	32°C
pH	7.46	6.75
Alkalinity	4.87 meq/L	4.88 meq/L
Sulfate (as S)	0.10 mmol/L	0.08 mmol/L
Chloride	0.26 mmol/L	0.12 mmol/L
Fluoride	0.01 mmol/L	0.01 mmol/L
Nitrate (as N)	not detected	not detected
Calcium	1.19 mmol/L	1.42 mmol/L
Magnesium	0.87 mmol/L	0.81 mmol/L
Potassium	0.69 ^(a) mmol/L	0.18 mmol/L
Sodium	0.24 mmol/L	1.18 mmol/L
Dissolved silica (as Si)	0.15 mmol/L	0.27 mmol/L
Iron	0.03 mmol/L	0.03 mmol/L

(a) Value is high compared to average well B potassium concentration of 0.19 mmol/L.

Table 5.3 shows the 1982 ambient ground-water characteristics and the average concentrations of chemical species in source water at the start of LT2. Although chloride concentrations and pH were lower than in the cold water test of 1982, the water temperature and the concentrations of calcium, sodium, and dissolved silica were all significantly higher at the start of LT2. The increased source water temperature in 1986 is a direct result of residual heat from previous test cycles. The higher silica values reflect the higher solubility of quartz at elevated temperatures.

Sodium concentrations reflect the use of a sodium-charged ion-exchange resin to soften the ground water prior to heating during LT1. The sodium entered the aquifer at the storage well where it exhibited close to conservative chemistry. The sodium concentrations were maintained in the LT1 water as it was stored, recovered, and returned to the source well, where it

later became the LT2 source water. The only major loss process for sodium was dilution with ambient ground water at the fringe of the storage zone.

The calcium concentration at the start of LT2 surprisingly was higher than in the cold ambient ground water. Chemical equilibrium modeling indicated that the ambient water was slightly supersaturated, and the LT2 source water was slightly undersaturated, with respect to calcite.

5.2.2 Long-Term Cycle 2 Concentration Trends

Temperatures of water sampled during LT2 are shown in Figure 5.3. Figures 5.4 through 5.16 present analytical results for many chemical species plotted against a function of cumulative volume of water pumped (injected/recovered). No graphs are presented for manganese, nitrate, nitrite, or phosphate because all samples were at or near the detection limits of methods used. Dissolved oxygen is not graphed because all values were very low.

The labeling of the abscissa in Figures 5.3 through 5.16 requires explanation. All the data are plotted as a function of cumulative volume of water pumped. The injection data are plotted above the negative x-axis; the volume of $-93,700 \text{ m}^3$ corresponds to the start of injection and $-60,000 \text{ m}^3$ corresponds to $33,700 \text{ m}^3$ of water injected into well A. The zero denotes the end of injection, the 60-day storage period, and the beginning of the recovery phase. This method of labeling allows easy comparison of the change in the chemistry of a particular parcel of water over the period of time in storage, assuming no mixing occurred in the aquifer. For example, in the absence of mixing, the parcel of water injected at $-60,000 \text{ m}^3$ (after $33,700 \text{ m}^3$ had been injected) should be the same parcel of water recovered at $+60,000 \text{ m}^3$.

The temperature and chemistry of the source water from well A for LT2 (sampling Port I) were influenced by LT1, which was completed 18 months before the initiation of LT2 (Perlinger et al. 1987), and to a lesser extent by the four short-term test cycles (Holm et al. 1987). The source water temperature ranged from 28°C to 38°C (82°F to 100°F), reaching a maximum temperature at a volume of approximately $17,700 \text{ m}^3$ ($-76,000 \text{ m}^3$, Figure 5.3), a result of returning warmer-than-ambient water to well B during the recovery phase of LT1 (Hoyer et al. 1991; see also Section 3). The injection temperatures of 110°C to 120°C (230°F to 248°F) were reflected in recovery temperatures, which

