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

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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 Department of Energy under contract DE-AC06-76RLO-1830.

This report describes the results of the first long-term heat injection/recovery cycle at the St. Paul (Minnesota) field test facility (FTF). 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 oepration of a high-temperature (>100°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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PREFACE

This report presents the preparations for and the results of the first long-term cycle (LT1) at the University of Minnesota Field Test Facility (FTF). LT1 is the first cycle of the second phase of the University of Minnesota Aquifer Thermal Energy Storage (ATES) Project. The first phase of the project included planning and constructing the FTF, characterizing the aquifer, preliminary experiments, and the four short-term ATES cycles at the FTF (Walton et al. 1991). Primary authors of the various sections of the report are listed below. Unless otherwise indicated, the investigators were at the University of Minnesota when the work was performed.

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Modeling of the aquifer and the cycle was done by R. Miller and G. Delin of the United States Geological Survey. Complete modeling results are to be published in a U. S. Geological Survey Professional Paper.

ABSTRACT

The technical feasibility of high-temperature (>100°C) 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 additions to the FTF for the long-term cycles and the details of the first long-term cycle (LT1) that was conducted from November 1984 through May 1985. Heat recovery; operational experience; and thermal, chemical, hydrologic, and geologic aspects of LT1 are reported.

The permits for the long-term cycles required the addition of a monitoring well 30.5 m from the storage well for monitoring near the edge of the thermally affected area and allowed the addition of a cation-exchange water softener to enable continuous operation during the injection phase.

Approximately 62% of the 9.47 GWh of energy added to the 9.21×10^4 m^3 of ground water stored in the aquifer during LT1 was recovered. Temperatures of the water stored and recovered averaged 108.5°C and 74.7°C, respectively. System operation during LT1 was nearly as planned, with the exception of problems during the injection phase with the newly installed water softener.

Ion-exchange water softening of the heated and stored ground water prevented scaling in the system heat exchangers and the storage well and changed the major-ion chemistry of the stored water. Total hardness was reduced from ~200 mg/L as calcium carbonate to <20 mg/L as calcium carbonate; sodium content increased from <20 mg/L to ~113 mg/L. Silica, calcium, and magnesium concentrations were significantly higher in recovered water than in injected water. Sodium ion concentrations decreased from ~105 mg/L to ~40 mg/L during recovery.

Temperatures at the storage horizons in site monitoring wells reached as high as 108°C during the injection phase of LT1. Following heat recovery, temperatures were <30°C at the same locations. Less permeable horizons underwent slow temperature changes. No thermal or chemical effects were observed at the remote monitoring site.

EXECUTIVE SUMMARY

The objective of the aquifer thermal energy storage (ATES) field test facility (FTF) at the University of Minnesota is to examine the technical feasibility of ATES at temperatures up to 150°C in a confined aquifer by conducting a series of experimental cycles in a confined aquifer at the St. Paul campus of the University. The initial phase included designing and constructing the FTF, conducting a series of tests on the aquifer, examining core from the site, preliminary modeling, and conducting four short-term ATES cycles (Hoyer et al. 1985; Miller 1985; Walton et al. 1991). The short-term cycles were conducted between May 1982 and December 1983. The second phase of the project, two long-term cycles requiring new operational permits and expansion of the FTF, began following the short-term cycles. This report covers the first long-term cycle (LT1), which began in November 1984 and was completed in May 1985.

The St. Paul FTF is designed to inject and recover heated water at a maximum rate of 5 MW (thermal) (1.71×10^7 Btu/hr), using a well doublet 255 m (835 ft) apart, pumping at a rate of 18.9 L/s (300 gpm) and maximum water temperature of 150°C (302°F). Design ΔT (temperature difference across heat exchanger) is 66°C (119°F). In the heat storage phase, water is pumped from the aquifer by the supply well, heated in a shell-and-tube counterflow condenser and subcooler, and injected into the aquifer at the storage well. In the heat recovery phase, water is pumped from the aquifer at the storage well, heat is discharged at a simulated load, a large radiator, and the water is returned to the aquifer at the supply well. Heat for the experimental ATES cycles is supplied by saturated steam from the St. Paul campus heating plant. A field office trailer houses the instrument recording equipment. Piping between the storage and source sites is routed through the preexisting steam tunnel.

The FTF 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 an approximately 300 m (1000 ft) thickness of almost flat-lying Paleozoic sandstone, dolostone, and shale. Three major confined aquifers are below the site: the Prairie du Chien-Jordan

(PdCJ), the Franconia-Ironton-Galesville (FIG), and the Mt.Simon-Hinckley (MtSH). These are separated by confining beds. Static water levels of each aquifer differ sufficiently to allow separation and identification of the aquifers.

The FIG aquifer was chosen for the ATES project because it is the least utilized aquifer in the area. The FIG aquifer has the lowest hydraulic conductivity and transmissivity of the aquifers. Its hydraulic gradient is very low (<0.004). Concerns for possible, but undetermined, environmental effects on the aquifer from high temperatures and temperature changes 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 testing confirmed that the FIG aquifer is highly stratified fine- to medium-grained sandstone and thin shale beds. It is areally and vertically anisotropic. The FIG aquifer is approximately 61-m (200-ft) thick at the ATES site. At the storage site, it is 181 m (594 ft) below the surface. Static water levels for the FIG aquifer are at a depth of about 55 m (180 ft). Hydraulic conductivity ranges from about <0.01 to 1.5 m/d (<0.03 to 5.0 ft/d); 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 permeability interbedded with beds of high conductivity reduce thermal convection and thermal stratification. Nine monitoring wells are instrumented to measure vertical temperature distribution, water levels (pressure), and to obtain water samples for chemical analysis. Wells are completed in the FIG aquifer and in over- and underlying units.

Each long-term cycle was planned to last 180 days; 60 days each of heated water injection, storage, and recovery. As a result of several equipment problems during LT1, the cycle LT1 required 197 days to complete. During LT1, a total of 9.21×10^4 m^3 (2.43×10^7 gal) of water heated to an average temperature of 108.5°C (227°F) was stored in the FIG aquifer. The flow rate averaged 18.03 L/s (286 gpm). An attempt was made to maintain a relatively constant injection rate and injection temperature. However, as a result of variation in source water temperature, campus steam demand, and water softener regeneration, flow and injection temperature varied with time. For 35 days of injection, the injection temperature was 110°C (230°F) or higher; most were during the first half of the injection when the source water was warmer. The source waters were not isothermal, but reached a high temperature of 30.5°C (87°F) about 8 days into the cycle and declined slowly to 13.0°C (56°F) by the end of the injection period. The peak source-water temperature occurred when about 12,000 m^3 had been pumped from the source well; a volume about equal to that pumped during each of the last three short-term cycles. Mean source water temperature was 19.7°C (67°F). It took 74.7 days to complete 59.1 days of heated water injection. Scheduled shutdowns accounted for 7 of the additional days; the remainder were caused by weather, power failures, and equipment failures. After storage for 64 days, heat recovery began and continued until 9.22×10^4 m^3 (2.44×10^7 gal) were recovered 58.0 days later. The temperature of the recovered water averaged 74.7°C (166°F). During recovery, a peak temperature of 93.3°C (200°F) was reached after about 2 days of pumping. The temperature decline was very slow during the recovery of first 3.0×10^4 m^3 (7.9×10^6 gal) of water. The final temperature of the recovered water was 45.6°C (114°F). Flow during recovery averaged 18.4 L/s (292 gpm).

If the energy balance is taken from the ambient ground-water temperature of 11°C (53°F), then 10.4 GWh (3.55×10^{10} Btu) were stored and 6.79 GWh (2.32×10^{10} Btu) were recovered during LT1, resulting in an energy recovery ratio of 0.65. If one considers only energy added to the water during this cycle, then 9.47 GWh (3.23×10^{10} Btu) were stored and 5.86 GWh (2.00×10^{10} Btu) were recovered, for an energy recovery ratio of 0.62. For any full-scale operating system, the important values are how much of the energy returns at a usable temperature and at what rate the energy returns. These values will be functions of the end use and interfacing exchangers for a full-scale operating system.

Temperatures observed in monitor wells reflected the layered nature of the FIG aquifer. Profiles exhibited an hourglass shape. Highest temperatures reached about 105°C (221°F) at Ironton-Galesville levels and about 100°C (212°F) at upper Franconia levels in the monitor wells 7 m from the storage well. Following heat recovery, highest temperatures of about 55°C (131°F) were present just above the more permeable portions of the aquifer. During heat recovery, temperatures declined steadily at the permeable horizons. The rock at horizons between the screened intervals and in confining beds warmed through the cycle. Field results are in close agreement with modeled results (Hoyer and Miller 1987; Hoyer et al. 1987).

The permit for the long-term cycles allowed the use of ion-exchange water softening to eliminate carbonate scaling. An ion-exchange water softening system was installed and an additional monitor well (AM4) located 30.5 m (100 ft) from the heat storage well was completed before the start of LT1. Ion-exchange water softening changes the ionic composition of the natural ground water but otherwise it has little effect on the system or the aquifer. Ion-exchange water softening effectively prevented the precipitation of calcium carbonate scale in the heat exchangers and storage well. Water treatment was essential for the success of LT1.

Composition of the ground water coming into the system after the short-term test cycles reflected equilibrium with respect to major ions. Silica concentrations in the source water show a direct correlation with temperatures. Calcium, magnesium, and alkalinity of source water were approximately constant during injection. Hardness values for the source water were quite close to what they would have been with entirely ambient temperature water from the source well. The water softener removed nearly all the hardness from the water when the softener was working properly. The primary effect of the water softener was to change the water from a calcium-magnesium bicarbonate water to a sodium-bicarbonate water. As expected, silica, calcium, and magnesium concentrations in the recovered water approached saturation values for the recovered water temperatures. Mass balance calculations and analyses indicate a net removal of silica, calcium, and magnesium from the storage site. Neither the supply nor the storage well showed any significant loss of efficiency during LT1.

A significant percentage (>60%) of heat may be recovered on a seasonal basis in a confined ATES system, even during an initial cycle. Water softening of naturally hard ground water can be successful in eliminating carbonate scaling.

ACKNOWLEDGMENTS

This work, supported by the U. S. Department of Energy, was performed by the University of Minnesota as part of the Underground Energy Storage Program at Pacific Northwest Laboratory. Pacific Northwest Laboratory is operated by Battelle Memorial Institute under contract DE-AC06-76RLO 1830. Special thanks go to program managers L. D. Kannberg and J. R. Raymond for their suggestions, encouragement, and guidance.

The Physical Plant of the University and the Minnesota Geological Survey were co-sponsors of the work. The cooperation and interest of the many individuals from the Physical Plant of the University of Minnesota Twin Cities Campus made the ATES experiment possible. Directors of the Physical Plant, Warren Soderberg and Tuncay Aydinalp; Fiscal Manager, Steve Richards; and many others from the Physical Plant were instrumental in the actual performance of the project.

Many staff members from the Minnesota Geological Survey and the U.S. Geological Survey, Water Resources Division, St. Paul office staffed the site around the clock during the pumping phases of the cycle.

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UNIVERSITY OF MINNESOTA
AQUIFER THERMAL ENERGY STORAGE (ATES) PROJECT
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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, 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, operate the facility for a series of test cycles. 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 the operations at the site, oversees the data from the experimental test cycles, and coordinates the water chemistry studies and monitoring being done at the Department of Civil and Mineral Engineering, Environmental Engineering Laboratory. The U.S. Geological Survey Water Resources Division, St. Paul, was responsible for data acquisition and aquifer modeling. All cores from the drilling phase are housed at the MGS. Other field studies related to effects of the heated water injection were conducted by PNL at the FTF using a field injectivity test stand (FITS).

The original purpose of the project was to acquire the basic hydrogeological, hydrogeochemical, and hydrogeothermal data to determine design parameters for a 20-MW ATES demonstration system using a confined aquifer to be incorporated into the University of Minnesota heating/cooling system. Program changes modified the purposes to obtaining the above data and operating parameters in short-term cycles (Phase 1) and long-term cycles (Phase 2) with the 5-MW experimental system.

Following the granting of a variance by the Minnesota Pollution Control Agency (MPCA) to allow the injection of waters for the Phase 1 cycles and the granting of appropriate permits from the Minnesota Department of Health (MDH) and Minnesota Department of Natural Resources (DNR), the final designs for the test facility and monitoring array were prepared. 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. Phase 1 test cycles were completed in December 1984. Published reports and papers outline the project through the short-term cycles (Hoyer et al. 1985; Miller 1983; Walton 1981, Walton et al. 1991); discuss aquifer characteristics (Kanivetsky and Hoyer 1986; Miller 1984); discuss aquifer modeling (Miller 1983, 1984, 1985, 1986; Miller and Voss 1986); outline the water chemistry (Holm et al. 1987; Hoyer et al. 1985; Walton et al. 1991), and report on flow experiments with the aquifer water (Blair 1985; Blair and Deutsch 1983; Blair, Deutsch and Kannberg 1984; Blair, Deutsch and Mitchell 1985).

Phase 2, consisting of two long-term cycles, required the granting of a new variance from MPCA and new permits from MDH and DNR. In August 1984 the permitting aspects were completed. Additions to the facility, a water softener and new monitor well, were completed in November 1984; the first long-term cycle (LT1) was conducted from November 1984 through May 1985. Published papers which include results from LT1 are Hoyer and Walton (1986), Hoyer and Splettstoesser (1987), and Perlinger et al. (1987).

This report is a summary of the first long-term cycle (LT1) and some conclusions (Section 2) from testing done at the University of Minnesota FTF. A description of the FTF and changes made since Phase 1 are presented in Section 3. Section 4 presents a description of LT1. The responses in the aquifer and surrounding rock are summarized in Section 5. Results of water analyses during the cycle and from monitoring wells are presented in Section 6. The modeling of the long-term cycles is being done by the U.S. Geological Survey (USGS). Their policies require publication of work performed by their staff through established USGS procedures. A published abstract (Hoyer and Miller 1987) includes some of the modeling results from LT1; complete reports on the modeling will be published by the USGS at a later date.

Tables of flow and temperature data from LT1 are provided in Appendix A. Tables of water analyses from LT1 and monitoring well samples are provided in Appendix B. A review of operating parameters and procedures for LT1 is presented in Appendix C. Review and analysis of the field injectivity testing with the field injectivity test stand conducted during LT1 by PNL and MGS personnel is presented in Appendix D.

2.0 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 LT1 experimental results agreed with the previously conducted short-term test cycles, as expected. A significant amount (62%) of the energy added to the ground water stored in the Franconia-Ironton-Galesville (FIG) confined aquifer during LT1 at the St. Paul FTF was recovered. This agrees quite closely with the energy recovery of 64% predicted by modeling the cycle.

Characterization of the aquifer prior to site development must be done to anticipate potential problems, determine the feasibility of particular well-field designs, plan monitoring, and model energy and mass-flows of the system. All of the initial aquifer characterization work (cores, geophysical logs, pumping tests...) for the previously conducted short-term test cycles was applicable to LT1. Initial characterization has been summarized in several reports and papers (see Section 1.0). A more complete report characterizing the aquifer was recently published (Walton et al. 1991).

Characterization of the ground water is of critical importance. The temperature change of the water, and the aquifer, affects the chemical equilibria of the ground water. Potential problems with precipitation, rock dissolution, and/or corrosion must be addressed for a system to work. The hard ground water (200 mg/L as $CaCO_3$) at the St. Paul site required softening to prevent scaling of piping and the storage well. An ion-exchange water softening system was a satisfactory solution when operating properly.

The configuration of the heating/cooling system to be interfaced with an ATES system must be considered in attempting to design a suitable system. The system built at the University of Minnesota is designed to interface with a low-pressure steam system. When the system was built, it was anticipated that such a system might be used on the campus rather than the high-pressure steam system, which is in place. Following initial aquifer test analyses, a review of final cost and configurations to construct the originally planned 20-MW full-scale system, and current and near-term energy costs, it is highly unlikely that the University of Minnesota will construct the full-scale system in the near future.

LT1 cannot be used to directly evaluate the economics of such a system; however, it is noteworthy that energy for pumping was less than 3% of the energy recovered.

Specific conclusions resulting from LT1 include:

1. A significant percentage (>60%) of the energy added to the water stored in the FIG aquifer was recovered during this season-length experimental ATES cycle. During the first third (20 of 60 days) of recovery (3.0×10^4 m^3), the recovered water was at or above a temperature of 85°C (185°F), a useful minimum temperature for supplying conventional hot-water space heating. Future cycles, because of a preheated storage zone and higher storage temperature, would provide a higher proportion of "useful temperature" recovery water.
2. Ion-exchange water softening is effective in preventing scaling problems caused by heating the naturally-hard ground water. The sodium ion concentrations of the softened water were reasonably close to expected levels (113 mg/L vs 90 mg/L sodium for the injected water). Problems with the newly installed water softener did cause delays and required attention; however, they were caused by improper installation and solved during the injection phase of LT1. Performance of a water softener must be monitored frequently.
3. The highly layered nature of the FIG aquifer was reflected in the thermal responses at monitoring wells near the storage well. Temperatures above 80°C (176°F) were recorded at the most permeable aquifer horizons in wells located 7, 14, and 30.5 m from the storage well 2, 7, and 15 days after the start of heated water injection. Arrival of the thermal front followed a similar pattern. Temperatures in the low permeability parts of the aquifer only slowly rose, and never rose to above 80°C. The interbedded nature of the FIG aquifer tended to inhibit thermal stratification; however, some thermal stratification was observed during the 2 months of storage. Upper Franconia horizons cooled most rapidly during heat recovery. Temperatures recorded at Ironton-Galesville

horizons in the aquifer paralleled the temperature curve of the recovered water.

4. Chemistry of the water recovered from storage followed trends expected based upon the equilibrium modeling of the water. For example, higher temperature water had higher concentrations of silica and lower concentrations of calcium and magnesium than lower temperature recovery water. As during the short-term cycles, all the recovered water was essentially at equilibrium.

5. Mass balances of major ions present in the ground water indicate net changes as a result of water softening and reequilibration in the aquifer during storage. For the complete cycle, comparing recovered water with source water, there was net addition of sodium, from the softener, and loss of calcium and magnesium. Comparing recovered water with injected water, there was net addition of calcium and magnesium and loss of sodium. Mixing with native ground water may explain these effects. Future research needs to be directed at rock-water interactions and diffusion/dispersion effects.

6. Sodium concentrations during recovery declined as heat recovery progressed. Sodium concentrations began at 105 mg/L and ended at 40 mg/L. Dispersion and mixing may account for most of this decrease.

7. Source water for LT1 had retained enough heat from the short-term cycles completed 16 months previously to supply 10% of the heat above ambient conditions contained in the injected water.

8. Water level/pressure buildup from the injection phase of LT1 measured at monitoring wells was less than 15 psi (10.3 m, 34 ft). Such a response is entirely acceptable for the operation of this ATES system at temperatures above 100°C.

9. Effects of the heated water injection were restricted to the immediate vicinity of the storage well. No thermal or chemical effects have been observed during or following LT1 at monitoring well CM1, the remote site.

10. The softened water, with sodium concentrations considerably above ambient concentrations, serves as a very good tracer. This water served to

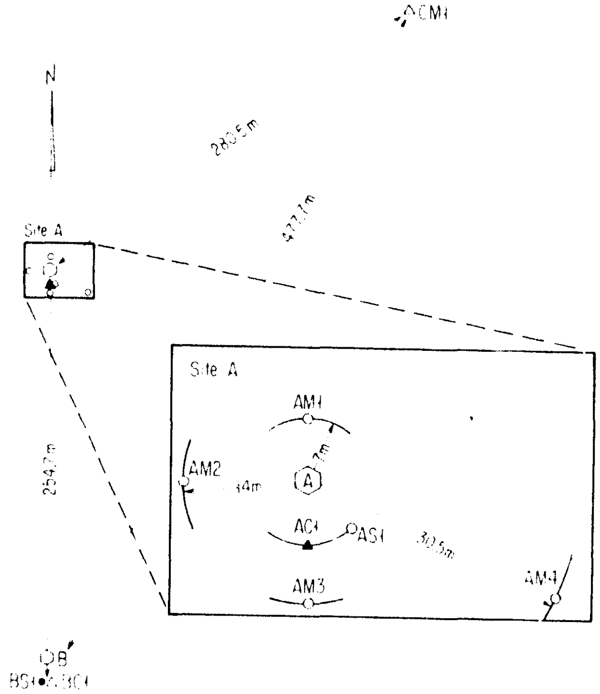
detect leakage between the FIG aquifer and the Mt. Simon aquifer during routine water analyses from monitoring wells. Post LT1 monitoring and testing revealed that a monitoring well was the conduit to the Mt. Simon aquifer.

3.0 FIELD TEST FACILITY

The FTF is located on the St. Paul campus of the University of Minnesota. For the long-term test cycle, the facility consisted of two pumping/injection (source and storage) wells completed in the FIG aquifer; nine monitoring wells completed in the FIG aquifer, its confining beds, and the Jordan and Mt. Simon aquifers; connecting piping, heat exchangers, and water softener between the source and storage wells; and piping to supply steam to heat the aquifer water (Figures 3.1, 3.2, 3.3 and 3.4).

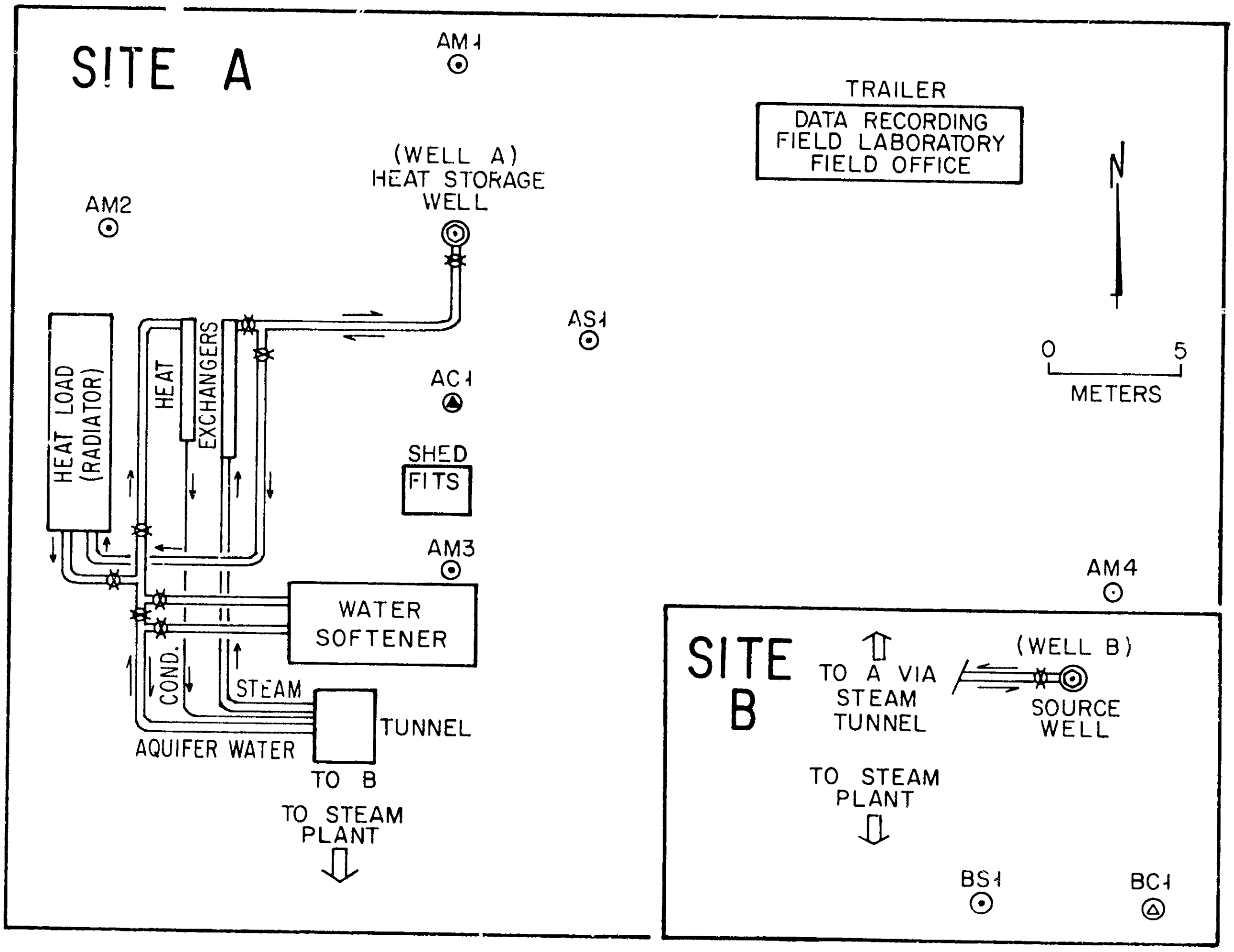
3.1 GEOLOGIC SETTING

The following is a summary of the geologic setting; Walton et al. (1991) presents a more complete description of the geologic setting of the FTF. The FTF is located near the center of the Twin Cities Artesian Basin, a Paleozoic



Storage site = Site A; Storage well = A
Source well = B
Core hole monitoring wells = AC1, BC1
Monitoring wells = AM1, AM2, AM3, AM4, AS1, BS1, CM1

FIGURE 3.1. Well Plan of the University of Minnesota ATES Field Test Facility



Site A is storage well site; Site B is source well site;
AC1, AM1, AM2, AM3, AM4, AS1, BC1, and BS1 are monitoring wells;
FITS is field injectivity test stand

FIGURE 3.2. Source and Storage Well Sites at the University of Minnesota ATES Field Test Facility, Long-Term Cycle 1

structural and stratigraphic basin subsidiary to the Hollandale Embayment. Beneath the site there is an approximately 300 m (1000 ft) thickness of almost flat-lying Paleozoic sandstone, dolostone, and shale. Three major confined aquifers are below the site: the Prairie du Chien-Jordan (PdCJ), the Franconia-Ironton-Galesville (FIG), and the Mt.Simon-Hinckley (MtSH). These are separated by confining beds. Each has static water levels sufficiently different to be able to identify the aquifer.