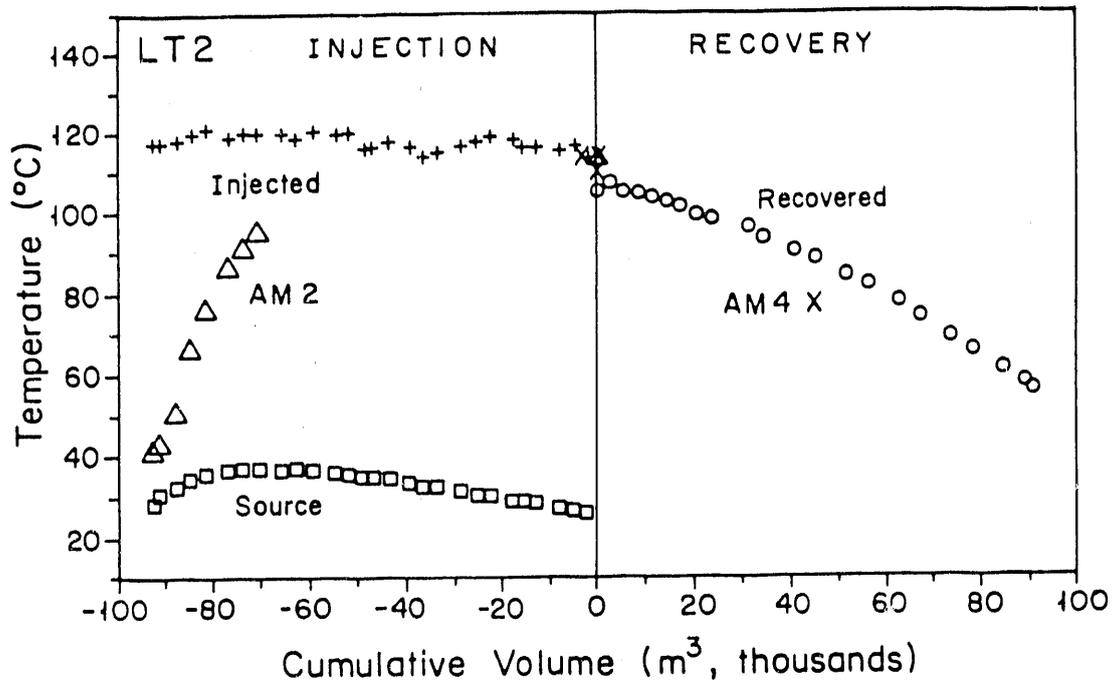


FIGURE 5.3. Water Temperatures at Sampling Times During Long-Term Cycle 2

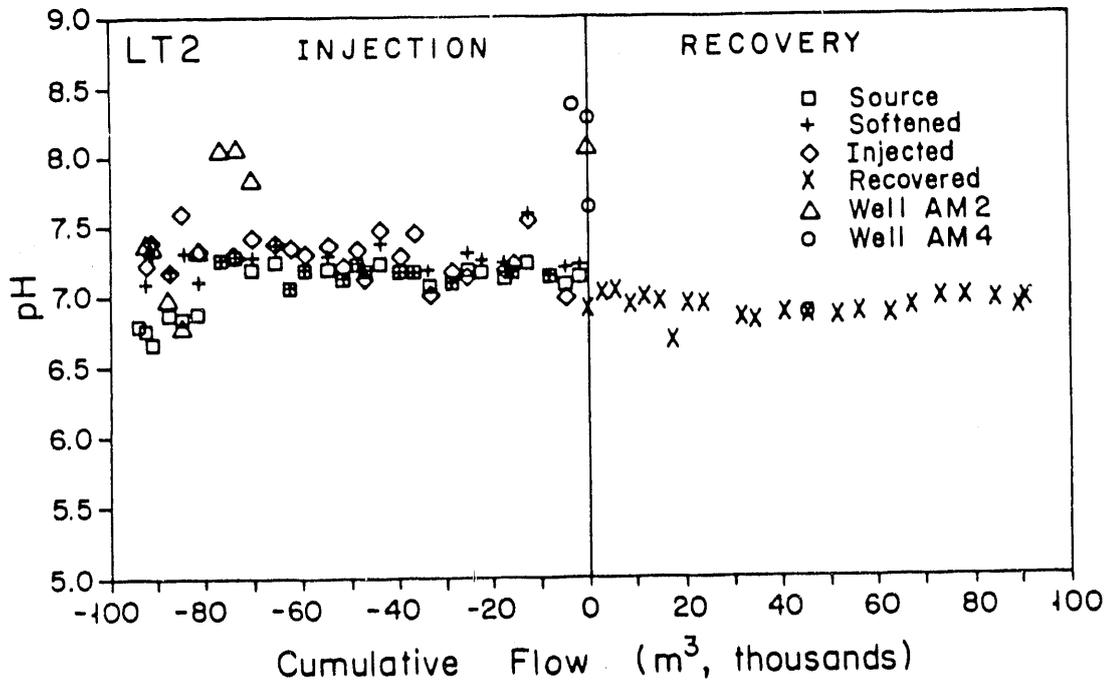


FIGURE 5.4. pH of Water Samples During Injection and Recovery, Long-Term Cycle 2

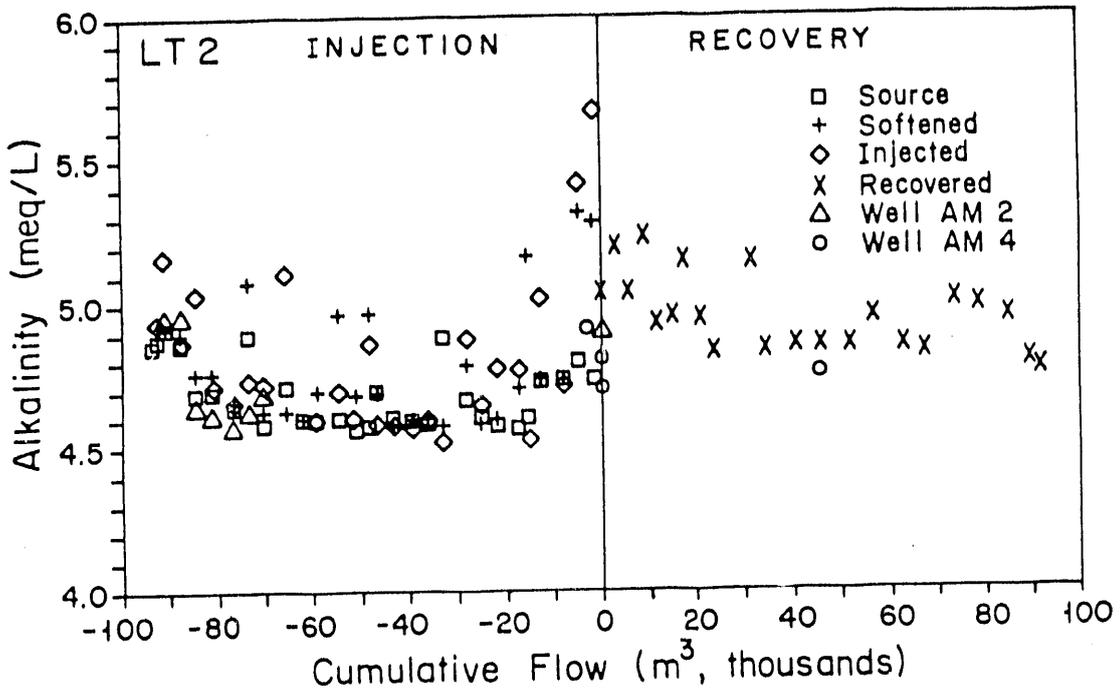


FIGURE 5.5. Alkalinity of Water Samples, Long-Term Cycle 2

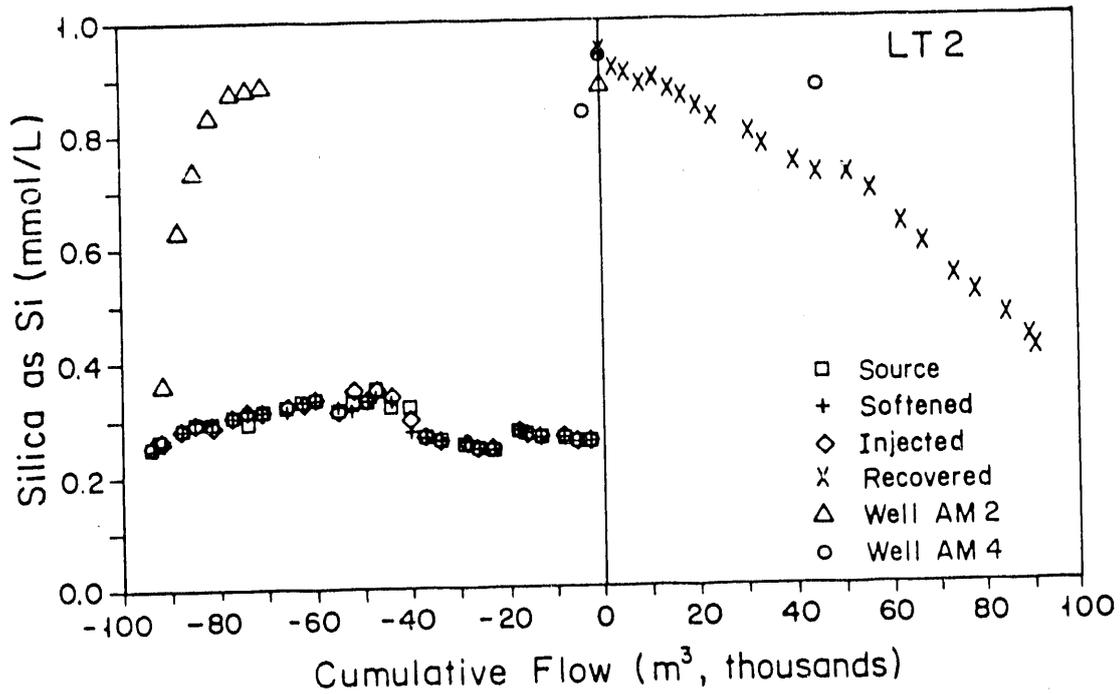


FIGURE 5.6. Silica (as Si) Concentration of Water Samples, Long-Term Cycle 2

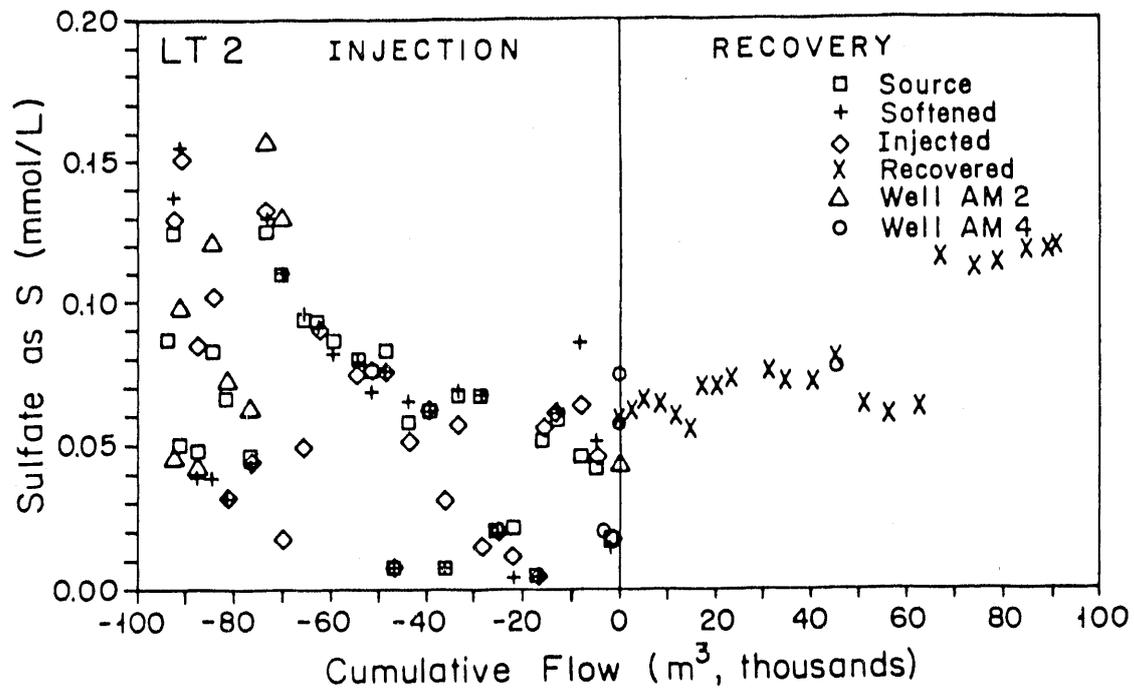


FIGURE 5.7. Sulfate Concentration of Water Samples, Long-Term Cycle 2

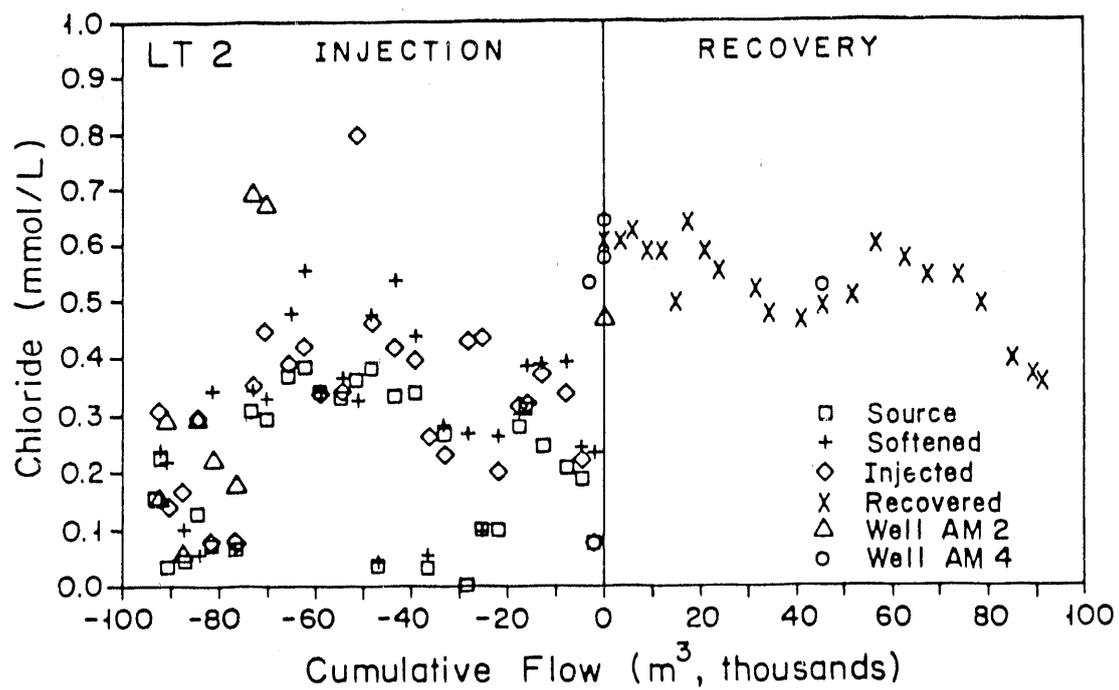


FIGURE 5.8. Chloride Concentration of Water Samples, Long-Term Cycle 2

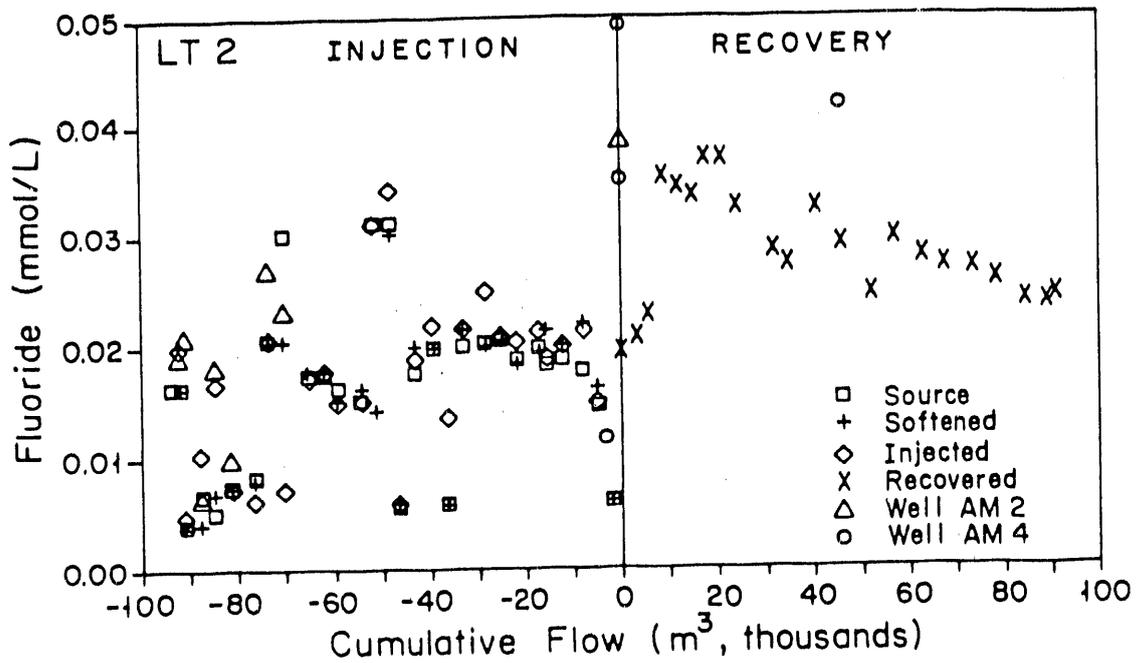


FIGURE 5.9. Fluoride Concentration of Water Samples, Long-Term Cycle 2

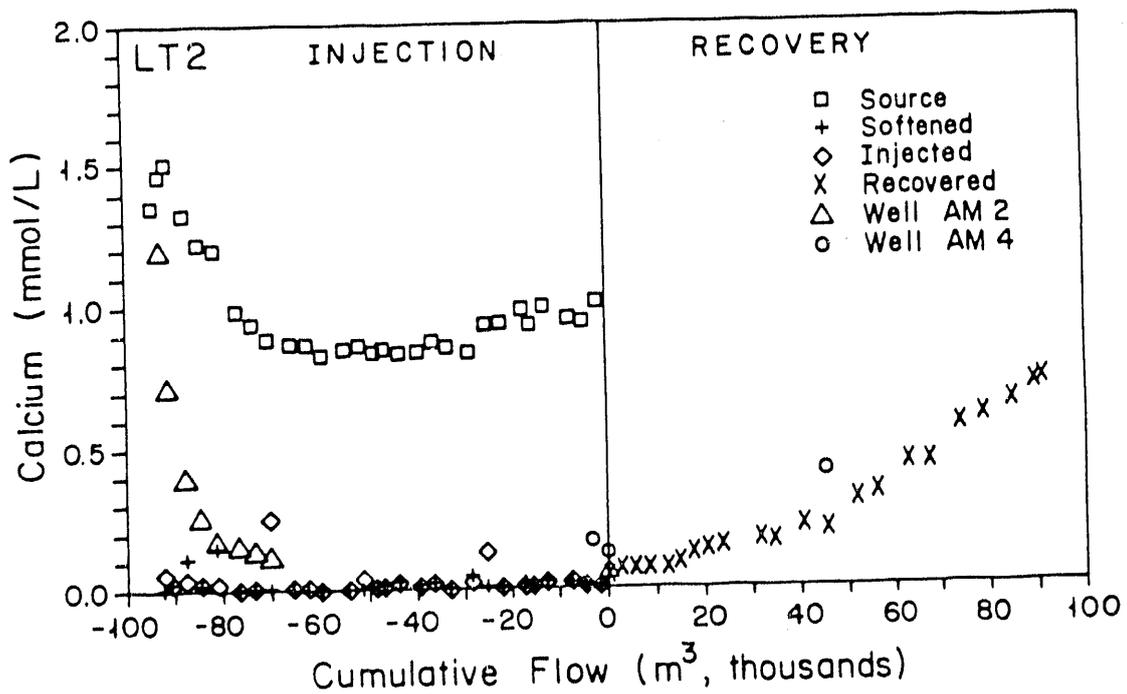


FIGURE 5.10. Calcium Concentration of Water Samples, Long-Term Cycle 2

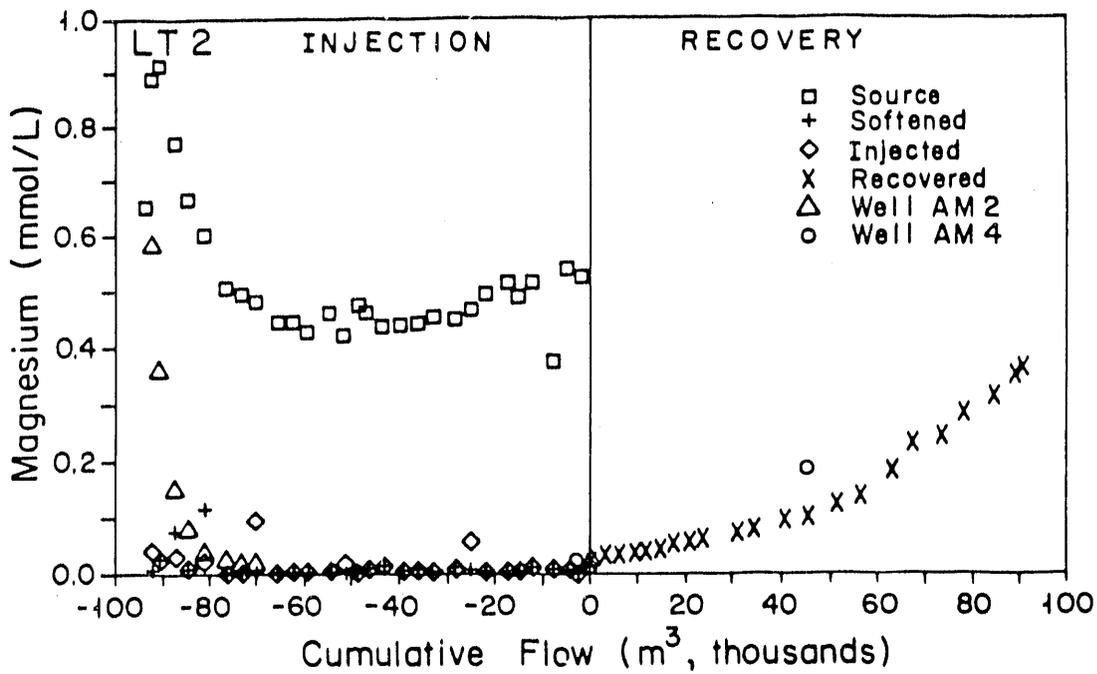


FIGURE 5.11. Magnesium Concentration of Water Samples, Long-Term Cycle 2

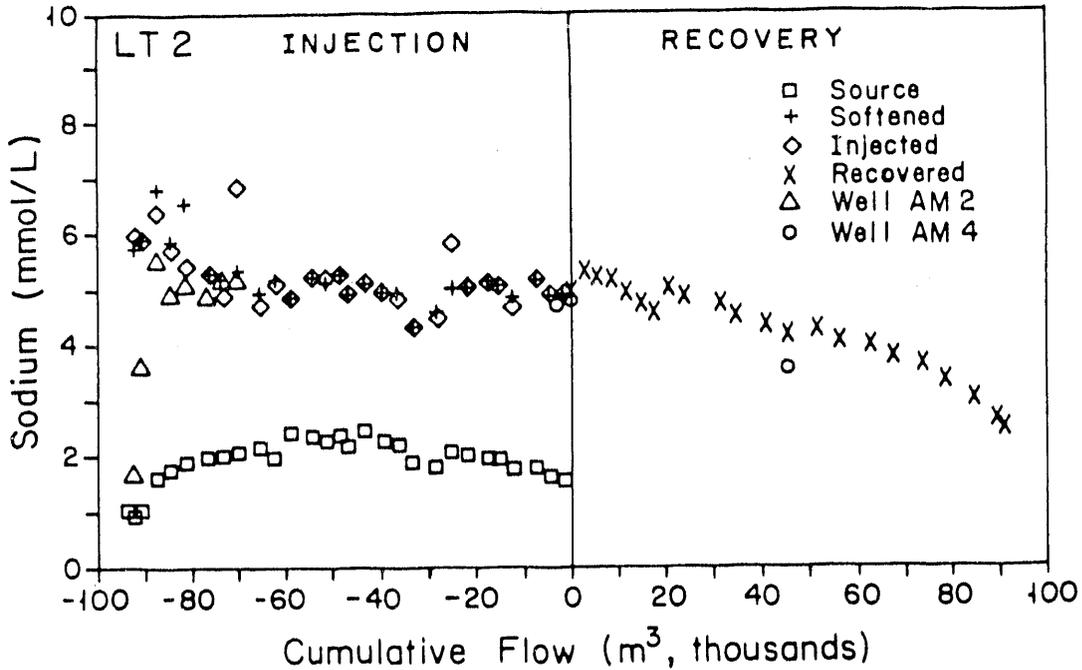


FIGURE 5.12. Sodium Concentration of Water Samples, Long-Term Cycle 2

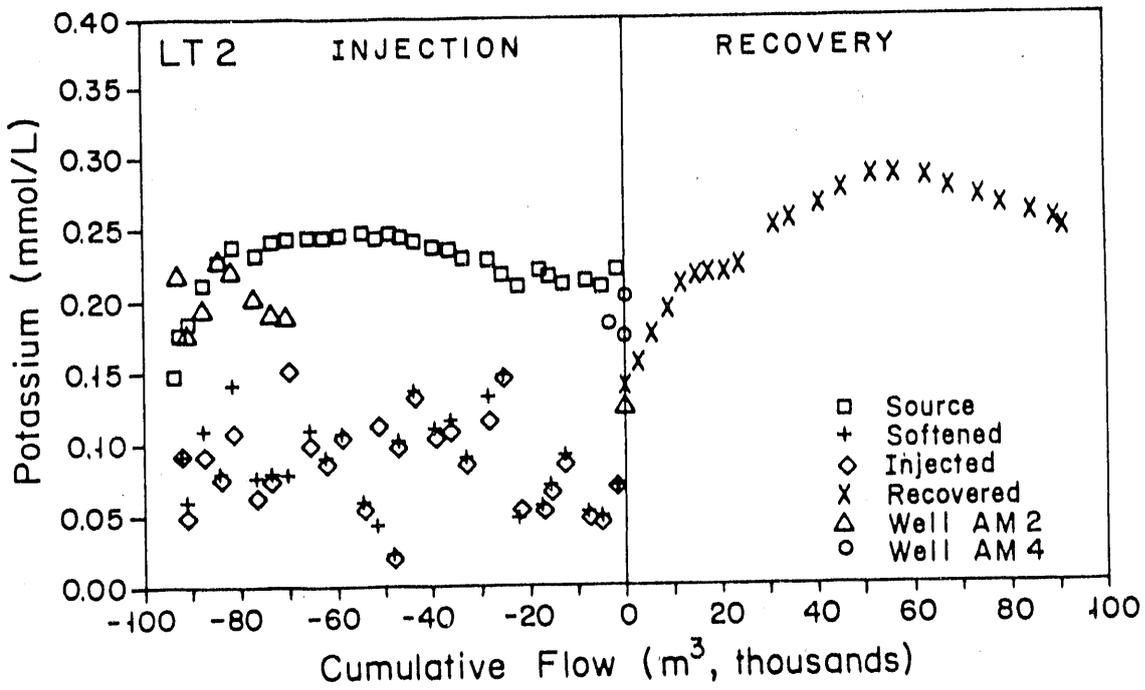


FIGURE 5.13. Potassium Concentration of Water Samples, Long-Term Cycle 2

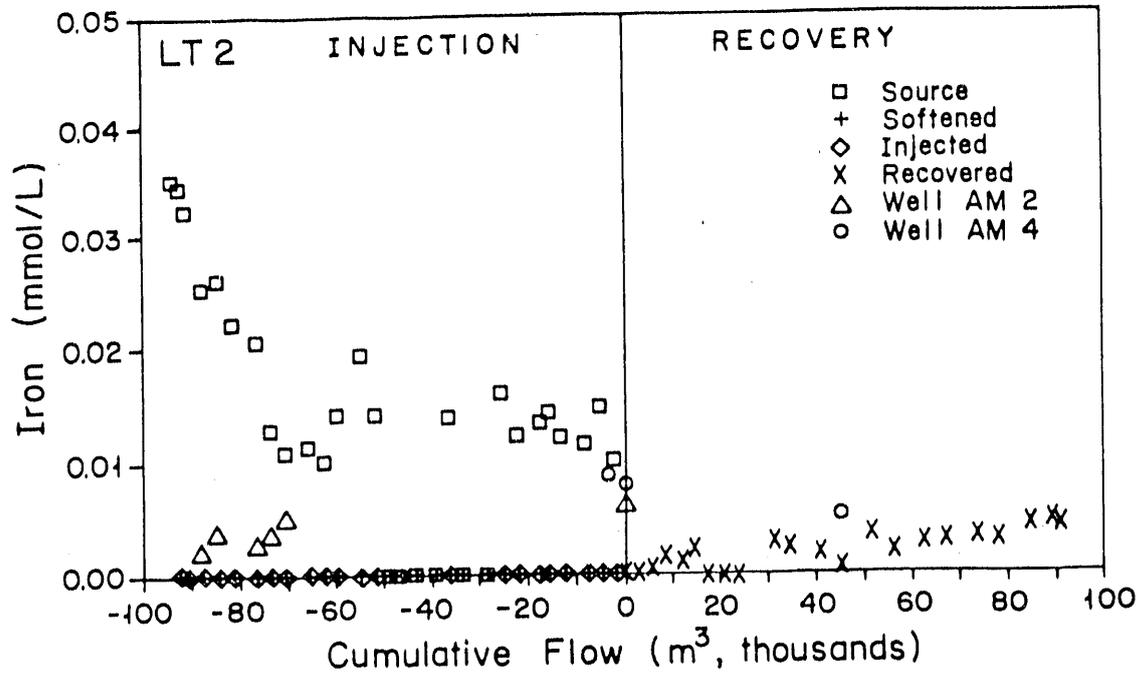


FIGURE 5.14. Iron Concentration of Water Samples, Long-Term Cycle 2

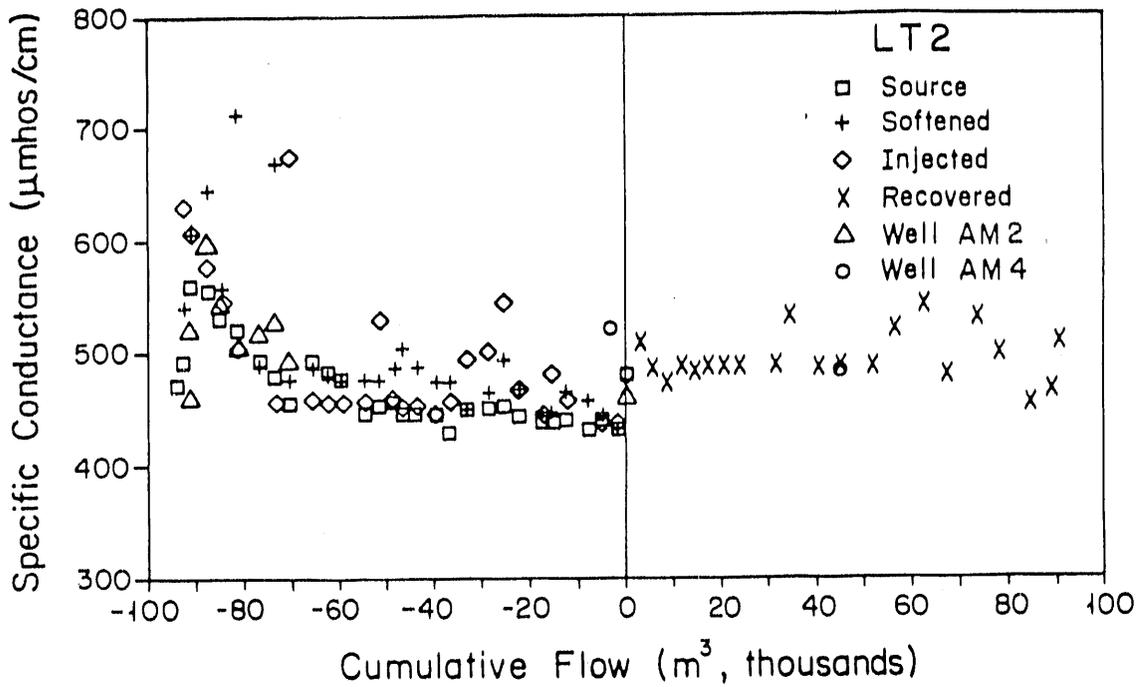


FIGURE 5.15. Specific Conductance of Water Samples, Long-Term Cycle 2

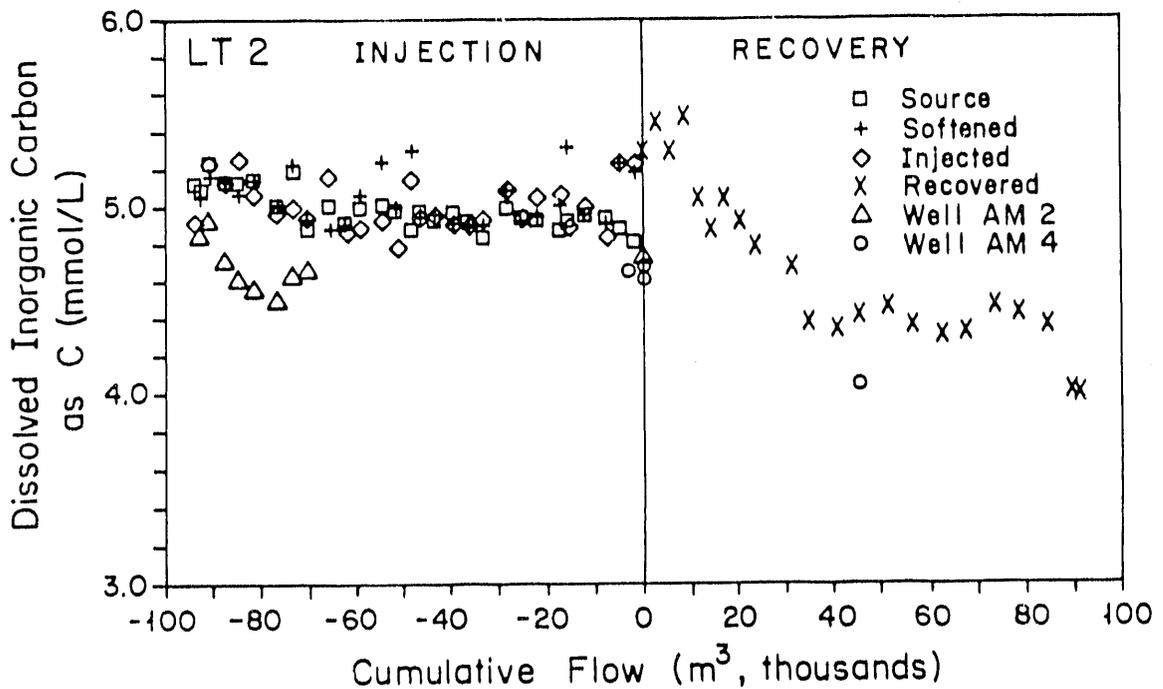


FIGURE 5.16. Dissolved Inorganic Carbon of Water Samples, Long-Term Cycle 2

reached a high of about 106°C (223°F) early in recovery and declined to nearly 60°C (140°F) at the end of the cycle. The pH of the source, injection, and recovery waters was in the vicinity of 7.0 (Figure 5.4). Alkalinity values for injection waters were about 4.6 to 4.8 meq/L, and the recovery waters ranged from 4.8 to 5.2 meq/L in a pattern somewhat similar to temperature (Figure 5.5).

The silica in injection water was nearly constant at about 0.30 mmol/L (Figure 5.6). The variation of silica in the recovery phase followed the water temperature, ranging from 0.95 (hottest) to 0.45 mmol/L (coolest). Frequent measurements of dissolved silica in well AM2 during injection showed silica peak at 0.89 mmol/L, reflecting the passage of stored hot and silica-rich water by the well. These relationships were expected given the temperature solubility relationship of quartz.

Sulfate (Figure 5.7), chloride (Figure 5.8), and fluoride (Figure 5.9) did not exhibit significant changes during the long-term test cycles. Calcium concentrations (Figure 5.10) exhibited trends in line with the temperature solubility relationship of calcite. The calcium concentrations in source water reflected previous test activity, and the low concentrations in Port III injection water resulted from softening in the sodium-zeolite exchanger. The calcium levels in the recovery water varied inversely with temperature, ranging from 0.15 mmol/L at the initiation of recovery [T = 106°C (222°F)] to 0.8 mmol/L at the end of recovery [T = 60°C (140°F)]. Magnesium levels generally mimicked the calcium fluctuations, reflecting the solubility controls of carbonate phases (Figure 5.11).

Sodium concentrations in the source water of well A (Figure 5.12) averaged about 2 mmol/L, resulting mostly from previous test cycles. After passing the sodium-zeolite softener, sodium concentrations increased to between 5.0 and 5.2 mmol/L (120 mg/L). Sodium in recovery water peaked at the initiation of the recovery phase at 5.5 mmol/L and decreased to about 3 mmol/L by the end of recovery. The decreasing sodium concentration is attributed to mixing (or dilution) of the softened, injected water with low-sodium ambient water at the fringe of the injected water (Perlinger et al. 1987).

Potassium (Figure 5.13) and iron concentrations (Figure 5.14) fluctuated over small ranges and are considered unimportant in controlling possible reactions (dissolution/precipitation). Specific conductance (Figure 5.15) in source and injection water was about 450 to 525 $\mu\text{mhos/cm}$ and was consistent at about 500 $\mu\text{mhos/cm}$ in the recovery water. Specific conductance was dominated by the sodium-bicarbonate pair in the recovery phase. Dissolved inorganic carbon (DIC) concentrations were about 5 mmol/L in the source and injection water (Figure 5.16). In the recovery phase, DIC concentrations decreased from 5.4 mmol/L at the start to about 4 mmol/L by the end. A DIC of 5 mmol/L corresponds to about 60 mg/L as carbon.

5.2.3 Chemical and Mass Balance of Long-Term Cycle 2

The chemical effects of softening, heating, and storage were quantified through the use of a mass balance. The total mass of each constituent to pass through each port was approximated using trapezoidal integration of the curves describing concentration versus cumulative volume (Tables 5.4 and 5.5). The general equation used for the trapezoidal integration is:

$$\text{Total Mass} = C_1(V_1 - V_0) + \frac{(C_i + C_{i-1})}{2} (V_i - V_{i-1}) + C_n(V_{n+1} - V_n) \quad (2)$$

where

- C_1 = solute concentration first sample
- V_1 = volume at C_1
- i = sample number
- C_i = solute concentration
- V_i = volume at C_i
- C_n = solute concentration last sample
- V_n = volume at C_n
- V_{n+1} = final volume pumped.

In calculating the total mass, the final injection volume of 93,800 m^3 was used for V_{n+1} for both the injection and recovery phases. The effects of softening, heating, and storage are best illustrated by constructing a mass balance around each process (Tables 5.6 and 5.7). The negative values indicate a loss of mass through that process and positive values indicate a gain.

The statistical significance of the total mass and mass balance values has been estimated using a propagation of errors method (Shoemaker et al. 1981). Through the use of partial differential equations, the error of each concentration and volume measurement is propagated to give a standard deviation for the mass (Tables 5.4 and 5.5). The general equation is:

$$S^2_{(F)} = \left[\frac{\partial F}{\partial x} \right]^2 S^2_{(x)} + \left[\frac{\partial F}{\partial y} \right]^2 S^2_{(y)} + \dots \quad (3)$$

where S^2 is the variance, F is a function, and x, y are variables of F . The equation is applied to the total mass equation to determine the error in the total mass at each port.

The two variables in the total mass equation are volume and concentration. The variance used for the concentration is the larger standard deviation of the laboratory and field replicates (Table 5.1). The variance of the hourly flow readings is used to determine the volume variance. The errors for the mass balance are determined using the same method (Tables 5.6 and 5.7).

The mass charge balances of the cations and the anions for each sampling point have differences of 1.4% to 2.8% (Figure 5.17). These percent differences compare very well to the ion imbalances (Figure 5.2) calculated for the individual samples.

The water softener [Port II - Port I] removed 284 keq of calcium, magnesium, and potassium from the source water (Figure 5.18). Sodium, the exchange ion, was added during the softening process to the extent of 302 keq. There was an addition of 17.7 keq of sodium above the amount needed for the softening process. The amount of chloride also increased by 9.0 keq during softening (Figure 5.18). The excess sodium and chloride can be attributed to the incomplete rinsing of the water softener following regeneration.

TABLE 5.4. Cumulative Mass of Dissolved Species in Source, Softened, Injected, and Recovered Water, Long-Term Cycle 2. Kiloequivalents, except as noted.

	Source	Softened	Injected	Recovered
Alkalinity	439.29 ±0.037	447.97 ±0.037	450.38 ±0.037	463.37 ±0.041
Silica (kmol)	27.2 ±0.13	27.2 ±0.13	26.8 ±0.13	65.8 ±0.68
DIC (kmol)	472 ±1.8	478 ±1.8	475 ±1.8	435 ±1.7
Sulfate	11.39 ±0.039	11.33 ±0.040	10.6 ±0.10	15.48 ±0.096
Chloride	19.0 ±0.33	28.0 ±0.33	29.4 ±0.34	49 ±1.7
Fluoride	1.53 ±0.067	1.48 ±0.066	1.55 ±0.066	2.7 ±0.28
Calcium	181.7 ±0.09	3.8 ±0.39	5.0 ±0.39	60 ±3.0
Magnesium	96.0 ±0.12	2.4 ±0.12	2.5 ±0.45	27.7 ±0.15
Sodium	184.8 ±0.67	486.7 ±0.67	485.7 ±0.67	390 ±1.7
Potassium	21.1 ±0.13	8.3 ±0.13	8.2 ±0.13	23.26 ±0.052
Iron	1.1 ±0.16	0	0	0.2 ±0.16
Manganese	0	0	0	0
Hardness	278 ±1.1	6 ±1.1	8 ±2.1	88 ±7.5
Total anions	471.2 ±0.34	488.8 ±0.34	491.9 ±0.90	530 ±1.7
Total cations	484.7 ±0.80	501.2 ±0.80	501.4 ±0.36	501 ±3.5

Source: Port I
 Softened: Port II
 Injected: Port III(i)
 Recovered: Port III(r)
 0 = Not detected

The only significant mass change across the heat exchanger [Port II - Port III(i)] is the addition of 2.4 keq of alkalinity.

Heated ATEs water stored for 59 days resulted in some dissolution and recovery of aquifer minerals. Silica, which had not changed during softening

TABLE 5.5. Cumulative Mass of Dissolved Species in Source, Softened, Injected, and Recovered Water, Long-Term Cycle 2. In kilograms.

	<u>Source</u>	<u>Softened</u>	<u>Injected</u>	<u>Recovered</u>
Alk as HCO_3^-	26801 ±2.2	27331 ±2.2	27477 ±2.2	28270 ±2.5
SiO_2 as Si	763 ±3.7	763 ±3.7	752 ±3.7	1850 ±19
DIC as C	5670 ±21	5740 ±21	5710 ±21	5220 ±20
SO_4 as S	182.7 ±0.74	181.5 ±0.75	170 ±2.0	248 ±1.8
Chloride	670 ±12	990 ±12	1040 ±12	1730 ±59
Fluoride	29 ±2.1	28 ±2.1	29 ±2.1	50 ±9.1
Calcium	3642 ±7.8	76 ±7.8	101 ±7.8	1200 ±60
Magnesium	1167 ±1.5	30 ±1.5	31 ±5.5	336 ±1.8
Sodium	4250 ±15	11190 ±15	11170 ±15	8980 ±40
Potassium	824 ±5.1	323 ±5.2	319 ±5.2	909 ±2.0
Iron	63 ±4.4	0	0	12 ±4.4
Manganese	0	0	0	0
Hardness as CaCO_3	13900 ±20	310 ±20	380 ±30	4400 ±150
Total anions	27680 ±12	28530 ±12	28720 ±12	30300 ±60
Total cations	9950 ±19	11620 ±18	11620 ±19	11440 ±73

Source : Port I
 Softened : Port II
 Injected : Port III(i)
 Recovered : Port III(r)
 0 = Not detected

and heating, gained 13 kmol during storage. The increase of silica was caused by dissolution of quartz in the aquifer at the elevated temperature of the injected water. The levels of calcium, magnesium, and potassium also increased by 55 keq, 25.2 keq, and 15.1 keq, respectively (Figure 5.19). The increase in recovery of chemical mass in the storage cycle has been attributed

TABLE 5.6. Mass Balance Across the Water Softener, Heat Exchanger, Aquifer Storage, and Total Cycle, Long-Term Cycle 2. Kiloequivalents, except as noted.

	<u>Water Softener</u>	<u>Heat Exchanger</u>	<u>Aquifer Storage</u>	<u>Total Cycle</u>
Alkalinity	8.68 ±0.052	2.40 ±0.052	12.99 ±0.055	24.08 ±0.055
Silica (kmol)	0.0 ±0.19	-0.4 ±0.19	39.1 ±0.69	38.7 ±0.69
DIC (kmol)	6 ±2.5	-3 ±2.5	-41 ±2.4	-38 ±2.4
Sulfate	-0.07 ±0.055	-0.7 ±0.11	4.9 ±0.14	4.1 ±0.10
Chloride	9.0 ±0.47	1.4 ±0.47	20 ±1.7	30 ±1.7
Fluoride	-0.05 ±0.094	0.08 ±0.094	1.1 ±0.29	1.1 ±0.29
Calcium	-177.9 ±0.55	1.2 ±0.55	55 ±3.0	-122 ±3.0
Magnesium	-93.5 ±0.17	0.1 ±0.47	25.2 ±0.48	-68.3 ±0.19
Sodium	301.9 ±0.95	-1.0 ±0.95	-95 ±1.9	206 ±1.9
Potassium	-12.8 ±0.19	-0.1 ±0.19	15.1 ±0.14	2.2 ±0.14
Iron	-1.1 ±0.16	0	0	-0.9 ±0.16
Manganese	0	0	0	0
Hardness	-271 ±1.6	1 ±2.2	80 ±2.4	-190 ±7.6

Softener: Chemical added/removed in the water softener, Port II - Port I

Exchanger: Chemical added/removed in the heat exchanger, Port III(i) - Port II

Storage: Chemical added/removed during aquifer storage
Port III(r) - Port III(i)

Cycle: Chemical added/removed during ATES test cycle, Port III(r) - Port I

0 = Not detected

to a combination of mineral dissolution and mixing of stored water with surrounding, ambient ground water. Sodium was lost during storage (95 keq). Of the total injected sodium from the water softening step, 80% was recovered; the 20% lost is believed to be the result of mixing. Small amounts of anions were also gained during storage (Figure 5.19).

TABLE 5.7. Mass Balance Across the Water Softener, Heat Exchanger, Aquifer Storage, and Total Cycle, Long-Term Cycle 2. In kilograms.

	<u>Water Softener</u>	<u>Heat Exchanger</u>	<u>Aquifer Storage</u>	<u>Total Cycle</u>
Alk as HCO ₃ ⁻	530 ±3.2	147 ±3.2	793 ±3.3	1469 ±3.3
SiO ₂ as Si	0 ±5.3	-11 ±5.3	1100 ±20	1090 ±20
DIC as C	70 ±30	-30 ±30	-490 ±29	-450 ±29
SO ₄ as S	-1 ±1.1	-12 ±2.1	78 ±2.7	66 ±2.0
Cl	320 ±17	50 ±17	690 ±60	1060 ±60
F	-1 ±3.0	1 ±3.0	21 ±9.3	21 ±9.3
Ca	-3570 ±11	20 ±11	1100 ±61	-2440 ±61
Mg	-1137 ±2.1	1 ±5.7	306 ±5.8	-830 ±2.3
Na	6940 ±22	20 ±22	-2190 ±43	4730 ±43
K	-501 ±7.3	-3 ±7.3	590 ±5.5	85 ±5.5
Fe	-63 ±4.4	0	0	-51 ±4.4
Mn	0	0	0	0
Hardness as CaCO ₃	-13580 ±28	60 ±36	4000 ±150	-9500 ±150

Softener: Chemical added/removed in the water softener, Port II- Port I
 Exchanger: Chemical added/removed in the heat exchanger, Port III(i)- Port II
 Storage: Chemical added/removed during aquifer storage,
 Port III(r)- Port III(i)
 Cycle: Chemical added/removed during ATEs test cycle, Port III(r)- Port I
 0 = Not detected

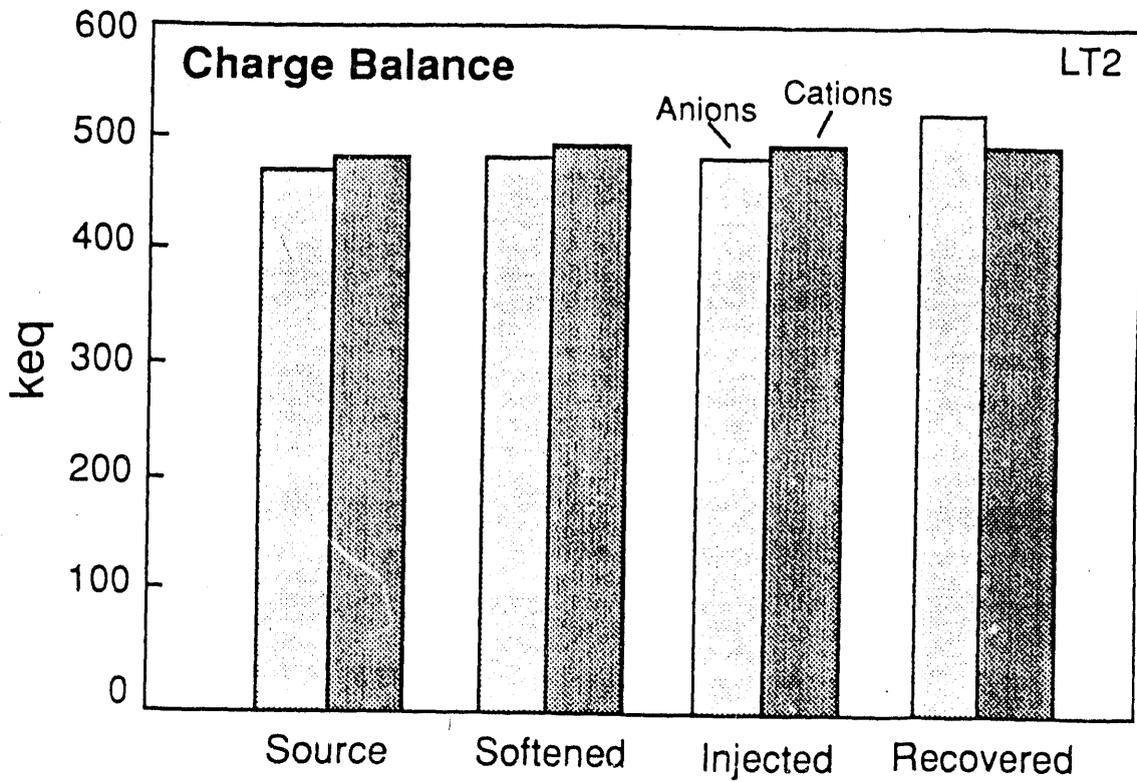


FIGURE 5.17. Anion and Cation Charge Balance of Source, Softened, Injected, and Recovered Water, Long-Term Cycle 2

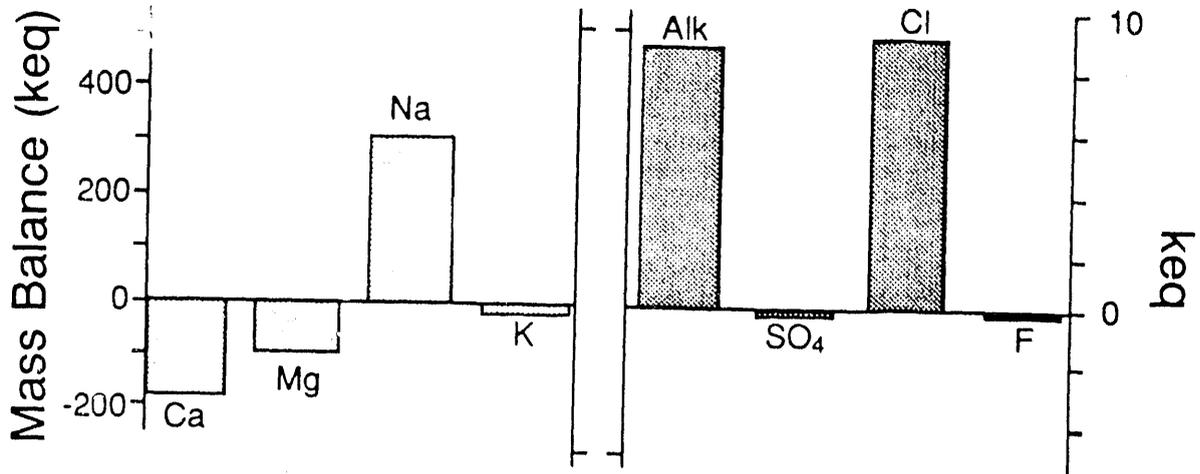


FIGURE 5.18. Mass Balance Across Water Softener (Softened-Source), Long-Term Cycle 2

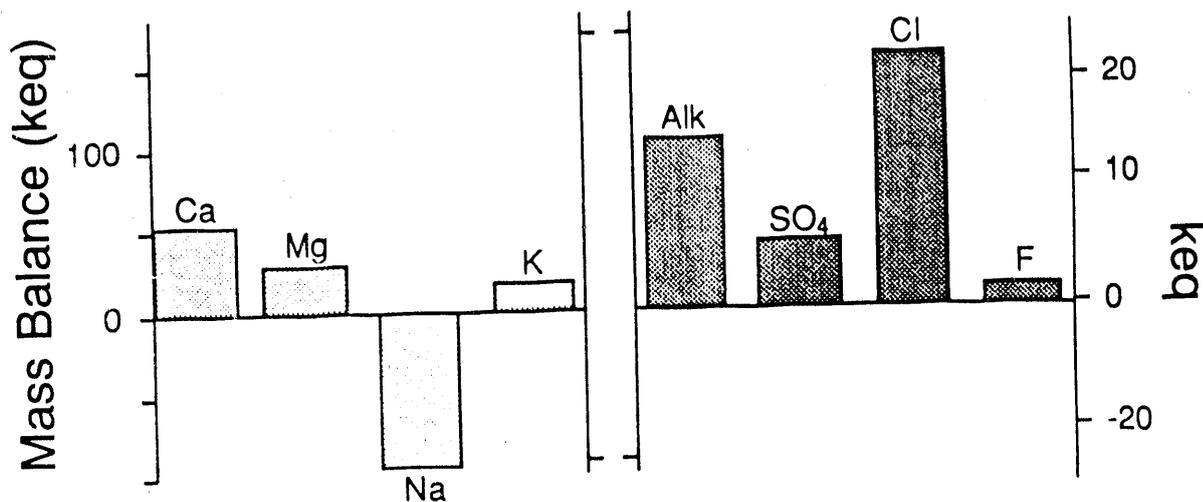


FIGURE 5.19. Mass Balance Across Aquifer Storage (Recovered-Injected), Long Term Cycle 2

5.2.4 Short-Term Fluctuations in Chemical Discharge from Water Softener

Occasionally, abnormally high levels of conductivity, sodium, calcium, and chloride were detected in the injection samples. Periods of higher levels were observed shortly after the water softener unit switched from a spent to a charged bed. These high levels suggest short-term fluctuations in the chemical quality of the ATEs water emerging from the water softener.

On December 3, 1986, during LT2, the conductivity of the softened water was monitored preceding and following the softening unit changeover (see Figure 5.20). The changeover occurred between samples taken at 30 and 35 min., with a corresponding increase in conductivity from 438 to 754 $\mu\text{mhos/cm}$, followed by a decrease approaching the levels preceding the changeover.

At December 5 changeover, samples of the softened and heated water (i.e., injected water) were collected to determine the contribution of the anions and cations to the increased conductivity observed previously. The conductivity of the source water was monitored to verify that the increases were caused by the softening and were not a function of the source water.

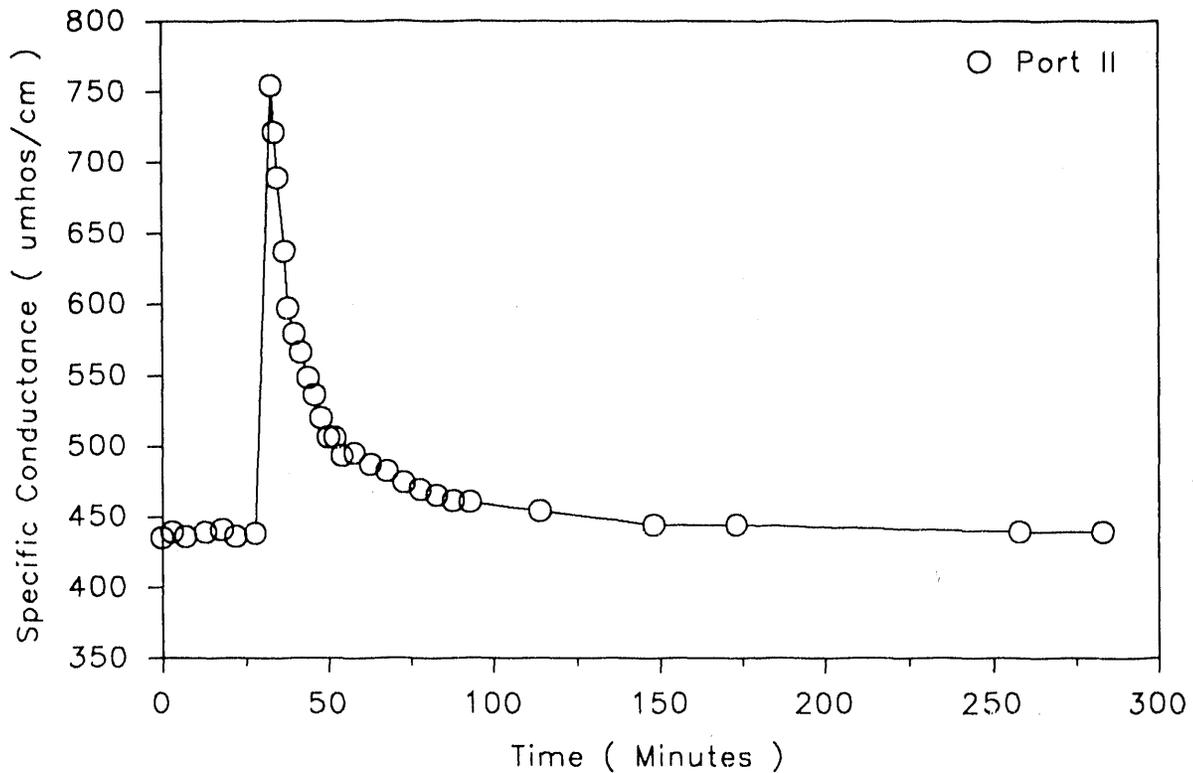


FIGURE 5.20. Specific Conductance of Softened Water, December 3, 1986, Plotted Against Sampling Time, 0=7:47 a.m.

Figure 5.21 shows the variation in the conductivity of the source and softened water. As expected, the source water shows no increase in conductivity, and the softened, heated water exhibits a conductivity pulse. The softened, heated water shows an increase in the cations and chloride values following the changeover while the remaining parameters remain constant (Figure 5.22). For example, the calcium concentrations increase from around 0.05 mmol/L prior to changeover to as high as 0.17 mmol/L just following changeover. This represents a 280-fold increase in concentration. The calcium concentration decreases exponentially to reach 0.1 mmol/L in about 1 hour. In general, magnesium, sodium, potassium, and chloride behave similarly.

The increase in ionic concentrations is caused by incomplete rinsing following the softener regeneration. The high levels of sodium and chloride are residuals from the brine solution used to regenerate the softening media. Because of the high levels of sodium in the water, the efficiency of the

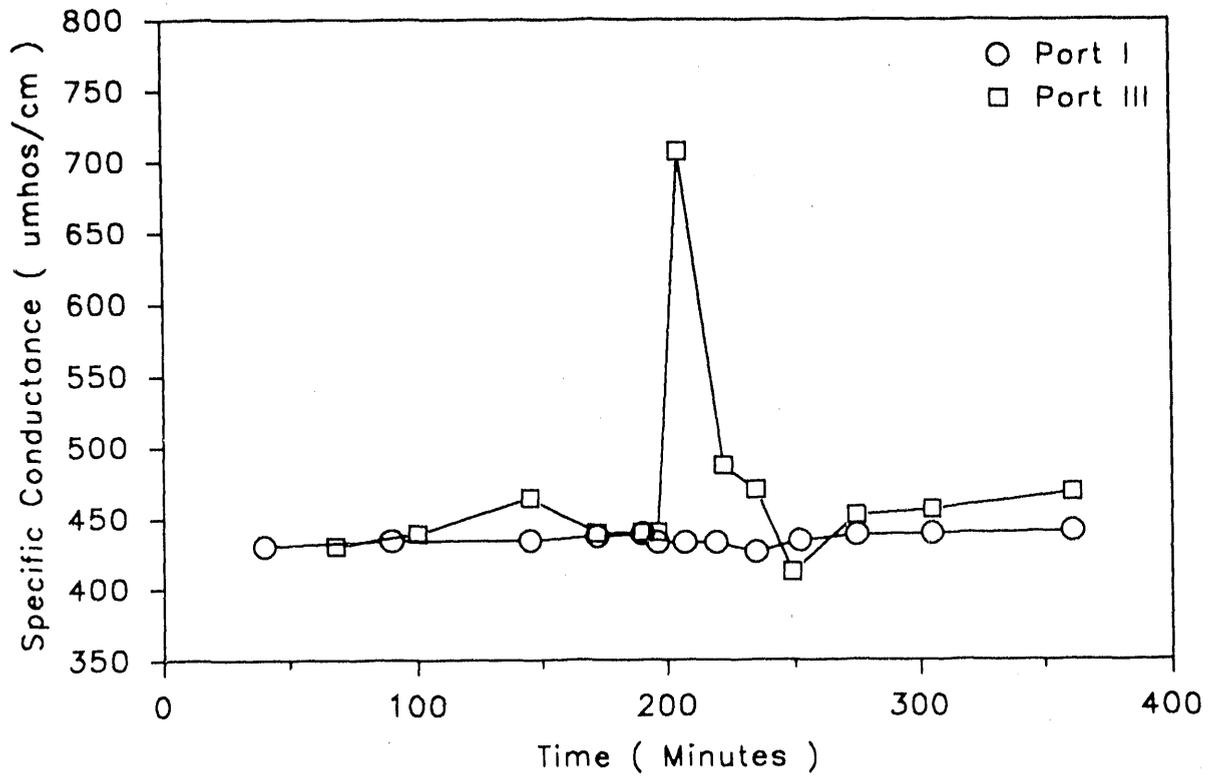


FIGURE 5.21. Specific Conductance of Source and Injected (Heated, Softened) Water, December 5, 1986, Plotted Against Sampling Time, 0=6:50 a.m.

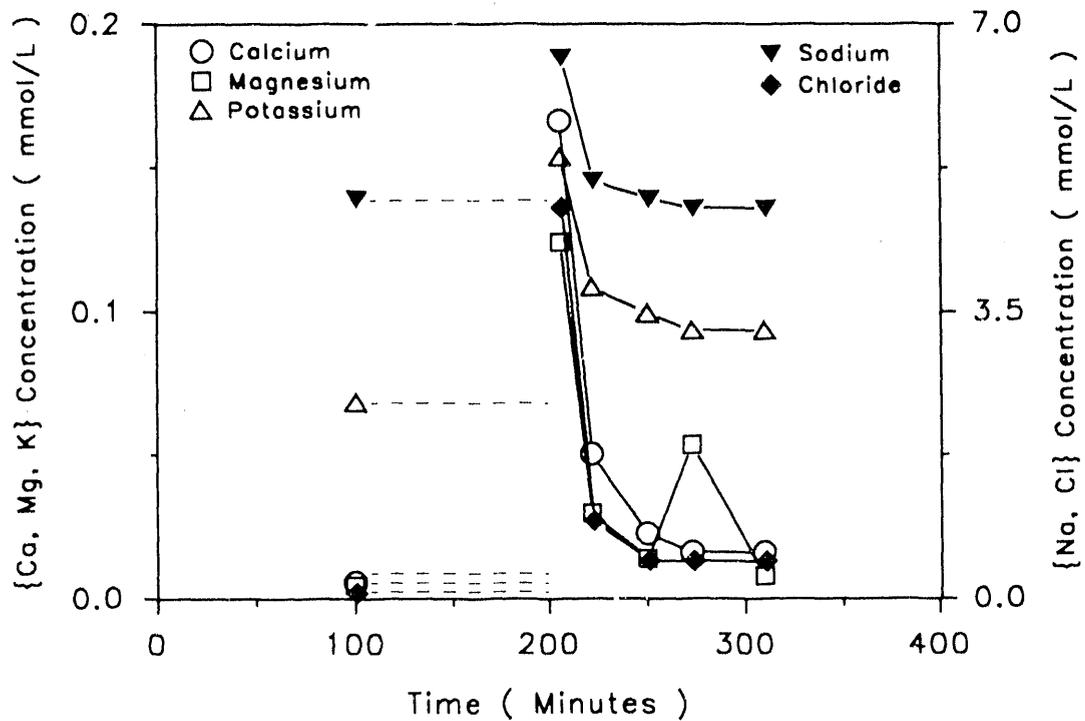


FIGURE 5.22. Calcium, Magnesium, Potassium, Sodium, and Chloride Concentrations of Injected Water, December 5, 1986, Plotted Against Sampling Time, 0=6:50 a.m.

exchange of sodium for calcium, magnesium, and potassium was reduced and thus their concentrations increased. During the injection phase of LT2, there were 290 softener changeovers. These short-term fluctuations in concentrations contributed to an unevaluated uncertainty in the final mass balance calculated for the softened and injected water.

5.2.5 Comparison of Long-Term Cycles 1 and 2

Figures 5.23 through 5.30 show (Port III) results of the two long-term cycles from the recovery phase for selected chemical species. Table 5.8 lists the Port I, II, and III (recovery and injection) mean concentrations of all species analyzed. The mean values represent a range of concentrations or intensity for species that varied systematically during the long-term cycles. For example, the average temperature of the recovery phase of LT1 and LT2 was 77°C (170°F) and 85°C (185°F), respectively, while the temperature range was 30°C (54°F). The difference was caused mainly by the higher storage

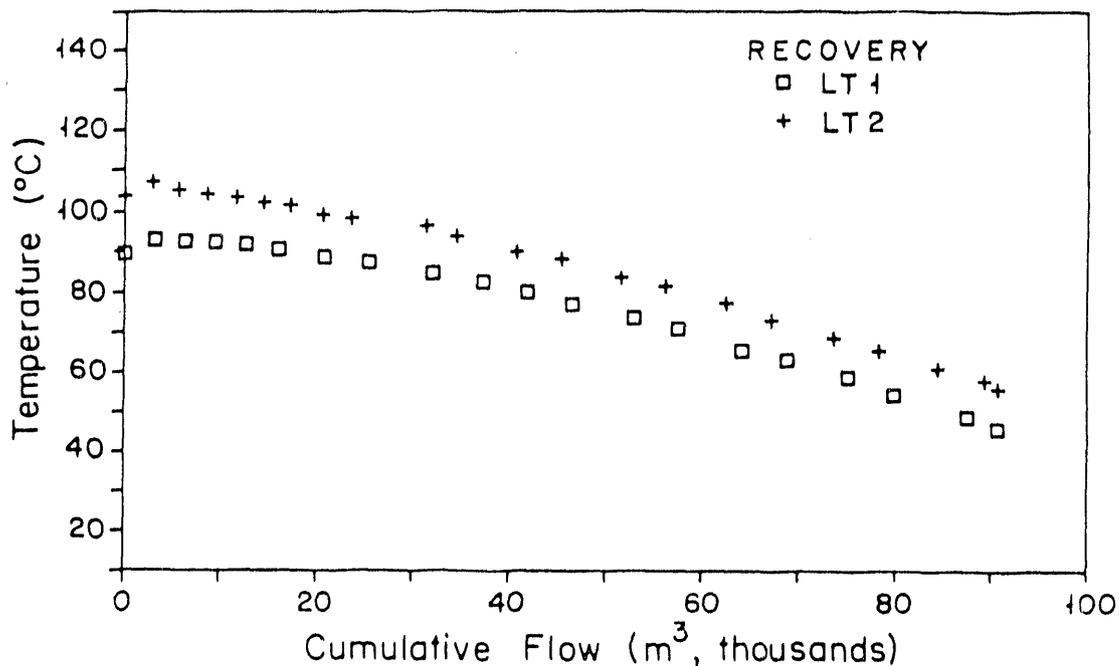


FIGURE 5.23. Temperature of Recovery Water Samples, LT1 and LT2

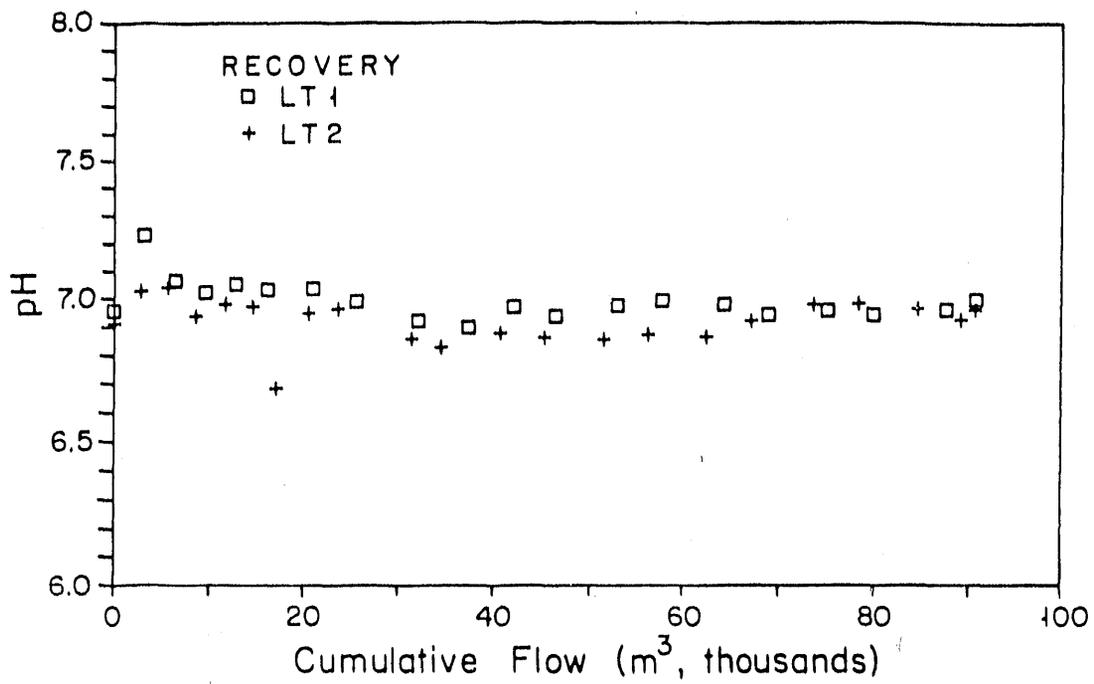


FIGURE 5.24. pH of Recovery Water Samples, LT1 and LT2

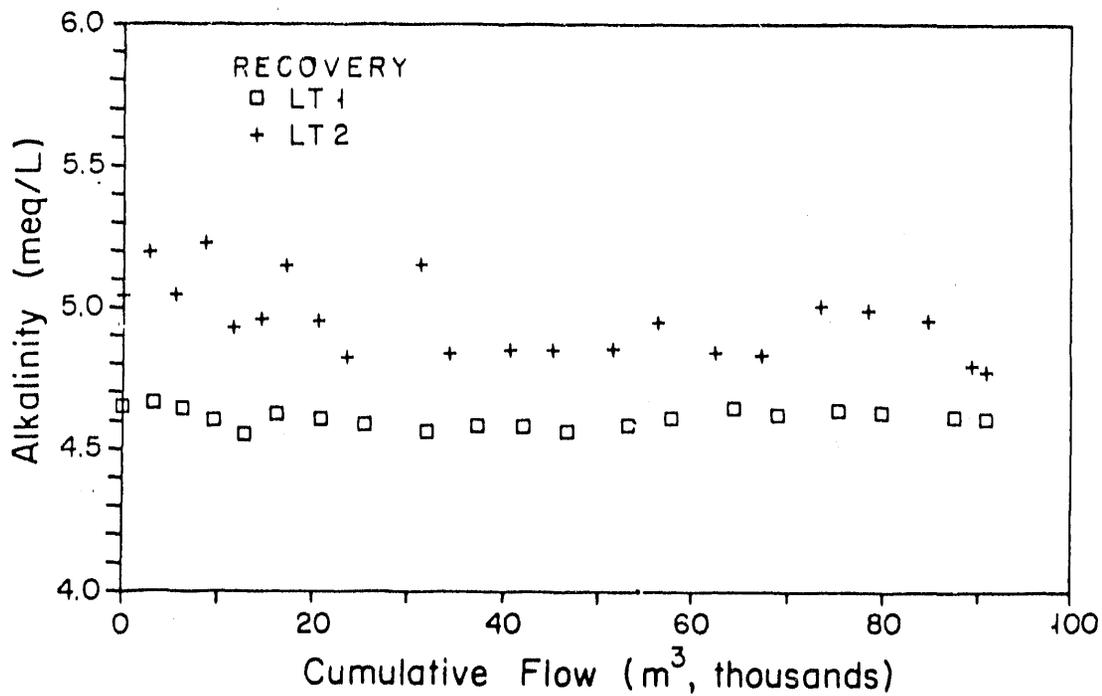


FIGURE 5.25. Alkalinity of Recovery Water Samples, LT1 and LT2

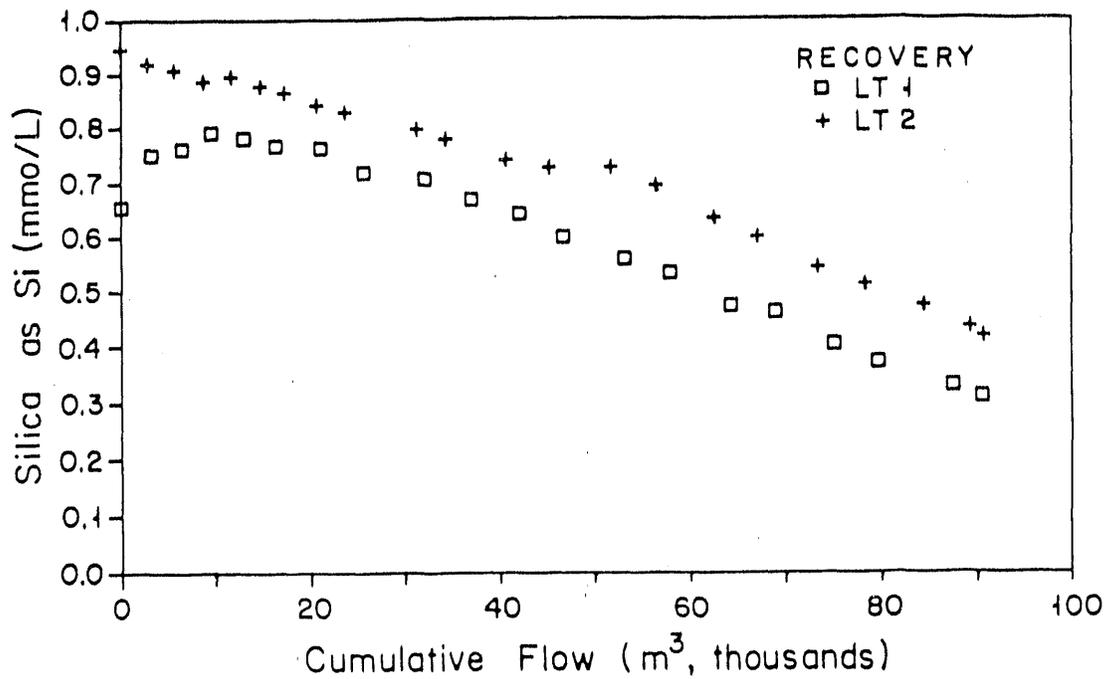


FIGURE 5.26. Silica (as Si) Concentrations of Recovery Water Samples, LT1 and LT2