The FIG aquifer was chosen for the ATES project because it is the least utilized aquifer in the area. The FIG aquifer has the lowest hydraulic

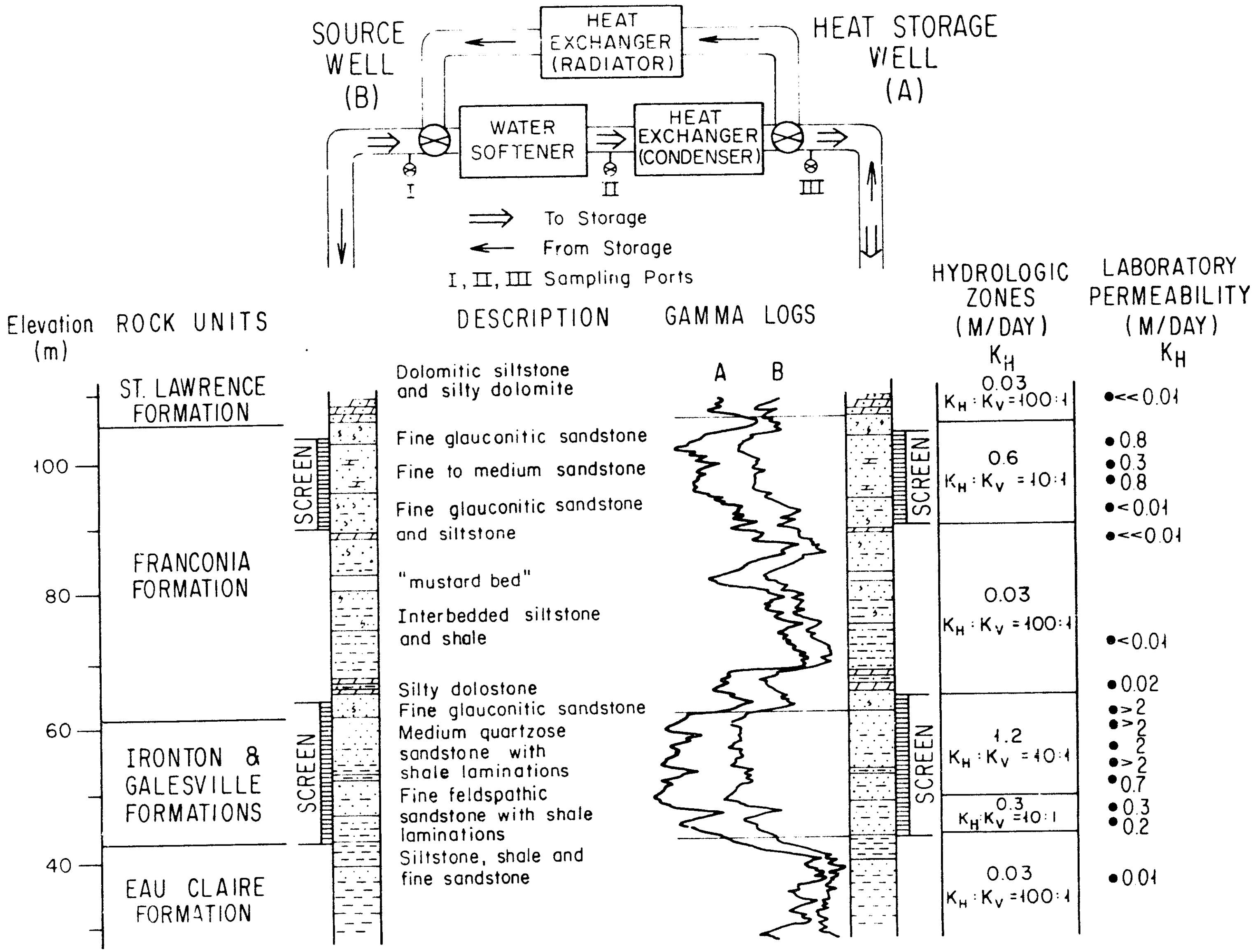


FIGURE 3.3. Stratigraphy, Hydrogeologic Units, and Flow Path at the University of Minnesota ATES Field Test Facility, Long-Term Cycle 1

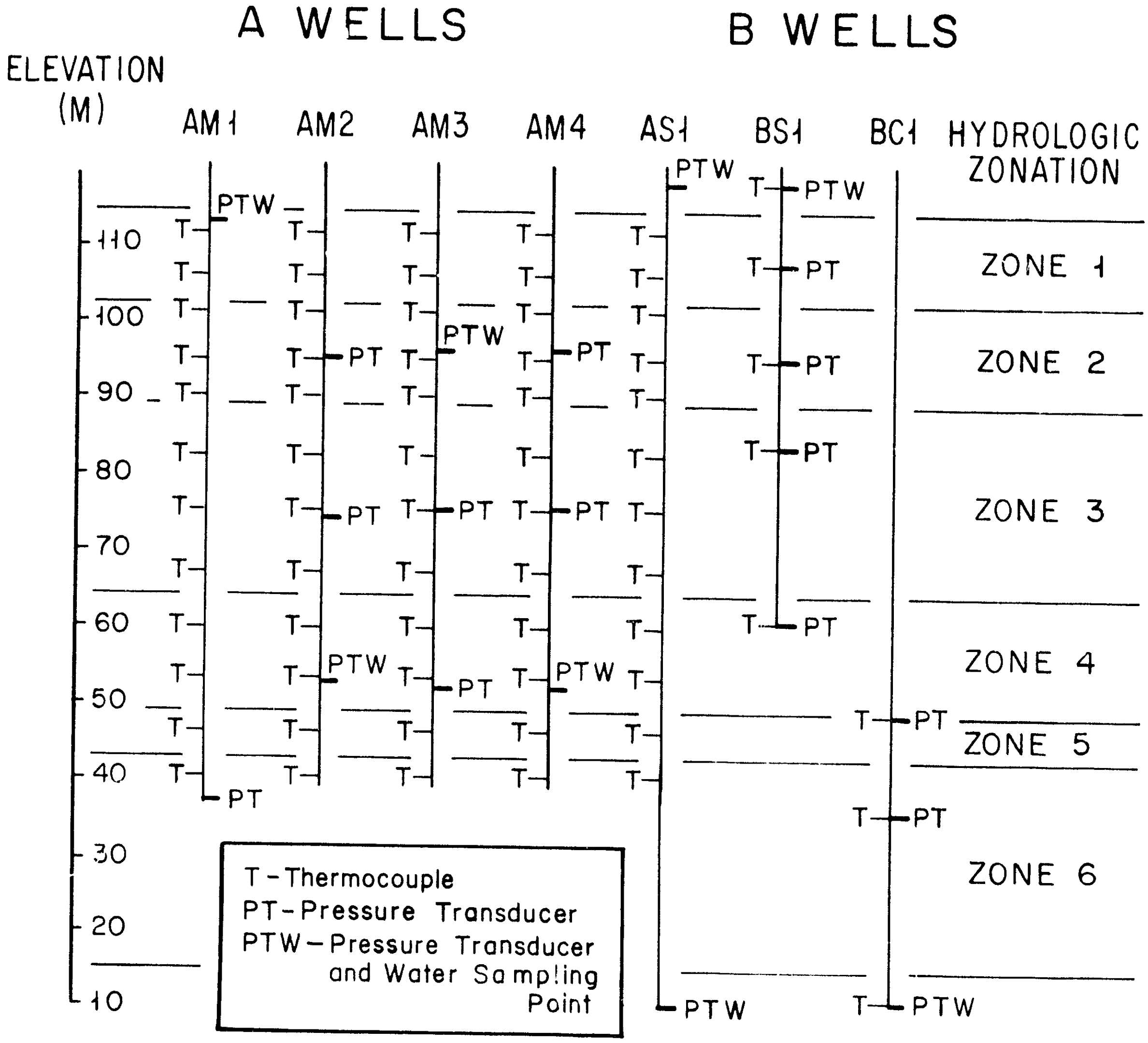


FIGURE 3.4. Monitoring Well Instrumentation, Storage and Source Sites

conductivity and transmissivity of these aquifers. Properties, thicknesses, and zonation of the aquifer are presented in Figure 3.3. The two water-yielding units of the FIG aquifer were screened; these are the Upper Franconia and the Ironton-Galesville portions (Figure 3.3). Hydraulic gradient in the FIG is very low (<0.004). The FIG aquifer is highly stratified fine- to medium-grained sandstone and thin shale beds. It is areally and vertically anisotropic. The FIG aquifer is approximately 61-m (200-ft) thick at the ATES site; the screened thickness is 35 m (115 ft). At the storage site the aquifer is 181 m (594 ft) below the surface. Static water levels for the FIG aquifer are at a depth of about 55 m (180 ft). Hydraulic conductivity ranges from about <0.01 to 1.5 m/d (<0.03 to 5.0 ft/d); 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 permeability interbedded with beds of high conductivity reduce thermal convection and thermal stratification.

3.2 SOURCE AND STORAGE WELLS

The source well (B) and the storage well (A) are each completed with two screened intervals in the FIG aquifer. The upper 13.7-m (45-ft) section of the 25-slot stainless steel screen is opposite the upper portion of the Franconia formation; the lower 22.9-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 3.3, 3.5). The construction of the lower parts of the wells is shown diagrammatically in Figure 3.5. The wells are constructed to accommodate thermal expansion in the screened interval and restrain it in the grouted interval. The turbine pumps in each well are set at a depth of 154 m, corresponding to an elevation of 133 m (436 ft) msl in well A and 124 m (406 ft) in well B.

3.3 MONITORING WELLS

The nine monitoring wells provide for instrumentation of the full stratigraphic interval affected by the system. Parameters measured at monitor wells are temperatures, pressures (water levels), and ground-water composition. These wells are located at the storage site (Site A), the source site (Site B), and at a site expected to be beyond any thermal effects of test cycles (Site C) located 280.5 m (920 ft) northeast of the storage well (Figure 3.1).

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 3.6). All wells were surveyed by a plumb bob method and/or by magnetic downhole multishot method

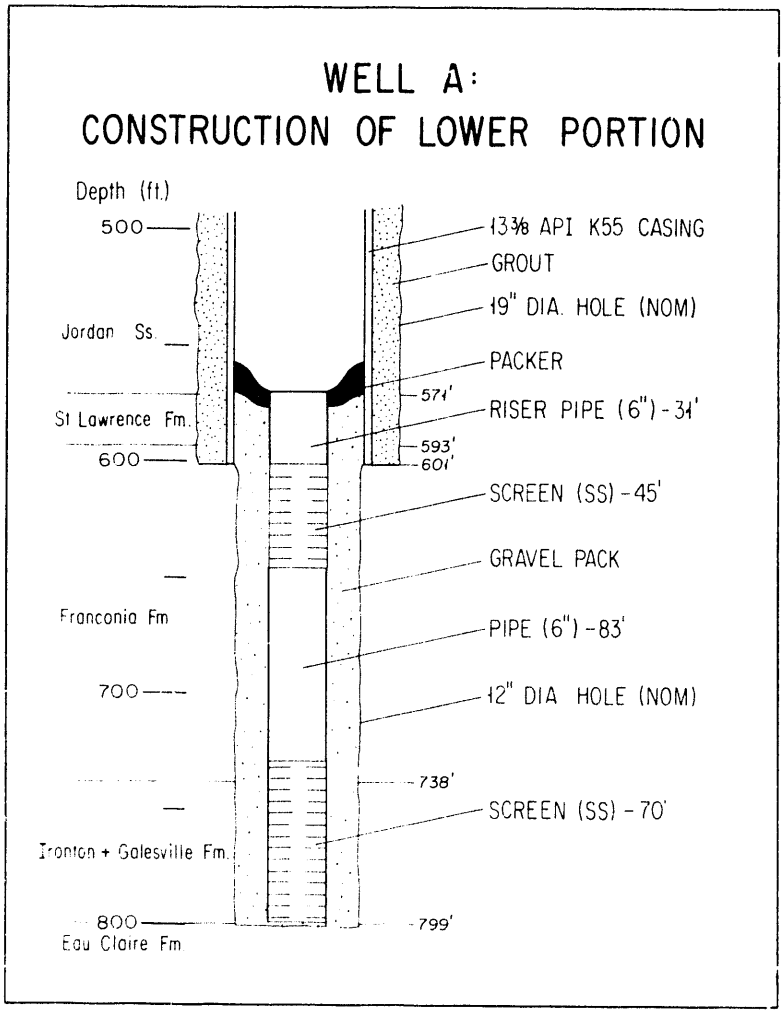


FIGURE 3.5. Diagram of Lower Portion of Heat Storage Well, Well A

when drilled; for those surveyed by downhole methods, the results were similar (Table 3.1). The survey results by the downhole methods are adequate for those wells that were impossible to survey with the gyroscopic tool because of insufficient pipe diameters. Difference in well bottom position between gyroscopic and multishot surveys of wells AM2 and AM3 are 0.74 and 0.27 m (2.43 and 0.89 ft), respectively. Well AM4 was drilled by cable-tool methods and shows a deviation opposite that of all the other surveyed wells, which were drilled by rotary methods (Figure 3 [illegible].

Wells at the storage site, with the exception of AC1 which was not used for monitoring because of problems in completion, have a multiple-pair thermocouple string. Because of failure of several thermocouples, a

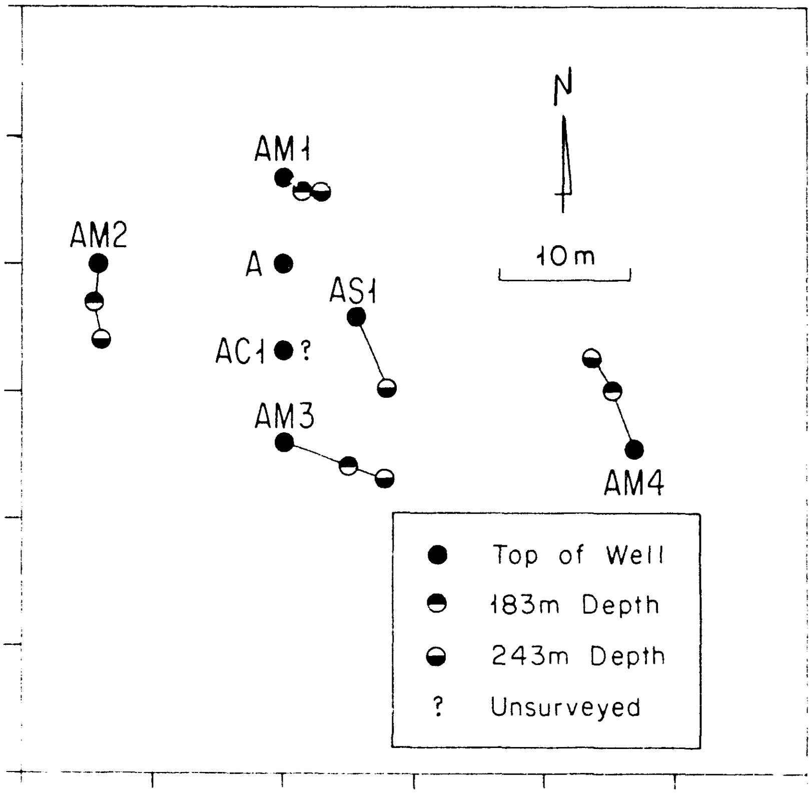


FIGURE 3.6. Surveyed Locations of Tops and Bottoms of Storage Site Wells

TABLE 3.1. Comparison Between Downhole Surveyed Positions of Monitoring Wells at 243 m 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) unable to survey; pipe too small for tool

replacement thermocouple string was installed in the open-ended pipe of AM1, which extends to the Eau Claire formation, prior to the start of LT1.

At the source site (B), the monitoring wells are 10 m (33 ft) from the source well. These wells have not been gyroscopically surveyed. The bottom of well BS1 is immediately adjacent to well B. While drilling 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 depths indicated in Figure 3.4. The Mt. Simon and Jordan pipes were installed to provide samples for water analyses, as well as to observe pressure (water level) and temperature. The remaining pipes are for monitoring pressure (water level) and temperature.

Water samples have been collected from the Jordan, Mt. Simon, and FIG aquifers at storage site before and after the tests conducted to date. The 0.03-m (1.25-in.) pipes in monitor wells AM1, AM2, AS1, BC1, BS1, and CM1 are the sampling pipes. Well AM4 has a 0.05-m (2-in.) pipe for sampling. The sampling pipe of AM3 is plugged, probably with grout; and the upper Franconia pipe in well CM1 was plugged with a pump while attempting to sample.

3.4 PIPING, HEAT EXCHANGERS, AND WATER SOFTENER

Physical arrangement of the facilities at the site is presented in Figure 3.2. A brief description follows.

3.4.1 Piping and Heat Exchangers

Piping connecting the wells and from the campus steam plant is routed through the pre-existing steam and utilities tunnel, which passes under the source and storage sites. A provision for sending water from the wells to waste, via the existing storm sewer, was added so that the system piping, heat exchangers, and wells may be flushed before beginning injection or recovery. The water softener has a drain to the sanitary sewer for the recharging brine and final rinse water. Diameter of steam and connective piping is 0.15 m (6 in.); diameter of condensate line is 0.05 m (2 in.); diameter of waste lines is 0.10 m (4 in.). Piping is all schedule 40 or 80.

Heating of the aquifer water takes place 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 psi 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 automatic mode. For LT1 it was operated in manual mode with a constant fan speed.

3.4.2 Water Softener

An ion-exchange water softener was installed before LT1 began to allow virtually uninterrupted operation by removing the hardness from the ground water before heating. The effect of the softener was to change the water from a calcium-magnesium bicarbonate water to a sodium-bicarbonate water. During injection, the water softener used approximately 684 kg (1500 lb) of solar salt (NaCl) per day for regenerations.

The water softener consists of three tanks containing the ion-exchange resin Aldex®(a), a brine tank, and a control system. During the heated-water injection phase, two units are in service at all times. The third unit is recharged and then placed on standby until the timing cycle is completed. Specifications called for each unit to be in service for at least 8 hours between regenerations and for the water to be brought to a hardness of approximately 0 grains. An acceptable level of hardness was approximately 1 grain. Problems with the softener were encountered. The problems, and their solutions, are detailed in Section 4.1.

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

4.0 LONG-TERM CYCLE 1

Following the completion of well AM4, granting of a permit, and the installation and initial testing of the water softener, LT1 began on November 14, 1984. Table 4.1 and Figure 4.1 summarize the cycle. Table 4.2 allows comparisons between LT1 and previous short-term cycles. Appendix A presents a summary of daily data; Appendix C presents an outline of observations made and operating parameters. Appendix D presents results of experiments with the field injectivity test stand during LT1.

The cycle was relatively trouble-free. However, problems were encountered with the water softener, weather, monitoring equipment, and flowmeter at different times during LT1. Manual measurements had to be taken of some key parameters when monitoring systems failed.

4.1 INJECTION PHASE

The injection phase of LT1 was conducted from November 14, 1984 to January 28, 1985. A total of 59.1 days of injection were completed during 74.7 days.

Mean flow rate was 18.03 L/s (285.8 gpm), mean source water temperature was 19.7°C (67°F), mean injected water temperature was 108.5°C (227.2°F), and mean delta T was 88.6°C (159.5°F). A total of 9.21 x 10^4 m^3 (2.43 x10^7 gal)

TABLE 4.1. Summary of Long-Term Cycle 1

	Duration (Days)	Average Temperature (°C)	Average Flow Rate (L/s)	Volume (10^4 m^3)	Energy (GWh)
Injection	59.1[(a)]	108.5	18.0	9.21	9.47
Storage	64.0				
Recovery	58.0[(b)]	74.7	18.4	9.22	5.86

Energy Recovery Factor

Using 19.7°C source water. . . . 0.619

Using ambient 11.0°C source water. . . . 0.653

(a) Over a period of 74.7 days.

(b) Over a period of 58.8 days.

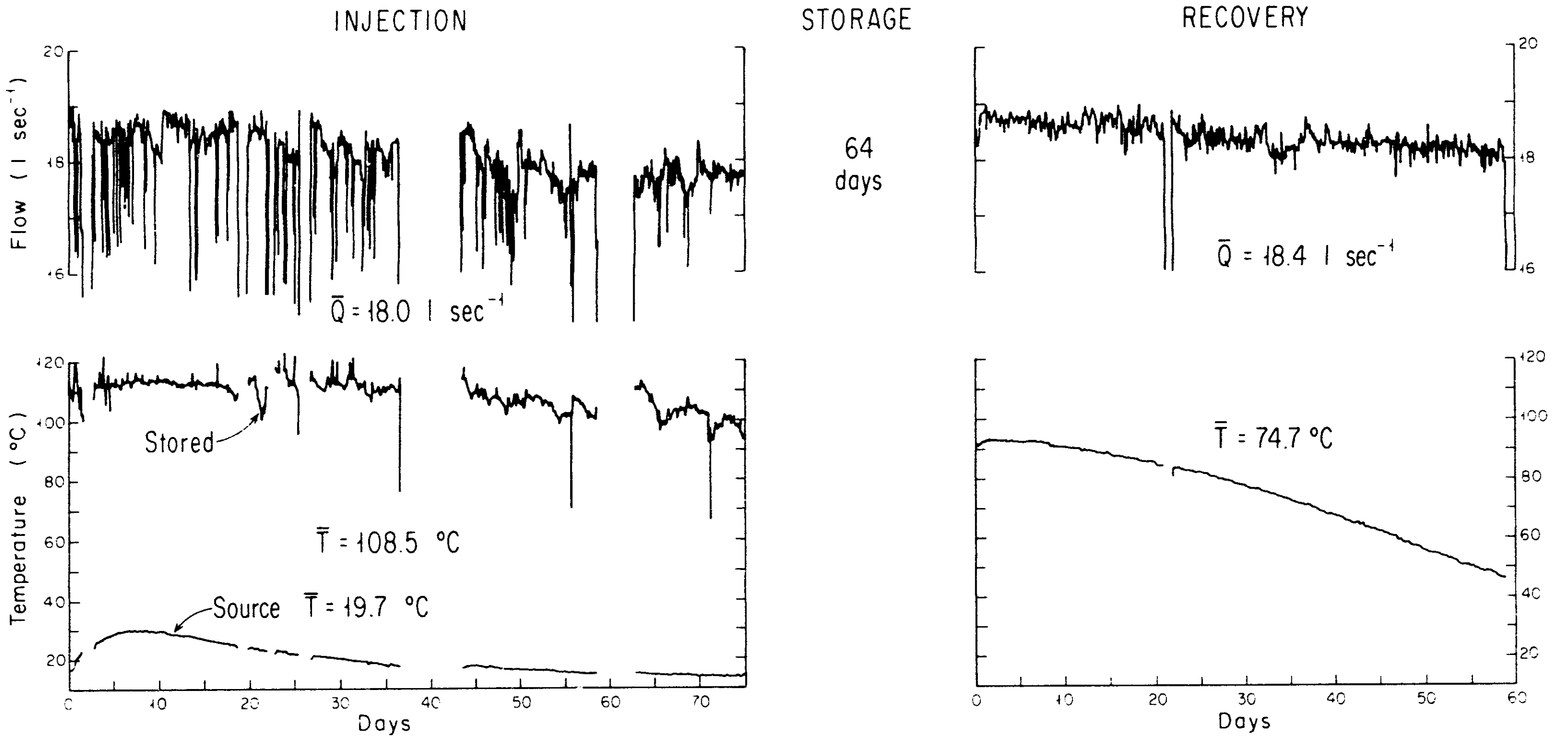


FIGURE 4.1. Flow and Temperature Plotted Against Time for Long-Term Cycle 1

TABLE 4.2. Summary of ATES Cycles at the University of Minnesota St. Paul Field Test Facility

	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Long-Term Cycle 1
Duration (days)					
Injection	5.2 of 17	8.0 of 10	7.7 of 10.4	7.7 of 12	59.1 of 74.7
Storage	13	90	9.7	10.1	64.0
Recovery	5.2 of 5.2	8.0 of 8.0	7.7 of 8.0	7.7 of 7.7	58.0 of 58.8
Temperature (°C)					
Source Water	11.0	20.5	36.1	52.6	19.7
Injected Water	89.4	97.4	106.1	114.8	108.5
Recovered Water	59.2	55.2	81.1	89.1	74.7
Flow Rate (L/s)					
Injection	18.4	17.6	18.3	17.9	18.0
Recovery	18.1	17.8	17.3	17.8	18.4
Volume (10^4 m^3)					
Injection	0.83	1.22	1.22	1.19	9.21
Recovery	0.81	1.23	1.18	1.19	9.22
Energy (GWh)					
Added	0.770	1.084	0.989	0.867	9.47
Recovered	0.453	0.495	0.617	0.503	5.86
Energy Recovery Factor					
(using source temperature)	0.59	0.46	0.62	0.58	0.62
(using ambient temperature)	0.59	0.52	0.71	0.75	0.65

of heated water was stored. A total of 9.47 GWh (3.23 x 10^{10} Btu) of heat was transferred from steam/condensate to the ground water. A total of 10.4 GWh (3.55 x 10^{10} Btu) of thermal energy (above ambient temperature conditions) was stored in the aquifer.

Interruptions during injection resulted from: malfunctioning of the water softener; malfunctioning of automatic safety shutoffs (weather related); scheduled shutdowns for system maintenance and repairs; and a holiday period. Severe weather affected the operations by affecting the steam pressure during extremely cold (<-20°C) days and nights in January 1985.

Temperature of the stored water fluctuated with the source-water temperature, steam setting adjustment, weather, and with the final-rinse part of the water softener regenerations. Steam flow was a function of the incoming steam pressure and valve settings. The steam controller was originally set to attempt maintenance of a temperature of approximately 115°C. Effect of water softener failure was clear during the first days of injection with the decrease in injected water temperature and increase in steam pressure as the condenser lost efficiency (Figure 4.1). The condenser tubes were cleaned before restarting.

Extreme cold reduced incoming steam pressure because of increased campus heating loads. The sudden decrease in temperature of injected water during the latter stages of injection was caused by the low steam pressure (Figure 4.1). In addition, shutdowns occurred when the automatic pressure shutoff switch froze. On January 12 the automatic shutoff turned the pump off. Because of the low air temperature at that time, the decision was made not to restart immediately.

The effect of the final rinse phase of water softener regeneration was observed throughout the injection phase. The diversion of a portion of the source water to waste decreased back pressure at the source well, and lowered the flow into the storage well (Figure 4.1). When some of the water was diverted through the regenerating tank to a sanitary sewer, the pressure on the system decreased, causing more water to be pumped from the source well than was injected during the final rinse. Measured flows during injection show this pattern. Typical injection flow decreased to between 16.4 and 17.0 L/s (260 and 270 gpm) during the final rinse. Flow to the sanitary sewer was 4.1 L/s (65 gpm). This lower flow rate was, on occasion, observed and recorded while making system checks. Temperature of the injected water rose briefly when final rinse began, until the steam control system adjusted to the lower flow rate through the heat exchangers. Upon resumption of normal flow, the steam flow rate was rapidly adjusted by the control system.

The source water was not isothermal, but reached a high temperature of 30.5°C (87°F) about 8 days into the test cycle and then declined slowly to 13.0°C (56°F) by the end of the injection period (Figure 4.1). Highest temperature of the source water was at approximately the time the volume pumped from the source well equalled the volume from the 8-day short-term test cycles (1.2×10^4 m^3), which were completed about 11 months earlier. Trends of calcium and magnesium concentrations, as well as alkalinity in the source water changed somewhat with the temperature. Hardness values for the source water were, however, quite close to what they would have been with entirely ambient water temperatures from the source well. The source water was saturated with respect to calcium carbonate. The greatest changes in solubility are at higher temperatures.

Source water for this cycle had a mean hardness of approximately 200 mg/L as $CaCO_3$. The water softener when it functioned properly, reduced this to <20 mg/L of hardness. There was an increase in sodium levels of the softened water to an average of 113 mg/L; the ambient level is <20 mg/L. The sodium values for the softened water were somewhat higher than had been predicted based on modeling. Fluctuations in the anion concentrations were observed on a short-time scale for the softened water. This probably reflected the short-term fluctuations in the performance of the water softener. Section 6 reports the water chemistry and Appendix B presents the analytical chemistry data on water samples.

Water samples taken downstream of the softener (ports 2, 3, Figure 3.3) reflect replacement of calcium and magnesium by sodium. The sample collected at well AM4 during the week prior to heat arrival was softened water.

Thermal response and pressure (water level) at the monitor wells was observed in a very short time. Residual heat present from the short-term test cycles reached monitoring wells 7 m from the storage well in less than 2 days. Pressure values are still being evaluated. Several pressure transducers failed during the test and key wells were measured manually. The responses indicated that there were no overpressuring problems. Pressure gauges on the surface piping were observed at least hourly during the pumping; the gauge immediately preceding well A reached a value of 707 kPa (109 psi) on only one occasion. During recovery, the pressure gauge that leads to well B never read higher than 824 kPa (127 psi). The highest pressure coincided with the lowest temperature, caused by the higher viscosity of water at low temperatures.

During injection, the water softener used approximately 684 kg (1500 lb) of solar salt (NaCl) per day for regenerations. The water softener consists of three ion-exchange resin tanks containing the resin Aldex®, a brine tank, and a control system. During the heated-water injection phase, two units are in service at all times. The third unit is being recharged and then placed on standby until the timing cycle is completed. Specifications called for each unit to be in service for 8 hours between regenerations and for the water to be brought to a hardness of approximately 0 grains.

The water softener was tested for several regeneration cycles. When it was determined that the softener seemed to be working properly, LT1 was begun. However, because the proper timing wheel had not been installed by the manufacturer; regenerations were taking place after a tank had only 4 hours of operation instead of the specified 8 hours. On the second day of injection, testing for hardness revealed that no softening was taking place and scaling of the condenser was significant. The softener resin was not being properly regenerated. The system was shut off, the manufacturer notified, and troubleshooting began. Adjustment was made of flows during various phases of the regeneration; successful regenerations took place, and the system was restarted. After a week, the proper timing wheels were obtained and installed. This time, with regenerations at the specified intervals, it became apparent that not enough ion exchange was taking place in the resin to provide softened water for 8 hours per regeneration. Adjustments of the brine draw and control valving seemed to solve the problem. However, repeated checks of softening revealed that the problem was not solved. The manufacturer then reported that they had improperly sized the orifice for drawing the brine. The result of the improper orifice was improper concentration and contact time for the brine during regeneration. Regenerations were not replacing the proper amount of calcium and magnesium ions with sodium ions on the softener resin. Following installation of the proper orifice unit, regenerations were consistent. However, the resin still did not provide the specified amount of softening to the source water to meet specifications. After several days, the manufacturer concluded that more resin was required. Specifications were met when 20% more resin was added to the tanks. The operating specifications were finally met during the last week of injection.