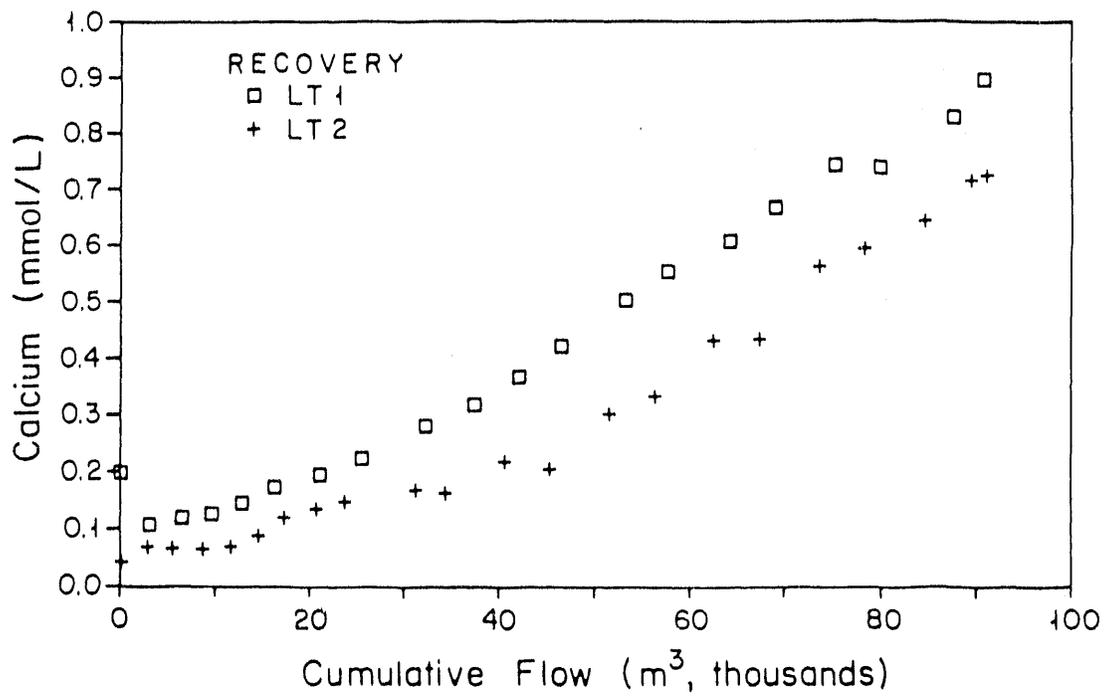


FIGURE 5.27. Calcium Concentrations of Recovery Water Samples, LT1 and LT2

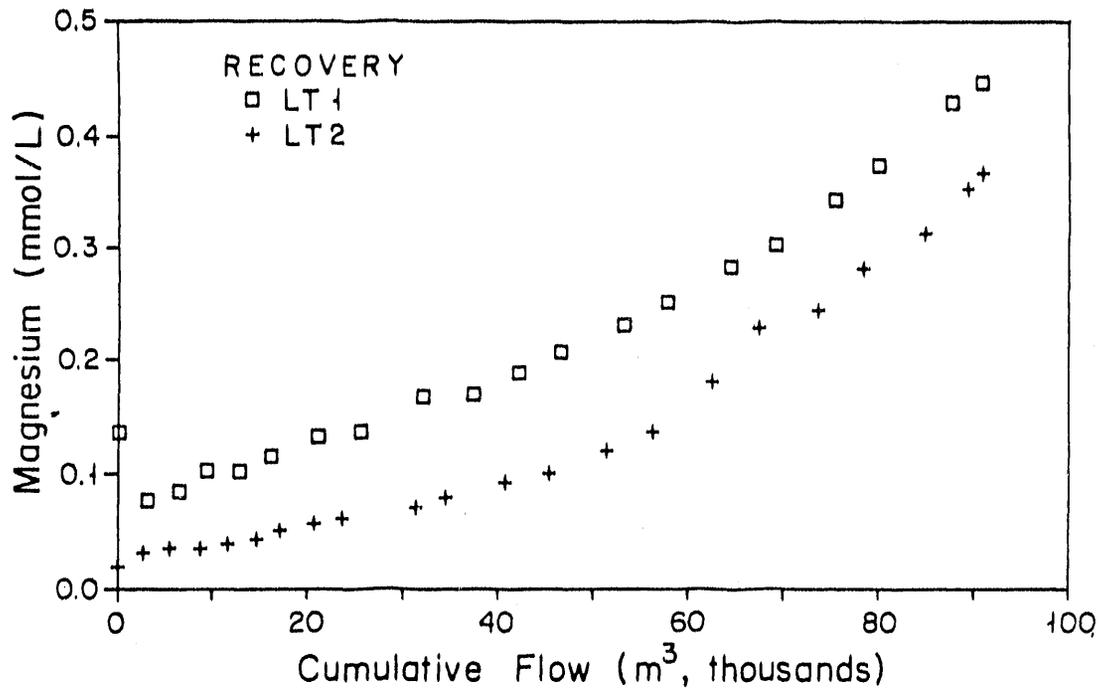


FIGURE 5.28. Magnesium Concentrations of Recovery Water Samples, LT1 and LT2

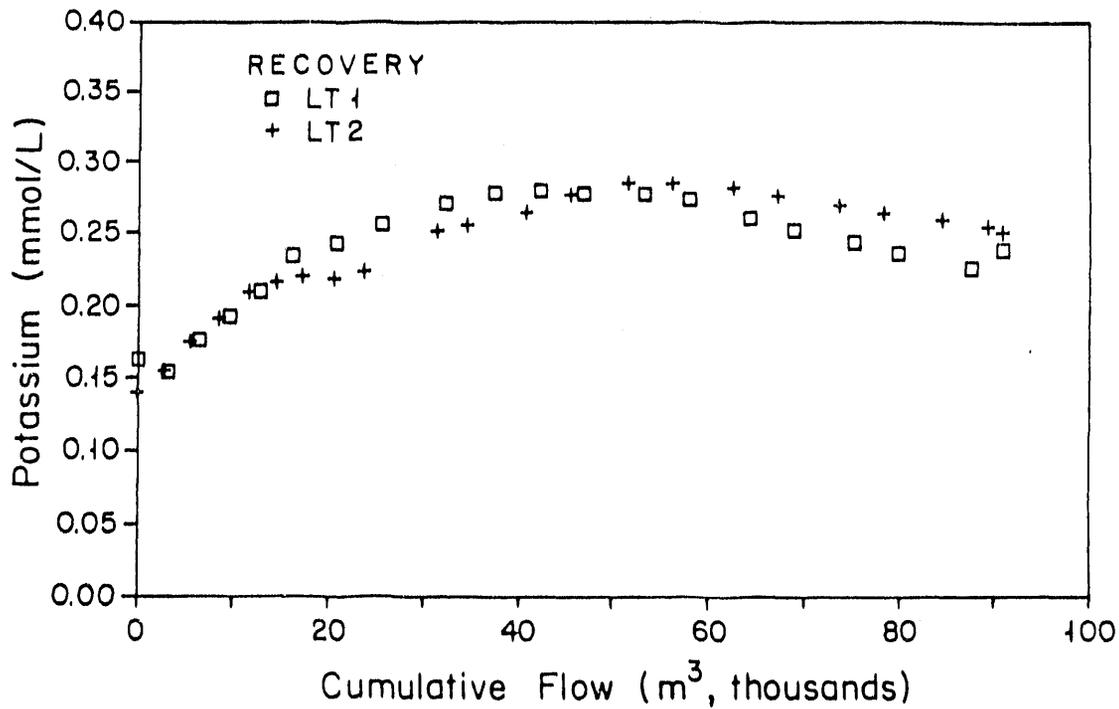


FIGURE 5.29. Potassium Concentrations of Recovery Water Samples, LT1 and LT2

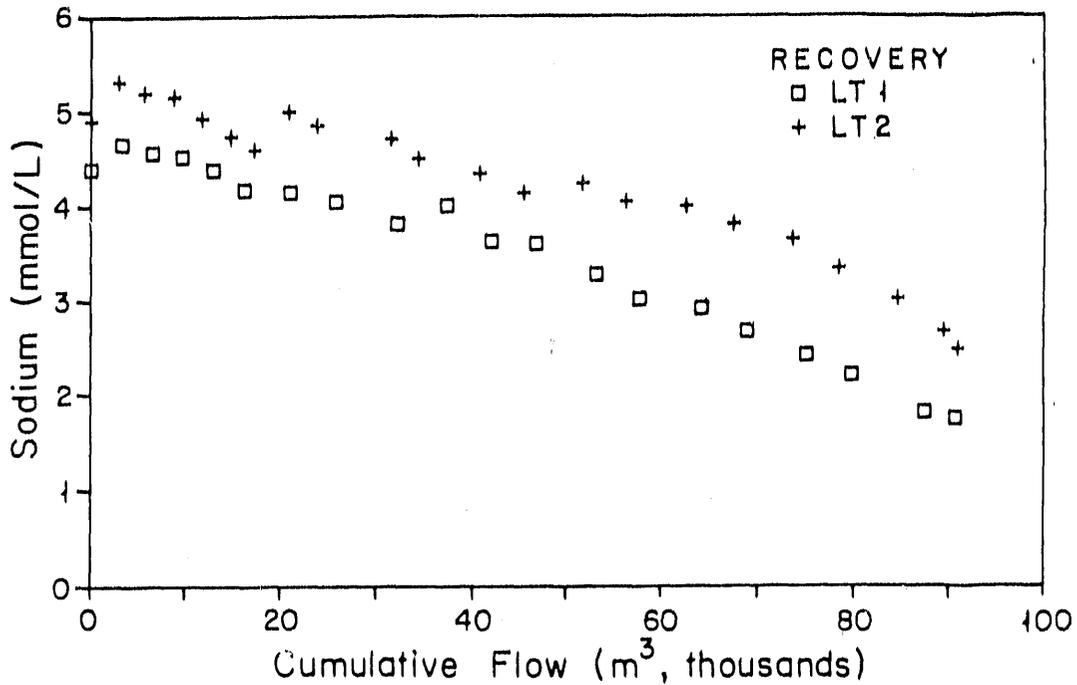


FIGURE 5.30. Sodium Concentrations of Recovery Water Samples, LT1 and LT2

temperature during the second cycle. Figure 5.24 shows the pH of recovery phase waters from LT1 and LT2, averaging about 7.00.

The principal differences in water chemistry between LT1 and LT2 can be attributed to LT2's higher alkalinity (Figure 5.25) and lower concentrations of calcium (Figure 5.27) and magnesium (Figure 5.28). The higher alkalinity of LT2 resulted from the conservative nature of bicarbonate ions in pH 7.00 water at similar temperatures. Calcium and magnesium concentrations in LT2 were about 1.3 and 1.5 times less than LT1, respectively, because of the lower solubility of controlling carbonate phases at higher temperature. This behavior supports the contention that additional injection, storage, and recovery cycles would continue to heat the rock of the aquifer, maintaining higher ambient temperatures and thus lowering hardness. This should result in lower softening requirements for consecutive cycles. If all warmed water is pumped out as planned, the ambient water will require more softening during a third cycle.

TABLE 5.8. Average Concentrations of Dissolved Species in Water Samples, LT1 and LT2

Sample Port Sample Type	Long-Term Cycle 1				Long-Term Cycle 2			
	I	II	IIIi	IIIr	I	II	IIIi	IIIr
	Source	Softened	Injected	Recovered	Source	Softened	Injected	Recovered
pH Temp. (°C)	17.5	18.3	82.8	60.0	25.8	28.3	88.8	70.6
pH	7.03	7.03	7.29	7.00	7.11	7.24	7.29	6.93
SC (µmho/cm) 25 °C	358	376	426	492	467	500	477	494
DO (mg/L)	0.19	0.16	0.19	0.86	0.60	0.40	0.50	0.20
Alkalinity (meq/L)	4.44	4.44	4.47	4.61	4.69	4.79	4.81	4.96
Silica (mmol/L)	0.188	0.188	0.192	0.635	0.289	0.289	0.286	0.729
DIC (mmol/L)	NA	NA	NA	NA	4.980	5.050	5.013	4.672
Sulfate (mmol/L)	0.059	0.059	0.072	0.068	0.061	0.061	0.062	0.080
Chloride (mmol/L)	0.050	0.176	0.229	0.513	0.208	0.293	0.322	0.529
Fluoride (mmol/L)	0.010	0.008	0.008	0.025	0.016	0.016	0.017	0.028
Calcium (mmol/L)	1.261	0.099	0.075	0.363	0.994	0.020	0.026	0.289
Magnesium (mmol/L)	0.651	0.086	0.055	0.190	0.527	0.013	0.014	0.134
Sodium (mmol/L)	0.316	4.390	4.925	3.704	1.917	5.209	5.202	4.263
Potassium (mmol/L)	0.205	0.090	0.098	0.238	0.220	0.870	0.086	0.222
Iron (mmol/L)	0.013	0.001	0.001	0.004	0.012	0.600	0.000	0.002
Hardness (mmol/L)	1.912	0.184	0.130	0.553	1.521	0.032	0.040	0.423

Other differences are attributable to LT2's higher water temperatures and the use of a water softener. Silica concentrations (Figure 5.26) in LT2 were about 1.14 times greater than in LT1 because of the increased solubility of quartz at higher temperatures. Perlinger et al. (1987) suggests that amorphous silica should not precipitate in the source well following recovery of stored hot water. Potassium concentrations (Figure 5.29) in LT2 were lower than concentrations measured during the first half of recovery for LT1 but were slightly higher than concentrations measured during the second half of recovery for LT1. This would be consistent with the dilution of ATES water with colder, more potassium-rich ambient ground water starting at about 45,000 m³ of water recovered. Sodium concentrations (Figure 5.30) were about 1.4 times higher in LT2 than LT1 because of the addition of softened water and the relatively conservative nature of sodium in the aquifer.

5.3 SUMMARY

Ground-water geochemistry was monitored during a second long-term test cycle to evaluate the feasibility of ATES. About 93,000 m³ of ground water was pumped from a source well, heated to about 120°C (248°F), and injected into the FIG aquifer consisting primarily of quartz sandstone with lesser amounts of dolomite, feldspar, and clay minerals. Softening the water prior to heating effectively prevented mineral precipitation in the heat exchanger and injection well.

Calculations performed for the recovery phase of LT1 showed saturation with respect to quartz, dolomite, and calcite, thus indicating mineral dissolution during hot water storage. Calculations for LT2 show similar characteristics. Loss of sodium in the aquifer is attributed to mixing of ambient ground water with heated ATES water in both LT1 and LT2. Predictions for subsequent test cycles (Perlinger et al. 1987) indicated softening requirements would decrease, and less mineral dissolution is expected to occur during aquifer storage. Evaluation of LT2 test data suggests this prediction is accurate.

6.0 CONCLUSIONS

Aquifer thermal energy storage in a deep, confined aquifer is a technically feasible method for storing available energy on a periodic basis for use at a later time. The second long-term cycle experimental results agreed with expectations and with the previously conducted long-term cycle. A significant amount (61%) of the energy added to the ground water stored in the FIG confined aquifer during LT2 was recovered. This agrees quite closely with the energy recovery of 62% predicted by modeling of the cycle. While this long-term test cycle cannot be used to directly evaluate the economics of an ATES system, it is noteworthy that energy used for pumping was less than 2% of the energy recovered.

The inhomogeneous, highly stratified FIG aquifer was characterized satisfactorily prior to this experimental cycle; performance during LT2 was quite close to the performance during LT1. The highly layered nature of the FIG aquifer was reflected in the arrival pattern of the thermal front measured at storage site monitoring well thermocouples and in the small amount of thermal stratification within the storage zone. Pressure (water level) changes observed at storage site monitoring wells were less than 15 psi (10.3 m) during LT2, well within the expected, and safe, range. The FIG aquifer remained well-separated from the overlying Jordan and underlying Mt. Simon aquifers.

Ion-exchange water softening was used successfully to prevent scaling of the heat exchangers and the storage well during LT2. Chemistry of the ground water injected to storage was changed by the softening. Sodium replaced the magnesium and calcium of the source water. The injected, stored water had an average total hardness of 4 mg/L as calcium carbonate. Water recovered from storage had an average total hardness of 42 mg/L as calcium carbonate, which was approximately equal to the saturation concentration.

Major ion concentrations in recovered water were approximately in equilibrium at all temperatures. Trends in the water chemistry were as predicted for water at the recovered temperatures. Silica concentrations directly reflected the temperature of the recovered water. Calcium and

magnesium concentrations increased as the temperature decreased, reflecting solubility trends. Net additions and subtractions from the pumped water were observed during storage, reflecting equilibration, and to a lesser extent, mixing with "native" FIG ground water.

Effects of heated-water injection, storage, and recovery were restricted to the immediate vicinity of the storage well. No thermal or chemical changes were detected at well CM1, the remote site, during or following LT2. Softened water, with higher sodium concentrations than ambient water, served as a very good tracer. Softened water was the initial evidence that there was leakage at monitoring well AC1 between the FIG and Mt. Simon aquifers. Thermal profiling confirmed leakage at AC1 and suggested that it was at a very low rate.

Long-term storage of heat in an aquifer having moderate conductivity, low regional hydraulic gradient, and many barriers to vertical flow is feasible. Water obtained from the source well had retained heat from LT1, which had been completed 18 months prior to LT2. Source water had retained 39% of the heat sent to the source well site during LT1 recovery. Heat supplied by the source water amounted to 21% of the total heat stored during LT2 above ambient conditions.

Monitoring wells, which are essential for temperature and pressure observations near injection and recovery wells of an ATEs system, must be constructed in a manner to prevent cross-connection of the storage aquifer with other aquifers in an area.

Regulatory issues surrounding the softening, heating, and simply the reinjection of ground water were carefully scrutinized in the permitting process prior to conducting the long-term cycles at the site. Meeting permit requirements significantly affected the planning and operations at the St. Paul FTF. The use of potable ground water from the FIG aquifer caused significant interest from the general public in any aspects that were perceived as a possible threat to ground-water use. The fact that the FIG aquifer is the least used and lowest yielding of the aquifers in the Twin Cities Basin was a significant factor in obtaining approvals for conducting any tests requiring return of the ground water to the aquifer. This was true

even though the use of the ground water for the ATES cycles did not adversely affect the use of the FIG water. Changes in temperature and equilibrium concentrations of dissolved constituents were all in the ranges expected. Maintaining communication with regulatory agencies was and continues to be a high priority.

Future work must be done in the following areas:

- Rock-water interaction - Model expected interactions to observe effects and determine the impact of these effects on rock and/or ground water subjected to ATES.
- Control systems ability to meet a real heating load - Actual ATES cycle(s) should be conducted to meet a real heating load. Capital and operating costs should be determined and methods to automate the operation of an ATES system as much as possible should be identified and incorporated.
- Regulatory and institutional issues and impacts - Further review of issues that affect the application and operation of an ATES system is required. This should include investigation of the suitability of nonpotable (e.g., saline, mineralized, geothermal) aquifer waters as storage media; investigation of water-use law as it relates to thermal changes and injection of ground water in different areas; and investigation of appropriate regulations for ATES systems.
- Economic issues - The economics of ATES coupled with different interfaces, types of loads, temperature ranges, and sources of usable heat should be examined.

7.0 REVIEW AND DISCUSSION

The four short-term cycles and the first long-term cycle revealed a number of design, construction, and operating characteristics of the ATES FTF, which had to be modified or corrected before LT2 to complete an uninterrupted cycle. Many problems were mechanical, such as lineshaft bearing failures, power failures, and well construction problems. The most serious problems concerned carbonate scaling during the heating-injection phase of the cycles. Problems were dealt with successfully as they arose during the course of the project (Walton 1981a, 1981b; Walton and Hoyer 1982; Hoyer and Walton 1983, 1986; Hoyer and Spletstoeser 1987). This provided essential information that allowed LT2 to be conducted almost exactly as planned.

The short-term cycles, which had many interruptions, provided much useful information about the behavior of the system and the FIG aquifer (Walton et al. 1991). The effects of flow interruptions, variations in injection temperatures, flow rates, storage periods, and source water temperatures complicated comparisons between cycles and introduced complex signals into the FIG aquifer. Interpretation of thermal data was made more difficult by these fluctuations; however, the fluctuations allowed observation of the transient conditions on a repeating basis, which provided additional information on the reaction of the aquifer to the thermal injection and recovery.

The long-term cycles (LT1 and LT2) provided experiments much closer to the planned symmetrical test cycles. Interruptions and variations in flow and temperature were much less a feature of these experiments. The ion-exchange water softener permitted operation at a more constant temperature and flow rate than was possible when the condenser was scaling up with calcium carbonate. LT1 was subject to some interruptions until the water softener was operating properly (Hoyer et al. 1991).

Temperatures of source, injected, and recovered water during LT1 and LT2 are plotted against total volume in Figure 7.1. The residual heat from previous cycles is clearly seen on the source temperature curves. The

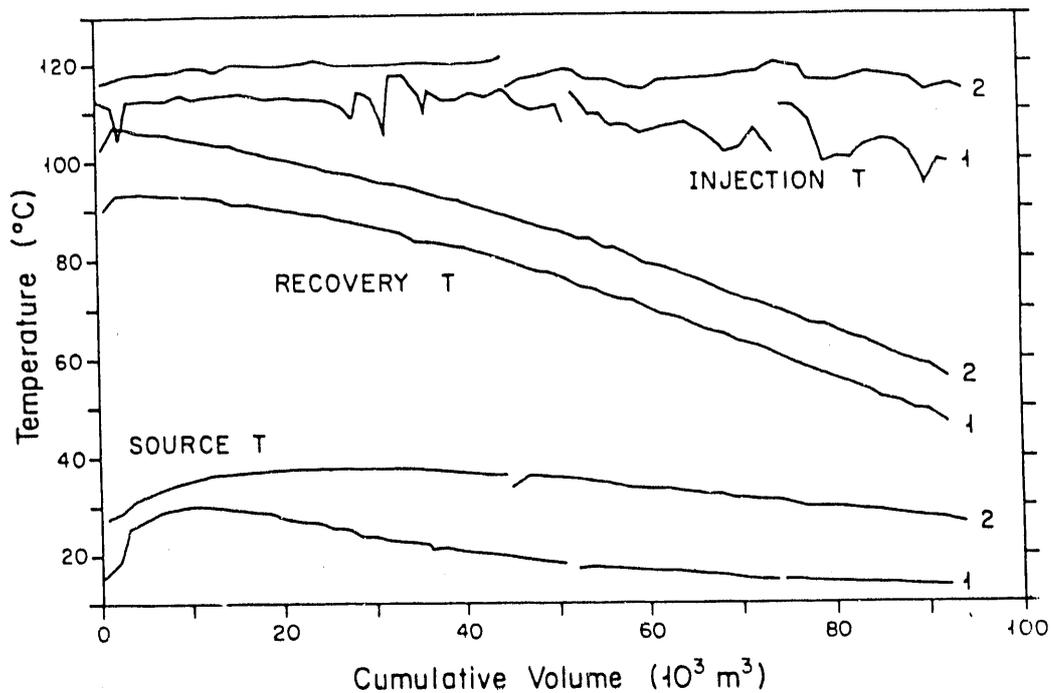


FIGURE 7.1. Temperatures of Source, Injected, and Recovered Water During LT1 and LT2

injection temperature curve for LT1 shows the effects of water softener problems and decreasing source water temperatures, and has more variation than the LT2 injection temperature curve. The recovery temperature curves are offset by the approximately 9°C (16°F) temperature difference of the injected water temperatures. The LT1 curve is flatter at the beginning of recovery because of the decreasing injection temperature during the latter stages of LT1 injection. Results are consistent; LT2 confirmed system behavior.

The objective of these experiments was to determine the technical feasibility of ATEs in a confined aquifer at temperatures above 100°C (212°F). Technical issues relating to the operation of the system under a nearly constant flow regime were addressed for these (planned) symmetrical tests. Technical and economic issues related to the fluctuating availability of thermal energy for storage or the fluctuating need for thermal energy during recovery were not thoroughly addressed during these cycles. Future cycles should be conducted that address these issues as well as to further assess water-rock interactions.

Regulatory issues surrounding the softening, heating, and simply the reinjection of ground water were carefully scrutinized in the permitting process prior to conducting the long-term cycles at the site. Meeting permit requirements significantly affected the planning and operations at the St. Paul FTF. The use of potable ground water from the FIG aquifer caused significant interest by the general public. The fact that the FIG aquifer is the least used and lowest yielding of the aquifers in the Twin Cities Basin was a significant factor in obtaining approvals for conducting any tests requiring return of the ground water to the aquifer. This was true even though the use of the ground water for the ATEs cycles did not adversely affect the use of the FIG water. Changes in temperature and equilibrium concentrations of dissolved constituents were all in the ranges expected. Maintaining frequent communication with regulatory agencies during all aspects of the operation must be a high priority.

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APPENDIX A

DAILY FLOW AND TEMPERATURE DATA FOR LONG-TERM CYCLE 2

TABLE A.1. Daily Flows and Temperatures for Long-Term Cycle 2 Injection

Date	Days Inj	Hours /Day	Cum Days (pump)	Cum Days (total)	Source Temp	Inject Temp	M**3/hr	M**3/day	CumM**3 (1000s)
02-Oct	0		0	0					0
02-Oct-86	0.375	9	0.375	0.375	27.03	116.03	67.92	611.3	0.611
03-Oct	1.375	24	1.375	1.375	28.77	117.33	67.73	1625.6	2.237
04-Oct	2.375	24	2.375	2.375	30.91	118.08	66.88	1605.1	3.842
05-Oct	3.375	24	3.375	3.375	32.18	118.08	66.96	1607.1	5.449
06-Oct	4.375	24	4.375	4.375	33.16	118.41	66.93	1606.3	7.055
07-Oct	5.375	24	5.375	5.375	34.20	118.24	66.48	1595.6	8.651
08-Oct	6.375	24	6.375	6.375	35.09	119.13	65.29	1567.0	10.218
09-Oct	7.375	24	7.375	7.375	35.75	119.21	66.75	1601.9	11.820
10-Oct	8.375	24	8.375	8.375	36.10	118.24	66.47	1595.4	13.415
11-Oct	9.375	22.38	9.308	9.375	36.29	119.74	66.18	1481.4	14.897
12-Oct	10.37	24	10.308	10.375	36.63	119.85	65.72	1577.4	16.474
13-Oct	11.37	24	11.308	11.375	36.91	119.32	65.92	1582.0	18.056
14-Oct	12.37	24	12.308	12.375	37.07	119.28	66.08	1585.8	19.642
15-Oct	13.37	24	13.308	13.375	37.28	119.43	66.54	1597.0	21.239
16-Oct	14.37	24	14.308	14.375	37.26	119.70	65.87	1580.8	22.820
17-Oct	15.37	24	15.308	15.375	37.29	120.43	64.35	1544.5	24.364
18-Oct	16.37	24	16.308	16.375	37.21	119.58	65.62	1574.9	25.939
19-Oct	17.37	24	17.308	17.375	37.31	119.56	66.47	1595.4	27.534
20-Oct	18.37	24	18.308	18.375	37.29	119.35	66.32	1591.7	29.126
21-Oct	19.37	24	19.308	19.375	37.28	119.50	65.91	1581.7	30.708
22-Oct	20.37	24	20.308	20.375	37.23	119.43	66.44	1594.7	32.302
23-Oct	21.37	24	21.308	21.375	36.94	119.78	66.53	1596.7	33.899
24-Oct	22.37	24	22.308	22.375	36.93	119.89	66.77	1602.4	35.502
25-Oct	23.37	24	23.308	23.375	36.84	119.53	66.56	1597.4	37.099
26-Oct	24.37	24	24.308	24.375	36.53	119.62	66.52	1596.5	38.695
27-Oct	25.37	24	25.308	25.375	36.38	119.49	66.09	1586.3	40.282
28-Oct	26.37	24	26.308	26.375	36.16	119.52	64.59	1550.1	41.832
29-Oct	27.37	24	27.308	27.375	35.96	120.19	65.49	1571.7	43.404
30-Oct	28.37	13.41	27.867	28.375	36.11	120.83	65.97	885.1	44.289
31-Oct	29.37	0	27.867	29.375					44.289
01-Nov	30.37	0	27.867	30.375					44.289
02-Nov	31.37	0	27.867	31.375					44.289
03-Nov	32.37	8.316	28.214	32.375	33.39	114.54	67.17	558.6	44.847
04-Nov	33.37	24	29.214	33.375	35.51	116.32	66.47	1595.4	46.443
05-Nov	34.37	24	30.214	34.375	35.42	116.82	66.95	1606.7	48.049
06-Nov	35.37	24	31.214	35.375	35.32	117.62	66.50	1596.0	49.645
07-Nov	36.37	24	32.214	36.375	35.09	118.41	66.53	1596.7	51.242
08-Nov	37.37	16.1	32.885	37.375	34.72	117.97	66.76	1074.9	52.317
09-Nov	38.37	22.1	33.806	38.375	34.48	116.16	66.23	1463.6	53.781
10-Nov	39.37	24	34.806	39.375	33.94	115.95	65.84	1580.1	55.361

TABLE A.1. (contd)

Date	Days Inj	Hours /Day	Cum Days (pump)	Cum Days (total)	Source Temp	Inject Temp	M**3/hr	M**3/day	CumM**3 (1000s)
11-Nov	40.37	24	35.806	40.375	33.48	115.33	66.62	1599.0	56.960
12-Nov	41.37	21.18	36.689	41.375	33.08	114.10	66.70	1413.0	58.373
13-Nov	42.37	24	37.689	42.375	32.83	114.02	67.07	1609.7	59.982
14-Nov	43.37	24	38.689	43.375	32.83	115.95	66.54	1597.0	61.579
15-Nov	44.37	24	39.689	44.375	32.36	115.81	66.72	1601.3	63.181
16-Nov	45.37	24	40.689	45.375	32.18	116.32	66.79	1603.1	64.784
17-Nov	46.37	24	41.689	46.375	31.62	116.40	66.70	1600.8	66.385
18-Nov	47.37	24	42.689	47.375	31.46	116.74	65.98	1583.5	67.968
19-Nov	48.37	24	43.689	48.375	30.92	117.51	66.37	1592.9	69.561
20-Nov	49.37	24	44.689	49.375	30.78	117.88	66.23	1589.4	71.150
21-Nov	50.37	24	45.689	50.375	30.41	118.37	66.53	1596.7	72.747
22-Nov	51.37	24	46.689	51.375	30.22	119.58	62.91	1509.9	74.257
23-Nov	52.37	24	47.689	52.375	29.79	118.89	65.35	1568.3	75.825
24-Nov	53.37	12.75	48.22	53.375	29.42	118.33	65.34	833.1	76.658
25-Nov	54.37	13.25	48.772	54.375	29.00	115.61	63.98	847.8	77.506
26-Nov	55.37	24	49.772	55.375	29.31	115.81	65.33	1567.8	79.074
27-Nov	56.37	24	50.772	56.375	28.90	115.67	65.72	1577.2	80.651
28-Nov	57.37	24	51.772	57.375	28.61	116.71	64.62	1550.8	82.202
29-Nov	58.37	24	52.772	58.375	28.42	117.52	63.76	1530.2	83.732
30-Nov	59.37	24	53.772	59.375	27.94	116.71	64.66	1551.8	85.284
01-Dec	60.37	24	54.772	60.375	27.52	116.47	64.38	1545.2	86.829
02-Dec	61.37	24	55.772	61.375	27.28	115.75	65.27	1566.5	88.396
03-Dec	62.37	21.66	56.675	62.375	26.84	113.29	64.72	1402.3	89.798
04-Dec	63.37	24	57.675	63.375	26.76	114.25	65.07	1561.7	91.360
05-Dec	64.37	24	58.675	64.375	26.25	114.81	65.19	1564.7	92.924
06-Dec	64.96	14.05	59.26	64.960	26.22	113.83	64.87	911.4	93.836
06-Dec				64.960					
TOTAL	64.96		59.26	64.960					93.836
AVERAGE		21.55			33.05	117.65	65.99		

TABLE A.2. Daily Flows and Temperatures for Long-Term Cycle 2 Recovery

Date	Days Rec	Hours /Day	Cum Days (pump)	Cum Days (total)	Return Temp	Recov Temp	M**3/hr	M**3/day	CumM**3 (1000s)
02-Feb-87	0	0	0						0
03-Feb	0.35	8.4	0.35	124.025	73.27	102.36	62.22	522.6	0.523
04-Feb	1.35	24	1.35	124.375	70.80	106.88	60.51	1452.2	1.975
05-Feb	2.35	24	2.35	125.375	72.97	106.46	60.47	1451.3	3.426
06-Feb	3.35	24	3.35	126.375	73.67	105.58	60.50	1452.0	4.878
07-Feb	4.35	24	4.35	127.375	75.29	105.28	60.46	1451.1	6.329
08-Feb	5.35	24	5.35	128.375	69.91	105.03	60.84	1460.2	7.789
09-Feb	6.35	24	6.35	129.375	71.26	104.27	61.25	1470.0	9.259
10-Feb	7.35	24	7.35	130.375	71.52	103.63	61.38	1473.1	10.733
11-Feb	8.35	24	8.35	131.375	72.07	103.40	61.77	1482.4	12.215
12-Feb	9.35	24	9.35	132.375	71.09	102.77	61.76	1482.2	13.697
13-Feb	10.35	24	10.35	133.375	70.86	102.53	61.99	1487.7	15.185
14-Feb	11.35	24	11.35	134.375	69.98	101.32	62.12	1490.9	16.676
15-Feb	12.35	24	12.35	135.375	68.68	100.72	62.39	1497.4	18.173
16-Feb	13.35	24	13.35	136.375	67.65	100.34	62.99	1511.7	19.685
17-Feb	14.35	24	14.35	137.375	67.20	99.49	62.90	1509.7	21.195
18-Feb	15.35	24	15.35	138.375	67.13	98.61	63.29	1519.0	22.714
19-Feb	16.35	24	16.35	139.375	67.22	98.16	63.52	1524.5	24.238
20-Feb	17.35	24	17.35	140.375	67.66	97.21	63.84	1532.2	25.770
21-Feb	18.35	24	18.35	141.375	67.53	96.92	63.14	1515.4	27.286
22-Feb	19.35	24	19.35	142.375	67.73	96.08	63.94	1534.5	28.820
23-Feb	20.35	24	20.35	143.375	66.64	95.03	64.53	1548.8	30.369
24-Feb	21.35	24	21.35	144.375	67.47	94.51	64.43	1546.3	31.915
25-Feb	22.35	24	22.35	145.375	66.50	94.04	64.51	1548.3	33.464
26-Feb	23.35	24	23.35	146.375	66.71	93.16	64.57	1549.7	35.013
27-Feb	24.35	24	24.35	147.375	65.32	92.31	64.74	1553.8	36.567
28-Feb	25.35	24	25.35	148.375	66.27	91.63	64.71	1553.1	38.120
01-Mar	26.35	24	26.35	149.375	64.32	91.02	64.89	1557.4	39.678
02-Mar	27.35	24	27.35	150.375	63.23	89.98	64.97	1559.2	41.237
03-Mar	28.35	24	28.35	151.375	61.28	89.18	64.74	1553.8	42.791
04-Mar	29.35	24	29.35	152.375	63.16	88.41	64.67	1552.2	44.343
05-Mar	30.35	24	30.35	153.375	63.24	87.58	64.66	1551.7	45.894
06-Mar	31.35	24	31.35	154.375	64.09	86.45	64.88	1557.2	47.452
07-Mar	32.35	24	32.35	155.375	65.58	85.76	64.77	1554.5	49.006
08-Mar	33.35	24	33.35	156.375	61.98	85.10	64.98	1559.5	50.566
09-Mar	34.35	24	34.35	157.375	57.59	83.92	64.92	1558.1	52.124
10-Mar	35.35	24	35.35	158.375	56.66	83.38	65.11	1562.6	53.686
11-Mar	36.35	24	36.35	159.375	56.92	81.82	65.37	1569.0	55.255
12-Mar	37.35	24	37.35	160.375	57.13	81.23	65.47	1571.3	56.827
13-Mar	38.35	24	38.35	161.375	57.53	80.03	65.30	1567.2	58.394
14-Mar	39.35	21.83	39.26	162.375	58.30	78.42	66.05	1442.1	59.836

TABLE A.2. (contd)

Date	Days Rec	Hours /Day	Cum Days (pump)	Cum Days (total)	Return Temp	Recov Temp	M**3/hr	M**3/day	CumM**3 (1000s)
15-Mar	40.35	24	40.26	163.375	57.43	78.17	65.84	1580.1	61.416
16-Mar	41.35	24	41.26	164.375	56.52	77.12	66.54	1596.9	63.013
17-Mar	42.35	24	42.26	165.375	56.45	75.95	65.80	1579.2	64.592
18-Mar	43.35	24	43.26	166.375	55.80	74.99	64.44	1546.5	66.139
19-Mar	44.35	24	44.26	167.375	54.92	73.44	66.45	1594.9	67.733
20-Mar	45.35	24	45.26	168.375	54.88	72.06	66.17	1588.1	69.322
21-Mar	46.35	24	46.26	169.375	54.13	71.19	66.00	1584.0	70.906
22-Mar	47.35	24	47.26	170.375	53.46	70.10	66.01	1584.2	72.490
23-Mar	48.35	24	48.26	171.375	53.16	69.03	65.87	1580.8	74.071
24-Mar	49.35	24	49.26	172.375	52.20	67.65	65.91	1581.9	75.653
25-Mar	50.35	24	50.26	173.375	49.78	66.30	65.93	1582.4	77.235
26-Mar	51.35	24	51.26	174.375	48.36	65.72	65.96	1583.1	78.816
27-Mar	52.35	24	52.26	175.375	47.15	64.12	65.83	1579.9	80.398
28-Mar	53.35	24	53.26	176.375	44.34	63.46	65.82	1579.7	81.978
29-Mar	54.35	24	54.26	177.375	42.99	62.48	65.64	1575.4	83.553
30-Mar	55.35	24	55.26	178.375	42.04	60.93	65.73	1577.6	85.131
31-Mar	56.35	24	56.26	179.375	43.23	59.71	65.81	1579.4	86.710
01-Apr	57.35	24	57.26	180.375	42.62	58.67	65.83	1579.9	88.290
02-Apr	58.35	24	58.26	181.375	40.88	57.89	65.74	1577.9	89.868
03-Apr	59.35	24	59.26	182.375	40.08	56.41	65.64	1575.4	91.443
04-Apr	59.75	9.6	59.66	183.775	39.22	55.61	65.51	628.9	92.072
TOTAL	59.75		59.66	183.775					92.072
AVERAGE		23.47			60.38	85.10	64.30		

APPENDIX B

ANALYTICAL RESULTS OF WATER SAMPLE ANALYSES FOR LONG-TERM CYCLE 2

TABLE B.1. Factors to Convert Between mmol/L and mg/L

<u>Parameter</u>	<u>mmol/L to mg/L multiply mmol/L by:</u>	<u>mg/L to mmol/L multiply mg/L by:</u>
SiO ₂ as Si	28.08	0.03561
DIC as C	12.01	0.08326
SO ₄ as S	32.06	0.03119
Cl	35.45	0.02821
F	19.00	0.05263
Ca	40.08	0.02495
Mg	24.31	0.04114
Na	22.99	0.04350
K	39.09	0.02558
Fe	55.84	0.01791
Hardness as CaCO ₃	100.09	0.00999

TABLE B.2. Water Analyses for LI2 Injection Phase, October to December 1986

Well	A	A	B	AM2	AM2	B	B	AM2	B	B	B	B	B	B
Sample Type	III	III	I	AIR LIFT	AIR LIFT	I	II	III	AIR LIFT	I	II	III	III	III
Date sampled	861001	861001	861001	861003	861003	861003	861003	861003	861004	861004	861004	861004	861004	861004
Time	930	1135	1445	1000	1000	925	1135	1215	1020	815	900	1015	1015	1015
No. days since start	-1	-1	-1	1	1	1	1	1	2	2	2	2	2	2
Volume m ³	0	0	0	1322	1322	1322	1322	1322	2812	2812	2812	2812	2812	2812
Neg graph volume				-92478	-92478	-92478	-92478	-92478	-90988	-90988	-90988	-90988	-90988	-90988
Replication	1	1	1	1	2	1	1	1	1	1	1	1	1	2
Water Temp C				41.9	41.9	28.77	28.77	118	43.3	30.91	30.91	118	118	118
pH Temp C	24.6	25.9	25.9	18.8	18.5	24.9	25.6	87.7	19.7	25.8	26.8	89.8	89.8	89.8
pH	6.76	6.75	6.81	7.1	7.68	6.78	7.09	7.22	7.34	6.67	7.28	7.37	7.37	7.37
SC (umho/cm)	446	442	472	462	455	492	541	633	524	559	607	607	607	607
DO (mg/L)	0.4	0.3	0.4	6	6	0.4	0.8	0.6	6	0.4	0.3	0.8	0.8	0.8
Alk (meq/L)	4.74	4.8	4.86	4.93	4.88	4.88	4.90	4.94	4.96	4.93	4.94	5.42	5.42	4.92
SiO2 (mmol/L)	0.197	0.197	0.251	0.255	0.254	0.267	0.251	0.249	0.366	0.256	0.262	0.264	0.264	0.251
DIC (mmol/L)	5.012	5.018	5.123	4.882	4.821	5.098	5.052	4.895	4.923	5.242	5.166	5.381	5.381	5.117
IC Analysis:														
SO4 (mmol/L)	0.031	0.032	0.087	0.044	0.048	0.125	0.137	0.130	0.098	0.051	0.155	0.149	0.149	0.153
Cl (mmol/L)	0.021	0.058	0.160	0.155	0.167	0.227	0.240	0.311	0.296	0.033	0.215	0.194	0.194	0.098
F (mmol/L)	0.008	0.018	0.016	0.019	0.019	0.016	0.016	0.003	0.021	0.004	0.004	0.003	0.003	0.007
NO3 (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
NO2 (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
PO4 (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
AA Analysis:														
Ca (mmol/L)	1.522	1.522	1.361	1.168	1.221	1.472	0.006	0.063	0.720	1.517	0.041	0.028	0.028	0.027
Mg (mmol/L)	0.650	0.646	0.655	0.590	0.589	0.889	0.006	0.043	0.362	0.914	0.027	0.022	0.022	0.019
Na (mmol/L)	0.582	0.612	1.066	1.763	1.702	0.945	5.760	6.003	3.641	1.036	5.942	5.900	5.900	5.760
K (mmol/L)	0.191	0.191	0.149	0.220	0.220	0.177	0.092	0.095	0.180	0.185	0.058	0.050	0.050	0.050
Fe (mmol/L)	0.025	0.019	0.035	0.000	0.000	0.034	0.000	0.000	0.000	0.032	0.000	0.000	0.000	0.000
Mn (mmol/L)	0.002	0.002	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Hardness (mmol/L)	2.172	2.168	2.015	1.758	1.810	2.361	0.011	0.105	1.082	2.431	0.068	0.050	0.050	0.046

TABLE B.2. (contd)

Well	AM2	B	B	B	B	B	B	B	B	B	B	AM2	FIELD BLANK	AM2	B	B
Sample Type	AIR LIFT	I	II	III	III	I	II	III	III	III	III	AIR LIFT	I	AM2	B	B
Date sampled	861006	861006	861006	861006	861006	861008	861008	861008	861008	861008	861008	861008	861008	861010	861010	861010
Time	1400	1200	1235	1315	1315	830	930	1000	1000	1000	1000	1110	1130	1000	750	750
No. days since start	4	4	4	4	4	6	6	6	6	6	6	6	6	8	8	8
Volume m ³	6272	6272	6272	6272	6272	9206	9206	9206	9206	9206	9206	9206	9206	12378	12378	12378
Neg graph volume	-87528	-87528	-87528	-87528	-87528	-84594	-84594	-84594	-84594	-84594	-84594	-84594	-84594	-81422	-81422	-81422
Replication	1	1	1	2	2	1	1	1	1	1	2	1	1	1	1	1
Water Temp C	50.9	33.16	33.16	118	118	35.09	35.09	120	120	120	66.9	76.5	NA	26.5	20.0	20.0
pH Temp C	22.7	26.8	30.2	83.0	83.0	28.3	29.5	96.8	96.8	96.8	22.9	NA	NA	7.35	6.89	6.89
pH	7.00	6.89	7.20	7.17	7.17	6.86	7.32	7.60	7.60	7.60	6.79	NA	NA	505	521	521
SC (umho/cm)	599	557	645	578	578	530	557	547	547	547	550	NA	NA	0.3	0.1	0.1
DO (mg/L)	4.0	0.1	0.2	0.4	0.4	0.1	0.3	0.2	0.2	0.2	6	NA	0.02	4.61	4.70	4.70
Alk (meq/L)	4.96	4.86	4.90	4.87	4.86	4.69	4.76	5.33	5.33	4.76	4.64	0.00	0.00	0.835	0.292	0.292
SiO2 (mmol/L)	0.634	0.280	0.284	0.285	0.285	0.292	0.297	0.294	0.294	0.300	0.739	0.000	0.000	0.835	0.292	0.292
DIC (mmol/L)	4.707	5.146	5.133	5.141	5.143	5.133	5.067	5.433	5.433	5.083	4.606	0.086	0.086	4.561	5.147	5.147
IC Analysis:																
SO4 (mmol/L)	0.043	0.048	0.039	0.132	0.039	0.083	0.039	0.102	0.102	0.102	0.122	0.000	0.000	0.072	0.066	0.066
Cl (mmol/L)	0.057	0.047	0.098	0.297	0.052	0.130	0.054	0.298	0.298	0.291	0.297	0.002	0.002	0.225	0.071	0.071
F (mmol/L)	0.006	0.007	0.004	0.017	0.004	0.005	0.007	0.019	0.019	0.014	0.018	0.000	0.000	0.010	0.007	0.007
NO3 (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
NO2 (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
PO4 (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
AA Analysis:																
Ca (mmol/L)	0.397	1.329	0.114	0.040	0.036	1.221	0.013	0.012	0.012	0.013	0.253	0.001	0.001	0.173	1.203	1.203
Mg (mmol/L)	0.151	0.771	0.075	0.030	0.027	0.666	0.009	0.006	0.006	0.006	0.080	0.000	0.000	0.038	0.602	0.602
Na (mmol/L)	5.568	1.650	6.801	6.475	6.329	1.759	5.858	5.749	5.749	5.713	4.915	0.000	0.000	5.133	1.868	1.868
K (mmol/L)	0.195	0.213	0.110	0.094	0.091	0.228	0.080	0.076	0.076	0.072	0.228	0.000	0.000	0.223	0.238	0.238
Fe (mmol/L)	0.002	0.025	0.000	0.000	0.000	0.052	0.000	0.000	0.000	0.000	0.004	0.000	0.000	0.000	0.022	0.022
Mn (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Hardness (mmol/L)	0.548	2.100	0.189	0.070	0.063	1.887	0.022	0.018	0.018	0.018	0.333	0.001	0.001	0.210	1.806	1.806

TABLE B.2. (contd)

Well	B	B	B	B	B	B	B	B	B	B	AM2	FIELD BLANK	B	B
Sample Type	II	III	III	I	II	III	III	III	III	III	AM2 AIR LIFT	III	II	
Date sampled	861010	861010	861010	861013	861013	861013	861013	861013	861013	861013	861013	861013	861015	861015
Time	845	920	920	940	1010	1115	1115	1115	1115	1115	1230	1315	1040	1115
No. days since start	8	8	8	11	11	11	11	11	11	11	11	11	13	13
Volume m ³	12378	12378	12378	17126	17126	17126	17126	17126	17126	17126	17126	17126	20300	20300
Neg graph volume	-81422	-81422	-81422	-76674	-76674	-76674	-76674	-76674	-76674	-76674	-76674	-76674	73500	-73500
Replication	1	1	2	1	1	1	2	2	2	3	1	1	1	1
Water Temp C	36.1	121	121	36.91	36.91	119	119	119	119	119	86.8	37.28	37.28	37.28
pH Temp C	29.9	90.0	90.0	31.1	31.2	90.5	90.5	90.5	90.5	93.2	24.8	NA	29.1	29.3
pH	7.12	7.31	7.31	7.28	7.26	7.28	7.28	7.28	7.28	7.24	8.07	NA	7.30	7.32
SC (umho/cm)	712	505	505	492	489	1050	1050	1050	1050	485	520	NA	480	667
DO (mg/L)	0.2	0.3	0.3	0.4	0.1	0.4	0.4	0.4	0.4	0.3	6	NA	2.5	0.2
Alk (meq/L)	4.76	4.73	4.71	4.64	4.66	4.65	4.62	4.62	4.62	4.65	4.57	0.03	4.90	5.08
SiO2 (mmol/L)	0.300	0.303	0.286	0.303	0.305	0.300	0.299	0.299	0.299	0.299	0.878	0.000	0.295	0.313
DIC (mmol/L)	5.145	5.069	5.069	5.016	5.016	4.975	4.952	4.952	4.952	4.946	4.499	0.072	5.180	5.227
IC Analysis:														
SO4 (mmol/L)	0.031	0.031	0.031	0.047	0.043	0.046	0.043	0.043	0.043	0.143	0.063	0.000	0.126	0.130
Cl (mmol/L)	0.341	0.082	0.071	0.067	0.071	0.100	0.065	0.065	0.065	0.371	0.179	0.000	0.311	0.348
F (mmol/L)	0.007	0.007	0.007	0.008	0.008	0.005	0.007	0.007	0.007	0.018	0.006	0.000	0.021	0.021
NO3 (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
NO2 (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
PO4 (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
AA Analysis:														
Ca (mmol/L)	0.158	0.027	0.025	0.000	0.005	0.005	0.374	0.008	0.008	0.008	0.152	0.000	0.943	0.004
Mg (mmol/L)	0.115	0.020	0.018	0.000	0.002	0.002	0.159	0.006	0.006	0.006	0.026	0.000	0.495	0.004
Na (mmol/L)	6.547	5.495	5.387	0.000	5.291	5.291	7.890	5.171	5.171	4.931	0.204	0.000	2.053	5.091
K (mmol/L)	0.142	0.110	0.109	0.000	0.076	0.064	0.148	0.084	0.084	0.084	0.204	0.000	0.241	0.080
Fe (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.000	0.000	0.000	0.003	0.000	0.013	0.000
Mn (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Hardness (mmol/L)	0.273	0.046	0.043	0.000	0.007	0.007	0.533	0.014	0.014	0.178	0.000	0.000	1.437	0.007

TABLE B.2. (contd)

Well	B	B	AM2	FIELD	B	B	AM2	FIELD	B	B	AM2	FIELD	B	B
	III	III AIR LIFT	AM2	FIELD	B	B	AM2	FIELD	B	B	AM2	FIELD	B	B
Sample Type	861015	861015	861015	861015	861017	861017	861017	861017	861017	861017	861017	861017	861020	861020
Date sampled	1145	1145	1215	1230	905	1205	1226	1130	955	1035	1115	1130	1035	1115
Time	13	13	13	13	15	15	15	15	18	18	18	15	18	18
No. days since start	20300	20300	20300	20300	23495	23495	23495	23495	28217	28217	28217	23495	28217	28217
Volume m ³	-73500	-73500	-73500	-73500	-70305	-70305	-70305	-70305	-65583	-65583	-65583	-70305	-65583	-65583
Neg graph volume	1	2	1	1	1	1	1	1	1	1	1	1	1	1
Replication	120	120	91.6	37.29	37.29	37.29	120	95.4	37.29	37.29	37.29	37.29	37.29	120
Water Temp C	92.2	92.2	31.5	NA	29.9	31.1	91.1	23.7	30.0	19.9	93.4	NA	19.9	93.4
pH Temp C	7.32	7.32	8.09	NA	7.21	7.28	7.43	7.86	7.25	7.39	7.36	NA	7.39	7.36
pH	457	457	530	NA	456	476	675	495	493	487	460	NA	487	460
SC (umho/cm)	0.3	0.3	6	NA	0.2	0.4	0.3	6	0.5	0.4	0.4	NA	0.4	0.4
DO (mg/L)	4.81	4.67	4.62	0.25	4.58	4.63	4.64	4.68	4.72	4.63	5.23	ND	4.63	5.23
Alk (meq/L)	0.317	0.316	0.885	0.000	0.314	0.310	0.310	0.890	0.320	0.314	0.320	0.000	0.314	0.320
SiO2 (mmol/L)	5.077	4.933	4.634	0.187	4.881	4.930	4.893	4.676	5.008	4.883	5.202	0.571	4.883	5.202
DIC (mmol/L)														
IC Analysis:														
SO4 (mmol/L)	0.141	0.126	0.157	0.000	0.110	0.110	0.018	0.130	0.094	0.096	0.007	0.000	0.094	0.007
Cl (mmol/L)	0.384	0.329	0.694	0.000	0.293	0.329	0.536	0.676	0.372	0.483	0.368	0.000	0.372	0.368
F (mmol/L)	0.022	0.019	0.027	0.000	0.030	0.021	0.007	0.023	0.017	0.018	0.016	0.000	0.017	0.016
NO3 (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
NO2 (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
PO4 (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
AA Analysis:														
Ca (mmol/L)	0.004	0.003	0.139	0.002	0.887	0.004	0.303	0.111	0.846	0.009	0.006	0.000	0.846	0.006
Mg (mmol/L)	0.002	0.002	0.021	0.000	0.487	0.002	0.114	0.020	0.448	0.004	0.003	0.000	0.448	0.003
Na (mmol/L)	5.011	4.731	5.230	0.000	2.010	5.323	7.100	5.279	2.157	4.921	4.815	0.000	2.157	4.815
K (mmol/L)	0.075	0.073	0.193	0.000	0.244	0.079	0.159	0.192	0.245	0.110	0.101	0.000	0.245	0.101
Fe (mmol/L)	0.000	0.000	0.210	0.000	0.011	0.000	0.000	0.005	0.011	0.000	0.000	0.000	0.011	0.000
Mn (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Hardness (mmol/L)	0.006	0.006	0.160	0.002	1.374	0.006	0.418	0.131	1.293	0.013	0.009	0.000	1.293	0.009

TABLE B.2. (contd)