The initial testing immediately following installation did not reveal the problems because it took many hours of operation with the incomplete regenerations to completely deplete sodium ions from exchangeable sites in the ion-exchange media. Several days of operation were necessary to convince the manufacturer that the units were not performing properly.

4.2 STORAGE PHASE

Storage lasted from January 28 to April 2, 1985, a total of 64.0 days. The storage period lasted more than the planned 60 days because of a leak in the radiator and an inoperative flowmeter. Repairs to the radiator and replacement of the flowmeter sensor were completed on April 2, and heat recovery began.

During the first 3 weeks of storage, water samples were collected weekly from well AM4. Temperatures and pressures (water levels) were monitored periodically during storage. Water levels observed reflected the seasonal trend for the February-March interval.

4.3 RECOVERY PHASE

The recovery phase of the test began on April 2, 1985 at 1400 hrs and ended on May 31, 1985 at 0935 hrs. Figure 4.1 shows the flow rate and temperature during the recovery phase plotted against time. The recovery phase was interrupted by only one power outage. Recovery continued for 58.0 days until 9.22×10^4 m^3 (2.44×10^7 gal) of water, a volume approximately equal to that stored, was recovered. Temperatures of the recovered water reached a high of 93.3°C (200°F) after about 2 days of pumping. The final water temperature was 45.6°C (114°F). Mean temperature of the recovered water was 74.7°C (166°F). Flow during recovery averaged 18.4 L/s (292 gpm). Water was returned to the source well at a mean temperature of 68.0°C (154°F). All water was returned to the source site at temperatures below 85°C (185°F).

In general, temperatures in the monitoring wells at the storage site declined during the recovery phase. However the temperature increased throughout the cycle in low permeability horizons.

5.0 THERMAL AND HYDROLOGIC RESPONSE

Monitor wells at the storage site measured aquifer response to the injection, storage, and recovery of the heated water during the cycle. The aquifer thermal and hydrologic responses are reported and discussed in this section. Field injectivity test results are summarized in this section.

5.1 THERMAL RESPONSE

Temperatures recorded in monitor wells at the storage site increased during the injection phase of the cycle. The pattern of temperature increase was a relatively rapid increase in temperature in the more permeable zones of the FIG aquifer and a slow increase in temperature in the less permeable zones and adjacent confining beds.

Initial temperatures in all monitoring wells except well AM4 were significantly above ambient (11°C) at the FIG aquifer. The above ambient temperatures are caused by heat remaining from the short-term cycles completed 11 months earlier. The source water temperature curve (Figure 4.1) indicates that residual heat from the short-term test cycles also remained at the source site. In fact, the energy contained in the source water equalled about 10% of the energy added by steam during LT1 (and returned to the source site during the last short-term cycle). Figures 5.1 through 5.5 are thermal profiles of monitoring wells at Site A before, during, and after LT1. The hourglass shape of the temperature profiles during the cycle reflects the two permeable and screened zones of the FIG aquifer. Temperatures at the upper Eau Claire and lower St. Lawrence formations increased during the entire test cycle.

As during the short-term cycles, thermal response to heated-water injection was observed in the monitor wells located 7 and 14 m from the storage well after less than 2 days of injection. Hot water reached the well located 30.5 m from the storage well after 7 days of injection. Responses were not uniform through the aquifer, but reflected the hydraulic conductivities and porosities of the particular zone of the aquifer being monitored. Figures 5.6 through 5.10 plot temperatures at five horizons in wells AM1, AM2, AM3, AM4, and AS1 during the injection and recovery phases of

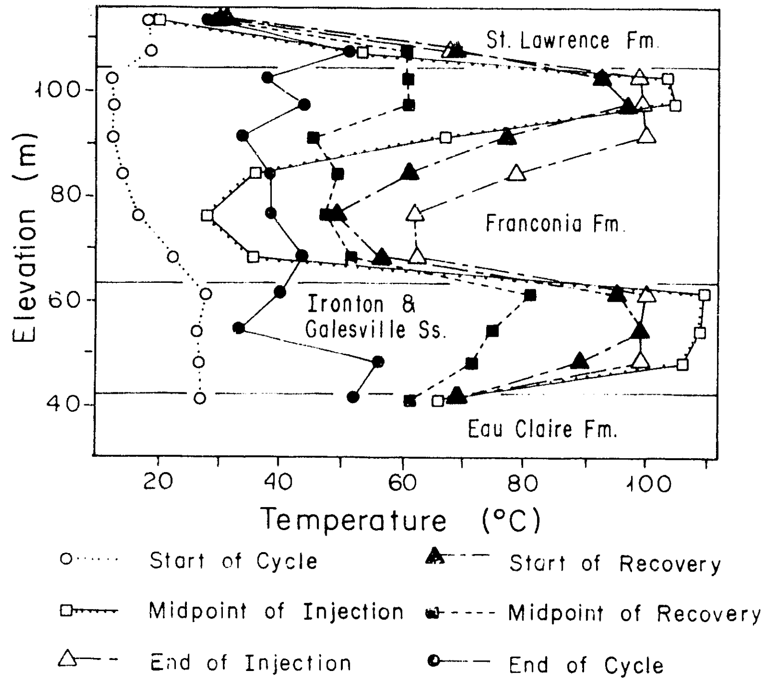


FIGURE 5.1. Temperature Profiles of Well AM1 During LT1

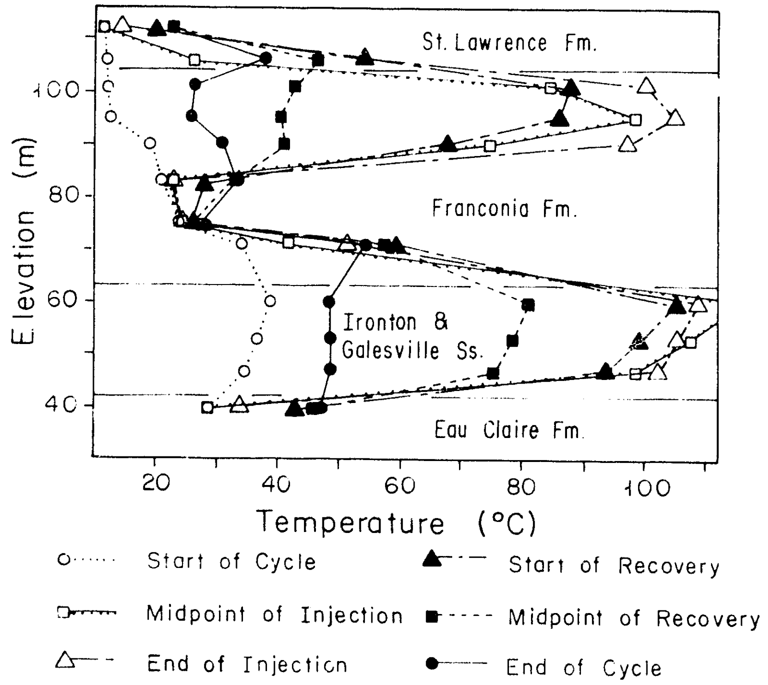


FIGURE 5.2. Temperature Profiles of Well AM2 During LT1

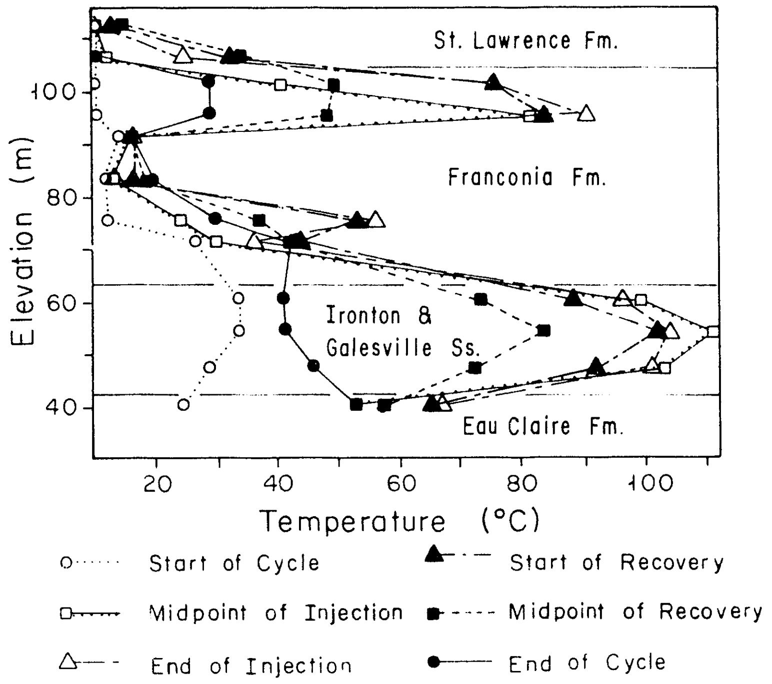


FIGURE 5.3. Temperature Profiles of Well AM3 During LT1

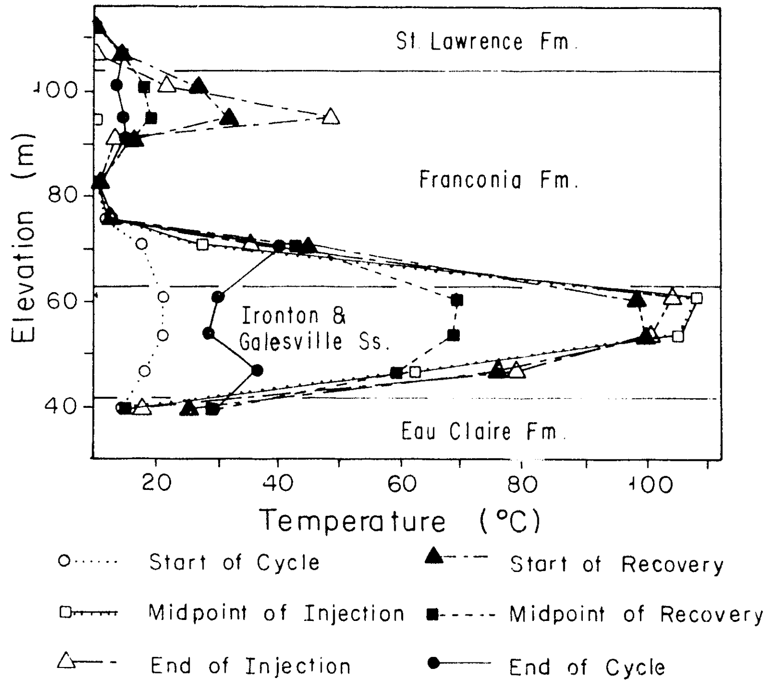


FIGURE 5.4. Temperature Profiles of Well AM4 During LT1

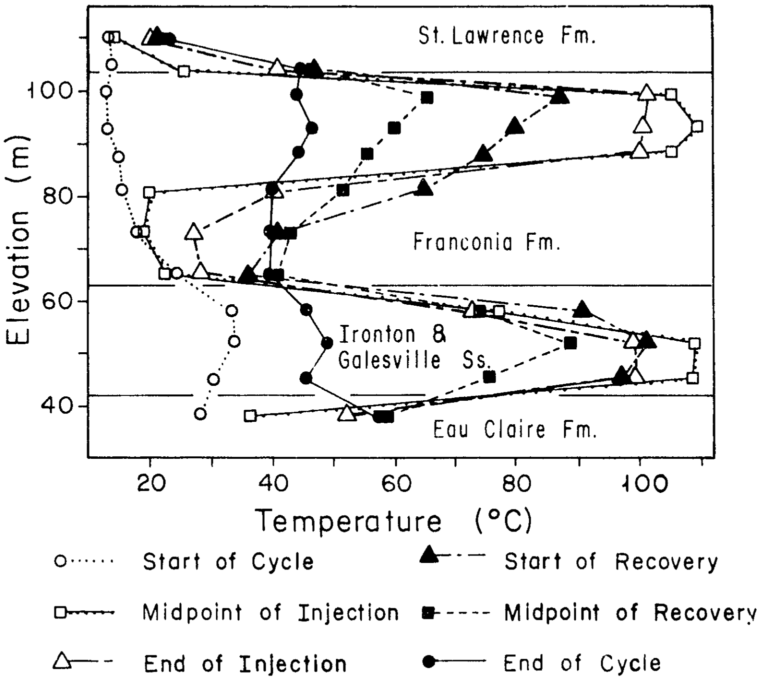


FIGURE 5.5. Temperature Profiles of Well AS1 During LT1

the cycle. Notice that the arrival of heat is not uniform, and that the response to pump shutoff is different at different parts of the aquifer.

Highest temperatures in the permeable parts of the Ironton-Galesville portion of the FIG aquifer were reached in well AM1 after only a few days. The temperatures in these permeable zones decreased slowly as the injection proceeded. This decrease in temperature paralleled the temperature decrease of the injected water (Figure 4.1), and it may also reflect a changing of the aquifer hydraulic characteristics in response to the heated-water injection. However, the close following of all temperature changes suggests that it is the result simply of translation of a thermal "wave".

When injection was interrupted, the temperatures at some horizons changed immediately, some increasing (for example, see LIG, Figure 5.10), some decreasing (for example, see UF, Figure 5.10). At horizons where interbedded shales and sandstone were present, this effect was greater. This trend continued during the storage period, where several horizons were warmer following the storage interval than they were when injection stopped.

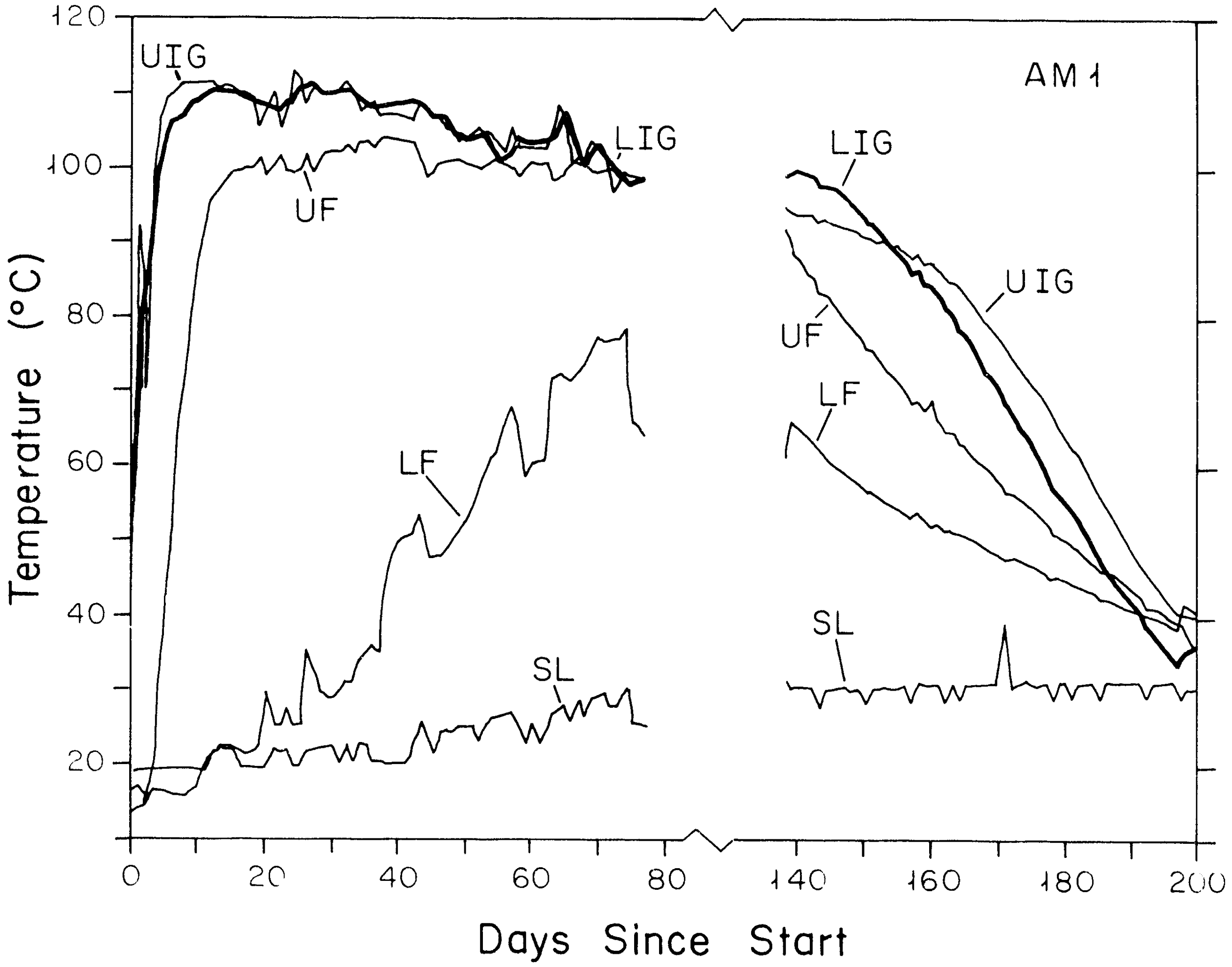


FIGURE 5.6. Temperatures in Well AM1 During LT1.
LIG = Lower Ironton-Galesville; UIG = Upper Ironton-Galesville;
LF = Lower Franconia; UF = Upper Franconia; SL = St. Lawrence

The confining beds and slowly permeable beds of the lower Franconia Formation show a temperature increase through the period of storage and, at some wells, through the entire cycle.

Temperatures in porous and permeable portions of the aquifer declined during the recovery phase (for example, see Figures 5.6 through 5.10, IG and UF). The heat that went into the less permeable portions of the aquifer and confining beds remained; some horizons continued to increase in temperature throughout recovery (see LF and SL curves in Figures 5.6 through 5.10).

Temperatures in AS1 suggest thermal tilting in the upper Franconia portion of the storage zone during the cycle (Figure 5.5). Few interbeds of shale are in the upper Franconia portion of the aquifer to inhibit buoyancy

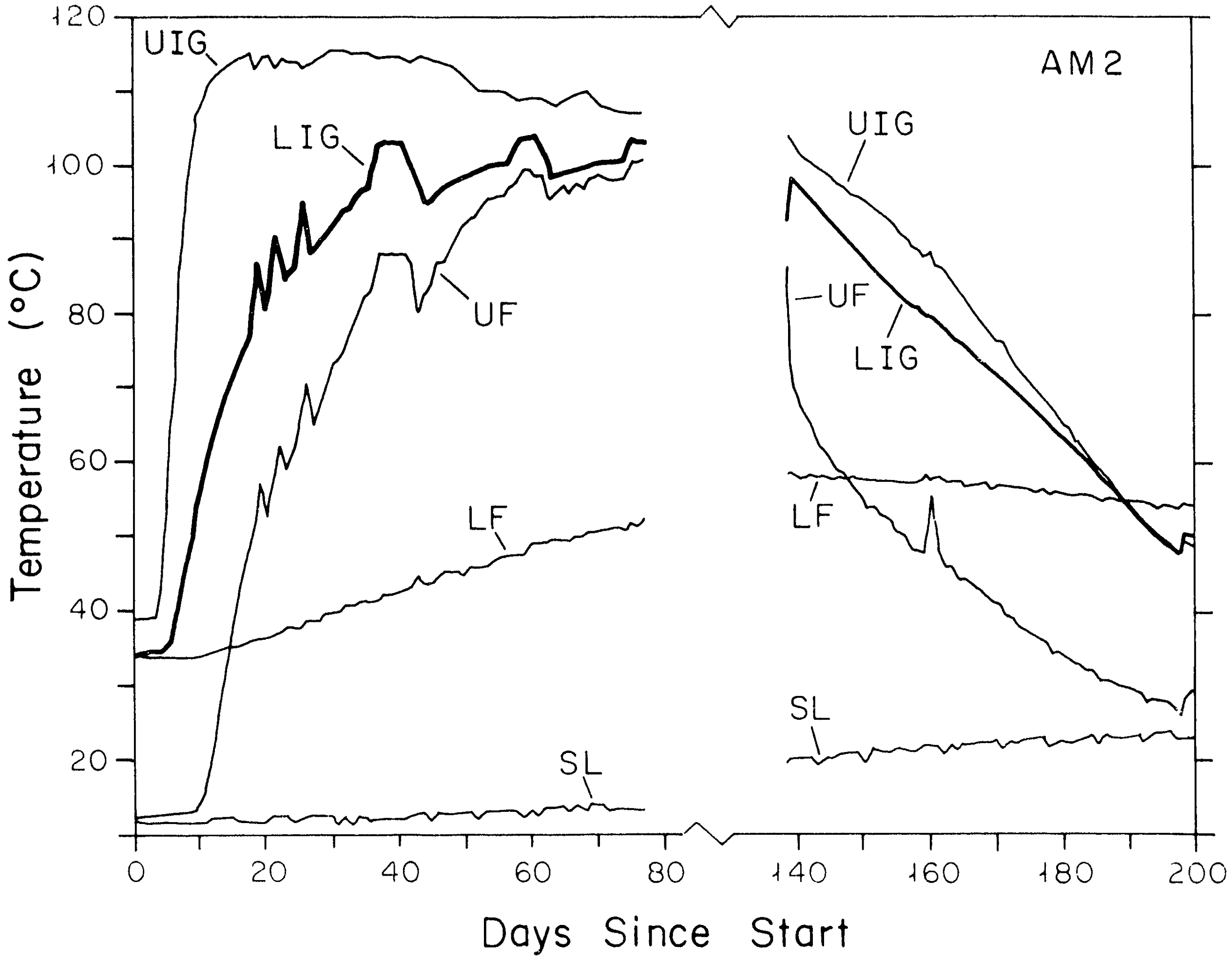


FIGURE 5.7. Temperatures in Well AM2 During LT1.
LIG = Lower Ironton-Galesville; UIG = Upper Ironton-Galesville;
LF = Lower Franconia; UF = Upper Franconia; SL = St. Lawrence

flow, which puts less dense warmer water at the top of the zone and cooler water at the bottom.

A few thermocouples failed during the course of the cycle. These showed up when recorded temperatures were beyond the range of possible temperatures (<10 or >125°C), or by a sudden (and permanent) shift of the recorded temperature to unreasonable values. The thermocouple in the middle of the Ironton-Galesville portion of the aquifer in well AM2 failed. The temperatures plotted on AM2 profiles (Figure 5.2) are the averages of the LIG and UIG thermocouples from the Ironton-Galesville portion of the aquifer (Figure 5.7).

Bad scans on the datalogger were recognized by many spurious readings (for example, temperatures of >>105°C); usually these were caused by the

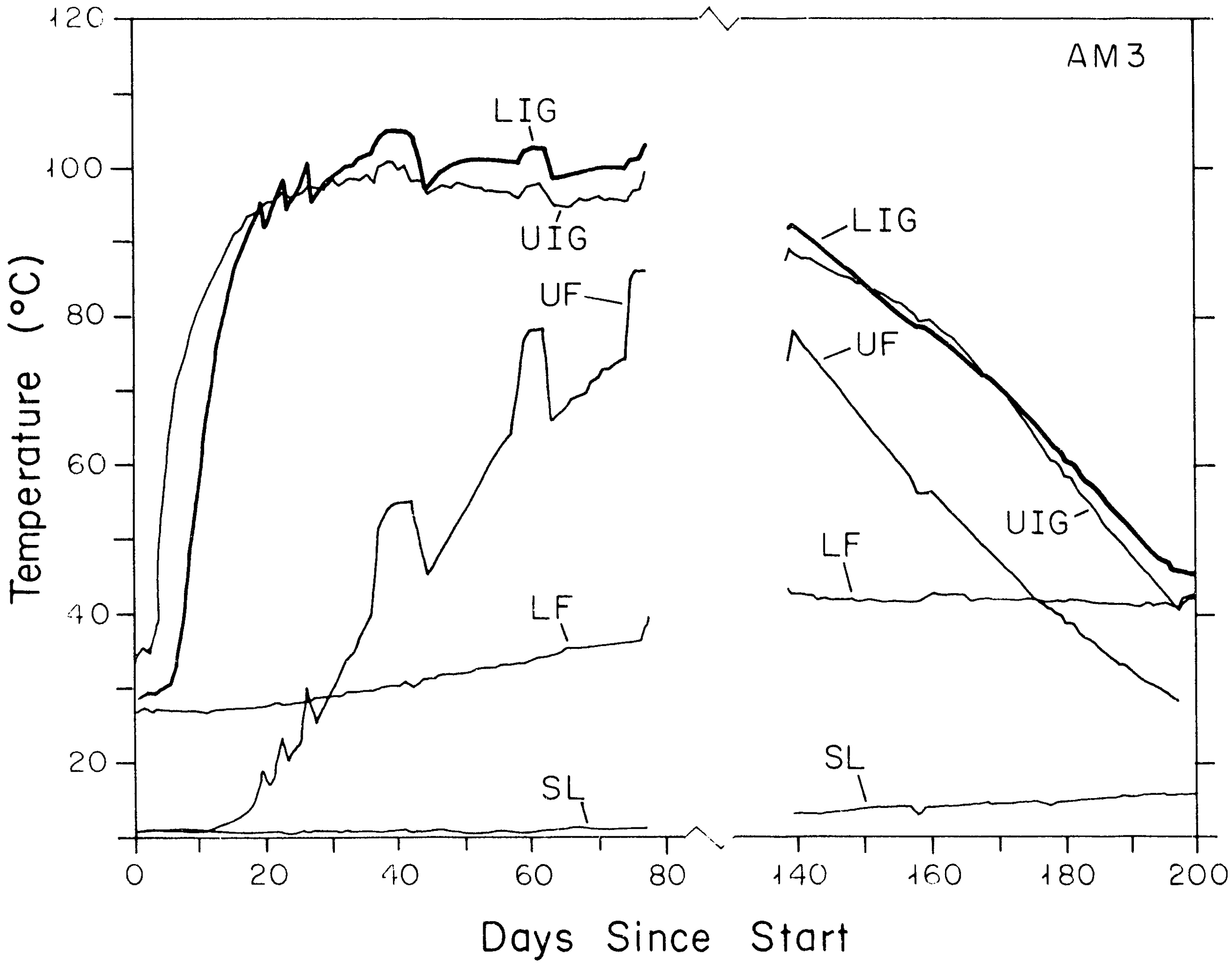


FIGURE 5.8. Temperatures in Well AM3 During LT1.
LIG = Lower Ironton-Galesville; UIG = Upper Ironton-Galesville;
LF = Lower Franconia; UF = Upper Franconia; SL = St. Lawrence

datalogger being overheated. Bad scans were deleted from the dataset. During the pumping phases of the cycle, the datalogger room was monitored regularly. However, during storage, the datalogger was checked only occasionally, and often had bad scans because of poor temperature control in the trailer.

Figure 5.11 illustrates temperatures recorded at the remote monitoring well, CM1, in the Ironton-Galesville portion of the FIG aquifer before, during, and after the cycle. Temperatures, as expected, were not affected by LT1.

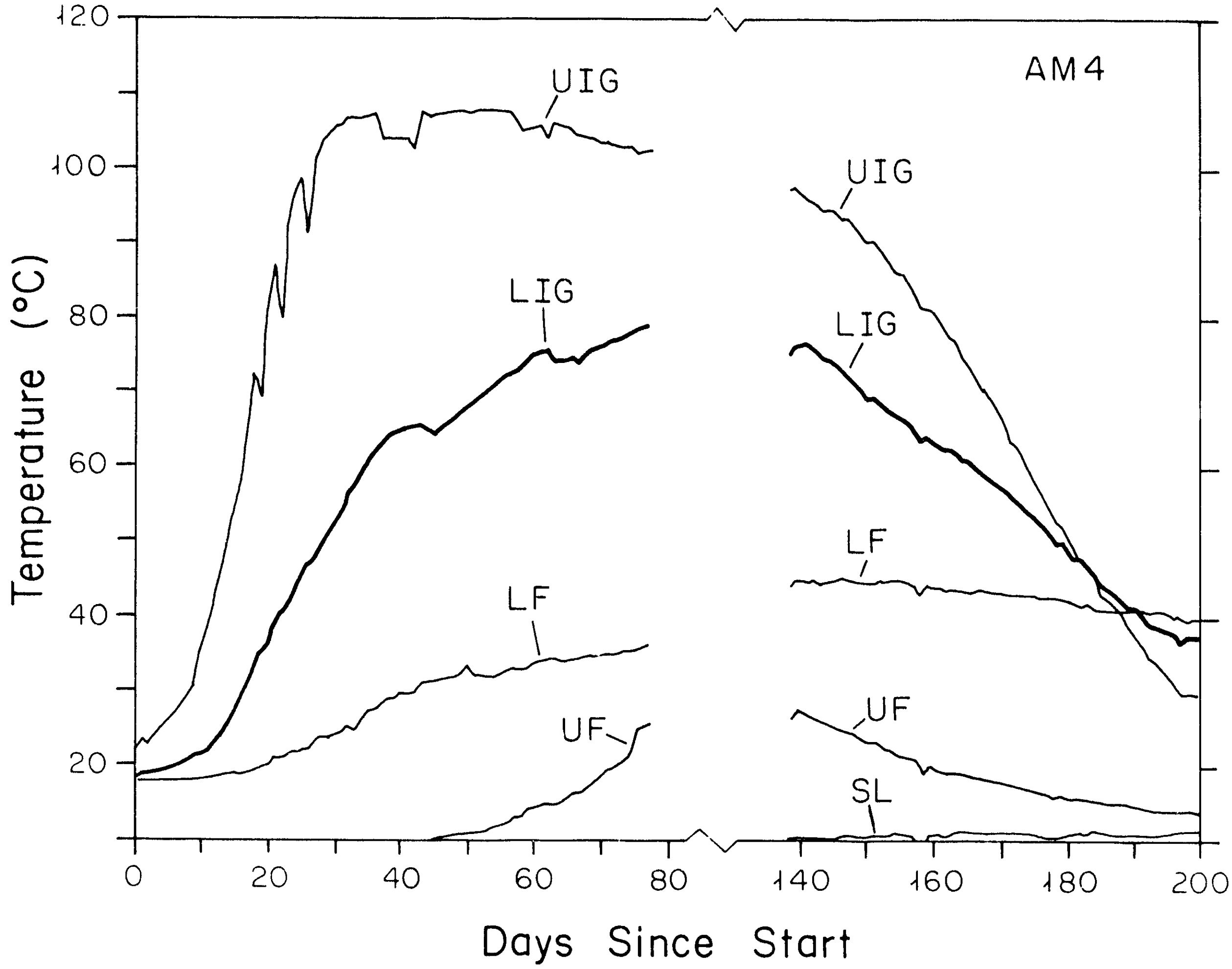


FIGURE 5.9. **Temperatures in Well AM4 During LT1.**
LIG = Lower Ironton-Galesville; UIG = Upper Ironton-Galesville;
LF = Lower Franconia; UF = Upper Franconia; SL = St. Lawrence

5.2 HYDROLOGIC RESPONSE

Hydrologic response to injection and recovery was monitored with pressure transducers and water-level measurements. The water-level measurements were made manually in key monitor wells where pressure transducers failed. Failure of pressure transducers was a recurring problem; by the end of LT1 most pressure transducers had failed.

Pressures (water levels) at the storage site increased (rose) during the injection phase in response to the injected water. Pressure response was not uniform through the FIG aquifer. The pressure buildup was approximately 20 psi (138 kPa, ~14 m) in wells 7 and 14 m from the injection well. This is approximately what was expected.

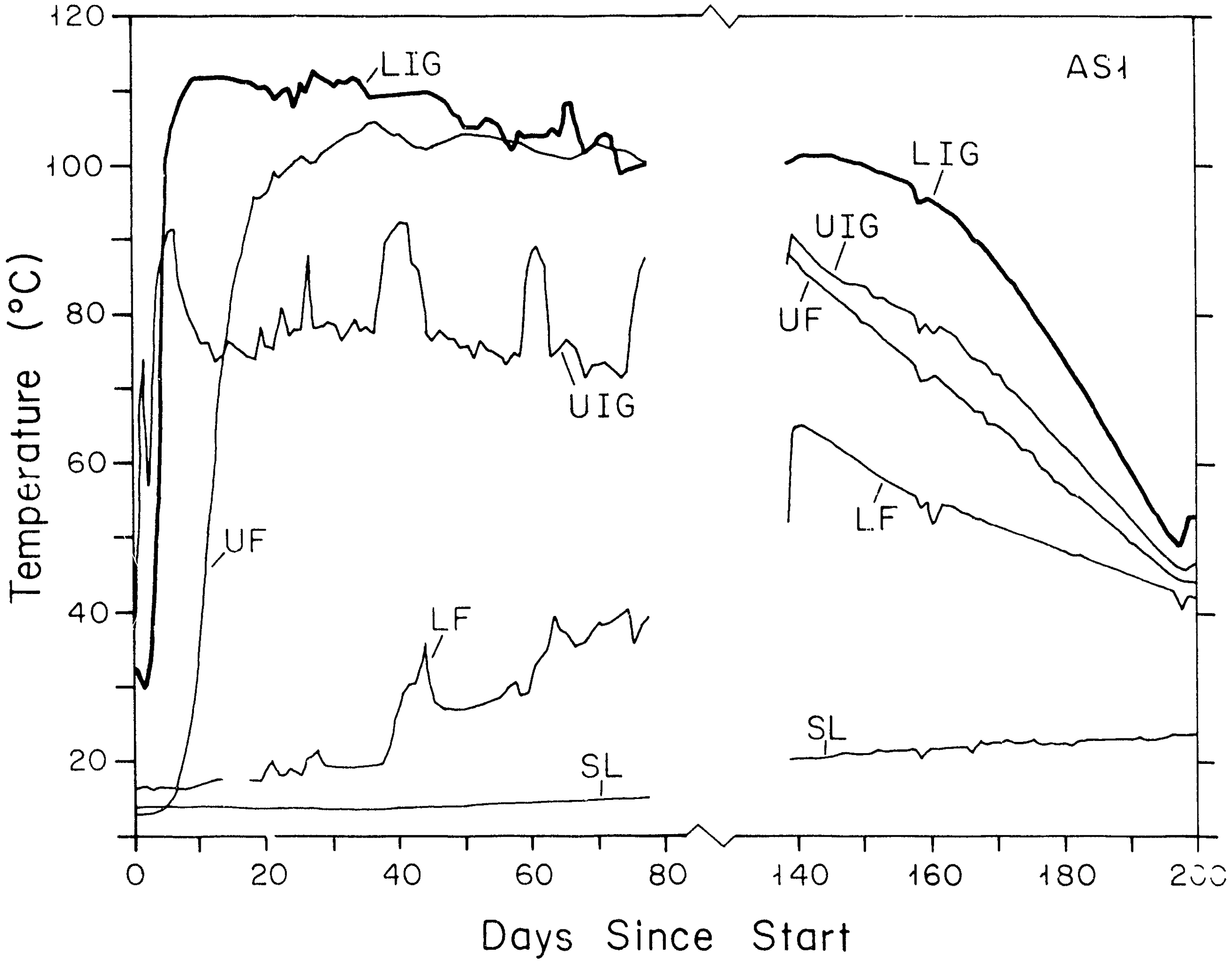


FIGURE 5.10. Temperatures in Well AS1 During LT1.
LIG = Lower Ironton-Galesville; UIG = Upper Ironton-Galesville; LF = Lower Franconia; UF = Upper Franconia; SL = St. Lawrence

A recurring problem was the failure of pressure transducers. As pressure transducers failed, key wells were manually measured periodically (as conditions allowed) to monitor the pressure changes occurring in the FIG aquifer. Manually measured water levels are a substitute for pressure transducer measurements for this experimental facility; however, for a commercial or continuously operating system, the costs of manual measurements would be prohibitive. Reliable pressure transducers would allow a considerable reduction of staffing requirements for an installation.

Figure 5.12 presents the pressure/water-level data from the lower Franconia piezometers of AM3 and AM4. Figure 5.13 presents water-level data from the Ironton-Galesville piezometer of AM2.

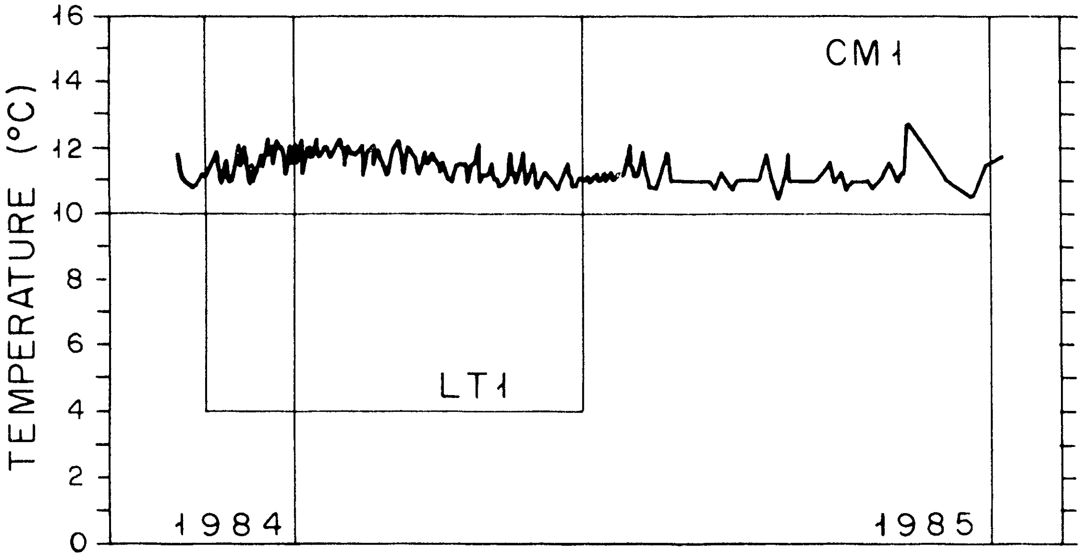


FIGURE 5.11. Temperatures at Well CM1, 1984-1985

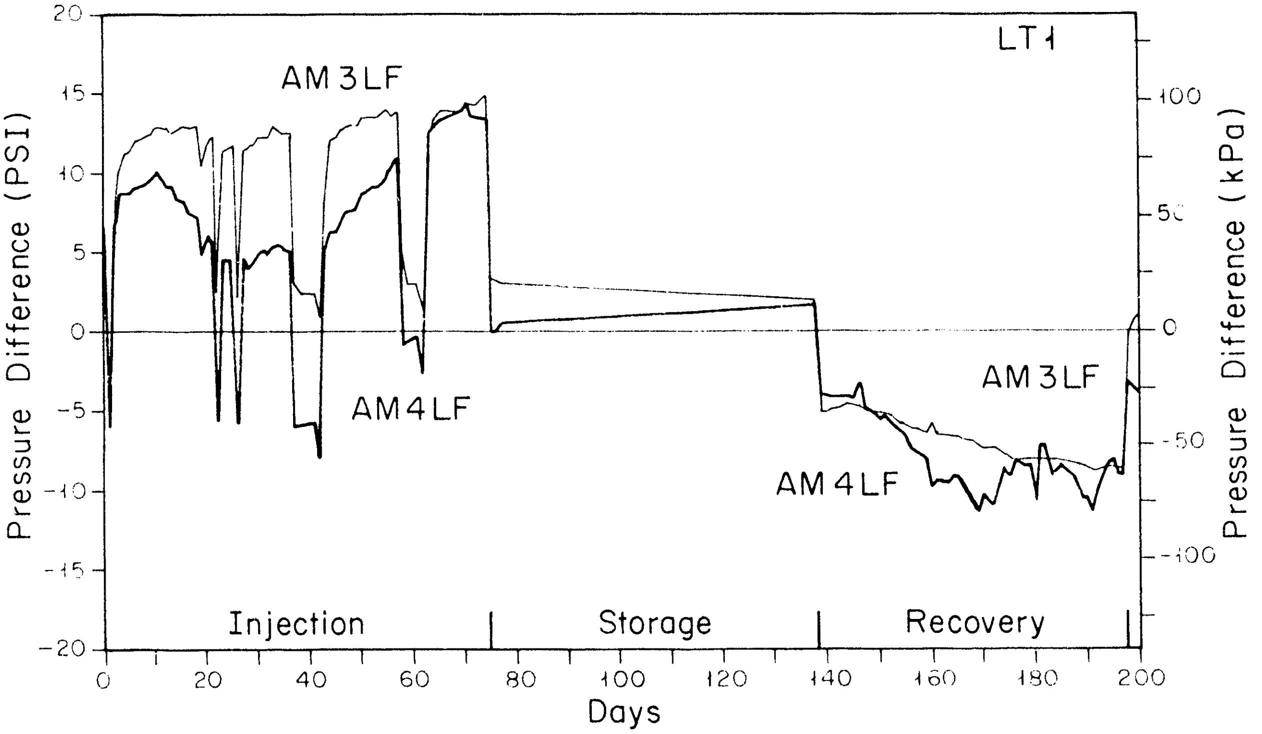


FIGURE 5.12. Pressure Response at the Lower Franconia Piezometers, Wells AM3 and AM4 During LT1

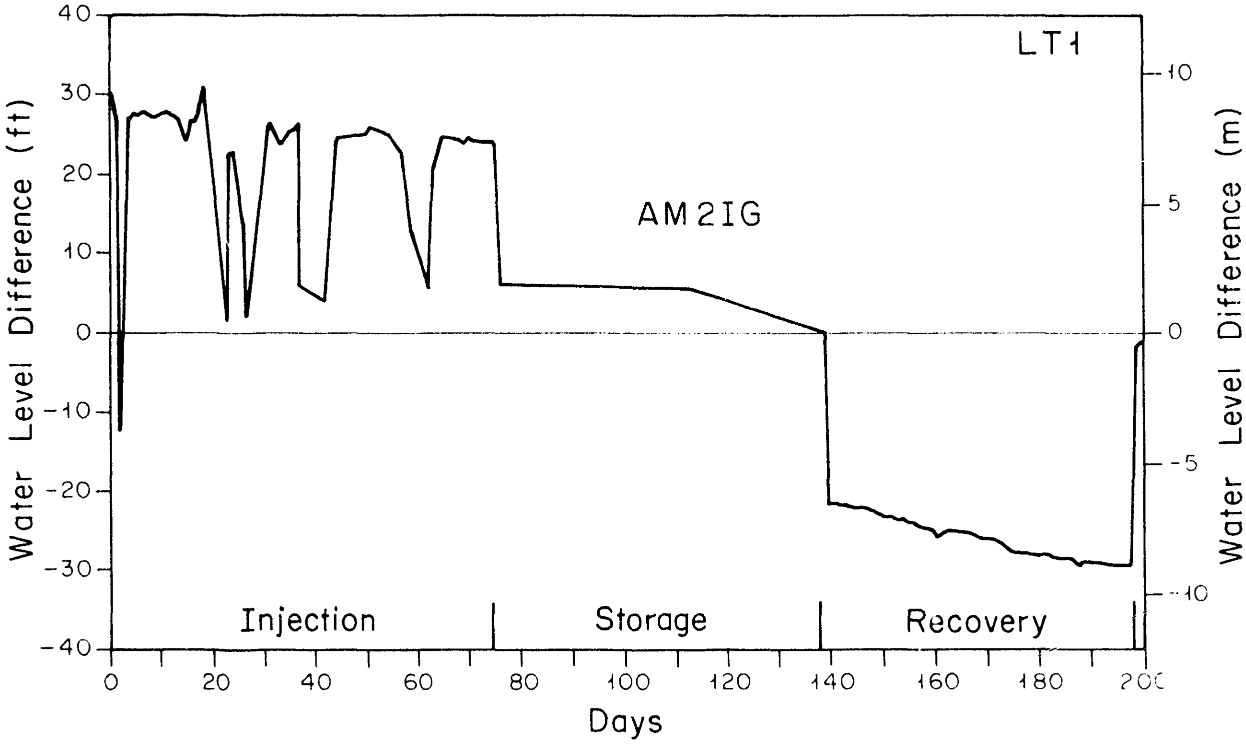


FIGURE 5.13. Water Levels at the Ironton-Galesville Piezometer at Well AM2 During LT1

The lower Franconia pressure transducers operated through all of LT1. The responses observed are appropriate to the relative distances [14 m (AM3) and 30.5 m (AM4)] from the storage well (Figure 5.12).

The pressure transducer at the Ironton-Galesville horizon in AM2 failed shortly after LT1 began. Water levels were measured periodically during injection and storage. A new pressure transducer was installed during storage and lasted through recovery. Pressure response was converted to elevation for the figure. Maximum pressure buildup was 15 m during injection; maximum drawdown was 12 m during recovery.

5.3 INJECTIVITY BEHAVIOR

The hydrologic performance of the system can be strongly affected by the presence of fine particles in the fluid stream. These particles can plug pores in the rock substantially reducing the permeability of the aquifer. Few changes have been observed in the injection pressures from values observed during previous hydraulic tests that cannot be explained by viscosity changes. However, early laboratory testing indicated the potential for disaggregation of the rock and release of many fines that could significantly reduce the bulk permeability of the aquifer (Blair 1985; Blair, Deutsch, and Mitchell 1985).

A special facility, the field injectivity test stand (FITS), was employed to monitor the suspended solids and predict the probability that the particles present would reduce the hydraulic performance of the aquifer in the storage zone. Injectivity studies conducted during LT1 are described and compared to results for earlier short cycle testing in Appendix D. The results of these studies are summarized below.

Membrane filter tests were conducted to determine the total suspended solids in the flow stream at various locations in the piping system during injection and recovery. Filter tests using 0.4-μm, 0.45-μm, and 10-μm filters indicate that the total suspended solids content was good for both injection and recovery. Total suspended solids decreased from a range of 0.04 to 0.09 ppm in the injected water to a range of 0.01 to 0.06 ppm for recovered water. Overall the filter tests indicate that, at temperatures to 115°C (238°F), well impairment caused by suspended solids is not a problem.

Core flooding tests were conducted using three sets of stacked core samples from the FTF site. Each stacked core set was mounted in the FITS and heated ground water from the system allowed to flow through the core stack at a controlled rate of 0.2 L/m. One set was tested during injection; two sets were tested during recovery. Results from these core flooding tests indicate that more than 20,000 pore volumes of fluid at a temperature range of 93 to 110°C (199 to 230°F) could be passed through representative core samples with no significant loss of permeability.

Together, these results indicate that generation of fines that might threaten the injectivity of the heated or recovered ground water was not a problem at the test site during LT1. Furthermore, any changes that may have been experienced in the aquifers did not significantly affect hydrologic performance.

6.0 WATER CHEMISTRY

Major-ion chemistry of the water at the ATES field test facility has been a part of the monitoring and experimental studies programs. Samples of the source, softened, stored, and recovered water from LT1 were collected and analyzed. Perlinger et al. (1987) presents a review and summary of the water chemistry of LT1 water samples. Samples from monitoring wells were collected and analyzed as part of the site monitoring program.

6.1 METHODS

Sampling procedures and analytical techniques used on samples from LT1 and monitoring wells are presented below.

6.1.1 Sampling During LT1

Samples were taken three times per week (M-W-F) throughout the injection phase, except during the first week when samples were collected every day. On each sampling day water was collected from each of three ports on the system (Figure 6.1): port I taps the source water before it is softened, port II taps water that passed through the softening units before it is heated, and port III taps the heated water before it is injected. For each sample dissolved oxygen was analyzed directly at the port using a field kit. An

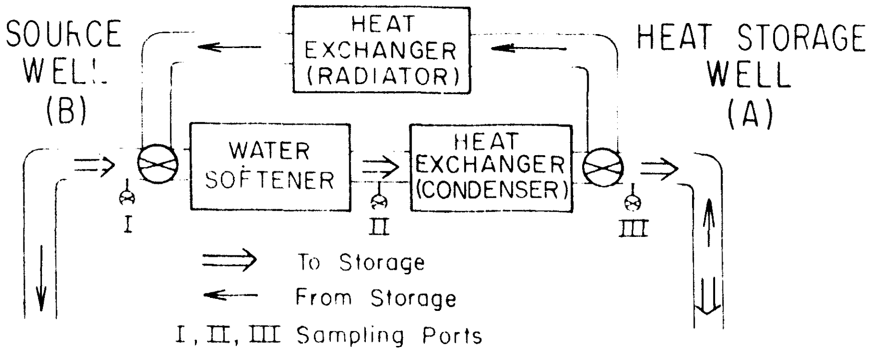


FIGURE 6.1. Above-Ground Piping Configuration of the ATES FTF. Port I taps source water; Port II taps softened water; Port III taps heated water during injection and recovered water during recovery.

unfiltered sample was then 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 in conjunction with a temperature-resistant pH probe to provide an accurate pH reading at near the actual injection temperature. Because the pressurization of the system allowed the injection temperature of the water to be greater than 100°C (212°F), port III water had to pass through a cooling coil prior to sampling, to lower the temperature into the 90 to 95°C (194-203°F) range. Filtered samples, for use in all laboratory analyses, were collected directly at each port using 0.45-μm membrane filters. For each port, filtered samples were placed in two polyethylene bottles, a 250-ml bottle (full, never acid-washed) for anion, silica, and alkalinity analyses and a 1000-ml bottle (half-full, acid-washed) for cation analyses. In the field the cation sample was acidified to about 2% with concentrated HCl to lower the sample pH to well below 2. The anion sample was refrigerated upon arrival in the laboratory later in the day. Field blanks were collected each sampling day by passing deionized water through the filter apparatus into separate bottles for anion and cation analyses, and then were processed like other samples. Samples for oil and grease analysis were collected about every other week from port III in amber 1-L bottles. During the recovery phase of the cycle, samples were collected twice each week from port III in the same manner as described above for this port. Blanks were collected once each week.

6.1.2 Sampling Monitoring Wells

Monitor wells are sampled once each quarter, except when the ATES FTF is in operation. For each well an air hose is lowered approximately 60 m (200 ft) below the water level, and the well is purged by air-lifting until about three well-pipe volumes are pumped. Samples may then be collected normally. To attempt to obtain a low-oxygen sample from the fresh aquifer water entering through the screen at the bottom of the well, a bailer-type sampler is lowered to the well bottom. This sample may be used to ascertain iron speciation; however, it is generally difficult to obtain an absolutely oxygen-free sample, and, hence, iron speciation is difficult to quantify with assurance. All other chemical parameters besides iron speciation and oxygen content, and perhaps pH, are unaffected by sampling method (either air-lifting or bailer).

At each well an unfiltered sample is immediately analyzed for oxygen content, pH, and specific conductance. A 1-L bottle is filled at the well site, and then taken to the field trailer where the water is filtered through a 0.45-μm membrane filter using a hand-pressurized system. Alternatively, for bailer-sampled wells near the field trailer, the samples are gravity filtered directly from the bailer. Blanks are collected and filtered samples treated in the same manner as water samples taken from the ports during the cycle. A 1-L sample for oil and grease analysis is generally collected in an amber bottle each time the complete set of monitor wells is sampled.

The exception to the above sampling technique is well AM4, which is of large enough diameter [0.05 m (2-in.)] to allow the use of a bladder pump. Unfortunately, this pump has a slow leak in the air line, and the pumping rate gradually declines over a period of 4 to 6 weeks of submergence. Thus, good samples were obtained immediately upon lowering the pump into the well, but as the pump capacity declined, the sample quality may have suffered because of inadequate well flushing. The pump was installed at the start of LT1, and the well was sampled weekly during the injection phase. Early in the storage phase, however, no more samples could be obtained using the pump. Well AM4 also can be, and has been, sampled using the standard air-lift flushing method; however, the larger diameter of the pipe reduces the flushing efficiency.

6.1.3 Analysis

As mentioned above, dissolved oxygen was quantified in the field using a kit from Chemetrics, Inc. All pH readings were obtained on a Beckman Model Phi-21 meter with an automatic temperature compensating (ATC) probe and a combination pH probe, which was either an Orion Ross or a Phoenix gel-filled probe. The pH probe and meter were 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 about 0.02 N H_2SO_4 (Stumm and Morgan 1981). Soluble reactive silicate was measured colorimetrically using a reduced-silicomolybdate complex method (Strickland and Parsons 1972). Anion analysis was performed via ion chromatography (O'dell et al. 1984; American Society for Testing and Materials 1984). The six anions examined were fluoride, chloride, nitrite, nitrate, phosphate, and sulfate, but only fluoride, chloride, and sulfate were regularly found. All of the above parameters were quantified usually within 1 week of sampling. Cations were quantified using atomic absorption flame spectroscopy, and included calcium, magnesium, sodium, potassium, iron (total), and occasionally manganese. Iron speciation was checked occasionally using the colorimetric phenanthroline method [American Public Health Assoc., American Water Works Assoc., and Water Pollution Control Fed. 1980 (Standard Methods 1980)]. Hardness was calculated directly from the calcium and magnesium values obtained in the atomic absorption analysis. Although acidification stabilized the cation samples almost indefinitely, cation analyses were usually completed within 1 month after sampling. Oil and grease analyses were done at the end of the long-term cycle using the partition-gravimetric technique (Standard Methods 1980).

6.1.4 Quality Control

To ensure quality control, a system of field replicates, laboratory replicates, field blanks, field spikes, and Environmental Protection Agency (EPA) quality assurance samples was established. During LT1, each port III and AM4 sample was collected in replicate. About 20% of all samples collected were field replicates. One field replicate was collected each time the monitor wells were sampled, usually from well AM2 or AM4. Laboratory replicates comprise at least 10% but not more than 20% of the analyses. Standard deviations for sample values were calculated for each of the field and laboratory replicate data sets; the larger of these two values is reported in Table 6.1 for each parameter. Except for species present in very minor amounts, the coefficients of variation were usually below 5%, and often below 1%. Field blanks showed no identifiable sample contamination by our sampling and filtering techniques. Any species found in the field blanks were at or below the detection limit. Spikes of anions and cations were added to the appropriate bottles of an extra replicate sample to test any effect of the sample matrix upon the recovery of various ions. During LT1, this extra sample was collected weekly from port III; during monitor-well sampling, the extra sample was taken from either well AM4 or AM2. Recoveries of added ions were regularly between 95 and 105%, indicating no significant effect of the sample matrix. To check laboratory techniques of making appropriate standards and sample dilutions, a series of EPA quality-assurance samples were run with every sample batch during routine laboratory analysis. In general, test results agreed with the concentration values supplied by EPA (Table 6.2). However, the EPA quality-assurance samples pointed out an analytical problem with fluoride analyses during the injection phase of the long-term cycle; the problem was corrected by the start of the recovery phase.