Well	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B
Sample type	II	III	III	I	II	III	III	I	II	III	I	II	III	I	II	III	III
Date sampled	861027	861027	861027	861027	861029	861029	861029	861029	861029	861029	861029	861029	861029	861029	861029	861029	861029
Time	935	1010	1010	750	820	850	850	850	850	850	850	850	850	850	850	850	850
No. days since start	25	25	25	27	27	27	27	27	27	27	27	27	27	27	27	27	27
Volume m ³	39310	39310	39310	42362	42362	42362	42362	42362	42362	42362	42362	42362	42362	42362	42362	42362	42362
Neg graph volume	-54490	-54490	-54490	-51438	-51438	-51438	-51438	-51438	-51438	-51438	-51438	-51438	-51438	-51438	-51438	-51438	-51438
Replication	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	2
Water Temp C	36.38	120	120	35.96	35.96	121	121	121	35.96	35.96	121	121	35.51	35.51	116	116	116
pH Temp C	32.9	93.3	93.3	29.2	31.8	91.6	91.6	91.6	29.2	31.8	91.6	91.6	18.9	30.7	90.2	90.2	90.2
pH	7.3	7.37	7.37	7.13	7.13	7.23	7.23	7.23	7.13	7.13	7.23	7.23	7.24	7.22	7.35	7.35	7.35
SC (umho/cm)	476	458	458	453	476	531	531	531	453	476	531	531	457	487	461	461	461
DO (mg/L)	0.6	0.4	0.4	0.6	0.6	0.3	0.3	0.3	0.6	0.6	0.3	0.3	0.4	0.6	0.4	0.4	0.4
Alk (meq/L)	4.97	4.77	4.64	4.57	4.68	4.58	4.63	4.63	4.57	4.68	4.58	4.63	4.58	4.97	4.57	4.57	4.57
SiO2 (mmol/L)	0.323	0.321	0.321	0.334	0.317	0.365	0.338	0.338	0.334	0.317	0.365	0.338	0.327	0.340	0.326	0.326	0.337
DIC (mmol/L)	5.246	4.980	4.893	4.975	5.000	4.791	4.782	4.782	4.975	5.000	4.791	4.782	4.881	5.306	4.949	4.949	5.363
IC Analysis:																	
SO4 (mmol/L)	0.079	0.067	0.082	0.076	0.068	0.077	0.076	0.076	0.076	0.068	0.077	0.076	0.084	0.076	0.076	0.076	0.075
Cl (mmol/L)	0.364	0.311	0.375	0.363	0.327	0.899	0.702	0.702	0.363	0.327	0.899	0.702	0.382	0.478	0.469	0.469	0.452
F (mmol/L)	0.016	0.014	0.017	0.031	0.014	0.031	0.031	0.031	0.031	0.014	0.031	0.031	0.031	0.030	0.037	0.037	0.031
NO3 (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
NO2 (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
PO4 (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
AA Analysis:																	
Ca (mmol/L)	0.001	0.002	0.001	0.000	0.001	0.034	0.029	0.029	0.000	0.001	0.034	0.029	0.698	0.003	0.003	0.003	0.003
Mg (mmol/L)	0.002	0.002	0.002	0.000	0.002	0.018	0.015	0.015	0.000	0.002	0.018	0.015	0.476	0.004	0.003	0.003	0.003
Na (mmol/L)	5.220	5.170	5.361	2.282	5.125	5.267	5.220	5.220	0.000	5.125	5.267	5.220	2.377	5.267	5.242	5.267	5.267
K (mmol/L)	0.059	0.054	0.054	0.000	0.042	0.114	0.112	0.112	0.000	0.042	0.114	0.112	0.226	0.021	0.020	0.020	0.020
Fe (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mn (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Hardness (mmol/L)	0.003	0.004	0.003	0.000	0.003	0.052	0.045	0.045	0.000	0.003	0.052	0.045	1.174	0.008	0.006	0.006	0.006

TABLE B.2. (contd)

Well	FIELD BLANK	B	B	B	B	B	FIELD BLANK	B	B	B	B	FIELD BLANK	B	B
Sample Type	III	I	II	III	III	I	FIELD BLANK	I	III	III	III	FIELD BLANK	I	II
Date sampled	861104	861105	861105	861105	861105	861107	861105	861107	861107	861107	861107	861107	861110	861110
Time	1000	830	855	940	940	835	1020	835	900	940	940	1030	850	925
No. days since start	33	34	34	34	34	36	34	36	36	36	36	36	39	39
Volume m ³	45406	47025	47025	47025	47025	50224	47025	50224	50224	50224	50224	50224	54380	54380
Neg graph volume	-48394	-46775	-46775	-46775	-46775	-43576	-46775	-43576	-43576	-43576	-43576	-43576	-39420	-39420
Replication	1	1	1	1	2	1	2	1	1	1	2	1	1	1
Water Temp C	35.42	35.42	35.42	117	117	35.09		35.09	35.09	118	118		33.94	33.94
pH Temp C	NA	27.0	30.4	88.6	88.6	29.2	NA	29.2	29.7	92.9	92.9	NA	24.8	28.9
pH	NA	7.21	7.20	7.16	7.16	7.24	NA	7.24	7.39	7.49	7.49	NA	7.19	7.18
SC (umho/cm)	NA	446	505	455	455	444	NA	444	488	454	454	NA	447	474
DO (mg/L)	NA	0.3	0.6	0.4	0.4	0.3	NA	0.3	0.3	0.2	0.2	NA	0.3	0.4
Alk (meq/L)	ND	4.68	4.69	4.58	4.59	4.61	ND	4.61	4.58	4.57	4.57	ND	4.59	4.60
SI02 (mmol/L)	0.000	0.353	0.333	0.358	0.335	0.320	0.000	0.320	0.330	0.328	0.357	0.000	0.319	0.276
DIC (mmol/L)	0.067	4.977	4.922	4.909	4.967	4.909	0.065	4.909	4.964	4.914	4.959	0.063	4.975	4.914
IC Analysis:														
SO4 (mmol/L)	0.000	0.008	0.007	0.007	0.008	0.058	0.000	0.058	0.065	0.054	0.051	0.000	0.061	0.061
Cl (mmol/L)	0.036	0.034	0.045	0.040	0.043	0.337	0.000	0.337	0.539	0.440	0.401	0.000	0.341	0.440
F (mmol/L)	0.000	0.005	0.006	0.006	0.006	0.018	0.000	0.018	0.020	0.020	0.018	0.000	0.020	0.020
NO3 (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
NO2 (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
PO4 (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
AA Analysis:														
Ca (mmol/L)	0.000	0.955	0.011	0.008	0.009	1.040	0.000	1.040	0.024	0.015	0.016	0.000	0.898	0.012
Mg (mmol/L)	0.000	0.462	0.006	0.005	0.005	0.436	0.000	0.436	0.014	0.009	0.009	0.000	0.440	0.005
Na (mmol/L)	0.000	2.187	4.872	4.780	4.780	2.465	0.000	2.465	5.104	5.104	5.058	0.000	2.267	4.934
K (mmol/L)	0.000	0.200	0.102	0.097	0.096	0.241	0.000	0.241	0.137	0.131	0.133	0.000	0.237	0.110
Fe (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mn (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Hardness (mmol/L)	0.000	1.416	0.017	0.013	0.014	1.477	0.000	1.477	0.037	0.024	0.025	0.000	1.338	0.017

TABLE B.2. (contd)

Well	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B
Sample Type	II	III	I	II	III												
Date sampled	861117	861117	861117	861119	861119	861119	861119	861119	861119	861119	861121	861121	861121	861121	861121	861121	861121
Time	835	1005	1005	805	830	905	905	905	805	835	800	835	800	835	800	835	910
No. days since start	46	46	46	48	48	48	48	48	48	48	50	50	50	50	50	50	50
Volume m ³	65371	65371	65371	68519	68519	68519	68519	68519	68519	68519	71702	71702	71702	71702	71702	71702	71702
Neg graph volume	-28429	-28429	-28429	-28429	-25281	-25281	-25281	-25281	-25281	-25281	-22098	-22098	-22098	-22098	-22098	-22098	-22098
Replication	1	1	2	1	1	1	1	2	1	1	1	1	1	1	1	1	2
Water Temp C	31.62	117	117	30.92	30.92	118	118	118	30.92	30.92	30.41	30.41	30.41	30.41	30.41	119	119
pH Temp C	29.2	94.0	94.0	26.3	27.9	82.9	82.9	82.9	26.3	27.9	23.7	26.2	23.7	26.2	23.7	93.1	93.1
pH	7.14	7.19	7.19	7.2	7.32	7.14	7.14	7.14	7.2	7.32	7.19	7.27	7.19	7.27	7.19	7.25	7.25
SC (umho/cm)	464	503	503	452	493	547	547	547	452	493	443	468	443	468	443	467	467
DO (mg/L)	0.2	0.4	0.4	0.4	0.2	0.4	0.4	0.4	0.4	0.2	0.6	0.2	0.6	0.2	0.6	0.3	0.3
Alk (meq/L)	4.79	4.76	5.01	4.61	4.58	4.68	4.68	4.63	4.61	4.58	4.57	4.60	4.57	4.60	4.57	4.77	4.78
SiO2 (mmol/L)	0.263	0.256	0.255	0.000	0.247	0.251	0.251	0.251	0.000	0.246	0.241	0.244	0.241	0.244	0.241	0.241	0.248
DIC (mmol/L)	5.080	5.026	5.137	4.942	4.923	4.974	4.974	4.933	4.942	4.923	4.929	4.946	4.929	4.946	4.929	5.040	5.077
IC Analysis:																	
SO4 (mmol/L)	0.067	0.030	0.019	0.019	0.019	0.019	0.019	0.019	0.019	0.019	0.021	0.004	0.021	0.004	0.021	0.019	0.019
Cl (mmol/L)	0.267	0.421	0.438	0.098	0.098	0.441	0.441	0.434	0.098	0.098	0.098	0.266	0.098	0.266	0.098	0.098	0.098
F (mmol/L)	0.020	0.011	0.020	0.021	0.021	0.021	0.021	0.022	0.021	0.021	0.019	0.018	0.019	0.018	0.021	0.021	0.021
NO3 (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
NO2 (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
PO4 (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
AA Analysis:																	
Ca (mmol/L)	0.040	0.020	0.020	0.935	0.005	0.151	0.151	0.116	0.935	0.005	0.943	0.003	0.943	0.003	0.943	0.003	0.003
Hg (mmol/L)	0.012	0.012	0.007	0.470	0.005	0.065	0.065	0.053	0.470	0.005	0.495	0.004	0.495	0.004	0.495	0.003	0.003
Na (mmol/L)	4.575	4.483	4.437	2.095	5.002	5.912	5.912	5.677	2.095	5.002	2.036	5.031	2.036	5.031	5.002	5.002	5.002
K (mmol/L)	0.132	0.117	0.116	0.217	0.149	0.149	0.149	0.142	0.217	0.149	0.211	0.048	0.211	0.048	0.054	0.056	0.056
Fe (mmol/L)	0.000	0.000	0.000	0.016	0.000	0.000	0.000	0.000	0.016	0.000	0.012	0.000	0.012	0.000	0.000	0.000	0.000
Kn (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Hardness (mmol/L)	0.052	0.032	0.027	1.405	0.010	0.216	0.216	0.169	1.405	0.010	1.438	0.007	1.438	0.007	1.438	0.007	0.007

TABLE B.2. (contd)

Well	FIELD BLANK	B	B	B	B	FIELD BLANK	B	B	B	B	FIELD BLANK	B	B
Sample Type		I	II	III	III		I	II	III	III		I	II
Date sampled	861121	861124	861124	861124	861124	861124	861126	861126	861126	861126	861126	861128	861128
Time	1000	830	905	945	945	1040	905	930	1000	1000	1030	830	850
No. days since start	50	53	53	53	53		55	55	55	55	55	57	57
Volume m ³	71702	76400	76400	76400	76400	76400	78114	78114	78114	78114	78114	81213	81213
Neg graph volume	-22098	-17400	-17400	-17400	-17400	-17400	-15686	-15686	-15686	-15686	-15686	-12587	-12587
Replication	1	1	1	2	2		1	1	1	2		1	1
Water Temp C		29.42	29.42	118	118		29.31	29.31	116	116		28.61	28.61
pH Temp C	NA	22.1	27.0	91.6	91.6	NA	23.6	25.2	93.7	93.7	NA	22.9	24.9
pH	NA	7.14	7.25	7.19	7.19	NA	7.18	7.22	7.25	7.25	NA	7.25	7.60
SC (umho/cm)	NA	436	447	443	443	NA	438	447	483	483	NA	439	465
DO (mg/L)	NA	0.6	0.2	0.4	0.4	NA	0.3	0.3	0.3	0.3	NA	0.6	0.1
Alk (meq/L)	1.05	4.57	4.71	4.56	4.98	ND	4.61	5.17	4.53	4.55	ND	4.72	4.75
SiO2 (mmol/L)	0.000	0.278	0.278	0.279	0.278	0.000	0.272	0.276	0.278	0.281	0.000	0.267	0.270
DIC (mmol/L)	0.112	4.880	5.008	4.885	5.269	0.014	4.923	5.320	4.869	4.881	0.000	4.964	4.954
IC Analysis:													
SO4 (mmol/L)	0.000	0.004	0.004	0.005	0.004	0.000	0.052	0.004	0.061	0.052	0.000	0.058	0.063
Cl (mmol/L)	0.000	0.282	0.303	0.310	0.303	0.000	0.311	0.389	0.341	0.311	0.000	0.249	0.389
F (mmol/L)	0.000	0.020	0.019	0.022	0.022	0.000	0.018	0.022	0.019	0.018	0.000	0.019	0.020
NO3 (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
NO2 (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
PO4 (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
AA Analysis:													
Ca (mmol/L)	0.000	0.985	0.007	0.005	0.005	0.000	0.935	0.008	0.006	0.006	0.000	0.994	0.018
Mg (mmol/L)	0.000	0.515	0.005	0.005	0.005	0.000	0.491	0.005	0.004	0.004	0.000	0.516	0.011
Na (mmol/L)	0.000	1.970	5.126	5.094	5.036	0.000	1.940	5.066	5.005	4.975	0.000	1.788	4.823
K (mmol/L)	0.000	0.220	0.057	0.052	0.051	0.000	0.217	0.072	0.067	0.066	0.000	0.211	0.093
Fe (mmol/L)	0.000	0.014	0.000	0.000	0.000	0.000	0.014	0.000	0.000	0.000	0.000	0.012	0.000
Mn (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Hardness (mmol/L)	0.000	1.500	0.012	0.010	0.010	0.000	1.426	0.013	0.011	0.011	0.000	1.510	0.029

TABLE B.2. (contd)

Well	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	Field BLANK	AM4
Sample Type	III	III	I	II	III	III	I	II	III	III	I	II	III	III	III		
Date sampled	861128	861128	861201	861201	861201	861201	861201	861201	861201	861201	861203	861203	861203	861203	861203	861203	861204
Time	850	850	900	930	1005	1005	1005	1005	1005	1055	1005	1040	1105	1105	1200	1315	
No. days since start	57	57	59	59	59	59	59	59	59	59	61	61	61	61	61	62	
Volume m ³	81213	81213	85883	85883	85883	85883	85883	85883	85883	85883	89069	89069	89069	89069	89069	90468	
Neg graph volume	-12587	-12587	-7917	-7917	-7917	-7917	-7917	-7917	-7917	-7917	-4731	-4731	-4731	-4731	-4731	-3332	
Replication	1	2	1	1	1	2	1	1	2	1	1	1	1	1	2	1	
Water Temp C	117	117	27.52	27.52	116	116	26.84	26.84	117		26.84	26.84	117	117		114.4	
pH Temp C	91.5	91.5	23.7	25.0	91.6	91.6	20.5	25.3	90.5	NA	20.5	25.3	90.5	90.5	NA	31.4	
pH	7.55	7.55	7.15	7.16	7.15	7.15	7.10	7.22	6.99	NA	7.10	7.22	6.99	6.99	NA	8.35	
SC (umho/cm)	458	458	433	457	457	457	442	444	434	NA	442	444	434	434	NA	519	
DO (mg/L)	0.40	0.4	0.6	0.1	0.4	0.4	0.2	0.2	0.2	NA	0.2	0.2	0.2	0.2	NA	5	
Alk (meq/L)	4.82	5.22	4.75	4.73	4.72	4.72	4.81	5.32	5.38	ND	4.81	5.32	5.38	5.45	ND	4.91	
SiO2 (mmol/L)	0.274	0.263	0.264	0.262	0.265	0.263	0.257	0.260	0.260	0.000	0.257	0.260	0.260	0.260	0.000	0.833	
DIC (mmol/L)	4.900	5.137	4.941	4.915	4.850	4.832	4.889	5.227	5.205	0.010	4.889	5.227	5.205	5.270	0.124	4.597	
IC Analysis:																	
SO4 (mmol/L)	0.061	0.060	0.046	0.086	0.060	0.069	0.042	0.051	0.043	0.000	0.042	0.051	0.043	0.050	0.000	0.019	
Cl (mmol/L)	0.380	0.370	0.209	0.394	0.307	0.375	0.190	0.243	0.214	0.000	0.190	0.243	0.214	0.233	0.000	0.530	
F (mmol/L)	0.020	0.021	0.018	0.022	0.020	0.023	0.015	0.016	0.015	0.000	0.015	0.016	0.015	0.016	0.000	0.012	
NO3 (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
NO2 (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
PO4 (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
AA Analysis:																	
Ca (mmol/L)	0.016	0.012	0.952	0.015	0.012	0.011	0.943	0.009	0.009	0.000	0.943	0.009	0.009	0.008	0.000	0.155	
Mg (mmol/L)	0.009	0.009	0.379	0.009	0.007	0.007	0.542	0.007	0.006	0.000	0.542	0.007	0.006	0.006	0.000	0.018	
Na (mmol/L)	4.732	4.641	1.785	5.164	5.096	5.061	1.648	4.856	4.891	0.000	1.648	4.856	4.891	4.891	0.000	4.652	
K (mmol/L)	0.087	0.085	0.212	0.051	0.046	0.046	0.210	0.048	0.045	0.000	0.210	0.048	0.045	0.045	0.000	0.182	
Fe (mmol/L)	0.000	0.000	0.012	0.000	0.000	0.000	0.015	0.000	0.000	0.000	0.015	0.000	0.000	0.000	0.000	0.009	
Mn (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
Hardness (mmol/L)	0.026	0.021	1.330	0.024	0.019	0.019	1.485	0.016	0.015	0.000	1.485	0.016	0.015	0.015	0.000	0.173	

TABLE B.2. (contd)

Well	B	B	B	B	B	B	B	B	B	B	B	B	FIELD BLANK
Sample Type	I	II	III										
Date sampled	861205	861205	861205	861205	861205	861205	861205	861205	861205	861205	861205	861205	861205
Time	730	800	830	1016	1032	1100	1100	1100	1100	1100	1100	1100	1230
No. days since start	63	63	63	63	63	63	63	63	63	63	63	63	63
Volume m ³	91868	91868	91868	91868	91868	91868	91868	91868	91868	91868	91868	91868	91868
Neg graph volume	-1932	-1932	-1932	-1932	-1932	-1932	-1932	-1932	-1932	-1932	-1932	-1932	-1932
Replication	1	1	1	2	3	4	5	5	5	5	5	5	6
Water Temp C	26.25	26.25	114	114	114	114	114	114	114	114	114	114	114
pH Temp C	NA	19.9	23.9	93.5	94.1	89.0	86.3	90.2	91.8	91.8	91.8	91.8	NA
pH	NA	7.15	7.24	7.23	7.31	7.19	7.11	7.17	7.18	7.18	7.18	7.18	NA
SC (umho/cm)	NA	430	433	439	707	487	412	452	456	456	456	456	NA
DO (mg/L)	NA	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	NA
Alk (meq/L)	ND	4.74	5.28	5.67	4.87	4.76	4.71	5.15	4.74	4.74	4.74	4.74	ND
SiO ₂ (mmol/L)	0.000	0.255	0.255	0.262	0.243	0.257	0.261	0.254	0.254	0.254	0.254	0.254	0.000
DIC (mmol/L)	0.115	4.816	5.180	5.241	4.718	4.709	4.653	4.957	4.731	4.731	4.731	4.731	0.102
IC Analysis:													
SO ₄ (mmol/L)	0.000	0.017	0.014	0.016	0.081	0.043	0.043	0.036	0.036	0.036	0.036	0.036	0.000
Cl (mmol/L)	0.000	0.074	0.235	0.074	4.770	0.946	0.465	0.457	0.386	0.386	0.386	0.386	0.000
F (mmol/L)	0.000	0.006	0.006	0.006	0.021	0.023	0.020	0.020	0.019	0.019	0.019	0.019	0.000
NO ₃ (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
NO ₂ (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
PO ₄ (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
AA Analysis:													
Ca (mmol/L)	0.000	1.012	0.006	0.006	0.166	0.050	0.022	0.016	0.017	0.017	0.017	0.017	0.000
Mg (mmol/L)	0.000	0.527	0.905	0.005	0.124	0.030	0.014	0.053	0.008	0.008	0.008	0.008	0.000
Na (mmol/L)	0.000	1.581	4.910	4.873	6.594	5.097	4.873	4.761	4.484	4.484	4.484	4.484	0.000
K (mmol/L)	0.000	0.222	0.071	0.068	0.154	0.109	0.100	0.094	0.092	0.092	0.092	0.092	0.000
Fe (mmol/L)	0.000	0.010	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mn (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Hardness (mmol/L)	0.000	1.539	0.012	0.010	0.291	0.080	0.036	0.070	0.025	0.025	0.025	0.025	0.000

TABLE B.3. Water Analyses for LT2 Recovery Phase, February to April 1987

Well	AM4	AM2	FIELD BLANK	AM4	FIELD BLANK	B	A	FIELD BLANK	A	FIELD BLANK	A
Sample Type	AIR LIFT	AIR LIFT	AIR LIFT	AIR LIFT	AIR LIFT	I	III	III	III	III	III
Date sampled	861209	861210	861210	870114	870114	870203	870203	870203	870205	870205	870207
Time	1250	1445	1530	1345	1445	1349	1640	1640	1730	1430	1045
No. days since start	---	---	---	---	---	0	0	0	0	2	4
Volume m ³	---	---	---	---	---	---	18.7	18.7	18.7	2809	5531
Replication	1	1	1	1	1	1	1	2	1	2	1
Water Temp C	114.4	114.6	110.2	19	105	105	107	107	107	105	105
pH Temp C	25.9	20.2	19.2	17.2	87.0	87.0	86.3	86.3	86.3	88.1	88.1
pH	8.26	8.07	7.63	6.86	6.92	6.92	7.03	7.03	7.03	7.05	7.05
SC (umho/cm)	479	462	481	489	474	474	510	510	510	485	485
DO (mg/L)	5	4	5	0.6	0.8	0.8	0.2	0.2	0.2	0.2	0.2
Alk (meq/L)	4.80	4.91	4.70	5.20	5.23	4.86	5.43	4.96	4.96	ND	5.12
SiO2 (mmol/L)	0.938	0.887	0.000	0.228	0.939	0.958	0.916	0.922	0.922	0.000	0.906
DIC (mmol/L)	4.629	4.696	0.134	4.569	5.319	5.418	5.635	5.288	5.288	0.058	5.378
IC Analysis:											
SO4 (mmol/L)	0.057	0.043	0.000	0.074	0.000	0.156	0.057	0.060	0.064	0.000	0.065
Cl (mmol/L)	0.575	0.473	0.000	0.641	0.000	0.214	0.608	0.608	0.608	0.000	0.608
F (mmol/L)	0.035	0.038	0.000	0.049	0.000	0.017	0.019	0.020	0.022	0.000	0.023
NO3 (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
NO2 (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
PO4 (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
AA Analysis:											
Ca (mmol/L)	0.111	0.054	0.000	0.111	0.000	1.204	0.046	0.043	0.075	0.000	0.069
Mg (mmol/L)	0.016	0.010	0.000	0.019	0.000	0.730	0.023	0.020	0.033	0.000	0.035
Na (mmol/L)	4.904	4.989	0.000	4.730	0.000	1.004	4.932	4.932	5.320	0.000	5.195
K (mmol/L)	0.171	0.125	0.000	0.201	0.000	0.172	0.140	0.138	0.157	0.000	0.174
Fe (mmol/L)	0.008	0.006	0.000	0.011	0.000	0.026	0.001	0.000	0.000	0.000	0.000
Mn (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Hardness (mmol/L)	0.128	0.064	0.000	0.130	0.000	1.934	0.069	0.064	0.108	0.000	0.104

TABLE B.3. (contd)

Well	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Sample Type	III													
Date sampled	870207	870209	870209	870211	870211	870211	870211	870211	870213	870213	870213	870215	870215	870217
Time	1045	1450	1530	1445	1445	1445	1445	1445	1455	1455	1455	915	915	1455
No. days since start	4	6	6	8	8	8	8	8	10	10	10	12	12	14
Volume m ³	5531	8696	8696	11647	11647	11647	11647	11647	14621	14621	14621	17256	17256	20622
Replication	2	1	2	1	2	2	1	1	1	2	2	1	2	2
Water Temp C	105	104	104	103	103	103	103	102	102	102	102	101	101	99
pH Temp C	88.1	86.0	86.0	84.9	84.9	84.9	84.9	82.8	82.8	82.8	82.8	80.4	80.4	82.3
pH	7.05	6.99	6.90	6.99	6.99	6.99	6.99	6.98	6.98	6.98	6.98	6.69	6.69	6.96
SC (umho/cm)	485	474	474	488	488	488	488	483	483	483	483	488	488	488
DO (mg/L)	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.3	0.3	0.1
Alk (meq/L)	4.96	5.04	5.42	4.93	4.93	4.93	4.93	5.00	4.91	4.91	4.91	4.90	4.90	4.82
SiO2 (mmol/L)	0.909	0.887	0.889	0.895	0.895	0.899	0.899	0.876	0.877	0.877	0.877	0.860	0.867	0.864
DIC (mmol/L)	5.218	5.353	5.619	5.228	5.228	4.886	4.886	4.924	4.838	4.838	4.838	4.867	4.867	4.858
IC Analysis:														
SO4 (mmol/L)	0.067	0.064	0.065	0.060	0.060	0.060	0.060	0.057	0.053	0.053	0.053	0.070	0.070	0.070
Cl (mmol/L)	0.641	0.571	0.604	0.604	0.604	0.571	0.571	0.473	0.522	0.522	0.522	0.620	0.620	0.587
F (mmol/L)	0.023	0.034	0.036	0.034	0.034	0.034	0.034	0.034	0.033	0.033	0.033	0.037	0.037	0.037
NO3 (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
NO2 (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
PO4 (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
AA Analysis:														
Ca (mmol/L)	0.067	0.069	0.063	0.069	0.069	0.075	0.075	0.087	0.093	0.093	0.093	0.121	0.121	0.139
Mg (mmol/L)	0.034	0.035	0.035	0.038	0.038	0.041	0.041	0.046	0.042	0.042	0.042	0.052	0.051	0.057
Na (mmol/L)	5.195	5.164	5.137	4.949	4.949	4.918	4.918	4.764	4.733	4.733	4.733	4.610	4.579	4.984
K (mmol/L)	0.176	0.189	0.194	0.203	0.203	0.216	0.216	0.216	0.216	0.216	0.216	0.219	0.218	0.213
Fe (mmol/L)	0.001	0.002	0.002	0.001	0.001	0.002	0.002	0.002	0.002	0.002	0.002	0.000	0.000	0.000
Mn (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Hardness (mmol/L)	0.102	0.104	0.099	0.107	0.107	0.116	0.116	0.133	0.134	0.134	0.134	0.173	0.179	0.193