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

$$\frac{[(\Sigma \text{ meq cations}) - (\Sigma \text{ meq anions})] \times 100}{(\Sigma \text{ meq cations}) + (\Sigma \text{ meq anions})}$$

TABLE 6.1. Ranges of Concentrations and Standard Deviations (SD) of Constituents Analyzed from Port III Field and Laboratory Replicates

	Injection			Recovery		
	Range	S.D.	(n)	Range	S.D.	(n)
H+ (μeq/L)	0.01 - 0.19	0.090	(48)	0.06 - 0.12	0.090	(48)
Alkalinity (meq/L) as HCO_3	4.16 - 4.91	0.014	(16)	4.56 - 4.68	0.010	(16)
SiO_2 (mg/L) as Si	3.99 - 8.51	0.091	(29)	12.5 - 22.3	0.34	(16)
SO_4^{2} (mg/L) as S	1.51 - 2.79	0.047	(29)	1.66 - 2.81	0.053	(16)
Cl^{-} (mg/L)	0.8 - 136.5	0.29	(16)	6.7 - 25.1	0.38	(16)
F (mg/L)	0.00 - 0.37	0.009	(13)	0.4 - 0.6	0.38	(16)
Ca (mg/L)	0.0 - 16.9	0.15	(29)	4.3 - 16.2	0.65	(10)
Mg (mg/L)	0.0 - 12.0	0.25	(16)	1.9 - 11.1	0.29	(10)
Na (mg/L)	59 - 193	5.8	(29)	39 - 109	1.7	(16)
K (mg/L)	0.0 - 198	0.10	(29)	6 - 11	1.7	(16)
Fe (mg/L)	0.00 - 0.23	0.048	(29)	0.1 - 0.6	0.08	(16)

TABLE 6.2. Agreement with EPA Quality Assurance Standards

Constituent	% Error	No. of Measurements
Calcium	6.85	13
Magnesium	2.37	8
Sodium	6.08	12
Potassium	3.89	12
Sulfate	5.60	28
Chloride	4.65	24
Fluoride	316.66	18

A positive imbalance indicates an excess of cations, and a negative imbalance indicates an excess of anions. Sample ion balances clustered tightly in the -5 to +5% range (Figure 6.2). Samples with an imbalance greater than 5% indicate a problem in analysis (either improper analysis or

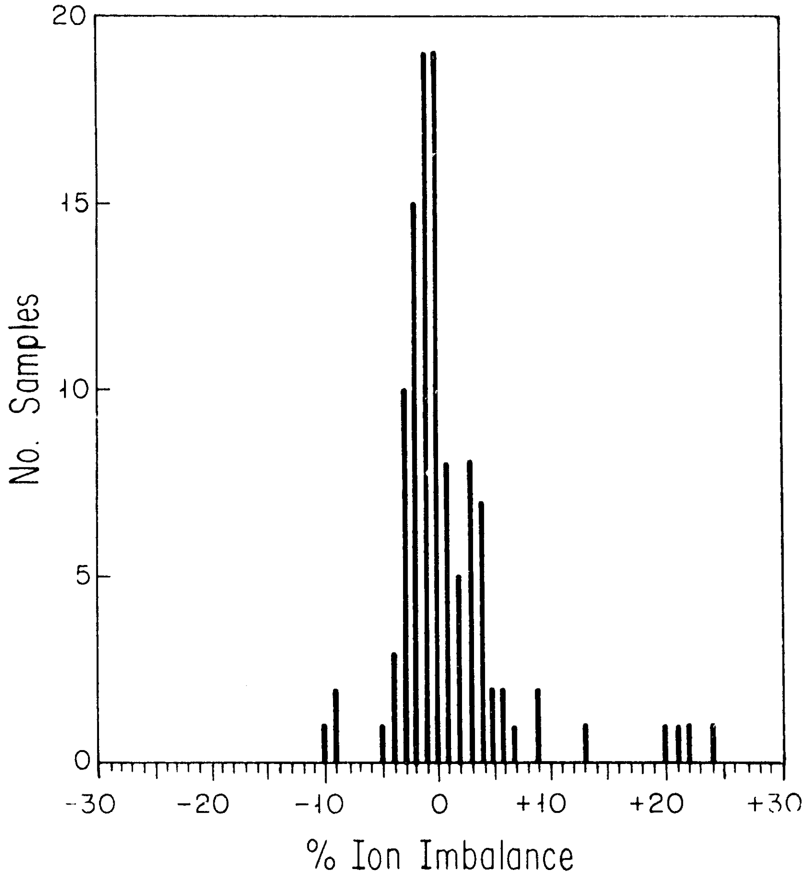


FIGURE 6.2. Frequency Histogram of Percent Ion Imbalance. See text for definition.

lacking a major ion) or in sampling. (The anion sample analyzed may be actually different from the cation sample if not properly split in the field.) In Figure 6.2, the few large positive imbalances were from samples collected early in the injection phase and may have resulted from either or both analysis or (and) sampling errors while routines for field and laboratory work were being refined.

6.2 RESULTS

6.2.1 Ambient Ground-Water Characteristics

Ambient ground-water composition is difficult to characterize for some chemical parameters because well construction disturbs the aquifer at that location. It is never known with certainty that the chemistry of the samples obtained is not an artifact of the presence of the well. The best samples to call "ambient" are those that have been collected after a long period of continuous pumping, which should flush out the well to such a degree that the chemistry of the water settles down to relatively constant values. Early in 1982 the ATES system was run with cold water only to test the pumping and piping arrangements. Water collected at that time may be considered ambient for most parameters (Table 6.3), the exception being an anomalously high potassium value. Analyses of subsequent samples collected near the end of the injection phase of LT1, after more than 90,000 m^3 had been pumped through the

TABLE 6.3. Chemical Composition of F1G Water Collected During the Cold Water Injection Test, 5-2-82

Temperature	12°C
pH	7.46
Alkalinity	4.87 meq/L
Sulfate	3.21 mg/L as S
Chloride	0.92 mg/L
Fluoride	0.27 mg/L
Nitrate	not detected
Calcium	47.7 mg/L
Magnesium	21.1 mg/L
Potassium	27.0 mg/L(a)
Sodium	5.5 mg/L
Dissolved Silica	4.34 mg/L as Si
Iron	1.45 mg/L

(a) Value is higher than average well B concentration of 7.5 mg/L.

system, suggest that a better value for "ambient" potassium concentrations is approximately 7.5 mg/L. In general water from the FIG aquifer is characterized as calcium and magnesium bicarbonate water in approximate equilibrium with calcite and quartz at 11°C (53°F).

6.2.2 LT1 Results

6.2.2.1 Concentration Trends

Appendix B displays the chemical parameters quantified during the injection and recovery phases, respectively, of LT1 (Tables B.1 and B.2). Figures 6.3 through 6.14 illustrate water chemistry trends. Parameters not tabulated include oil and grease, and manganese. All samples analyzed for oil and grease by the partition-gravimetric technique (Standard Methods 1980) had values below the detection limit (<10 mg/L), and all samples analyzed for manganese had values near the detection limit of atomic absorption flame spectroscopy (0.100 mg/L).

The labeling of the abscissa in Figures 6.3 to 6.14 requires explanation. All of the data are plotted as a function of cumulative volume of water pumped. The injection data are plotted above the negative abscissa, the more negative the value, the more volume remaining to be pumped. For example, -92,100 m^3 corresponds to the start of injection, -80,000 m^3 corresponds to a point at which 12,100 m^3 had been pumped, and zero corresponds to the end of injection, after 92,100 m^3 had been pumped into well A. The zero also represents the entire 60-day storage period, and then the start of the recovery phase. This method of labeling the abscissa allows easy comparison of the change in the chemistry of a particular parcel of water over the period of time of storage, assuming no mixing in the aquifer: e.g., the parcel of water injected at -60,000 m^3 (after 32,100 m^3 had been injected) should be the same parcel of water recovered at +60,000 m^3. Table B.1 includes this negative "plotting volume," as well as the actual cumulative volume injected, for reference.

The chemistry of the source water (port I) from the source well (well B) was influenced by the last short-term cycle, which was completed 11 months before the start of LT1. The source-water temperature curve (Figure 6.3) shows a maximum source water temperature at about -80,000 m^3, a result of

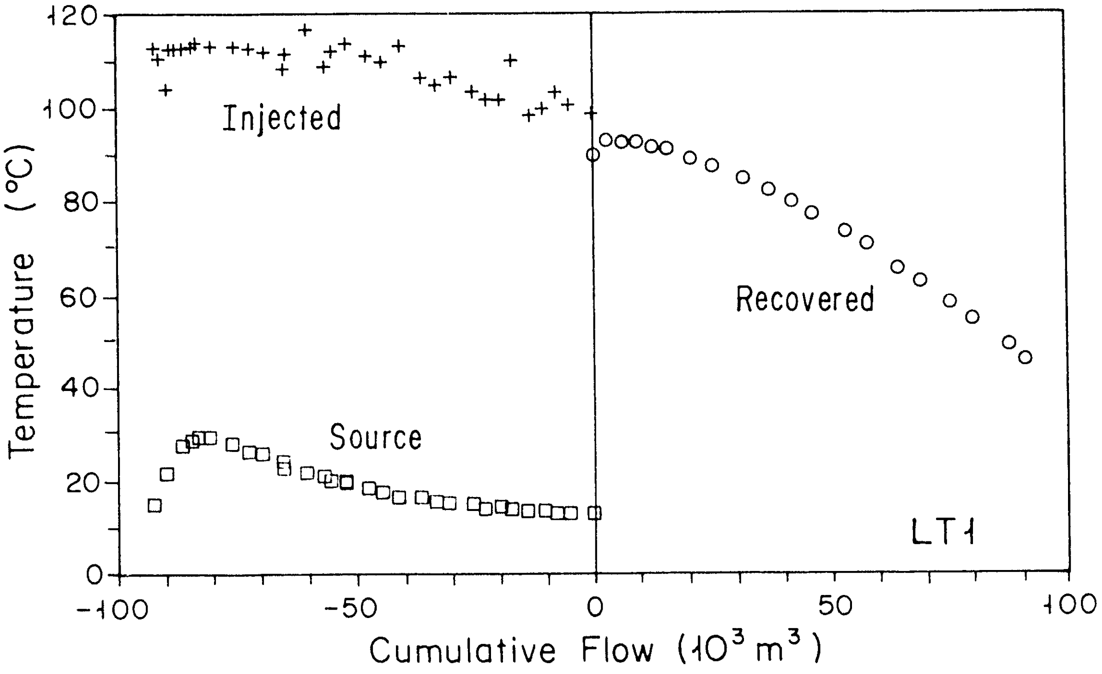


FIGURE 6.3. Water Temperatures During LT1 Plotted as a Function of Cumulative Flow.
Injection data plotted over negative x-axis; recovery data plotted over positive x-axis, as explained in the text.

pumping warmer-than-ambient water into the source well during the recovery phase of the last short-term cycle. Silica (Figure 6.6), and to some degree potassium (Figure 6.13), match the form of the temperature curve exactly, while pH (Figure 6.4) and alkalinity (Figure 6.5) inversely follow temperature. These results are expected given the temperature and solubility relationships of quartz and carbonate rocks, although calcium (Figure 6.10) and magnesium (Figure 6.11) had been expected to mimic the form of the alkalinity curve more closely than they did.

After the water passed through the ion exchange units (port II), the concentrations of calcium, magnesium, iron, and potassium decreased and the concentration of sodium increased (Figures 6.10 through 6.14). The softening units effectively changed the water from a calcium-magnesium bicarbonate to a sodium bicarbonate water. Heating the water (port III) raised the pH (Figure 6.4), possibly because of carbon dioxide degassing or because of changing acid-dissociation constants with temperature. During recovery (port IIIr, in

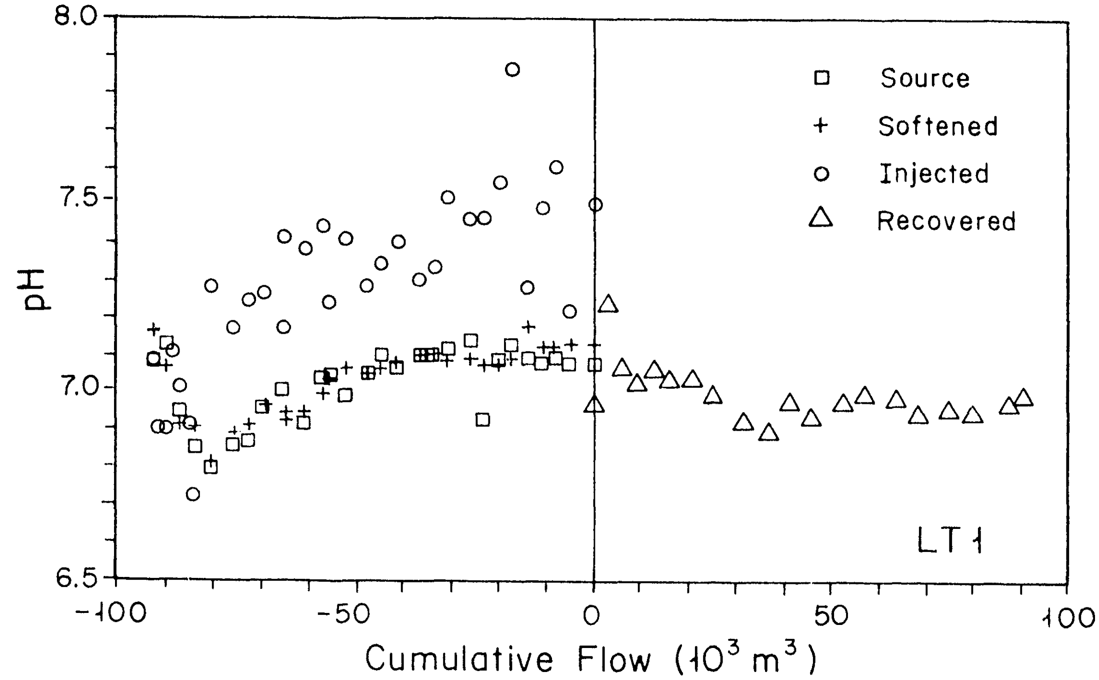


FIGURE 6.4. pH During LT1 Plotted as a Function of Cumulative Flow. Injection data plotted above negative x-axis; recovery data plotted above positive x-axis, as explained in the text.

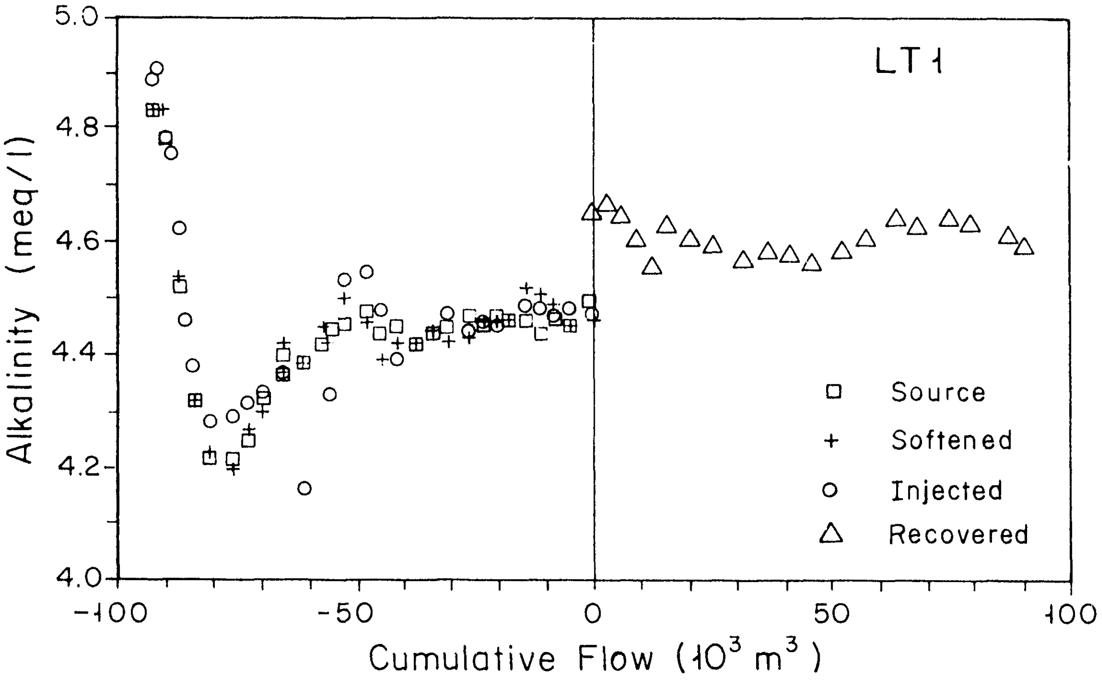


FIGURE 6.5. Alkalinity During LT1 Plotted as a Function of Cumulative Flow. Injection data plotted above negative x-axis; recovery data plotted above positive x-axis, as explained in the text.

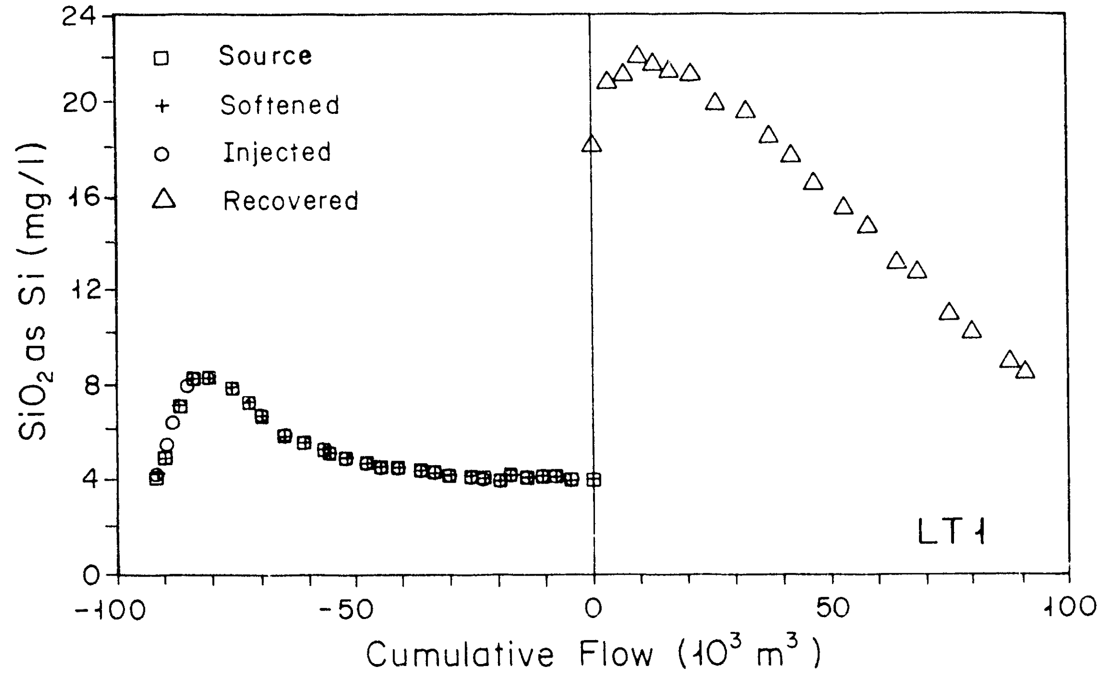


FIGURE 6.6. Silica (as Si) During LT1 Plotted as a Function of Cumulative Flow. Injection data plotted above negative x-axis; recovery data plotted above positive x-axis, as explained in the text.

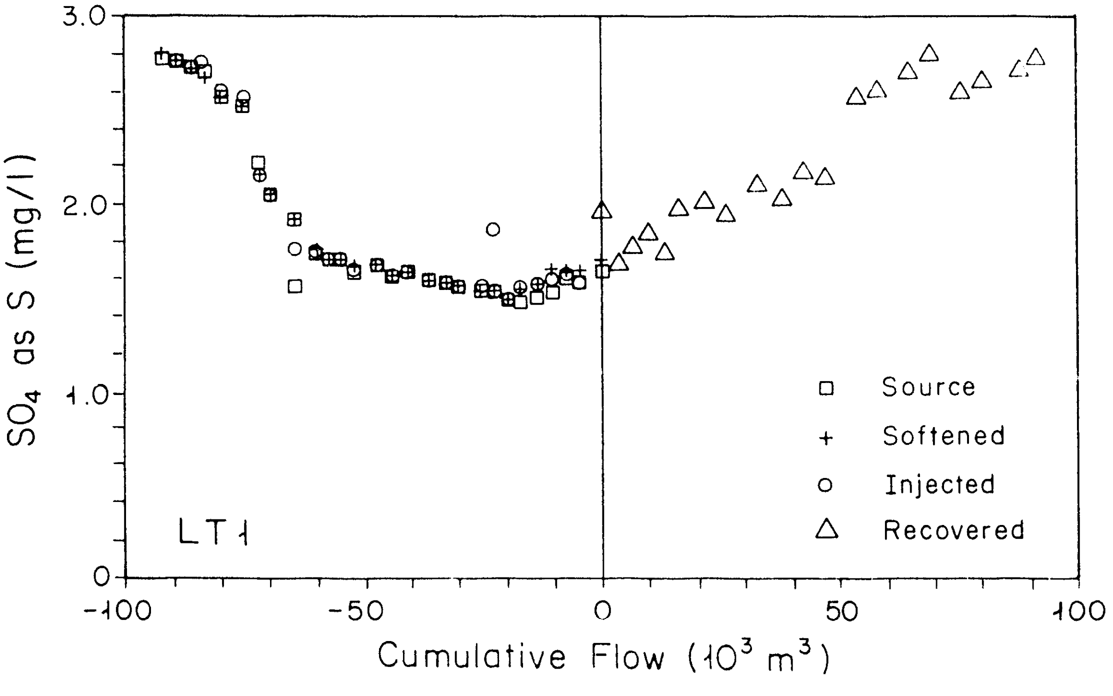


FIGURE 6.7. Sulfate (as S) During LT1 Plotted as a Function of Cumulative Flow. Injection data plotted above negative x-axis; recovery data plotted above positive x-axis, as explained in the text.

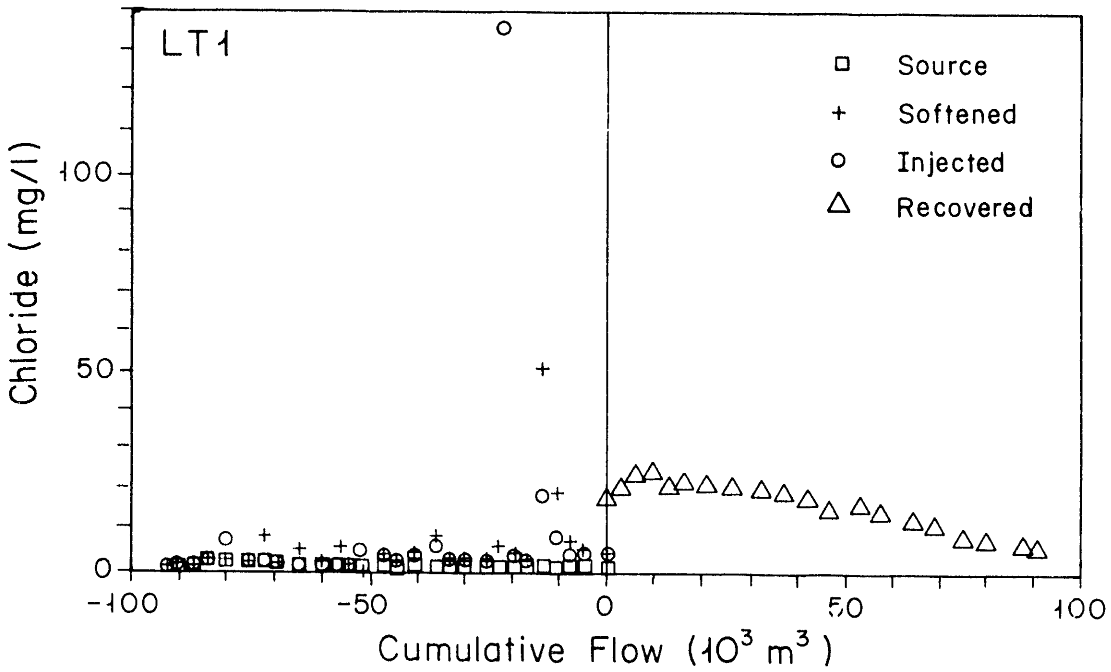


FIGURE 6.8. Chloride During LT1 Plotted as a Function of Cumulative Flow. Injection data plotted above negative x-axis; recovery data plotted above positive x-axis, as explained in the text.

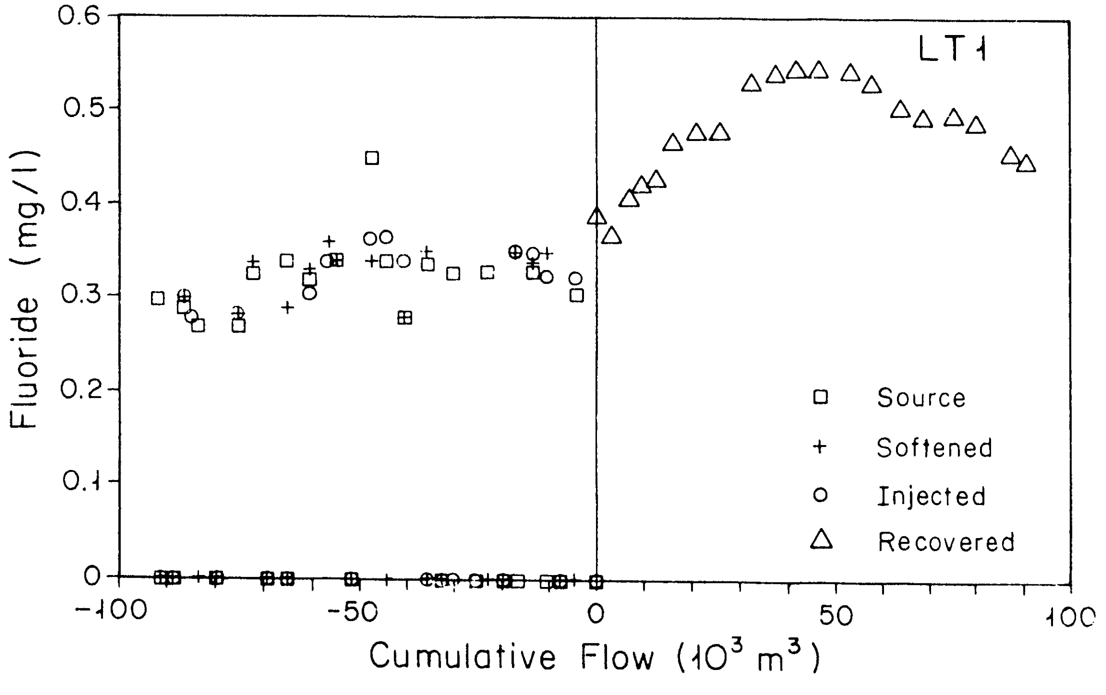


FIGURE 6.9. Fluoride During LT1 Plotted as a Function of Cumulative Flow. Injection data plotted above negative x-axis; recovery data plotted above positive x-axis, as explained in the text.

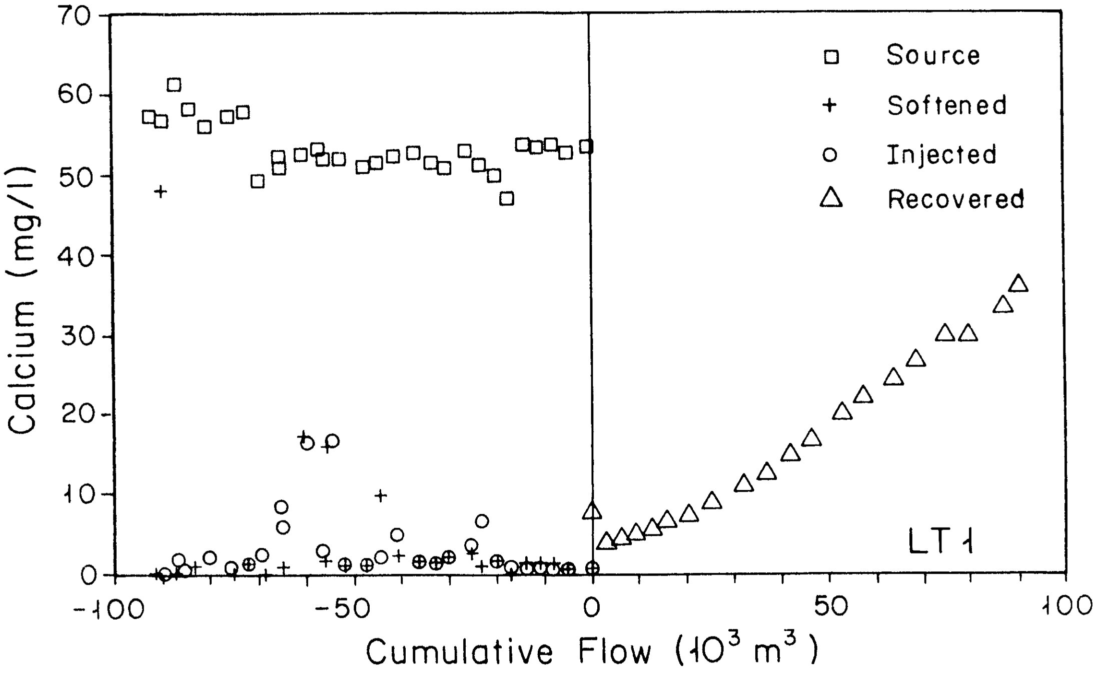


FIGURE 6.10. Calcium During LT1 Plotted as a Function of Cumulative Flow. Injection data plotted above negative x-axis; recovery data plotted above positive x-axis, as explained in the text.

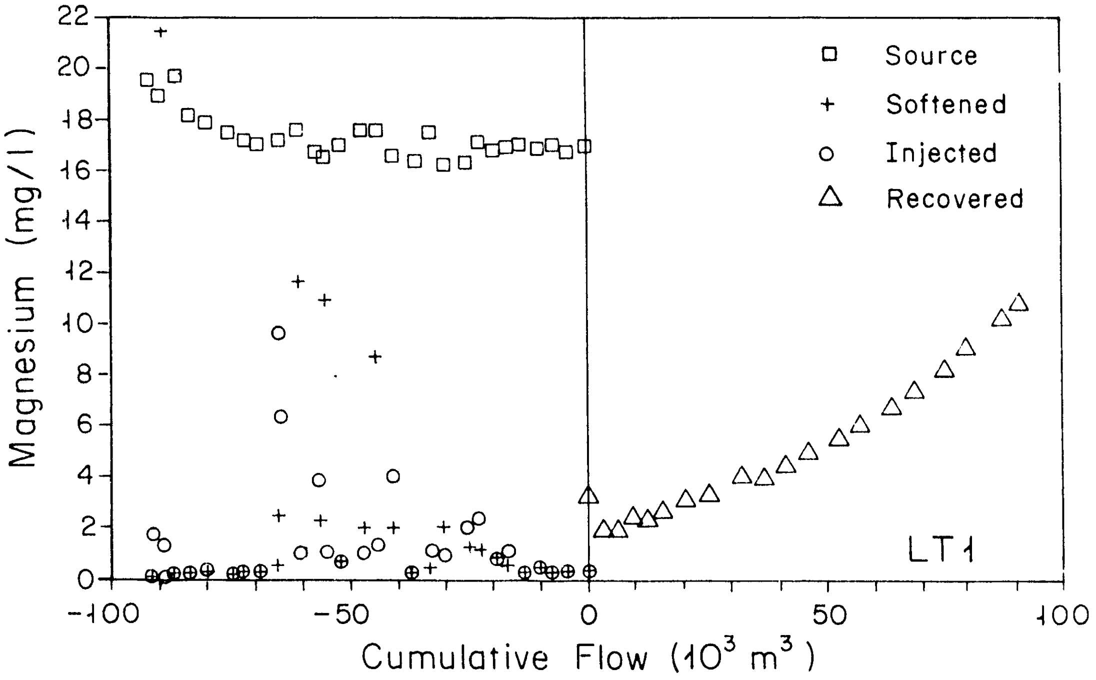


FIGURE 6.11. Magnesium During LT1 Plotted as a Function of Cumulative Flow. Injection data plotted above negative x-axis; recovery data plotted above positive x-axis, as explained in the text.

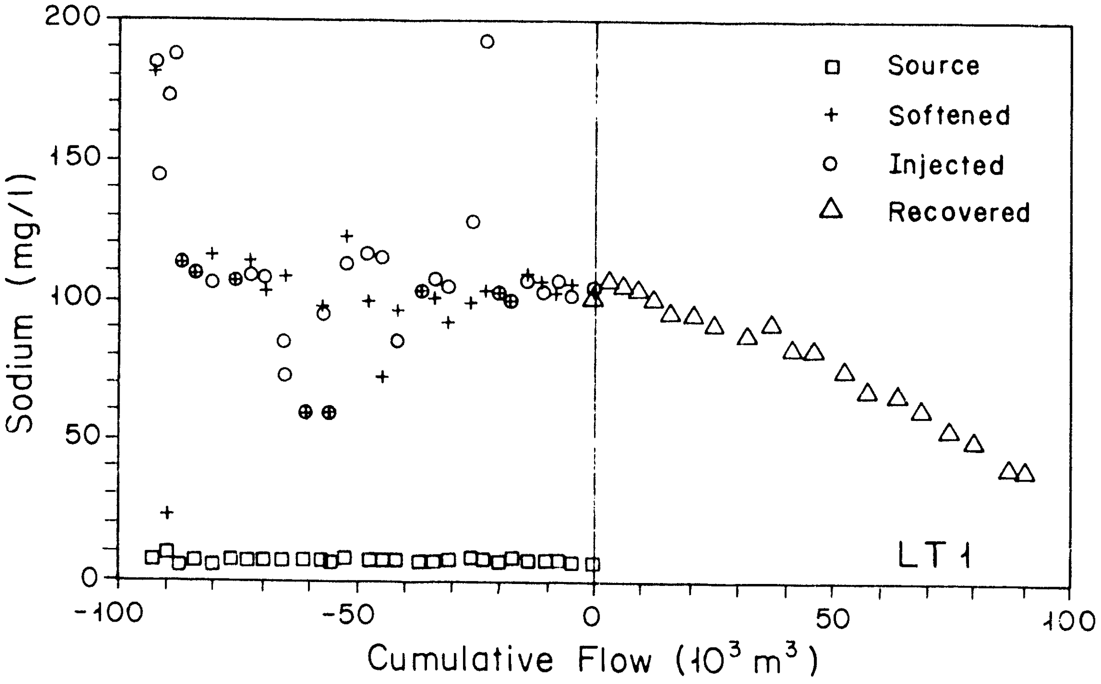


FIGURE 6.12. Sodium During LT1 Plotted as a Function of Cumulative Flow. Injection data plotted above negative x-axis; recovery data plotted above positive x-axis, as explained in the text.

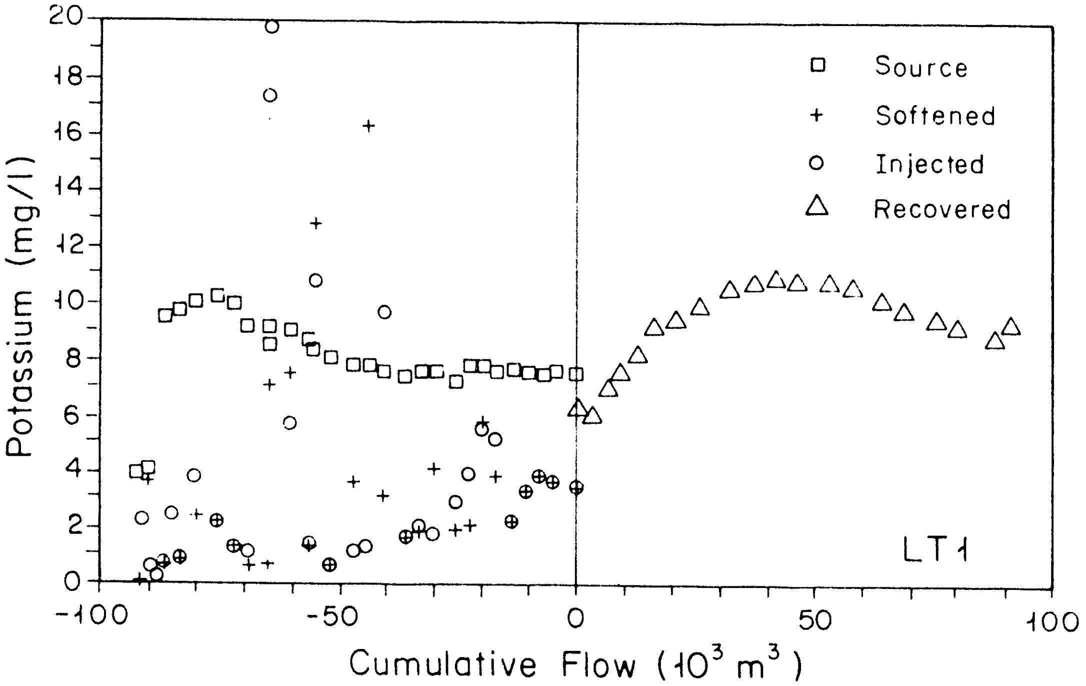


FIGURE 6.13. Potassium During LT1 Plotted as a Function of Cumulative Flow. Injection data plotted above negative x-axis; recovery data plotted above positive x-axis, as explained in the text.

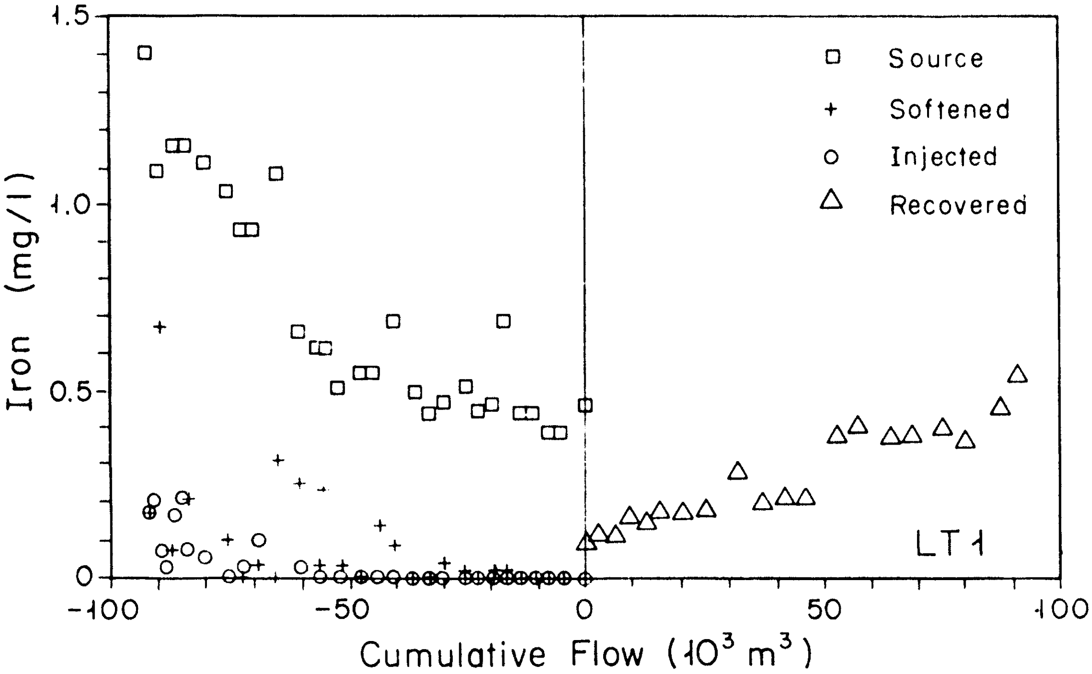


FIGURE 6.14. Iron During LT1 Plotted as a Function of Cumulative Flow. Injection data plotted above negative x-axis; recovery data plotted above positive x-axis, as explained in the text.

the figures, above the positive x-axis) temperature declined steadily, and was again matched by silica, but not potassium (Figures 6.3, 6.6, and 6.13). Alkalinity was slightly higher, and pH slightly lower, upon recovery than in the source water (Figures 6.4 and 6.5). Both alkalinity and pH varied little during recovery, and their minor fluctuations seemed to match each other until near the end of recovery. Calcium and magnesium concentrations gradually increased over the recovery phase, while sodium gradually decreased (Figures 6.10 through 6.12). In general, during storage the concentrations of all ions except sodium increased with respect to their injection values.

6.2.2.2 Mass Balance Considerations

The masses of various aqueous chemical constituents passing through each part of the ATES system were calculated by trapezoidal integration of the concentration versus cumulative pumped volume curves (Table 6.4). The total effects on cumulative mass of these chemical constituents caused by each part of the ATES system (viz., the softening units, the heat exchanger, and the FIG aquifer around the storage well) are summarized in Table 6.5. Positive values

TABLE 6.4. Cumulative Masses of Water Sample Constituents, LT1

	Port I Source	Port II Softened	Port III(I) Injected	Port III(R) Recovered
Silica (kg) as Si	491	492	494	1519
Sulfate (kg) as S	172	183	184	213
Chloride (kg)	167	570	789	1520
Fluoride (kg)	30	30	30	45
Calcium (kg)	4618	350	296	1645
Magnesium (kg)	1437	20	119	509
Sodium (kg)	667	9185	9984	7184
Potassium (kg)	748	320	347	883
Iron (kg)	65	7	3	27
Total Carbon (kmol)	520	515	472	522

indicate kilograms added to the water and negative values indicate kilograms removed from the water, during the course of LT1. All masses were calculated on the basis of 92,100 m^3 injected into and recovered from the storage well.

Significance of mass balance results was estimated by propagating the errors in concentration and volume measurements through the use of partial differential equations. Most of the resulting standard deviations are very small, implying that most often quantities are highly significantly different from zero (p=<0.001).

The water softener clearly removed most of the major cations and replaced them with more than 8 tons of sodium (negative signs for calcium, magnesium, potassium, and iron, and a positive sign for sodium in Table 6.5, Water Softener - Mass Added). Apparently some chloride and sulfate were added by the softener.

The effect of the heat exchanger is more problematic. The water temperature was elevated sufficiently in the exchanger so that aragonite was saturated despite the low levels of calcium. Thus, the loss of calcium may be explained by a small amount of aragonite precipitation in the heat exchanger. However, the apparent addition of sodium, chloride, and potassium by the exchanger is currently unexplained.

During storage in the aquifer, the water picked up masses of all components except sodium. The concentrations of these components were greater in the recovery water than in the injection water (see above). More than 1

TABLE 6.5. Mass Balances Across Water Softener, Heat Exchanger, Aquifer Storage, and Total Cycle, LT1

	Water Softener Port II-Port I Softened-Source		Heat Exchanger Port III(I)-Port II Injected-Softened		Aquifer Storage Port III(R)-Port III(I) Recovered-Injected		Total Cycle Port III(R)-Port I Recovered-Source	
	Mass Added[(a)]	Standard Deviation	Mass Added	Standard Deviation	Mass Added	Standard Deviation	Mass Added	Standard Deviation
Silica (kg) as Si	0.8	2.2	1.7	2.2	1025*	3.0	1027*	3.0
Sulfate (kg) as S	11.4*[(b)]	1.16	0.7	0.82	28.6*	7.42	40.6*	7.42
Chloride (kg)	404*	6.6	219*	5.1	730*	9.6	1353*	9.2
Fluoride (kg)	0.25	0.33	0.12	0.2	15	8.1	15	8.1
Calcium (kg)	-4268*	3.8	-54*	2.7	1349*	3.0	-2973*	3.0
Magnesium (kg)	-1247*	6.2	-72*	4.4	390*	7.7	-928*	7.7
Sodium (kg)	8520*	143	799*	100	-2800*	105	6520*	108
Potassium (kg)	-428*	2.5	27*	1.8	540*	36	130*	36

(a) Mass differences measured at respective sampling ports. Negative values indicate mass loss.
(b) * = value significantly different from zero at the 0.001 level.

metric ton of both silica (as silicon) and calcium was added to the 92,100 m^3 of water recovered, compared to the injected mass of silica and calcium. Less than half of the sodium that was injected was recovered during heat recovery.

The final part of Table 6.5 (Total Cycle, Mass Added) merely integrates the total effects of the entire ATES system. The softening, heating, and aquifer storage during LT1 added more than 6 metric tons of sodium and about 1 metric ton each of silicon and chloride to the original 92,100 m^3 of source water. The cycle removed about 3 tons of calcium and 1 ton of magnesium. Overall, the calcium-magnesium bicarbonate source water was changed into a mixed sodium-calcium-magnesium bicarbonate water.

6.2.3 Monitor Well Results

Monitor wells were sampled in June, September, and December 1985. Unfortunately because of failure of some AAS lamps, not all cation results were available for the September and December samples until late February 1986. The June samples were collected immediately following the completion of the long-term cycle and should show most strongly any effects of the ATES operation on the water chemistry collected from the monitor wells. Monitoring well data are presented in Appendix B, Tables B.3 to B.10.

At the storage site (A) there is apparently a substantial quantity of partially softened water present, as shown by the sodium values in wells AM1, AM2, and AM4. [AM1 is screened in the St. Lawrence confining bed; as noted in Walton et al. (1991), it behaves as a Franconia well because of the location of the grout plug.] The sodium concentration decreases with distance away from the storage well: AM1 has 44 mg/L at 7 m; AM2 has 39 mg/L at 14 m; AM4 has 29 mg/L at 30.5 m. Calcium and magnesium (and therefore, hardness) values are correspondingly lower than ambient levels in all three wells. No major changes were found in well AS1 in the Jordan aquifer. An obstruction in the Mt. Simon pipe prevented sampling in June. By the September sampling date, the obstruction had been removed and samples were collected. Analyses of the September and December samples from AS1-Mt. Simon indicate that some of the softened injection water reached the Mt. Simon aquifer. Sodium values were higher, and calcium and magnesium values lower, than pre-test levels. Both the AS1 and AC1 wells penetrate the Eau Claire formation, which separates the

Ironton-Galesville aquifer from the Mt. Simon aquifer. Problems with either of these wells may allow the softened Ironton-Galesville water to leak down into the Mt. Simon aquifer. An investigation of the source of the problem is continuing (see Hoyer et al. 1991).

Essentially no change was found in the water chemistry of the Mt. Simon water at BC1. A very slight increase in sodium and chloride was observed in the Jordan aquifer at well BS1. Calcium and magnesium were affected very little. No changes in the water chemistry of the FIG water were found at well CM1.

6.3 SUMMARY

Injection and recovery waters were analyzed for major cations and anions, and general ground water quality parameters. Ambient ground water had a composition typical of calcium-magnesium-bicarbonate water. Injected water as affected by the ion-exchange softening unit was typically a sodium bicarbonate water. Storage of the hot water in the FIG aquifer when viewed from a mass balance perspective dissolved significant quantities of silica, sulfate, chloride, fluoride, calcium, magnesium, potassium, and iron. Sodium from the ion-exchange softening unit increased in concentration above ambient levels. The chemistry of both short-term and long-term test cycles has been adequately modeled by chemical equilibrium techniques. Calcium carbonate and silica dissolution/precipitation reactions dominate changes in water chemistry. The water chemistry of hot water stored in aquifers showed that water quality was not adversely impacted by ATES and the use of the ion-exchange softener unit solved the scaling problems in the heat exchanger and pumps.

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APPENDIX A

DAILY FLOW AND TEMPERATURE DATA, LONG-TERM CYCLE 1

TABLE A.1. Daily Flow and Temperature Data, LT1 Injection

Date	Pumping Hours	Total Hours	Flow (L/sec)	Flow (m3/day)	CumFlow (m3)	Inject. T (°C)	Source T (°C)	Delta T (°C)
14-Nov-84	4.00	4.0	18.71	269	269	112.7	15.4	97.2
15-Nov	28.00	28.0	18.41	1590	1859	110.9	18.8	92.1
16-Nov	38.00	52.0	18.25	657	2516	104.6	22.3	82.3
17-Nov	48.00	76.0	18.32	659	3175	112.1	25.1	86.9
18-Nov	72.00	100.0	18.24	1576	4751	112.7	26.6	86.0
19-Nov	96.00	124.0	18.15	1568	6319	112.4	28.2	84.2
20-Nov	120.00	148.0	18.43	1591	7910	112.6	29.0	83.6
21-Nov	144.00	172.0	18.42	1591	9501	113.4	29.7	83.7
22-Nov	168.00	196.0	18.60	1607	11108	112.4	29.8	82.6
23-Nov	192.00	220.0	18.49	1597	12705	113.1	29.6	83.5
24-Nov	216.00	244.0	18.06	1560	14265	113.3	29.2	84.1
25-Nov	240.00	268.0	18.60	1607	15872	113.5	28.8	84.7
26-Nov	264.00	292.0	18.71	1616	17488	112.9	28.2	84.8
27-Nov	288.00	316.0	18.67	1613	19101	112.2	27.8	84.4
28-Nov	311.15	340.0	18.51	1542	20643	112.8	26.8	86.0
29-Nov	335.15	364.0	17.91	1547	22190	112.5	26.6	85.9
30-Nov	358.97	388.0	18.41	1578	23768	112.1	26.1	86.1
01-Dec	382.97	412.0	18.40	1589	25357	112.1	25.3	86.8
02-Dec	406.97	436.0	18.47	1595	26952	110.6	24.8	85.8
03-Dec	424.82	460.0	18.67	1200	28152	108.1	24.1	84.0
04-Dec	432.57	484.0	18.20	508	28660	113.7	23.5	90.2
05-Dec	456.57	508.0	18.53	1601	30261	111.9	23.2	88.8
06-Dec	476.19	532.0	18.55	1310	31571	104.9	22.4	82.5
07-Dec	485.19	556.0	17.96	582	32152	117.1	22.3	94.8
08-Dec	509.19	580.0	18.06	1560	33713	117.2	22.1	95.1
09-Dec	533.19	604.0	17.95	1551	35264	112.9	21.4	91.5
10-Dec	540.69	628.0	18.10	489	35752	109.1	21.6	87.5
11-Dec	548.69	652.0	18.43	531	36283	114.3	20.7	93.6
12-Dec	572.69	676.0	18.41	1590	37873	112.1	20.7	91.4
13-Dec	596.69	700.0	18.13	1567	39439	111.7	20.3	91.3
14-Dec	620.69	724.0	17.93	1548	40988	113.4	19.9	93.5
15-Dec	644.69	748.0	18.24	1575	42563	112.7	19.6	93.2
16-Dec	668.69	772.0	17.91	1547	44110	114.2	19.0	95.1
17-Dec	692.69	796.0	17.86	1543	45652	111.1	18.7	92.4
18-Dec	716.69	820.0	17.88	1544	47196	109.6	18.3	91.3
19-Dec	740.69	844.0	18.14	1567	48763	110.2	17.9	92.3
20-Dec	764.69	868.0	18.04	1558	50322	111.0	17.6	93.4
21-Dec	775.69	892.0	18.14	718	51040	107.4	17.6	89.7
22-Dec	775.69	916.0		0	51040			
23-Dec	775.69	940.0		0	51040			
24-Dec	775.69	964.0		0	51040			

TABLE A.1. (continued)

Date	Pumping Hours	Total Hours	Flow (L/sec)	Flow (m3/day)	CumFlow (m3)	Inject. T (°C)	Source T (°C)	Delta T (°C)
25-Dec	775.69	988.0		0	51040			
26-Dec	775.69	1012.0		0	51040			
27-Dec	775.69	1036.0		0	51040			
28-Dec	788.94	1060.0	18.31	873	51913	113.4	16.8	96.6
29-Dec	812.94	1084.0	18.47	1595	53509	108.8	17.2	91.6
30-Dec	836.94	1108.0	17.81	1539	55047	108.7	16.8	91.9
31-Dec	860.94	1132.0	17.93	1549	56596	106.5	16.6	89.9
01-Jan-85	884.94	1156.0	17.85	1542	58138	106.6	16.4	90.2
02-Jan	908.94	1180.0	17.52	1513	59651	105.0	16.1	88.9
03-Jan	932.94	1204.0	17.42	1504	61155	106.3	16.1	90.2
04-Jan	956.94	1228.0	17.90	1546	62701	106.6	16.0	90.6
05-Jan	980.94	1252.0	17.88	1544	64245	107.4	15.6	91.7
06-Jan	1004.94	1276.0	17.92	1548	65793	105.8	15.6	90.2
07-Jan	1028.94	1300.0	17.67	1526	67319	103.7	15.2	88.4
08-Jan	1052.94	1324.0	17.37	1500	68819	100.7	15.0	85.7
09-Jan	1073.44	1348.0	17.41	1284	70103	101.9	14.6	87.3
10-Jan	1097.44	1372.0	17.66	1526	71629	106.0	14.7	91.3
11-Jan	1121.44	1396.0	17.76	1534	73163	102.0	14.6	87.4
12-Jan	1131.27	1420.0	17.67	625	73788	101.1	14.4	86.8
13-Jan	1131.27	1444.0		0	73788			
14-Jan	1131.27	1468.0		0	73788			
15-Jan	1131.27	1492.0		0	73788			
16-Jan	1141.94	1516.0	17.61	677	74465	110.5	14.3	96.2
17-Jan	1165.94	1540.0	17.60	1521	75985	110.4	14.5	95.9
18-Jan	1189.94	1564.0	17.66	1525	77511	106.3	14.2	92.2
19-Jan	1213.94	1588.0	17.60	1521	79032	98.8	13.9	84.9
20-Jan	1237.94	1612.0	17.83	1540	80572	99.9	13.9	86.0
21-Jan	1261.94	1636.0	17.69	1528	82100	99.9	13.8	86.0
22-Jan	1285.94	1660.0	17.34	1498	83598	102.6	13.8	88.8
23-Jan	1309.94	1684.0	17.74	1533	85131	103.6	13.6	90.0
24-Jan	1333.94	1708.0	17.82	1539	86670	103.0	13.5	89.4
25-Jan	1357.94	1732.0	17.70	1529	88199	100.7	13.5	87.2
26-Jan	1381.94	1756.0	17.78	1535	89734	94.1	13.3	80.8
27-Jan	1405.94	1780.0	17.72	1530	91265	99.0	13.3	85.7
28-Jan	1418.94	1793.0	17.71	828	92093	99.1	13.2	85.9
TOTALS	1418.94	1793.0			92093			
AVERAGES			18.03	1558		108.5	19.7	88.8
				64.9	m3/hr			

TABLE A.2. Daily Flow and Temperature Data, LT1 Recovery

Date	Pumping Hours	Total Hours	Flow (L/sec)	Flow (m3/day)	CumFlow (m3)	Inject. T (°C)	Return T (°C)	Delta T (°C)
02-Apr-85	10.00	10.0	18.63	670.58	671	89.9	82.0	7.9
03-Apr	34.00	34.0	18.85	1628.74	2299	92.8	83.0	9.8
04-Apr	58.00	58.0	18.80	1624.65	3924	93.1	82.8	10.3
05-Apr	82.00	82.0	18.72	1617.38	5541	92.8	82.7	10.1
06-Apr	106.00	106.0	18.75	1620.11	7161	92.7	82.7	10.0
07-Apr	130.00	130.0	18.77	1621.47	8783	92.6	82.2	10.4
08-Apr	154.00	154.0	18.73	1618.51	10401	92.3	81.4	10.9
09-Apr	178.00	178.0	18.69	1614.65	12016	92.2	84.4	7.8
10-Apr	202.00	202.0	18.64	1610.11	13626	91.7	82.3	9.3
11-Apr	226.00	226.0	18.59	1606.25	15232	90.9	82.4	8.5
12-Apr	250.00	250.0	18.64	1610.11	16843	90.7	82.2	8.4
13-Apr	274.00	274.0	18.62	1608.75	18451	90.2	80.7	9.5
14-Apr	298.00	298.0	18.74	1618.74	20070	89.7	80.1	9.6
15-Apr	322.00	322.0	18.73	1618.06	21688	89.2	80.5	8.7
16-Apr	346.00	346.0	18.66	1612.15	23300	88.5	79.3	9.2
17-Apr	370.00	370.0	18.77	1622.15	24922	88.3	80.1	8.2
18-Apr	394.00	394.0	18.74	1619.20	26542	87.4	80.0	7.4
19-Apr	418.00	418.0	18.42	1591.48	28133	86.8	79.8	7.0
20-Apr	442.00	442.0	18.54	1601.71	29735	86.3	78.8	7.4
21-Apr	466.00	466.0	18.66	1612.38	31347	85.5	78.0	7.5
22-Apr	490.00	490.0	18.63	1609.20	32956	84.9	77.5	7.4
23-Apr	504.42	514.0	18.45	957.54	33914	84.0	76.4	7.6
24-Apr	517.48	538.0	18.61	875.36	34789	83.1	76.9	6.2
25-Apr	541.48	562.0	18.47	1595.57	36385	82.9	75.6	7.3
26-Apr	565.48	586.0	18.36	1586.49	37971	82.4	74.5	7.9
27-Apr	589.48	610.0	18.54	1602.16	39573	82.0	74.0	8.0
28-Apr	613.48	634.0	18.39	1588.74	41162	81.0	73.9	7.1
29-Apr	637.48	658.0	18.40	1589.89	42752	79.9	73.0	6.9
30-Apr	661.48	682.0	18.35	1585.58	44338	79.1	72.4	6.7
01-May	685.48	706.0	18.36	1586.49	45924	78.3	71.6	6.7
02-May	709.48	730.0	18.31	1582.40	47507	77.3	71.0	6.3
03-May	733.48	754.0	18.41	1590.57	49097	76.7	70.8	5.9
04-May	757.48	778.0	18.51	1599.21	50696	75.7	69.9	5.8
05-May	781.48	802.0	18.10	1563.54	52260	74.3	68.4	5.9
06-May	805.48	826.0	18.13	1566.04	53826	73.5	67.1	6.4
07-May	829.48	850.0	18.20	1572.17	55398	72.2	66.5	5.7
08-May	853.48	874.0	18.25	1576.72	56975	71.4	65.9	5.4
09-May	877.48	898.0	18.51	1598.98	58574	70.8	65.5	5.3
10-May	901.48	922.0	18.31	1582.17	60156	69.3	64.6	4.8
11-May	925.48	946.0	18.35	1585.80	61742	68.1	63.0	5.2
12-May	949.48	970.0	18.30	1581.03	63323	67.4	61.4	6.0

TABLE A.2. (continued)

Date	Pumping Hours	Total Hours	Flow (L/sec)	Flow (m3/day)	CumFlow (m3)	Inject. T (°C)	Return T (°C)	Delta T (°C)
13-May	973.48	994.0	18.31	1581.72	64905	65.9	60.6	5.3
14-May	997.48	1018.0	18.26	1578.08	66483	65.0	59.4	5.6
15-May	1021.48	1042.0	18.27	1578.53	68061	64.3	58.6	5.7
16-May	1045.48	1066.0	18.30	1580.81	69642	62.9	56.8	6.1
17-May	1069.48	1090.0	18.27	1578.31	71220	62.0	56.3	5.7
18-May	1093.48	1114.0	18.29	1580.12	72800	60.9	55.8	5.1
19-May	1117.48	1138.0	18.12	1565.36	74366	59.4	54.8	4.5
20-May	1141.48	1162.0	18.18	1570.36	75936	58.1	53.0	5.1
21-May	1165.48	1186.0	18.15	1568.31	77504	56.9	52.2	4.7
22-May	1189.48	1210.0	18.18	1570.58	79075	55.7	51.4	4.4
23-May	1213.48	1234.0	18.20	1572.63	80648	54.7	50.0	4.8
24-May	1237.48	1258.0	18.21	1573.31	82221	53.8	49.7	4.0
25-May	1261.48	1282.0	18.24	1576.04	83797	52.7	49.0	3.7
26-May	1285.48	1306.0	18.11	1564.91	85362	50.9	47.0	3.9
27-May	1309.48	1330.0	18.21	1573.08	86935	50.3	46.4	3.8
28-May	1333.48	1354.0	18.07	1561.04	88496	49.0	45.5	3.5
29-May	1357.48	1378.0	18.04	1558.77	90055	48.3	44.6	3.7
30-May	1381.48	1402.0	18.13	1566.04	91621	46.9	43.9	3.0
31-May	1391.07	1411.6	18.06	623.02	92244	46.1	42.7	3.4
TOTALS	1391.07	1411.6			92244			
AVERAGES			18.42	1591 66.3 m^3/hr		74.7	68.0	6.6

APPENDIX B

TABLES OF ANALYTICAL RESULTS OF WATER SAMPLES

APPENDIX B

TABLES OF ANALYTICAL RESULTS OF WATER SAMPLES

This appendix includes a series of tables presenting the results of analyses of water samples collected during LT1 (Tables B.1 and B.2) and from monitoring wells (Tables B.3 through B.10). Table B.1 presents data from samples collected during the injection phase of LT1. Table B.2 presents data from samples collected during the storage and recovery phases of LT1. Tables B.3 through B.10 present data from samples collected from monitoring wells between January 1982 and December 1985. Table B.11 gives the conversion factors to convert between mg/L and mmol/L.