TABLE B.3. (contd)

Well	FIELD BLANK	A	A	FIELD BLANK												
Sample Type		III	III													
Date sampled	870217	870219	870219	870219	870224	870224	870224	870224	870226	870226	870226	870226	870226	870302	870302	870302
Time	1530	1445	1445	1530	1500	1500	1530	1450	1450	1450	1450	1450	1450	1455	1455	1525
No. days since start	14	16	16	16	21	21	21	23	23	23	23	23	23	27	27	27
Volume m ³	20622	23660	23660	23660	31335	31335	31335	34419	34419	34419	34419	34419	34419	40646	40646	40646
Replication		1	2		1	2		1	2		1	2		1	2	
Water Temp C		98	98		96	96		93	93		93	93		90	90	
pH Temp C		80.5	80.5		73.1	73.1		73.1	73.1		73.1	73.1		74.5	74.5	
pH		6.97	6.97		6.86	6.86		6.83	6.83		6.83	6.83		6.88	6.88	
SC (umho/cm)		488	488		488	488		531	531		531	531		487	487	
DO (mg/L)		0.1	0.1		0.1	0.1		0.1	0.1		0.1	0.1		0.05	0.05	
ALK (meq/L)	ND	4.77	4.88		4.87	5.44	ND	4.86	4.81	ND	4.87	4.84	ND	4.84	ND	
SI02 (mmol/L)	0.000	0.831	0.822	0.000	0.798	0.795	0.000	0.775	0.776	0.000	0.738	0.745	0.000	0.738	0.745	0.000
DIC (mmol/L)	0.105	4.754	4.830	0.209	4.474	4.575	0.000	4.378	4.373	0.019	4.323	4.366	0.033	4.323	4.366	0.033
IC Analysis:																
SO4 (mmol/L)	0.000	0.070	0.075	0.000	0.079	0.071	0.000	0.079	0.064	0.000	0.064	0.079	0.000	0.064	0.079	0.000
Cl (mmol/L)	0.000	0.571	0.542	0.000	0.528	0.513	0.000	0.483	0.468	0.000	0.438	0.498	0.000	0.438	0.498	0.000
F (mmol/L)	0.000	0.037	0.028	0.000	0.029	0.028	0.000	0.028	0.026	0.000	0.034	0.031	0.000	0.034	0.031	0.000
NO3 (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
NO2 (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
PO4 (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
AA Analysis:																
Ca (mmol/L)	0.000	0.145	0.152	0.000	0.170	0.170	0.000	0.155	0.176	0.000	0.220	0.220	0.000	0.220	0.220	0.000
Mg (mmol/L)	0.000	0.062	0.062	0.000	0.072	0.071	0.000	0.083	0.077	0.000	0.093	0.093	0.000	0.093	0.093	0.000
Na (mmol/L)	0.000	4.845	4.879	0.000	4.706	4.741	0.000	4.497	4.532	0.000	4.358	4.323	0.000	4.358	4.323	0.000
K (mmol/L)	0.000	0.223	0.223	0.000	0.249	0.252	0.000	0.254	0.257	0.000	0.264	0.266	0.000	0.264	0.266	0.000
Fe (mmol/L)	0.000	0.000	0.000	0.000	0.004	0.002	0.000	0.002	0.003	0.000	0.002	0.002	0.000	0.002	0.002	0.000
Mn (mmol/L)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Hardness (mmol/L)	0.000	0.208	0.214	0.000	0.242	0.241	0.000	0.238	0.253	0.000	0.313	0.313	0.000	0.313	0.313	0.000

TABLE B.3. (contd)

Well	AM4	AM4	A	A	FIELD	A	A	FIELD	A	A	FIELD	A	A
		AIR LIFT	AM4	A	FIELD	A	A	FIELD	A	A	FIELD	A	A
		AIR LIFT	AM4	A	FIELD	A	A	FIELD	A	A	FIELD	A	A
Sample Type													
Date sampled	870305	870305	870305	870305	870305	870309	870309	870309	870312	870312	870312	870316	870316
Time	1310	1310	1445	1445	1345	1455	1455	1455	1440	1440	1520	1510	1510
No. days since start	30	30	30	30	30	34	34	34	37	37	37	41	41
Volume m ³	45300	45300	45300	45300	45300	51533	51533	51533	56218	56218	56218	62427	62427
Replication	1	2	1	2	1	1	2	1	1	2	1	1	2
Water Temp C	77.2	77.2	88	88		84	84		82	82		77	77
pH Temp C	20.8	20.8	71.5	71.5		66.1	66.1		67.5	67.5		55.6	55.6
pH	6.86	6.86	6.87	6.87		6.86	6.86		6.88	6.88		6.87	6.87
SC (umho/cm)	483	483	488	488		487	487		520	520		541	541
DO (mg/L)	5	5	0.05	0.05		0.1	0.1		0.1	0.1		0.1	0.1
Alk (meq/L)	4.77	4.73	4.85	4.86		4.86	4.86		4.88	5.02		4.86	4.83
SiO2 (mmol/L)	1.039	0.713	0.740	0.711		0.711	0.742		0.659	0.687		0.629	0.638
DIC (mmol/L)	3.970	4.006	4.420	4.411		4.485	4.446		4.299	4.412		4.319	4.304
IC Analysis:													
SO4 (mmol/L)	0.059	0.093	0.086	0.075		0.064	0.064		0.060	0.060		0.063	0.063
Cl (mmol/L)	0.575	0.475	0.513	0.468		0.537	0.480		0.590	0.505		0.569	0.573
F (mmol/L)	0.043	0.041	0.030	0.028		0.026	0.022		0.028	0.031		0.028	0.028
NO3 (mmol/L)	0.000	0.000	0.000	0.000		0.000	0.000		0.000	0.000		0.000	0.000
NO2 (mmol/L)	0.000	0.000	0.000	0.000		0.000	0.000		0.000	0.000		0.000	0.000
PO4 (mmol/L)	0.000	0.000	0.000	0.000		0.000	0.000		0.000	0.000		0.000	0.000
AA Analysis:													
Ca (mmol/L)	0.410	0.405	0.251	0.157		0.310	0.301		0.332	0.341		0.437	0.432
Mg (mmol/L)	0.190	0.171	0.104	0.096		0.121	0.121		0.137	0.138		0.182	0.179
Na (mmol/L)	3.489	3.489	4.184	4.109		4.274	4.245		4.070	4.040		4.029	3.998
K (mmol/L)	0.273	0.277	0.278	0.275		0.283	0.285		0.283	0.285		0.282	0.283
Fe (mmol/L)	0.013	0.008	0.001	0.000		0.004	0.003		0.002	0.002		0.002	0.003
Mn (mmol/L)	0.000	0.000	0.000	0.000		0.000	0.000		0.000	0.000		0.000	0.000
Hardness (mmol/L)	0.600	0.576	0.356	0.253		0.431	0.421		0.470	0.480		0.619	0.611

TABLE B.3. (contd)

Well	FIELD BLANK	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Sample Type		III																
Date sampled	870316	870319	870319	870319	870319	870319	870319	870319	870319	870319	870319	870319	870319	870319	870323	870323	870326	870326
Time	1535	1015	1117	1210	1315	1410	1515	1515	1515	1340	1450	1450	1450	1450	1530	1515	1515	1515
No. days since start	41	44	44	44	44	44	44	44	44	44	44	44	44	44	48	48	51	51
Volume m ³	62427	67155	67155	67155	67155	67155	67155	67155	67155	67155	67155	67155	67155	67155	73465	73465	78244	78244
Replication	1	2	2	3	4	5	6	6	6	1	1	1	1	1	2	2	1	2
Water Temp C		73	73	73	73	73	73	73	73	73	73	73	73	73	66	66	66	66
pH Temp C		57.8	58.9	60.2	58.1	59.5	60.4	60.4	60.4	56.3	56.3	56.3	56.3	56.3	53.3	53.3	53.3	53.3
pH		6.93	6.88	6.90	6.92	6.94	6.87	6.87	6.87	6.99	6.99	6.99	6.99	6.99	6.99	6.99	6.99	6.99
SC (umho/cm)		480	484	486	538	531	529	529	529	529	529	529	529	529	498	498	498	498
DO (mg/L)		0.2	0.1	0.2	0.05	0.05	0.1	0.1	0.1	0.05	0.05	0.05	0.05	0.05	0.1	0.1	0.1	0.1
Alk (meq/L)		4.83	4.85	4.84	4.83	4.83	4.86	4.86	4.86	ND	4.89	4.89	4.89	4.89	5.09	5.09	4.89	4.89
SiO2 (mmol/L)		0.000	0.598	0.600	0.600	0.598	0.601	0.587	0.587	0.000	0.542	0.542	0.542	0.542	0.000	0.513	0.509	0.509
DIC (mmol/L)		0.035	4.330	4.316	4.328	4.323	4.312	4.370	4.370	0.039	4.406	4.406	4.406	4.406	0.063	4.493	4.355	4.355
IC Analysis:																		
SO4 (mmol/L)		0.000	0.115	0.114	0.114	0.114	0.114	0.116	0.116	0.000	0.112	0.112	0.112	0.112	0.000	0.114	0.113	0.113
Cl (mmol/L)		0.000	0.544	0.551	0.544	0.547	0.554	0.545	0.545	0.000	0.552	0.552	0.552	0.552	0.000	0.498	0.493	0.493
F (mmol/L)		0.000	0.027	0.028	0.027	0.028	0.027	0.027	0.027	0.000	0.027	0.027	0.027	0.027	0.000	0.026	0.026	0.026
NO3 (mmol/L)		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
NO2 (mmol/L)		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
PO4 (mmol/L)		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
AA Analysis:																		
Ca (mmol/L)		0.000	0.437	0.442	0.437	0.432	0.437	0.447	0.447	0.000	0.567	0.567	0.567	0.567	0.000	0.589	0.606	0.606
Mg (mmol/L)		0.000	0.228	0.231	0.223	0.207	0.208	0.208	0.208	0.000	0.245	0.245	0.245	0.245	0.000	0.297	0.268	0.268
Na (mmol/L)		0.000	3.811	3.780	3.749	3.718	3.718	3.655	3.655	0.000	3.665	3.665	3.665	3.665	0.000	3.323	3.358	3.358
K (mmol/L)		0.000	0.275	0.275	0.275	0.275	0.275	0.273	0.273	0.000	0.269	0.269	0.269	0.269	0.000	0.262	0.264	0.264
Fe (mmol/L)		0.000	0.003	0.003	0.003	0.003	0.002	0.002	0.002	0.000	0.003	0.003	0.003	0.003	0.000	0.003	0.003	0.003
Mn (mmol/L)		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Hardness (mmol/L)		0.000	0.665	0.673	0.660	0.638	0.645	0.655	0.655	0.000	0.812	0.812	0.812	0.812	0.000	0.886	0.874	0.874

TABLE B.3. (contd)

Well	A	A	FIELD BLANK	A	FIELD BLANK	A	FIELD BLANK	A	FIELD BLANK
Sample Type	III	III	III	III	III	III	III	III	III
Date sampled	870330	870330	870330	870402	870402	870402	870402	870403	870403
Time	1515	1515	1545	1450	1450	1450	1450	1450	1520
No. days since start	55	55	55	58	58	58	58	59	59
Volume m ³	84559	84559	84559	89269	89269	89269	89269	90839	90839
Replication	1	2		1	2		1	2	
Water Temp C	61	61		58	58		56	56	
pH Temp C	50.2	50.2		48.0	48.0		48.9	48.9	
pH	6.97	6.97		6.93	6.93		6.97	6.97	
SC (umho/cm)	455	455		467	467		509	509	
DO (mg/L)	0.05	0.05					0.1	0.1	
Alk (meq/L)	4.89	5.02		4.79	4.80		4.79	4.75	ND
SiO2 (mmol/L)	0.475	0.469		0.431	0.442		0.399	0.434	0.000
DIC (mmol/L)	4.335	4.383		4.040	4.004		4.036	3.968	0.035
IC Analysis:									
SO4 (mmol/L)	0.112	0.124		0.121	0.116		0.121	0.119	0.000
Cl (mmol/L)	0.388	0.405		0.372	0.372		0.362	0.359	0.000
F (mmol/L)	0.024	0.024		0.024	0.024		0.024	0.024	0.000
NO3 (mmol/L)	0.000	0.000		0.000	0.000		0.000	0.000	0.000
NO2 (mmol/L)	0.000	0.000		0.000	0.000		0.000	0.000	0.000
PO4 (mmol/L)	0.000	0.000		0.000	0.000		0.000	0.000	0.000
AA Analysis:									
Ca (mmol/L)	0.640	0.651		0.721	0.718		0.733	0.724	0.000
Mg (mmol/L)	0.313	0.313		0.355	0.351		0.367	0.368	0.000
Na (mmol/L)	3.050	3.016		2.692	2.641		2.521	2.470	0.000
K (mmol/L)	0.258	0.258		0.253	0.254		0.249	0.250	0.000
Fe (mmol/L)	0.004	0.004		0.004	0.006		0.005	0.004	0.000
Mn (mmol/L)	0.000	0.000		0.000	0.000		0.000	0.000	0.000
Hardness (mmol/L)	0.953	0.964		1.077	1.069		1.099	1.092	0.000

TABLE B.4. Water Analyses for Monitoring Well AM1, 1986 to 1987

WELL AM1		4-3-86		6-23-86		9-26-86		4-14-86		5-26-87		9-10-87		12-02-87	
Date	Replication	1	1	1	1	1	1	1	1	1	1	1	1	1	1
pH Temp C		12.8	22.0	20.7	15.3	21.2	NA	13.0							
pH		7.27	8.14	6.51	7.60	6.74	NA	7.57							
SC (umho/cm)		467	470	412	470	461	475	503							
DO (mg/L)		8.0	7.0	8.0	5.0	4.0	6.0	5.0							
Alk (meq/L)		5.12	4.95	5.06	4.19	4.70	4.74	4.84							
SiO2 (mmol/L)		0.200	0.195	0.180	0.237	0.248	0.226	0.194							
IC Analysis:															
SO4 (mmol/L)		0.179	0.126	0.189	0.165	0.152	0.153	0.178							
Cl (mmol/L)		0.044	0.030	0.035	0.034	0.053	0.032	0.024							
F (mmol/L)		0.021	0.013	0.016	0.017	0.019	0.025	0.018							
NO3 (mmol/L)		NA	NA	NA	NA	NA	NA	NA							
NO2 (mmol/L)		NA	NA	NA	NA	NA	NA	NA							
PO4 (mmol/L)		NA	NA	NA	NA	NA	NA	NA							
AA Analysis:															
Ca (mmol/L)		1.512	1.599	1.583	1.617	1.643	1.635	1.652							
Mg (mmol/L)		0.847	0.905	0.893	0.815	0.812	0.889	0.893							
Na (mmol/L)		0.274	0.279	0.304	0.391	0.380	0.307	0.214							
K (mmol/L)		0.128	0.179	0.140	0.209	0.210	0.201	0.087							
Fe (mmol/L)		0.008	0.012	NA	NA	NA	NA	NA							
Mn (mmol/L)		0.003	0.003	0.005	NA	NA	NA	NA							
Hardness (mmol/L)		2.359	2.504	2.475	2.432	2.455	2.524	2.545							

TABLE B.5. Water Analyses for Monitoring Well AM2, 1986 to 1987

WELL AM2		4-3-86	4-3-86	6-23-86	6-23-86	9-27-86	9-27-86	9-27-86	4-14-87	4-14-87	5-29-87	5-29-87	9-14-87	9-14-87	12-4-87	12-4-87	
Date	Replication	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	
pH Temp C		18.9	20.4	21.5	21.6	20.1	24.8	22.7	22.7	22.7	24.0	24.0	NA	NA	13.0	13.0	
pH		7.42	7.79	7.77	8.07	6.79	6.63	7.12	7.12	7.12	6.79	6.79	NA	NA	7.49	7.49	
SC (umho/cm)		452	449	455	455	462	448	459	459	447	447	447	448	448	412	412	
DO (mg/L)		6	7	8	8	6	9	4	4	4	4	4	6	6	5	5	
Alk (meq/L)		4.78	4.78	4.64	4.82	4.84	4.85	4.63	4.66	4.40	4.38	4.40	4.68	4.68	4.47	4.49	
SiO2 (mmol/L)		0.285	0.290	0.270	0.283	0.233	0.238	0.414	0.401	0.417	0.412	0.399	0.398	0.398	0.204	0.204	
IC Analysis:																	
SO4 (mmol/L)		0.107	0.106	0.090	0.090	0.114	0.110	0.107	NA	0.104	NA	0.100	0.101	0.101	0.043	0.043	
Cl (mmol/L)		0.225	0.227	0.190	0.174	0.137	NA	0.243	NA	0.328	NA	0.311	0.310	0.310	0.054	0.054	
F (mmol/L)		0.035	0.035	0.025	0.025	0.245	0.025	0.031	NA	0.030	NA	0.037	0.037	0.037	0.027	0.027	
NO3 (mmol/L)		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	
NO2 (mmol/L)		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	
PO4 (mmol/L)		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	
AA Analysis:																	
Ca (mmol/L)		1.090	1.063	1.228	1.124	1.189	1.158	0.716	0.725	0.654	0.716	0.689	0.681	0.681	1.237	1.255	
Mg (mmol/L)		0.329	0.331	0.589	0.565	0.668	0.671	0.345	0.375	0.353	0.334	0.376	0.344	0.344	0.639	0.677	
Na (mmol/L)		1.392	1.405	1.526	1.540	1.039	0.977	2.908	2.801	2.828	2.841	2.962	2.921	2.921	0.605	0.565	
K (mmol/L)		0.182	0.179	0.222	0.229	0.200	0.209	0.193	0.189	0.187	0.187	0.181	0.176	0.176	0.217	0.175	
Fe (mmol/L)		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	
Mn (mmol/L)		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	
Hardness (mmol/L)		1.419	1.394	1.817	1.689	1.856	1.829	1.061	1.100	1.006	1.049	1.065	1.025	1.025	1.876	1.931	

TABLE B.6. Water Analyses for Monitoring Well AM4, 1986 to 1987

WELL AM4		4-4-86	6-26-86	9-29-86	4-14-87	4-14-87	6-2-87	6-2-87	9-9-87	9-9-87	12-4-87	12-4-87
Date	Replication	1	1	1	1	2	1	2	1	2	1	2
pH Temp C		17.8	22.1	16	17.2	17.2	21.5	21.5	18.7	18.7	11.0	11.0
pH		7.37	8.07	6.61	6.88	6.88	6.70	6.70	6.84	6.84	7.76	7.76
SC (umho/cm)		444	444	438	454	454	465	465	460	460	426	426
DO (mg/L)		8	8.0	8.0	6.0	6.0	6	6	6	6	5	5
Alk (meq/L)		4.67	4.75	4.80	4.54	4.42	4.37	4.36	4.73	4.54	4.65	4.62
SiO2 (mmol/L)		0.276	0.271	0.256	0.348	0.345	0.344	0.343	0.315	0.320	0.191	0.191
IC Analysis:												
SO4 (mmol/L)		0.109	0.085	0.123	0.122	0.120	0.129	0.130	0.137	0.144	0.016	0.016
Cl (mmol/L)		0.223	0.203	NA	0.212	0.210	0.303	0.303	0.026	0.026	0.145	0.146
F (mmol/L)		0.029	0.022	0.021	0.024	0.024	0.025	0.025	0.029	0.029	0.029	0.029
NO3 (mmol/L)		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
NO2 (mmol/L)		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
PO4 (mmol/L)		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
AA Analysis:												
Ca (mmol/L)		0.956	0.984	0.451	0.981	0.901	0.857	0.848	0.919	0.892	0.963	1.122
Mg (mmol/L)		0.514	0.498	0.519	0.487	0.442	0.423	0.420	0.480	0.467	0.588	0.588
Na (mmol/L)		1.701	1.944	2.232	2.372	2.279	2.372	2.426	2.239	2.292	1.288	1.261
K (mmol/L)		0.174	0.208	0.195	0.188	0.200	0.207	0.207	0.206	0.210	0.176	0.221
Fe (mmol/L)		NA	0.009	0.003	NA	NA	NA	NA	NA	NA	NA	NA
Mn (mmol/L)		0.003	0.003	0.005	NA	NA	NA	NA	NA	NA	NA	NA
Hardness (mmol/L)		1.470	1.482	0.969	1.468	1.344	1.281	1.268	1.399	1.360	1.551	1.710

TABLE B.7. Water Analyses for Monitoring Well AS1 Jordan, 1986 to 1987

Well AS1 JORDAN

Date	4-3-86	6-25-86	9-30-86	4-13-87	5-27-87	9-12-87	12-2-87
Replication	1	1	1	1	1	1	1
pH temp C	12.9	23.1	14.9	16.0	22.8	20.9	13.4
pH	7.49	8.06	6.49	6.82	7.06	7.53	7.70
SC (umho/cm)	470	481	479	496	497	514	554
DO (mg/L)	8	8.0	8	6	8	6	6
Alk (meq/L)	4.82	5.35	5.57	4.72	5.16	5.34	5.60
SiO2 (mmol/L)	0.154	0.153	0.148	0.167	0.175	0.186	0.185
IC Analysis:							
SO4 (mmol/L)	0.228	0.188	0.205	0.181	0.172	0.173	0.158
Cl (mmol/L)	0.038	0.031	0.028	0.023	0.021	0.019	0.022
F (mmol/L)	0.012	0.009	0.107	0.011	0.011	0.018	0.021
NO3 (mmol/L)	NA	NA	NA	NA	NA	NA	NA
NO2 (mmol/L)	NA	NA	NA	NA	NA	NA	NA
PO4 (mmol/L)	NA	NA	NA	NA	NA	NA	NA
AA Analysis:							
Ca (mmol/L)	1.432	1.575	1.573	1.723	1.741	1.758	1.820
Mg (mmol/L)	0.827	0.896	0.871	0.894	1.032	0.934	0.988
Na (mmol/L)	0.396	0.488	0.415	0.458	0.458	0.461	0.450
K (mmol/L)	0.215	0.257	0.204	0.244	0.248	0.250	0.192
Fe (mmol/L)	NA	0.009	0.000	NA	NA	NA	NA
Mn (mmol/L)	NA	NA	0.002	NA	NA	NA	NA
Hardness (mmol/L)	2.259	2.472	2.444	2.617	2.773	2.692	2.808

TABLE B.8. Water Analyses for Monitoring Well AS1 Mt. Simon, 1986 to 1987

Well AS1 Mt. Simon											
Date	3-31-86	4-4-86	4-10-86	6-2-86	9-30-86	4-13-87	5-27-87	9-12-87	12-1-87		
Replication	1	1	1	1	1	1	1	1	1	1	1
pH Temp C	17.9	14.1	16.4	22.2	17.0	20.7	21.7	19.9	14.0		
pH	6.63	7.11	7.88	8.03	6.39	6.97	6.85	7.43	7.47		
SC (umho/cm)	407	421	423	414	397	482	473	454	466		
DO (mg/L)	8	7	7	8	8	6	8	6	5		
Alk (meq/L)	4.28	4.47	4.52	4.16	4.39	4.47	4.95	4.81	4.73		
SiO2 (mmol/L)	0.298	0.308	0.314	0.306	0.295	0.471	0.477	0.435	0.395		
IC Analysis:											
SO4 (mmol/L)	0.108	0.110	0.101	0.090	0.100	0.081	0.073	0.084	0.089		
Cl (mmol/L)	0.192	0.192	0.178	0.121	0.115	0.449	0.392	0.263	0.222		
F (mmol/L)	0.029	0.029	0.029	0.025	0.259	0.035	0.035	0.041	0.044		
NO3 (mmol/L)	NA	NA	NA	NA	NA	NA	NA	NA	NA		
NO2 (mmol/L)	NA	NA	NA	NA	NA	NA	NA	NA	NA		
PO4 (mmol/L)	NA	NA	NA	NA	NA	NA	NA	NA	NA		
AA Analysis:											
Ca (mmol/L)	0.963	1.063	1.078	1.081	1.257	0.901	0.910	0.901	0.928		
Mg (mmol/L)	0.473	0.485	0.494	1.141	0.504	0.337	0.353	0.334	0.398		
Na (mmol/L)	1.244	1.253	1.244	1.248	1.100	2.734	2.774	2.426	2.105		
K (mmol/L)	0.251	0.246	0.243	0.300	0.246	0.305	0.301	0.294	0.191		
Fe (mmol/L)	NA	NA	NA	0.009	NA	NA	NA	NA	NA		
Mn (mmol/L)	NA	NA	NA	NA	0.003	NA	NA	NA	NA		
Hardness (mmol/L)	1.436	1.548	1.571	2.223	1.762	1.239	1.263	1.235	1.326		

TABLE B.9. Water Analyses for Monitoring Well BC1, 1986 to 1987

WELL BC1		4-2-86	6-24-86	9-25-86	4-15-87	5-28-87	9-13-87	12-3-87	
Date	Replication	1	1	1	1	1	1	1	
pH Temp C		15.0	19.7	20.7	18.0	21.4	23.5	10.5	
pH		6.64	7.98	6.51	6.78	6.94	7.52	7.01	
SC (umho/cm)		414	411	412	422	413	417	447	
DO (mg/L)		7	7	8	5	8	6	4	
Alk (meq/L)		4.29	4.31	4.38	4.34	4.44	4.46	4.34	
SiO2 (mmol/L)		0.202	0.191	0.177	0.190	0.182	0.173	0.225	
IC Analysis:									
SO4 (mmol/L)		0.226	0.207	0.236	0.213	0.219	0.213	0.036	
Cl (mmol/L)		0.060	0.063	NA	0.034	0.052	0.049	0.060	
F (mmol/L)		0.018	0.008	0.023	0.014	0.018	0.019	0.031	
NO3 (mmol/L)		NA	NA	NA	NA	NA	NA	NA	
NO2 (mmol/L)		NA	NA	NA	NA	NA	NA	NA	
PO4 (mmol/L)		NA	NA	NA	NA	NA	NA	NA	
AA Analysis:									
Ca (mmol/L)		1.315	1.386	1.522	1.423	1.476	1.414	1.140	
Mg (mmol/L)		0.708	0.700	0.693	0.718	0.689	0.747	0.750	
Na (mmol/L)		0.226	0.293	0.195	0.266	0.274	0.255	0.137	
K (mmol/L)		0.174	0.343	0.195	0.227	0.236	0.233	0.238	
Fe (mmol/L)		NA	0.009	0.003	NA	NA	NA	NA	
Mn (mmol/L)		0.002	0.003	0.004	NA	NA	NA	NA	
Hardness (mmol/L)		2.022	2.086	2.216	2.141	2.164	2.161	1.890	