The following note applies to the tables in Appendix B:

	Sample Type
Table B.1	I = Source water (unheated)
	II = Softened water (unheated)
	III = Heated water (injected)
Table B.2	III = Recovered water
Tables B.1 - B.10	0.00 = Not Detected
	NA = Not Available
	ND = Not Detected

TABLE B.1. Water Analyses, LT1, Injection Phase, November 1984 to January 1985

Well	AM4	A	B	B	B	B	Field Blank	B	B
Sample Type			I	II	III	III		III	I
Date sampled	841101	841108	841114	841114	841114	841114	841114	841115	841116
Time			2000	2030	2130	2145	2230	1130	1200
No. days since start	-13	-6	0	0	0	0	0	1	2
Cumulative vol m^3	-----	-----	10	10	10	10	10	1010	2510
Graph vol m^3	-----	-----	-92090	-92090	-92090	-92090	-92090	-91090	-89590
Replication	1	1	1	1	1	2		1	1
Temperature (deg C)	21.0	21.0	15.6	15.6	112.2	112.2		116.7	23.3
Temp @ pH deg C	20.0	20.0	15.9	15.6	92.9	92.9	NA	89.0	18.0
pH	7.80	7.24	7.08	7.16	7.09	7.09	NA	6.90	7.13
SC (umho/cm) @ 25 C	338	326	305	335	432	432	NA	420	328
DO (mg/L)	0.3	0.1	0.1	0.1	0.3	0.3	NA	0.3	0.2
Alk (meq/L)	4.73	4.92	4.84	4.84	4.90	4.88	-0.02	4.91	4.79
SiO2 (mg/L) as Si	7.28	3.89	4.14	4.25	4.41	4.35	0.00	4.41	4.98
IC Analysis:									
SO4 (mg/L) as S	2.29	3.55	2.79	2.82	2.79	2.79	0.00	2.79	2.77
Cl (mg/L)	2.7	1.2	1.1	2.3	1.6	1.6	0.0	0.8	1.0
F (mg/L)	0.25	0.28	0.30	NA	NA	NA	0.00	NA	NA
NO3 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NO2 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PO4 (mg/L) as P	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AA Analysis:									
Ca (mg/L)	52.2	61.2	57.7	0.0	0.0	0.0	0.0	0.0	56.9
Mg (mg/L)	21.6	19.3	19.6	0.0	0.0	0.0	0.0	1.7	18.9
Na (mg/L)	9	7	7	182	191	180	0	145	10
K (mg/L)	2.1	3.9	4.0	0.1	0.0	0.0	0.0	2.2	4.1
Fe (mg/L)	1.62	1.02	1.41	0.17	0.17	0.17	0.14	0.21	1.09
Hardness (mg/L) as CaCO3	219.3	232.0	224.6	0.1	0.1	0.1	0.1	7.0	220.0

TABLE B.1. (continued)

Well	B	Field Blank	B	B	B	B	B	B	B
Sample Type	II		III	III	III	I	II	III	III
Date sampled	841116	841116	841117	841117	841118	841119	841119	841119	841119
Time	1030	1330	1530	1600	1300	1015	1045	1130	1145
No. days since start	2	2	3	3	4	5	5	5	5
Cumulative vol m^3	2510	2510	2655	2655	4040	5475	5475	5475	5475
Graph vol m^3	-89590	-89590	-89445	-89445	-88060	-86625	-86625	-86625	-86625
Replication	1		1	2	1	1	1	1	2
Temperature (deg C)	23.3		112.2	112.2	111.7	27.8	27.8	112.2	112.2
Temp @ pH deg C	20.3	19.0	47.5	47.5	92.0	21.6	24.5	87.0	87.0
pH	7.06	5.40	6.90	6.90	7.10	6.95	6.91	7.01	7.01
SC (umho/cm) @ 25 C	338	2	436	436	427	351	362	438	438
DO (mg/L)	0.3	NA	0.3	0.3	0.3	0.1	0.1	0.4	0.4
Alk (meq/L)	4.84	0.01	4.79	4.79	4.76	4.52	4.54	4.63	4.62
SiO2 (mg/L) as Si	4.96	0.00	5.55	5.51	6.51	7.20	7.32	7.34	7.38
IC Analysis:									
SO4 (mg/L) as S	2.77	0.00	2.79	2.77	2.79	2.75	2.75	2.75	2.77
Cl (mg/L)	1.5	0.0	1.3	1.3	1.6	2.1	2.8	2.6	2.5
F (mg/L)	NA	0.00	NA	NA	NA	0.29	0.30	0.30	0.30
NO3 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NO2 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PO4 (mg/L) as P	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AA Analysis:									
Ca (mg/L)	43.8	0.0	0.4	0.4	0.0	61.6	0.4	2.2	2.2
Mg (mg/L)	21.4	0.0	1.1	1.6	0.0	19.8	0.2	0.1	0.2
Na (mg/L)	23	0	177	170	188	6	114	113	112
K (mg/L)	3.6	0.0	0.6	0.6	0.2	9.5	0.7	0.8	0.7
Fe (mg/L)	0.67	0.00	0.07	0.07	0.03	1.16	0.07	0.17	0.17
Hardness (mg/L) as CaCO3	197.7	0.1	5.3	7.3	0.1	235.3	1.8	6.1	6.2

TABLE B.1. (continued)

Well	Field Blank	B	B	B	B	B	Field Blank	AM4	AM4
Sample Type		III	I	II	III	III			
Date sampled	841119	841120	841121	841121	841121	841121	841121	841121	841121
Time	1300	930	930	1000	1030	1045	1115	1130	1130
No. days since start	5	6	7	7	7	7	7	7	7
Cumulative vol m^3	5475	7000	8590	8590	8590	8590	8590	8590	8590
Graph vol m^3	-86625	-85100	-83510	-83510	-83510	-83510	-83510	-83510	-83510
Replication		1	1	1	1	2		1	2
Temperature (deg C)		111.7	30.0	30.0	114.4	114.4		27.0	27.0
Temp @ pH deg C	20.2	39.0	23.5	26.2	45.0	45.0	NA	15.0	15.0
pH	4.87	6.91	6.85	6.90	6.72	6.72	NA	6.86	6.86
SC (umho/cm) @ 25 C	2	404	346	366	428	428	NA	378	378
DO (mg/L)	NA	0.2	0.1	0.1	0.1	0.1	NA	0.1	0.1
Alk (meq/L)	-0.01	4.46	4.32	4.32	4.38	4.38	0.00	4.92	4.90
SiO2 (mg/L) as Si	0.00	8.01	8.34	8.44	8.50	8.50	0.00	12.78	12.82
IC Analysis:									
SO4 (mg/L) as S	0.00	2.77	2.72	2.68	2.70	2.70	0.00	2.84	2.86
Cl (mg/L)	0.0	2.4	2.5	3.9	3.0	2.8	0.0	3.7	3.7
F (mg/L)	0.00	0.28	0.27	NA	NA	NA	NA	NA	NA
NO3 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NO2 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PO4 (mg/L) as P	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AA Analysis:									
Ca (mg/L)	0.2	1.1	58.5	0.9	1.4	1.6	0.6	32.1	32.1
Mg (mg/L)	0.0	0.1	18.3	0.2	0.2	0.2	0.0	8.5	8.5
Na (mg/L)	0	112	6	110	111	108	0	79	76
K (mg/L)	0.0	2.4	9.7	0.8	1.0	0.8	0.0	8.1	8.1
Fe (mg/L)	0.07	0.21	1.16	0.21	0.07	0.07	0.00	1.55	1.55
Hardness (mg/L) as CaCO3	0.4	2.9	221.5	3.2	4.2	4.6	1.5	115.0	115.0

TABLE B.1. (continued)

Well	B	B	B	B	Field Blank	B	B	B	B
Sample Type	I	II	III	III		I	II	III	III
Date sampled	841123	841123	841123	841123	841123	841126	841126	841126	841126
Time	1115	1145	1200	1205	1230	1015	1030	1100	1105
No. days since start	9	9	9	9	9	12	12	12	12
Cumulative vol m^3	11925	11925	11925	11925	11925	16640	16640	16640	16640
Graph vol m^3	-80175	-80175	-80175	-80175	-80175	-75460	-75460	-75460	-75460
Replication	1	1	1	2		1	1	1	2
Temperature (deg C)	30.6	30.6	112.8	112.8		28.3	28.3	112.8	112.8
Temp @ pH deg C	21.6	25.0	93.5	93.5	NA	22.2	24.0	89.0	89.0
pH	6.80	6.81	7.28	7.28	NA	6.86	6.89	7.17	7.17
SC (umho/cm) @ 25 C	341	357	424	424	NA	347	358	405	405
DO (mg/L)	0.1	0.1	0.1	0.1	NA	0.1	0.2	0.1	0.1
Alk (meq/L)	4.22	4.23	4.28	4.28	0.00	4.21	4.20	4.29	4.28
SiO2 (mg/L) as Si	8.42	8.64	8.53	8.49	0.00	8.02	7.86	7.90	8.10
IC Analysis:									
SO4 (mg/L) as S	2.58	2.58	2.62	2.62	0.00	2.53	2.53	2.58	2.58
Cl (mg/L)	2.6	2.6	8.6	7.7	0.0	2.8	3.4	3.0	3.0
F (mg/L)	NA	NA	0.31	NA	NA	0.27	0.28	0.29	0.28
NO3 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NO2 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PO4 (mg/L) as P	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AA Analysis:									
Ca (mg/L)	56.3	0.0	2.3	2.1	0.0	57.8	0.0	0.9	1.1
Mg (mg/L)	17.9	0.1	0.3	0.2	0.0	17.5	0.1	0.1	0.1
Na (mg/L)	7	116	106	107	0	7	107	107	108
K (mg/L)	10.0	2.4	3.8	3.8	0.0	10.2	2.2	2.3	2.0
Fe (mg/L)	1.11	0.00	0.06	0.06	0.00	1.04	0.10	0.00	0.00
Hardness (mg/L) as CaCO3	214.2	0.2	6.8	6.3	0.0	216.2	0.4	2.6	3.2

TABLE B.1. (continued)

Well	Field Blank	B	B	B	B	Field Blank	AM4	AM4	B
Sample Type		I	II	III	III				I
Date sampled	841126	841128	841128	841128	841128	841128	841128	841128	841130
Time	1200	1145	1205	1300	1305	1330	1430	1445	1015
No. days since start	12	14	14	14	14	14	14	14	16
Cumulative vol m^3	16640	19865	19865	19865	19865	19865	19865	19865	22925
Graph vol m^3	-75460	-72235	-72235	-72235	-72235	-72235	-72235	-72235	-69175
Replication		1	1	1	2		1	2	1
Temperature (deg C)		27.2	27.2	113.3	113.3		45.3	45.3	26.1
Temp @ pH deg C	NA	22.2	22.2	40.0	40.0	NA	13.0	13.0	20.9
pH	NA	6.87	6.91	7.24	7.24	NA	7.23	7.23	6.96
SC (umho/cm) @ 25 C	NA	340	377	399	399	2	363	363	344
DO (mg/L)	NA	0.2	0.1	0.1	0.1	NA	0.3	0.3	0.2
Alk (meq/L)	0.02	4.25	4.27	4.31	4.32	0.01	4.42	4.47	4.32
SiO2 (mg/L) as Si	0.00	7.40	7.34	7.44	7.50	0.00	13.12	14.02	6.80
IC Analysis:									
SO4 (mg/L) as S	0.00	2.23	2.17	2.14	2.15	0.00	1.66	1.70	2.06
Cl (mg/L)	0.0	2.6	8.8	3.2	3.2	0.0	6.4	6.6	2.2
F (mg/L)	0.00	0.33	0.34	0.34	0.33	0.00	1.03	NA	NA
NO3 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NO2 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PO4 (mg/L) as P	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AA Analysis:									
Ca (mg/L)	0.0	58.1	0.9	1.4	1.4	0.0	23.2	23.2	49.6
Mg (mg/L)	0.0	17.3	0.3	0.2	0.2	0.0	8.2	8.0	17.1
Na (mg/L)	0	7	114	114	104	0	77	73	7
K (mg/L)	0.0	10.0	1.3	1.1	1.1	0.2	7.5	7.6	9.2
Fe (mg/L)	0.00	0.93	0.00	0.00	0.06	0.00	3.75	3.68	0.93
Hardness (mg/L) as CaCO3	0.0	216.2	3.3	4.3	4.3	0.0	91.7	90.8	194.0

TABLE B.1. (continued)

Well	B	B	B	Field Blank	B	B	B	B	Field Blank
Sample Type	II	III	III		I	II	III	III	
Date sampled	841130	841130	841130	841130	841203	841203	841203	841203	841203
Time	1045	1110	1115	1200	1130	1200	1215	1220	1300
No. days since start	16	16	16	16	19	19	19	19	19
Cumulative vol m^3	22925	22925	22925	22925	27370	27370	27370	27370	27370
Graph vol m^3	-69175	-69175	-69175	-69175	-64730	-64730	-64730	-64730	-64730
Replication	1	1	2		1	1	1	2	
Temperature (deg C)	26.1	111.7	111.7		24.4	24.4	108.9	108.9	
Temp @ pH deg C	21.6	89.8	89.8	NA	20.3	21.1	86.9	86.9	NA
pH	6.97	7.26	7.26	NA	7.01	6.92	7.17	7.17	NA
SC (umho/cm) @ 25 C	356	399	399	NA	361	362	376	376	NA
DO (mg/L)	0.1	0.2	0.2	NA	0.3	0.1	0.1	0.1	NA
Alk (meq/L)	4.30	4.34	4.32	0.01	4.40	4.39	4.35	4.39	0.00
SiO2 (mg/L) as Si	6.86	6.78	6.78	0.00	6.17	6.15	6.13	6.13	0.00
IC Analysis:									
SO4 (mg/L) as S	2.05	2.05	2.06	0.00	1.93	1.92	1.65	1.89	0.00
Cl (mg/L)	2.7	2.5	2.5	0.0	2.2	2.6	2.3	2.3	0.0
F (mg/L)	NA	NA	NA	0.00	0.34	0.29	0.28	NA	0.00
NO3 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NO2 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PO4 (mg/L) as P	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AA Analysis:									
Ca (mg/L)	0.2	2.3	3.3	0.0	51.2	1.1	5.9	6.2	0.0
Mg (mg/L)	0.2	0.4	0.5	0.0	17.3	2.4	6.3	6.3	0.0
Na (mg/L)	103	113	103	0	7	109	88	83	0
K (mg/L)	0.7	1.1	1.1	0.1	8.5	7.1	17.2	17.6	0.0
Fe (mg/L)	0.03	0.06	0.14	0.00	1.09	0.32	0.21	0.24	0.00
Hardness (mg/L) as CaCO3	1.3	7.5	10.1	0.0	199.0	12.8	40.7	41.5	0.0

TABLE B.1. (continued)

Well	B	B	B	B	Field Blank	AM4	AM4	B	B
Sample Type	I	II	III	III				I	II
Date sampled	841205	841205	841205	841205	841205	841205	841205	841207	841207
Time	1130	1200	1300	1305	1330	1430	1440	1745	1815
No. days since start	21	21	21	21	21	21	21	23	23
Cumulative vol m^3	29490	29490	29490	29490	29490	29490	29490	31760	31760
Graph vol m^3	-62610	-62610	-62610	-62610	-62610	-62610	-62610	-60340	-60340
Replication	1	1	1	2		1	2	1	1
Temperature (deg C)	23.9	23.9	114.4	114.4		81.5	81.5	22.8	22.8
Temp @ pH deg C	19.6	20.7	92.6	92.6	NA	11.1	11.1	19.4	18.7
pH	7.01	6.94	7.41	7.41	NA	7.00	7.00	6.92	6.95
SC (umho/cm) @ 25 C	354	373	376	376	NA	375	375	358	359
DO (mg/L)	0.1	0.1	0.1	0.1	NA	0.2	0.2	0.3	0.1
Alk (meq/L)	4.36	4.42	4.37	4.36	0.01	4.38	4.40	4.39	4.38
SiO2 (mg/L) as Si	5.92	5.94	5.94	5.94	0.00	20.82	21.25	5.68	5.60
IC Analysis:									
SO4 (mg/L) as S	1.58	1.89	1.89	1.61	0.00	1.66	1.71	1.76	1.78
Cl (mg/L)	1.9	6.0	2.8	2.6	0.0	7.1	7.1	1.9	2.6
F (mg/L)	NA	NA	0.34	NA	0.00	1.35	NA	0.32	0.33
NO3 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NO2 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PO4 (mg/L) as P	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AA Analysis:									
Ca (mg/L)	52.6	1.0	8.4	8.9	0.0	16.4	16.6	52.8	17.5
Mg (mg/L)	17.2	0.5	9.7	9.5	0.0	3.6	3.6	17.7	11.7
Na (mg/L)	7	109	78	67	0	82	81	7	60
K (mg/L)	9.1	0.6	19.8	19.8	0.0	9.7	9.5	9.0	7.5
Fe (mg/L)	1.09	0.00	0.21	0.21	0.00	1.83	1.86	0.66	0.25
Hardness (mg/L) as CaCO3	202.0	4.5	60.7	61.3	0.0	55.9	56.3	204.5	91.8

TABLE B.1. (continued)

Well	B	B	Field Blank	B	B	B	B	Field Blank	B
Sample Type	III	III		I	II	III	III		I
Date sampled	841207	841207	841207	841210	841210	841210	841210	841210	841212
Time	1840	1845	1930	620	645	700	705	730	1000
No. days since start	23	23	23	26	26	26	26	26	28
Cumulative vol m^3	31760	31760	31760	35725	35725	35725	35725	35725	37025
Graph vol m^3	-60340	-60340	-60340	-56375	-56375	-56375	-56375	-56375	-55075
Replication	1	2		1	1	1	2		1
Temperature (deg C)	118.3	118.3		21.1	21.1	110.0	110.0		20.6
Temp @ pH deg C	93.0	93.0	NA	17.8	19.5	94.4	94.4	NA	18.4
pH	7.38	7.38	NA	7.04	7.00	7.44	7.44	NA	7.05
SC (umhc/cm) @ 25 C	365	365	NA	356	370	431	431	NA	359
DO (mg/L)	0.1	0.1	NA	0.2	0.1	0.1	0.1	NA	0.3
Alk (meq/L)	4.16	4.16	-0.01	4.42	4.45	4.45	4.46	0.00	4.45
SiO2 (mg/L) as Si	5.60	5.64	0.00	5.30	5.28	5.28	5.26	0.00	5.22
IC Analysis:									
SO4 (mg/L) as S	1.78	1.78	0.00	1.71	1.72	1.72	1.71	0.00	1.72
Cl (mg/L)	2.2	2.2	0.0	1.9	6.1	4.3	4.2	0.0	2.0
F (mg/L)	0.33	0.28	0.00	0.34	0.36	0.35	0.35	0.00	0.34
NO3 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NO2 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PO4 (mg/L) as P	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AA Analysis:									
Ca (mg/L)	16.4	16.9	0.0	53.6	1.6	3.2	3.2	0.2	52.3
Mg (mg/L)	12.0	12.0	0.0	16.8	2.3	3.8	4.0	0.0	16.6
Na (mg/L)	55	63	1	7	98	93	98	0	7
K (mg/L)	5.7	5.6	0.0	8.7	1.3	1.6	1.5	0.1	8.3
Fe (mg/L)	0.01	0.05	0.00	0.62	0.03	0.01	0.01	0.01	0.62
Hardness (mg/L) as CaCO3	90.3	91.5	0.0	203.0	13.2	23.8	24.5	0.5	199.0

TABLE B.1. (continued)

Well	B	B	B	Field Blank	AM4	AM4	B	B	B
Sample Type	II	III	III				I	II	III
Date sampled	841212	841212	841212	841212	841212	841212	841214	841214	841214
Time	1020	1040	1045	1330	1535	1550	1230	1250	1310
No. days since start	28	28	28	28	28	28	30	30	30
Cumulative vol m^3	37025	37025	37025	37025	37025	37025	40275	40275	40275
Graph vol m^3	-55075	-55075	-55075	-55075	-55075	-55075	-51825	-51825	-51825
Replication	1	1	2		1	2	1	1	1
Temperature (deg C)	20.6	111.7	111.7		101.0	101.0	20.0	20.0	114.4
Temp @ pH deg C	18.6	82.5	82.5	NA	11.8	11.8	18.8	17.8	93.9
pH	7.03	7.24	7.24	NA	6.98	6.98	6.99	7.06	7.41
SC (umho/cm) @ 25 C	371	358	358	NA	369	369	364	499	448
DO (mg/L)	0.1	0.1	0.1	NA	0.2	0.2	0.1	0.4	0.2
Alk (meq/L)	4.42	4.33	4.33	0.00	4.08	4.06	4.46	4.50	4.53
SiO2 (mg/L) as Si	5.18	5.18	5.18	0.00	19.25	19.41	5.04	5.06	4.97
IC Analysis:									
SO4 (mg/L) as S	1.71	1.72	1.70	0.00	0.67	0.77	1.65	1.67	1.65
Cl (mg/L)	3.2	3.0	2.7	0.0	7.0	7.0	1.6	NA	5.4
F (mg/L)	0.34	0.34	0.34	0.00	1.46	NA	NA	NA	NA
NO3 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NO2 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PO4 (mg/L) as P	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AA Analysis:									
Ca (mg/L)	16.2	16.9	16.9	0.7	16.2	16.4	52.3	1.1	1.3
Mg (mg/L)	10.8	11.3	11.5	0.0	3.6	3.6	17.2	0.7	0.7
Na (mg/L)	59	59	59	0	71	69	8	123	116
K (mg/L)	12.8	11.0	10.6	0.1	9.6	9.6	8.1	0.6	0.6
Fe (mg/L)	0.23	0.03	0.05	0.00	1.23	1.16	0.51	0.03	0.00
Hardness (mg/L) as CaCO3	84.9	88.7	89.4	1.6	55.3	55.6	201.2	5.5	6.1

TABLE B.1. (continued)

Well	B	Field Blank	B	B	B	B	Field Blank	B	B
Sample Type	III		I	II	III	III		I	II
Date sampled	841214	841214	841217	841217	841217	841217	841217	841219	841219
Time	1315	1345	1120	1140	1210	1210	1245	1130	1150
No. days since start	30	30	33	33	33	33	33	35	35
Cumulative vol m^3	40275	40275	44870	44870	44870	44870	44870	47980	47980
Graph vol m^3	-51825	-51825	-47230	-47230	-47230	-47230	-47230	-44120	-44120
Replication	2		1	1	1	2		1	1
Temperature (deg C)	114.4		18.9	18.9	111.7	111.7		17.8	17.8
Temp @ pH deg C	93.9	NA	14.0	17.1	89.5	89.5	NA	17.0	17.2
pH	7.41	NA	7.05	7.05	7.28	7.28	NA	7.10	7.06
SC (umho/cm) @ 25 C	448	NA	366	367	467	467	NA	355	366
DO (mg/L)	0.2	NA	0.3	0.3	0.3	0.3	NA	0.2	0.2
Alk (meq/L)	4.54	0.01	4.48	4.46	4.54	4.55	-0.02	4.44	4.39
SiO2 (mg/L) as Si	5.01	0.00	4.79	4.79	4.81	4.79	0.00	4.61	4.61
IC Analysis:									
SO4 (mg/L) as S	1.71	0.00	1.69	1.65	1.71	1.69	0.00	1.62	1.63
Cl (mg/L)	5.1	0.0	1.7	3.0	25.1	24.5	0.0	1.6	2.5
F (mg/L)	NA	0.00	0.45	0.34	0.36	0.37	0.00	0.34	NA
NO3 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NO2 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PO4 (mg/L) as P	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AA Analysis:									
Ca (mg/L)	1.3	0.0	51.2	1.2	1.6	1.6	0.0	51.6	10.0
Mg (mg/L)	0.7	0.0	17.7	2.0	1.0	1.0	0.0	17.7	8.7
Na (mg/L)	111	0	7	99	122	111	0	7	72
K (mg/L)	0.6	0.1	7.8	3.6	1.1	1.1	0.0	7.8	16.3
Fe (mg/L)	0.00	0.00	0.55	0.00	0.00	0.00	0.00	0.55	0.14
Hardness (mg/L) as CaCO3	6.1	0.0	200.5	11.2	8.2	8.2	0.0	201.6	60.5