TABLE B.10. Water Analyses for Monitoring Well BS1, 1986 to 1987

Well BS1													
Date	4-2-86	6-24-86	9-26-86	4-17-87	5-29-87	9-10-87	12-3-87						
Replication	1	1	1	1	1	1	1						
pH Temp C	17.4	21.7	19.8	22.8	19.4	21.3	9.9						
pH	6.93	7.82	6.64	6.99	6.56	6.97	7.20						
SC (umho/cm)	306	375	363	447	369	418	398						
DO (mg/L)	8	7	8	6	8	6	5						
Alk (meq/L)	4.20	4.08	4.16	4.78	4.66	4.54	4.44						
SiO2 (mmol/L)	0.202	0.194	0.200	0.275	0.255	0.234	0.183						
IC Analysis:													
SO4 (mmol/L)	0.050	0.046	0.046	0.062	0.062	0.049	0.226						
Cl (mmol/L)	0.064	0.052	NA	0.149	0.195	0.133	0.047						
F (mmol/L)	0.022	0.019	0.023	0.018	0.020	0.022	0.027						
NO3 (mmol/L)	NA	NA	NA	NA	NA	NA	NA						
NO2 (mmol/L)	NA	NA	NA	NA	NA	NA	NA						
PO4 (mmol/L)	NA	NA	NA	NA	NA	NA	NA						
AA Analysis:													
Ca (mmol/L)	1.058	1.094	1.211	1.007	0.990	1.078	1.414						
Mg (mmol/L)	0.675	0.679	0.675	0.692	0.644	0.706	0.820						
Na (mmol/L)	0.570	1.988	0.525	1.328	1.208	0.940	0.621						
K (mmol/L)	0.038	0.108	0.062	0.120	0.119	0.097	0.278						
Fe (mmol/L)	0.003	0.009	0.003	NA	NA	NA	NA						
Mn (mmol/L)	0.003	0.003	0.004	NA	NA	NA	NA						
Hardness (mmol/L)	1.733	1.772	1.886	1.700	1.634	1.784	2.233						

TABLE B.11. Water Analyses for Monitoring Well CM1, 1986 to 1987

Well CM1		4-2-86		6-24-86		9-26-86		4-20-87		6-2-87		9-14-87		11-30-87	
Date	Replication	1	1	1	1	1	1	1	1	1	1	1	1	1	1
pH Temp C		13.3	21.3	20.5	23.1	21.5	19.4	7.0							
pH		6.96	7.78	6.97	6.89	6.75	7.29	6.77							
SC (umho/cm)		377	378	361	399	394	358	400							
DO (mg/L)		8	8	8	8	6	6	3							
Alk (meq/L)		4.23	4.29	4.24	4.40	3.96	3.92	4.41							
SiO2 (mmol/L)		0.140	0.135	0.134	0.132	0.138	0.125	0.129							
IC Analysis:															
SO4 (mmol/L)		0.027	0.024	0.029	0.017	0.025	0.036	0.020							
Cl (mmol/L)		0.033	0.032	NA	0.023	0.027	0.025	0.019							
F (mmol/L)		0.017	0.013	0.016	0.014	0.015	0.015	0.024							
NO3 (mmol/L)		NA	NA	NA	NA	NA	NA	NA							
NO2 (mmol/L)		NA	NA	NA	NA	NA	NA	NA							
PO4 (mmol/L)		NA	NA	NA	NA	NA	NA	NA							
AA Analysis:															
Ca (mmol/L)		1.218	1.252	1.344	0.857	0.840	1.202	1.299							
Mg (mmol/L)		0.634	0.637	0.644	0.696	0.666	0.610	0.601							
Na (mmol/L)		0.270	0.286	0.275	0.304	0.304	0.253	0.285							
K (mmol/L)		0.128	0.172	0.147	0.178	0.180	0.165	0.175							
Fe (mmol/L)		NA	0.009	NA	NA	NA	NA	NA							
Mn (mmol/L)		0.002	0.003	0.003	NA	NA	NA	NA							
Hardness (mmol/L)		1.851	1.889	1.990	1.553	1.506	1.812	1.899							

APPENDIX C

OPERATING PARAMETERS FOR LONG-TERM CYCLE 2

APPENDIX C

OPERATING PARAMETERS FOR LONG-TERM CYCLE 2

WATER FLOW

Pumping rates for ground-water injection during LT2 were limited by permit to no more than 18.9 L/sec (68.1 m³/hr, 300 gpm). Water flow from the pumping well was controlled by adjusting the system flow control valve, which adjusted the back pressure that the constant speed turbine pumps worked against. The source well pump (B) delivered about 18.9 L/sec when the pressure at the entry point to Site A (ahead of water softener) was 1035 kPa (150 psi). The storage well pump (A) delivered about 18.9 L/sec when the pressure at the wellhead was 860 kPa (125 psi).

TEMPERATURE

Maximum temperature for injected water was 150°C (302°F) by permit. This was also a physical limitation of the heat source, 930 kPa (135 psig) saturated steam. The design delta T for the system was 66°C (119°F). All cycles, long and short, exceeded this delta T; however, the temperature never exceeded 150°C (302°F). The source water temperature was always less than the 85°C (185°F).

PRESSURES

Pressures inside the piping between the condenser and the storage well were always maintained higher than 345 kPa (50 psi). [395 kPa (357 psi) is required to prevent flashing to steam at 150°C (302°F).] (Lowest pressures occurred during the final rinse phase of the water softener; the booster pump could be reinstalled in the system to raise the pressure if higher temperatures were desired.)

WATER LEVEL

Water level changes observed in monitoring wells always maintained more than 88 m (290 ft) of head above the FIG aquifer (860 kPa). This was more than twice the level needed to prevent flashing to steam in the aquifer.

WATER HARDNESS

Hardness of the source water during LT2 averaged 160 mg/L as CaCO₃, significantly less than the 200 to 210 mg/L of ambient FIG ground water. This permitted the water softener tanks to be regenerated less frequently than during LT1. During LT2, each water softener tank operated for 6 hours before requiring regeneration, rather than 4 hours during LT1.

APPENDIX D

LEAKAGE BETWEEN HEAT STORAGE (FIG) AQUIFER AND MT. SIMON AQUIFER
AT THE STORAGE SITE

APPENDIX D

LEAKAGE BETWEEN HEAT STORAGE (FIG) AQUIFER AND MT. SIMON AQUIFER
AT THE STORAGE SITE

Following the first long-term cycle (LT1), the sodium concentration measured in samples collected from monitoring well AS1MS was 34 mg/L rather than the expected concentration of 7 mg/L (Table D.1, AS1MS 850917 and 840911 samples). The sodium concentration from AS1MS was quite close to that obtained from the Ironton-Galesville sample (AM2IG, 850917) of 41 mg/L following LT1. These results clearly suggested that during LT1, softened water injected into the FIG aquifer at the heat storage site had leaked to the Mt. Simon aquifer. The Minnesota Pollution Control Authority was immediately informed of the results and notified that an effort to check the result was being initiated. A careful check of the sample, and resampling and analysis confirmed the sodium concentration from well AS1MS. A sample from well AC1MS was taken, which agreed with the results from AS1MS. The sodium had served as a tracer of the softened water.

The water chemistry results clearly indicated that leakage had taken place, but the question of how and where it had occurred remained to be determined. Possible pathways for the FIG water to the Mt. Simon aquifer are through the rock of the Eau Claire confining bed, along the borehole of a monitoring well at the storage site (AS1 or AC1), and via the pipe installed in wells AS1 or AC1. A review of the hydraulic responses observed in AS1MS and AC1MS early in the project suggested that AC1MS, not AS1MS, was the site of the leakage.

TABLE D.1. Analytical Results of Selected Monitoring Well Water Samples

Well: Date:	AS1MS			AM2IG		
	840911	850917	860930	840911	850917	860927
pH	7.14	6.70	6.39	7.15	6.90	6.71
SC (μ mhos/cm)	280	412	397	384	424	455
SiO ₂ (mg/L)	7.21	9.13	8.29	6.19	9.55	6.69
Ca (mg/L)	58.79	36.11	50.39	58.68	34.05	46.42
Mg (mg/L)	17.08	10.10	12.26	22.88	11.75	16.32
Na (mg/L)	7.24	34.24	25.29	5.54	41.33	22.47

Thermal profiles using a type-T thermocouple were made of the three wells that penetrated to the Mt. Simon aquifer (AC1MS, AS1MS, BC1MS). The ATEs experiments had warmed the FIG aquifer, raising the temperatures at the FTF. Higher than ambient temperatures through the Eau Claire confining bed should indicate where the leakage had occurred.

The profile of BC1MS (Figure D.1) shows the type of profile that was expected with no leakage. It shows a higher temperature through the FIG aquifer and a return to ambient temperature with depth through the Eau Claire confining bed. The profile of AS1MS (Figure D.2) shows the trend toward ambient temperature through the upper part of the Eau Claire confining bed; however, it also shows an increase in temperature as the Mt. Simon aquifer is approached. The profile suggests that leakage occurred at a site other than well AS1MS.

The profile of AC1MS (Figure D.2) shows a constant and elevated [$\sim 40^{\circ}\text{C}$ ($\sim 104^{\circ}\text{F}$)] temperature through the entire thickness of the Eau Claire confining bed. This profile strongly suggests that the leakage occurred at well AC1MS. The thermal profiles do not answer the question of whether the leakage is inside the AC1MS pipe or along the outside of that pipe between the two aquifers (i.e., in the borehole of AC1).

Having established well AC1 as the source of the leakage, wells AS1MS and AC1MS were pumped to observe the pressure (water level) effects on the other well located 7 m (23 ft) away and on the other well completion in the same borehole (AS1J and AC1IG). The wells were pumped at a rate of about 9.5×10^{-2} L/sec ($0.3 \text{ m}^3/\text{hr}$, 1.5 gpm). Figures D.3 and D.4 present the observed responses. The temperature of the water withdrawn was measured periodically. Water level changes in the adjacent pipe show the effect of temperature change on the column of water in the pipe above the FIG aquifer. The difference in the responses suggests that AC1 is the source of the leakage. However, the response observed in AC1IG is so slight that the effect on the Iron-ton-Galesville part of the aquifer is nil at this pumping rate.

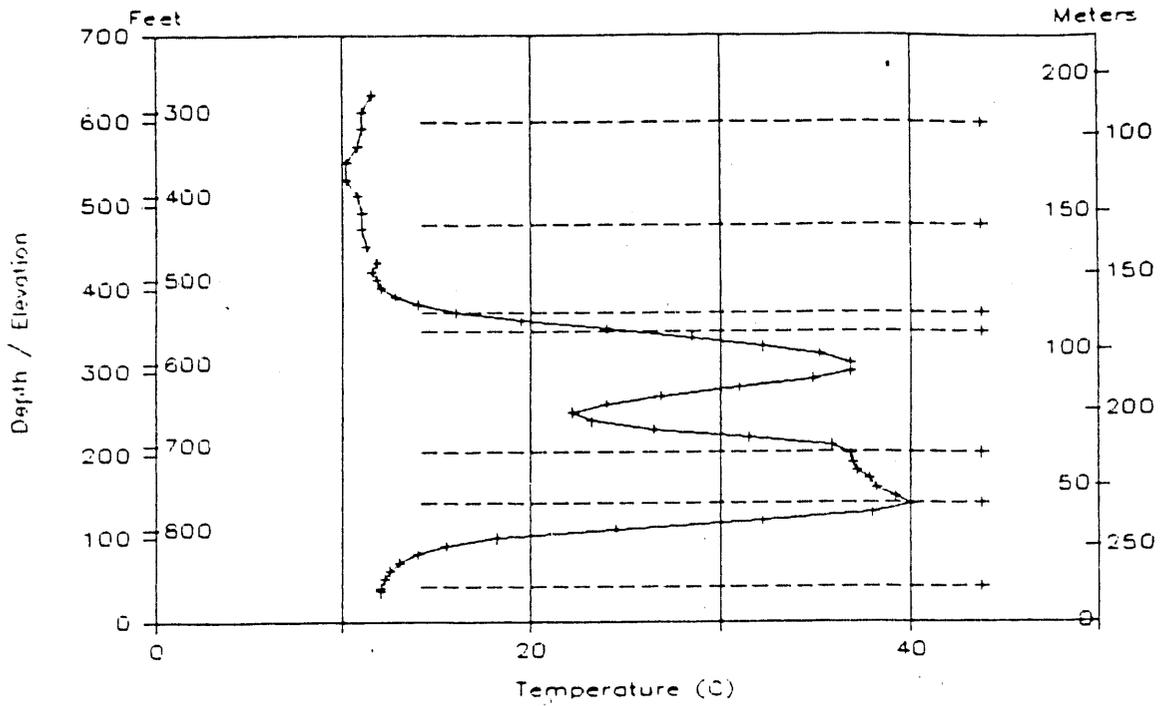


FIGURE D.1. Thermal Profile of BC1MS, March 1986

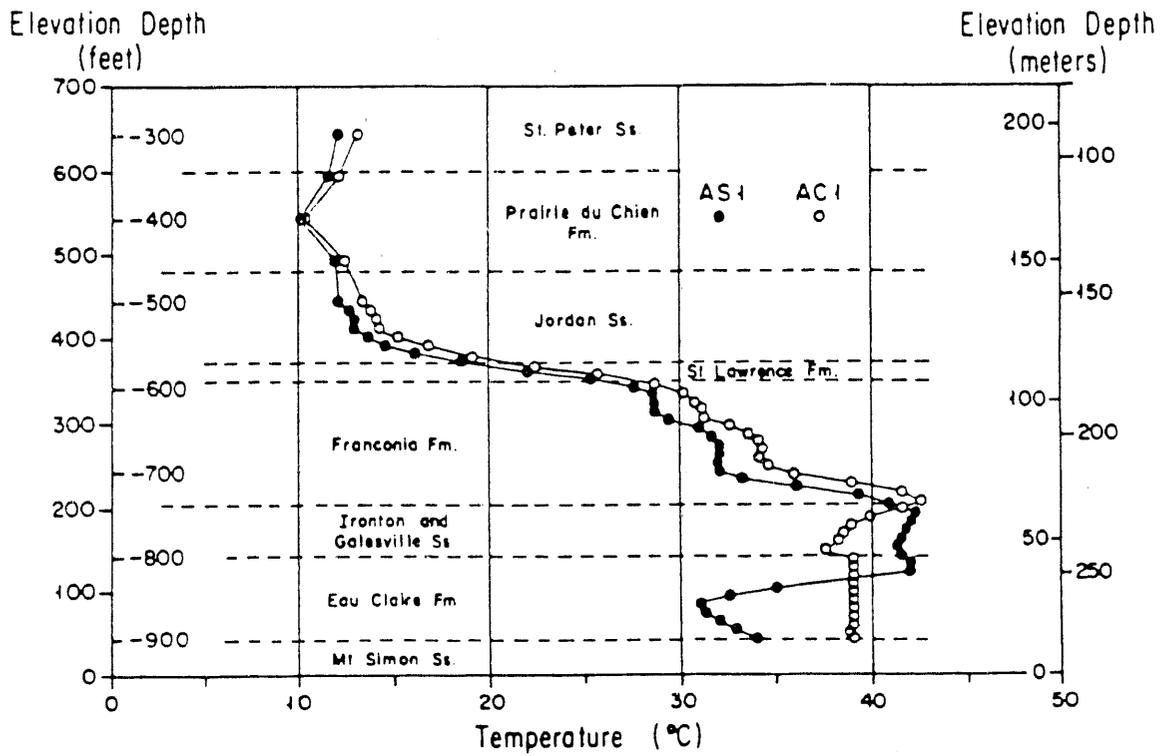


FIGURE D.2. Thermal Profiles of AC1MS and AS1MS, March 1986

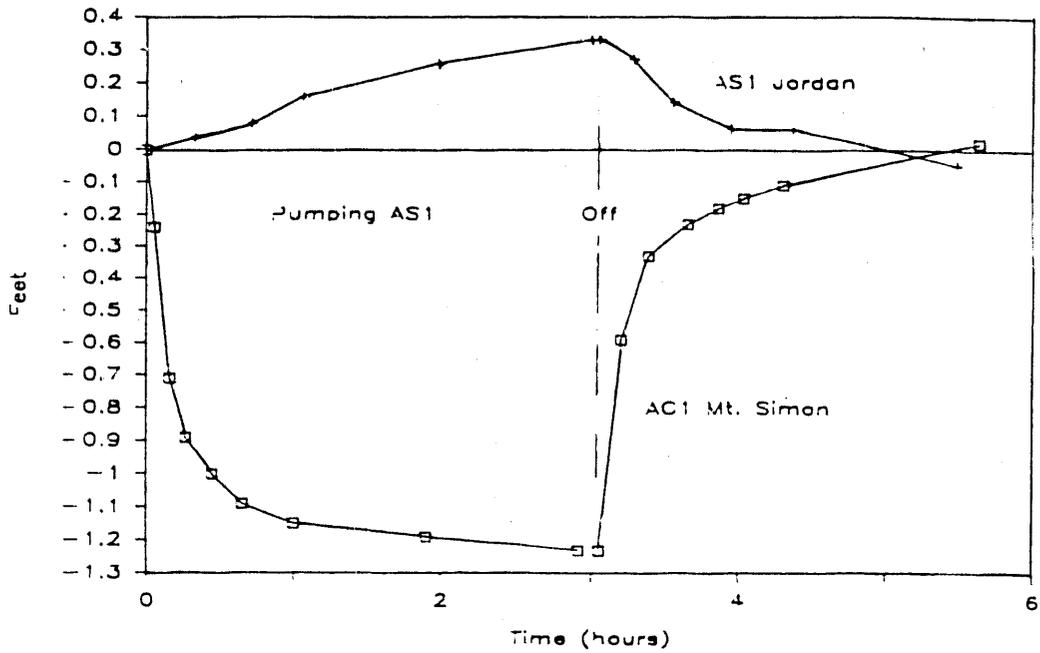


FIGURE D.3. Responses During Air-Lift Pumping of AS1MS, April 10, 1986

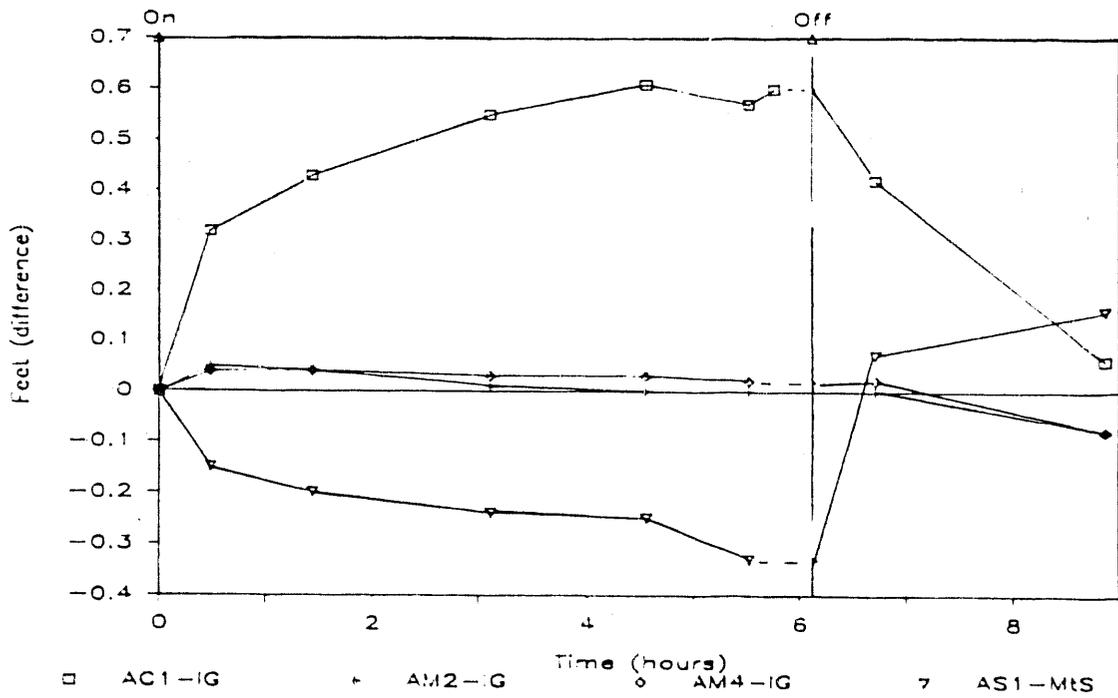


FIGURE D.4. Responses During Air-Lift Pumping of AC1MS, April 1, 1986

To further address the question of where the leakage occurred, a packer was installed in AC1MS just above the Mt. Simon aquifer to isolate the Mt. Simon well screen from the pipe above. The water level in the pipe above slowly rose toward the level of the FIG aquifer (Figure D.5). Over a 20-day period, the levels measured above the packer rose at a rate of 0.17 m/day (0.55 ft/day), which is a volume of about 0.13 L/day (0.034 gal/day). Following this period, water was added to the pipe to bring the level in the pipe up to approximately the static level of AC1IG. The water level stopped rising at this point, clearly suggesting a leakage into the pipe from the Iron-ton-Galesville portion of the FIG aquifer.

Prior to the start of LT2, the packer was removed from AC1MS to add a string of thermocouples above the packer, and the assembly was reinstalled (Figure 2.7). The purpose of the thermocouple string was to monitor the thermal response in and below the FIG aquifer during LT2 to see if the packer stopped the leakage to the Mt. Simon aquifer. Leakage would be detected by a rise in temperature at the thermocouple just above the packer (Figure 2.7).

The packer and air lines were not designed for exposure to high temperatures [$>60^{\circ}\text{C}$ (140°F)]; it was expected that during the course of LT2, the air line inflating the packer would fail. The air line lasted for 30 days into the cycle. Temperatures observed just above the packer did not rise until after the packer failed (Figure D.6). This strongly suggests that leakage is taking place inside the pipe between the two aquifers. However, this result does not eliminate the possibility of leakage occurring outside the pipe.

The thermal data give some idea of the rate of downhole migration from the FIG aquifer to the Mt. Simon aquifer. Obviously this only places some bounds on the downhole migration rate.

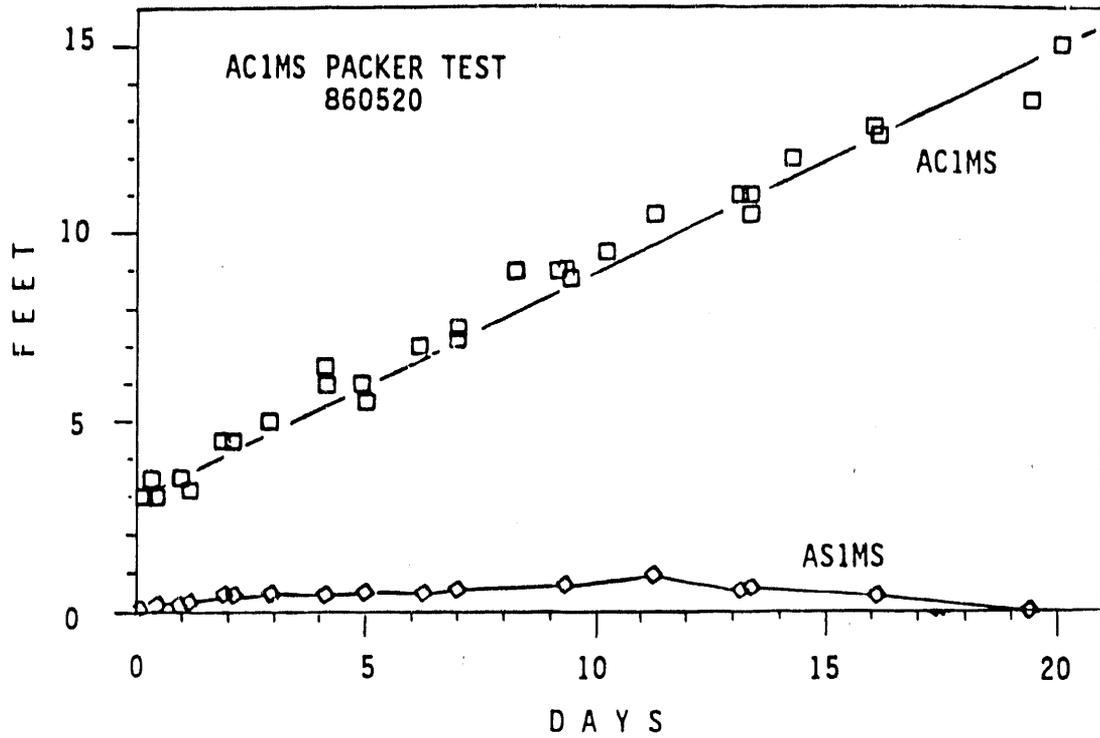


FIGURE D.5. Packer Test Results in AC1MS, 1986. Change in water level versus time.

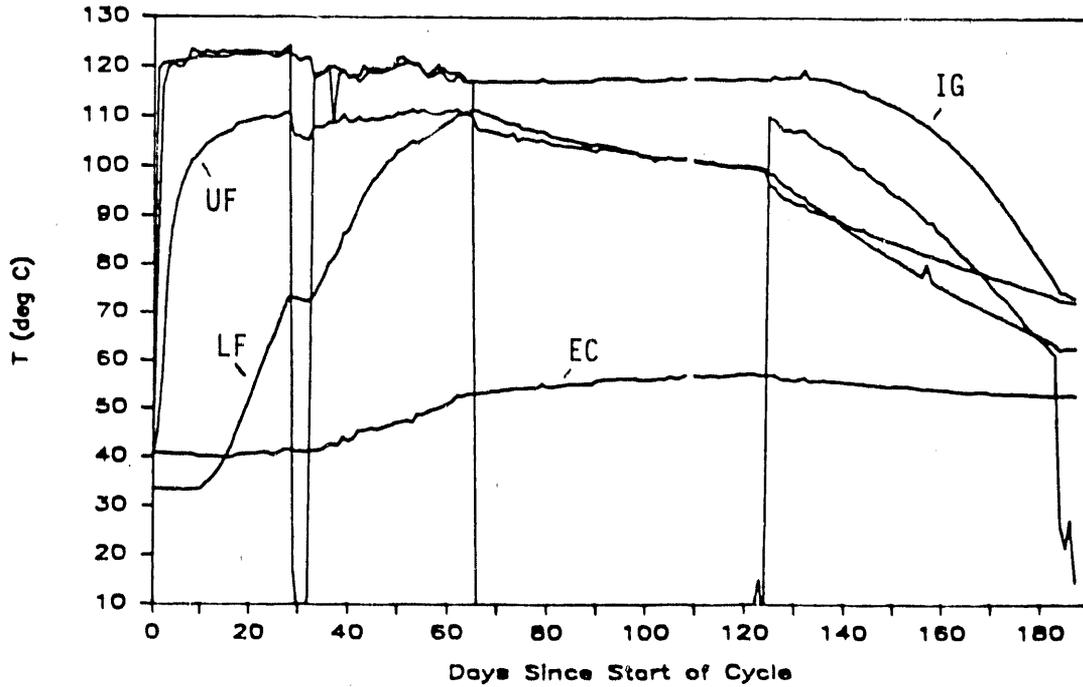


FIGURE D.6. Temperatures Recorded in Well AC1MS During Long-Term Cycle 2. UF = upper Franconia; LF = lower Franconia; EC = Eau Claire; unlabeled = injection/recovery water temperature.

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