TABLE B.1. (continued)

Well	B	B	Field Blank	AM4	AM4	B	B	B	B
Sample Type	III	III				I	II	III	III
Date sampled	841219	841219	841219	841219	841219	841228	841228	841228	841228
Time	1310	1310	1330	1540	1545	1400	1415	1440	1445
No. days since start	35	35	35	35	35	44	44	44	44
Cumulative vol m^3	47980	47980	47980	47980	47980	51330	51330	51330	51330
Graph vol m^3	-44120	-44120	-44120	-44120	-44120	-40770	-40770	-40770	-40770
Replication	1	2		1	2	1	1	1	2
Temperature (deg C)	110.6	110.6		106.8	106.8	16.7	16.7	115.0	115.0
Temp @ pH deg C	86.5	86.5	NA	12.1	12.1	17.8	17.7	90.4	90.4
pH	7.34	7.34	NA	7.03	7.03	7.07	7.08	7.40	7.40
SC (umho/cm) @ 25 C	417	417	NA	320	320	330	348	412	412
DO (mg/L)	0.2	0.2	NA	0.3	0.3	0.3	0.1	0.3	0.3
Alk (meq/L)	4.49	4.47	0.00	3.63	3.60	4.45	4.42	4.40	4.38
SiO2 (mg/L) as Si	4.59	4.65	0.00	11.66	11.86	4.53	4.51	4.57	4.55
IC Analysis:									
SO4 (mg/L) as S	1.65	1.67	0.00	0.16	0.34	1.64	1.64	1.68	1.64
Cl (mg/L)	31.1	30.8	0.0	7.9	8.2	1.9	4.8	3.8	3.8
F (mg/L)	0.35	0.38	0.00	1.34	NA	0.28	0.28	0.34	0.34
NO3 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NO2 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PO4 (mg/L) as P	0.00	0.00	0.00	0.55	0.55	0.00	0.00	0.00	0.00
AA Analysis:									
Ca (mg/L)	2.1	2.5	0.8	13.9	13.5	52.5	2.5	4.7	5.6
Mg (mg/L)	1.3	1.3	0.0	4.2	4.2	16.6	1.9	3.8	4.2
Na (mg/L)	112	119	0	63	66	7	97	36	85
K (mg/L)	1.2	1.3	0.0	8.9	8.9	7.6	3.1	9.3	10.2
Fe (mg/L)	0.00	0.01	0.01	0.08	0.64	0.69	0.09	0.00	0.00
Hardness (mg/L) as CaCO3	10.6	11.7	1.9	51.8	50.7	199.5	14.2	27.4	31.2

<u>TABLE B.1</u>. (continued)

Well	Field Blank	B	B	B	B	Field Blank	B	B	B
Sample Type		I	II	III	III		I	II	III
Date sampled	841228	841231	841231	841231	841231	841231	850102	850102	850102
Time	1530	1200	1230	1255	1300	1345	1325	1355	1420
No. days since start	44	47	47	47	47	47	49	49	49
Cumulative vol m^3	51330	55815	55815	55815	55815	55815	59000	59000	59000
Graph vol m^3	-40770	-36285	-36285	-36285	-36285	-36285	-33100	-33100	-33100
Replication		1	1	1	2	1	1	1	1
Temperature (deg C)		16.7	16.7	106.1	106.1		16.1	16.1	106.7
Temp @ pH deg C	NA	15.8	17.0	89.3	89.3	NA	16.2	16.2	83.9
pH	NA	7.10	7.10	7.30	7.30	NA	7.09	7.10	7.33
SC (umho/cm) @ 25 C	NA	357	375	430	430	NA	364	373	428
DO (mg/L)	NA	0.3	0.1	0.2	0.2	NA	0.1	0.1	0.2
Alk (meq/L)	-0.02	4.42	4.43	4.41	4.45	0.00	4.44	4.44	4.45
SiO2 (mg/L) as Si	0.00	4.41	4.43	4.43	4.45	0.00	4.39	4.39	4.37
IC Analysis:									
SO4 (mg/L) as S	0.00	1.60	1.61	1.61	1.61	0.00	1.59	1.60	1.57
Cl (mg/L)	0.0	1.6	9.3	6.5	6.3	0.0	1.4	3.5	3.1
F (mg/L)	0.00	0.34	0.35	NA	NA	0.00	NA	NA	0.33
NO3 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NO2 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PO4 (mg/L) as P	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AA Analysis:									
Ca (mg/L)	0.3	52.9	1.6	1.6	1.6	0.8	51.6	0.8	1.2
Mg (mg/L)	0.0	16.5	0.4	0.4	0.4	0.1	17.5	0.6	1.1
Na (mg/L)	1	7	103	103	104	0	7	101	102
K (mg/L)	0.1	7.5	1.6	1.6	1.6	0.0	7.6	1.8	2.1
Fe (mg/L)	0.00	0.50	0.00	0.00	0.00	0.00	0.45	0.00	0.00
Hardness (mg/L) as CaCO3	0.8	199.9	5.7	5.7	5.7	2.2	201.1	4.4	7.4

TABLE B.1. (continued)

Well	B	Field Blank	B	B	B	B	Field Blank	AM4	AM4
Sample Type	III		I	II	III	III			
Date sampled	850102	850102	850104	850104	850104	850104	850104	850104	850104
Time	1420	1500	1045	1155	1220	1220	1355	1500	1500
No. days since start	49	49	51	51	51	51	51	51	51
Cumulative vol m^3	59000	59000	61920	61920	61920	61920	61920	61920	61920
Graph vol m^3	-33100	-33100	-30180	-30180	-30180	-30180	-30180	-30180	-30180
Replication	2	1	1	1	1	2	1	1	2
Temperature (deg C)	106.7		15.6	15.6	106.1	106.1		107.4	107.4
Temp @ pH deg C	83.9	NA	17.6	17.6	86.6	86.6	NA	13.4	13.4
pH	7.33	NA	7.12	7.08	7.52	7.52	NA	7.10	7.10
SC (umho/cm) @ 25 C	428	NA	370	373	436	436	NA	319	319
DO (mg/L)	0.2	NA	0.2	0.3	0.3	0.3	NA	0.3	0.3
Alk (meq/L)	4.42	0.00	4.45	4.42	4.48	4.47	-0.01	3.40	3.39
SiO2 (mg/L) as Si	4.35	0.00	4.26	4.22	4.28	4.24	0.00	9.19	9.13
IC Analysis:									
SO4 (mg/L) as S	1.60	0.00	1.56	1.55	1.58	1.60	0.00	0.11	0.16
Cl (mg/L)	4.2	0.0	1.4	2.7	34.3	34.8	0.0	12.2	12.1
F (mg/L)	NA	0.00	0.33	NA	NA	NA	0.00	1.50	NA
NO3 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NO2 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PO4 (mg/L) as P	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.80	1.38
AA Analysis:									
Ca (mg/L)	1.6	0.3	50.9	2.3	2.3	2.3	0.0	9.5	9.5
Mg (mg/L)	1.0	0.0	16.4	2.0	1.0	0.9	0.2	2.9	2.8
Na (mg/L)	114	0	8	92	110	99	0	65	64
K (mg/L)	2.0	0.1	7.6	4.1	1.8	1.7	0.0	8.1	8.1
Fe (mg/L)	0.00	0.00	0.47	0.04	0.00	0.00	0.00	0.88	0.93
Hardness (mg/L) as CaCO3	8.2	0.8	194.5	13.9	9.8	9.4	0.6	35.6	35.3

TABLE B.1. (continued)

Well	B	B	B	B	Field Blank	B	B	B	B
Sample Type	I	II	III	III		I	II	III	III
Date sampled	850107	850107	850107	850107	850107	850109	850109	850109	850109
Time	1115	1135	1205	1205	1305	1220	1115	1140	1140
No. days since start	54	54	54	54	54	56	56	56	56
Cumulative vol m^3	66540	66540	66540	66540	66540	69325	69325	69325	69325
Graph vol m^3	-25560	-25560	-25560	-25560	-25560	-22775	-22775	-22775	-22775
Replication	1	1	1	2		1	1	1	2
Temperature (deg C)	15.0	15.0	104.4	104.4		15.0	15.0	100.6	100.6
Temp @ pH deg C	15.9	15.4	78.1	78.1	NA	13.0	15.3	77.2	77.2
pH	7.14	7.09	7.46	7.46	NA	6.93	7.07	7.46	7.46
SC (umho/cm) @ 25 C	375	378	389	389	NA	367	366	420	420
DO (mg/L)	0.2	0.1	0.2	0.2	NA	0.2	0.2	0.1	0.1
Alk (meq/L)	4.47	4.43	4.45	4.44	-0.01	4.45	4.45	4.45	4.47
SiO2 (mg/L) as Si	4.14	4.18	4.14	4.28	0.00	4.12	4.20	3.96	4.02
IC Analysis:									
SO4 (mg/L) as S	1.55	1.54	1.58	1.58	0.00	1.55	1.56	1.83	1.89
Cl (mg/L)	1.5	3.3	2.8	2.8	0.0	1.4	6.2	137.7	135.4
F (mg/L)	NA	NA	NA	NA	0.00	0.33	NA	0.42	NA
NO3 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NO2 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PO4 (mg/L) as P	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AA Analysis:									
Ca (mg/L)	53.2	2.7	4.1	3.6	0.0	51.3	1.3	6.8	6.8
Mg (mg/L)	16.4	1.2	1.9	2.0	0.1	17.3	1.2	2.4	2.4
Na (mg/L)	8	100	98	159	0	7	104	194	192
K (mg/L)	7.2	1.9	2.9	3.1	0.0	7.8	2.1	4.1	3.8
Fe (mg/L)	0.52	0.01	0.00	0.00	0.00	0.45	0.00	0.00	0.00
Hardness (mg/L) as CaCO3	200.2	11.8	18.2	17.3	0.3	199.2	8.2	26.7	26.9

TABLE B. (continued)

Well	Field Blank	B	B	B	B	Field Blank	B	B	B
Sample Type		I	II	III	III		I	II	III
Date sampled	850109	850111	850111	850111	850111	850111	850117	850117	850117
Time	1245	1245	1300	1325	1325	1515	1140	1200	1225
No. days since start	56	58	58	58	58	58	64	64	64
Cumulative vol m^3	69325	72450	72450	72450	72450	72450	75105	75105	75105
Graph vol m^3	-22775	-19650	-19650	-19650	-19650	-19650	-16995	-16995	-16995
Replication		1	1	1	2		1	1	1
Temperature (deg C)		14.4	14.4	102.2	102.2		14.4	14.4	111.1
Temp @ pH deg C	NA	13.7	14.9	83.7	83.7	NA	12.9	15.0	91.9
pH	NA	7.09	7.08	7.56	7.56	NA	7.13	7.09	7.86
SC (umho/cm) @ 25 C	NA	374	397	410	410	NA	380	387	463
DO (mg/L)	NA	0.4	0.2	0.2	0.2	NA	0.3	0.2	0.1
Alk (meq/L)	0.01	4.47	4.46	4.45	4.46	0.00	4.46	4.46	4.44
SiO2 (mg/L) as Si	0.00	4.10	4.12	4.06	4.12	0.05	4.21	4.21	4.15
IC Analysis:									
SO4 (mg/L) as S	0.00	1.49	1.48	1.53	1.49	0.00	1.49	1.54	1.57
Cl (mg/L)	0.0	1.4	5.5	4.0	4.0	0.0	1.6	2.4	2.3
F (mg/L)	0.00	NA	NA	NA	NA	0.00	NA	0.35	0.35
NO3 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NO2 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PO4 (mg/L) as P	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AA Analysis:									
Ca (mg/L)	0.0	50.0	1.8	1.8	1.8	0.4	47.3	0.0	0.9
Mg (mg/L)	0.2	16.9	0.9	0.7	0.7	0.0	17.0	0.5	1.1
Na (mg/L)	1	8	104	103	102	1	8	101	100
K (mg/L)	0.0	7.7	5.8	5.5	5.4	0.0	7.7	3.8	5.2
Fe (mg/L)	0.00	0.47	0.01	0.00	0.00	0.00	0.69	0.01	0.00
Hardness (mg/L) as CaCO3	0.8	194.5	8.0	7.2	7.2	1.1	187.9	2.1	6.5

TABLE B.1. (continued)

Well	B	Field Blank	B	B	B	B	Field Blank	B	B
Sample Type	III		I	II	III	III		I	II
Date sampled	850117	850117	850119	850119	850119	850119	850119	850121	850121
Time	1225	1300	1305	1325	1355	1355	1425	1350	1420
No. days since start	64	64	66	66	66	66	66	68	68
Cumulative vol m^3	75105	75105	78380	78380	78380	78380	78380	81515	81515
Graph vol m^3	-16995	-16995	-13720	-13720	-13720	-13720	-13720	-10585	-10585
Replication	2		1	1	1	2		1	1
Temperature (deg C)	111.1		13.9	13.9	100.6	100.6		13.9	13.9
Temp @ pH deg C	91.9	NA	14.4	14.0	72.2	72.2	NA	15.0	14.3
pH	7.86	NA	7.09	7.18	7.28	7.28	NA	7.08	7.12
SC (umho/cm) @ 25 C	463	NA	364	377	420	420	NA	389	427
DO (mg/L)	0.1	NA	0.2	0.1	0.1	0.1	NA	0.2	0.1
Alk (meq/L)	4.47	-0.01	4.46	4.52	4.50	4.47	0.01	4.44	4.51
SiO2 (mg/L) as Si	4.23	0.07	4.14	4.19	4.19	4.23	0.07	4.21	4.15
IC Analysis:									
SO4 (mg/L) as S	1.54	0.00	1.51	1.57	1.59	1.59	0.00	1.54	1.66
Cl (mg/L)	2.3	0.0	1.6	50.4	19.1	18.9	0.0	1.4	19.6
F (mg/L)	0.35	0.00	0.33	0.34	0.35	0.35	0.00	NA	0.35
NO3 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NO2 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PO4 (mg/L) as P	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AA Analysis:									
Ca (mg/L)	0.9	0.0	53.8	1.4	0.9	0.9	0.1	53.7	1.4
Mg (mg/L)	1.2	0.0	17.1	0.2	0.2	0.2	0.0	17.0	0.5
Na (mg/L)	98	1	8	110	111	105	0	8	107
K (mg/L)	5.2	0.0	7.6	2.2	2.1	2.2	0.0	7.5	3.3
Fe (mg/L)	0.00	0.00	0.45	0.00	0.00	0.00	0.00	0.45	0.00
Hardness (mg/L) as CaCO3	7.1	0.0	204.9	4.3	2.9	2.9	0.3	203.9	5.3

TABLE B.1. (continued)

Well	B	B	Field Blank	AM4	AM4	B	B	B	B
Sample Type	III	III				I	II	III	III
Date sampled	850121	850121	850121	850121	850121	850123	850123	850123	850123
Time	1445	1445	1525	1625	1625	1040	1100	1135	1135
No. days since start	68	68	68	68	68	70	70	70	70
Cumulative vol m^3	81515	81515	81515	81515	81515	84290	84290	84290	84290
Graph vol m^3	-10585	-10585	-10585	-10585	-10585	-7810	-7810	-7810	-7810
Replication	1	2		1	2	1	1	1	2
Temperature (deg C)	103.3	103.3		104.2	104.2	13.3	13.3	104.4	104.4
Temp @ pH deg C	78.2	78.2	NA	10.1	10.1	14.5	14.2	89.2	89.2
pH	7.49	7.49	NA	7.09	7.09	7.09	7.12	7.60	7.60
SC (umho/cm) @ 25 C	450	450	NA	358	358	375	397	458	458
DO (mg/L)	0.2	0.2	NA	0.3	0.3	0.1	0.1	0.1	0.1
Alk (meq/L)	4.49	4.47	0.00	3.67	3.66	4.46	4.49	4.45	4.49
SiO2 (mg/L) as Si	4.17	4.23	0.07	11.08	11.14	4.22	4.31	4.16	4.27
IC Analysis:									
SO4 (mg/L) as S	1.59	1.65	0.00	0.35	0.69	1.61	1.65	1.65	1.62
Cl (mg/L)	8.4	8.4	0.0	15.0	15.0	1.7	7.2	5.1	4.9
F (mg/L)	0.32	0.33	0.00	NA	1.30	0.31	NA	NA	NA
NO3 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NO2 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PO4 (mg/L) as P	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AA Analysis:									
Ca (mg/L)	0.9	0.9	0.0	8.0	8.2	53.8	1.4	0.9	0.9
Mg (mg/L)	0.3	0.3	0.0	2.2	2.3	17.1	0.2	0.2	0.3
Na (mg/L)	104	104	0	85	83	7	103	107	109
K (mg/L)	3.1	3.2	0.0	7.7	7.8	7.4	3.8	3.7	3.7
Fe (mg/L)	0.00	0.00	0.00	0.23	0.23	0.40	0.00	0.00	0.00
Hardness (mg/L) as CaCO3	3.4	3.2	0.0	29.2	29.9	204.7	4.3	2.9	3.2

TABLE B.1. (continued)

Well	Field Blank	B	B	B	B	Field Blank	B	B	B
Sample Type		I	II	III	III		I	II	III
Date sampled	850123	850125	850125	850125	850125	850125	850128	850128	850128
Time	1215	1100	1120	1150	1150	1240	1045	1110	1135
No. days since start	70	72	72	72	72	72	75	75	75
Cumulative vol m^3	84290	87420	87420	87420	87420	87420	91960	91960	91960
Graph vol m^3	-7810	-4680	-4680	-4680	-4680	-4680	-140	-140	-140
Replication		1	1	1	2		1	1	1
Temperature (deg C)		13.3	13.3	95.6	95.6		13.3	13.3	97.8
Temp @ pH deg C	NA	14.5	14.9	70.5	70.5	NA	16.1	14.6	83.7
pH	NA	7.08	7.13	7.22	7.22	NA	7.08	7.13	7.50
SC (umho/cm) @ 25 C	NA	381	394	402	402	NA	382	396	451
DO (mg/L)	NA	0.2	0.2	0.2	0.2	NA	0.2	0.4	0.2
Alk (meq/L)	0.01	4.45	4.45	4.49	4.47	0.02	4.50	4.47	4.49
SiO2 (mg/L) as Si	0.13	4.06	4.06	4.22	4.18	0.11	4.04	4.08	4.10
IC Analysis:									
SO4 (mg/L) as S	0.00	1.59	1.65	1.59	1.59	0.00	1.65	1.71	1.71
Cl (mg/L)	0.0	1.9	6.1	4.8	4.8	0.0	1.6	6.3	4.8
F (mg/L)	0.00	0.31	NA	0.32	0.33	NA	NA	NA	NA
NO3 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NO2 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PO4 (mg/L) as P	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AA Analysis:									
Ca (mg/L)	0.1	53.1	0.7	0.7	0.7	0.0	53.5	0.9	0.9
Mg (mg/L)	0.0	16.9	0.3	0.3	0.3	0.0	17.1	0.3	0.3
Na (mg/L)	0	7	106	103	102	0	7	103	105
K (mg/L)	0.0	7.7	3.6	3.6	3.6	0.0	7.6	3.6	3.5
Fe (mg/L)	0.00	0.40	0.00	0.00	0.00	0.00	0.47	0.00	0.00
Hardness (mg/L) as CaCO3	0.3	202.0	2.7	2.7	2.7	0.0	204.0	3.4	3.4

TABLE B.1. (continued)

Well	B	Field Blank
Sample Type	III	
Date sampled	850128	850128
Time	1135	1205
No. days since start	75	75
Cumulative vol m^3	91960	91960
Graph vol m^3	-140	-140
Replication	2	
Temperature (deg C)	97.8	
Temp @ pH deg C	83.7	NA
pH	7.50	NA
SC (umho/cm) @ 25 C	451	NA
DO (mg/L)	0.2	NA
Alk (meq/L)	4.46	-0.01
SiO2 (mg/L) as Si	4.18	0.13
IC Analysis:		
SO4 (mg/L) as S	1.65	0.00
Cl (mg/L)	4.8	0.0
F (mg/L)	NA	NA
NO3 (mg/L) as N	0.00	0.00
NO2 (mg/L) as N	0.00	0.00
PO4 (mg/L) as P	0.00	0.00
AA Analysis:		
Ca (mg/L)	0.9	0.0
Mg (mg/L)	0.3	0.0
Na (mg/L)	105	0
K (mg/L)	3.5	0.0
Fe (mg/L)	0.00	0.00
Hardness (mg/L) as CaCO3	3.4	0.0

TABLE B.2. Water Analyses, LT1, Storage and Recovery Phases, March to May 1985

Well	AM4	AM4	Field Blank	A	A	Field Blank	A	A	A
Sample Type				III	III		III	III	III
Date sampled	850321	850321	850321	850402	850402	850402	850404	850404	850406
Time	1600	1600		1540	1540		1415	1415	1315
No. days since start	-12	-12	-12	0	0	0	2	2	4
Cum. vol m^3	-----	-----	-----	112	112	112	3264	3264	6435
Replication	1	2		1	2		1	2	1
Temperature (deg C)	99.0	99.0		93.3	93.3		93.3	93.3	92.8
Temp @ pH deg C	20.3	20.3	NA	40.9	40.9	NA	34.7	34.7	68.8
pH	7.11	7.11	NA	6.97	6.97	NA	7.24	7.24	7.07
SC (umho/cm) @ 25 C	426	426	NA	490	490	NA	504	504	512
DO (mg/L)	<1	<1	NA	0.5	0.5	NA	0.5	0.5	1.5
Alk (meq/L)	4.82	4.85	-0.03	4.66	4.66	-0.01	4.66	4.68	4.66
SiO2 (mg/L) as Si	22.96	20.42	0.01	18.49	18.49	0.00	21.10	21.29	21.97
IC Analysis:									
SO4 (mg/L) as S	2.31	1.97	0.00	1.97	1.97	0.00	1.66	1.72	1.78
Cl (mg/L)	27.2	24.2	0.0	18.7	18.7	0.0	21.2	21.1	24.5
F (mg/L)	1.11	1.35	0.00	0.40	0.38	0.00	0.36	0.38	0.41
NO3 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NO2 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PO4 (mg/L) as P	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AA Analysis:									
Ca (mg/L)	14.4	16.8	0.0	7.9	7.9	0.0	4.3	4.3	4.8
Mg (mg/L)	1.0	1.0	0.0	3.4	3.3	0.0	1.9	1.9	2.1
Na (mg/L)	105	106	0	100	103	0	106	109	103
K (mg/L)	8.1	8.1	0.0	6.3	6.4	0.0	6.0	6.0	6.8
Fe (mg/L)	4.43	3.98	0.00	0.12	0.08	0.00	0.12	0.12	0.12
Hardness (mg/L) as CaCO3	40.1	46.1	0.0	33.6	33.3	0.0	18.6	18.6	20.6

TABLE B.2. (continued)

Well	A	A	A	Field Blank	A	A	AM4	AM4	A
Sample Type	III	III	III		III	III			III
Date sampled	850406	850408	850408	850408	850410	850410	850410	850410	850412
Time	1315	1225	1225		1310	1310	1435	1435	1520
No. days since start	4	6	6	6	8	8	8	8	10
Cum. vol m^3	6435	9631	9631	9631	12899	12899	12995	12995	16261
Replication	2	1	2		1	2	1	2	1
Temperature (deg C)	92.8	92.2	92.2		91.9	91.9	95.8	95.8	90.6
Temp @ pH deg C	68.8	68.5	68.5	NA	68.5	68.5	20.8	20.8	70.4
pH	7.07	7.03	7.03	NA	7.06	7.06	6.90	6.90	7.04
SC (umho/cm) @ 25 C	512	514	514	NA	513	513	446	446	510
DO (mg/L)	1.5	1.5	1.5	NA	2.0	2.0	0.3	0.3	0.8
Alk (meq/L)	4.64	4.61	4.61	-0.02	4.56	4.56	4.38	4.41	4.64
SiO2 (mg/L) as Si	21.10	22.28	22.28	0.00	22.15	21.78	20.98	21.10	21.78
IC Analysis:									
SO4 (mg/L) as S	1.78	1.84	1.87	0.00	1.70	1.78	1.78	1.70	2.00
Cl (mg/L)	25.1	25.1	25.1	0.0	21.6	21.6	20.5	20.5	22.6
F (mg/L)	0.41	0.42	0.43	0.00	0.43	0.43	1.19	1.19	0.47
NO3 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NO2 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PO4 (mg/L) as P	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AA Analysis:									
Ca (mg/L)	4.8	5.0	5.3	0.0	6.0	6.0	11.6	11.6	6.9
Mg (mg/L)	2.0	2.5	2.6	0.0	2.6	2.5	2.0	2.0	2.8
Na (mg/L)	108	108	101	0	102	101	100	97	95
K (mg/L)	7.1	7.6	7.6	0.0	8.3	8.2	10.6	10.8	9.2
Fe (mg/L)	0.12	0.15	0.18	0.00	0.15	0.15	0.51	0.51	0.18
Hardness (mg/L) as CaCO3	20.3	22.9	23.7	0.0	25.5	25.2	37.1	37.1	28.6

TABLE B.2. (continued)

Well	A	Field Blank	A	A	A	A	Field Blank	AM4	AM4
Sample Type	III		III	III	III	III			
Date sampled	850412	850412	850415	850415	850418	850418	850418	850418	850418
Time	1520		1315	1315	1055	1055		1400	1400
No. days since start	10	10	13	13	16	16	16	16	16
Cum. vol m^3	16261	16261	20963	20963	25659	25659	25659	25867	25867
Replication	2		1	2	1	2		1	2
Temperature (deg C)	90.6		89.4	89.4	87.5	87.5		87.8	87.8
Temp @ pH deg C	70.4	NA	72.5	72.5	63.9	63.9	NA	19.5	19.5
pH	7.04	NA	7.04	7.04	7.00	7.00	NA	6.92	6.92
SC (umho/cm) @ 25 C	510	NA	513	513	502	502	NA	411	411
DO (mg/L)	0.8	NA	0.6	0.6	1.0	1.0	NA	0.2	0.2
Alk (meq/L)	4.62	0.00	4.61	4.61	4.59	4.60	0.01	4.30	4.30
Si02 (mg/L) as Si	21.53	0.00	21.91	21.19	20.38	20.19	0.00	19.51	19.38
IC Analysis:									
S04 (mg/L) as S	1.96	0.00	2.00	2.04	1.86	2.03	0.00	2.07	2.03
Cl (mg/L)	22.6	0.0	22.1	22.1	20.7	21.7	0.0	18.3	18.3
F (mg/L)	0.47	0.00	0.48	0.48	0.47	0.49	0.00	1.04	1.05
N03 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
N02 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
P04 (mg/L) as P	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AA Analysis:									
Ca (mg/L)	6.9	0.0	7.8	7.8	9.1	9.1	0.0	13.5	13.5
Mg (mg/L)	2.9	0.0	3.2	3.2	3.4	3.4	0.0	3.6	3.5
Na (mg/L)	98	0	95	97	91	95	0	82	85
K (mg/L)	9.2	0.0	9.5	9.5	10.0	10.0	0.0	10.5	10.6
Fe (mg/L)	0.18	0.00	0.18	0.18	0.18	0.18	0.00	0.81	0.84
Hardness (mg/L) as CaC03	29.1	0.0	32.9	32.9	36.6	36.6	0.0	48.4	48.1

TABLE B.2. (continued)

Well	A	A	A	A	A	A	Field Blank	A	A
Sample Type	III	III	III	III	III	III		III	III
Date sampled	850422	850422	850426	850426	850429	850429	850429	850502	850502
Time	1150	1150	1400	1400	1420	1420		1100	1100
No. days since start	20	20	24	24	27	27	27	30	30
Cum. vol m^3	32141	32141	37310	37310	42112	42112	42112	46649	46649
Replication	1	2	1	2	1	2		1	2
Temperature (deg C)	85.3	85.3	82.5	82.5	79.4	79.4		77.5	77.5
Temp @ pH deg C	70.4	70.4	62.3	62.3	66.4	66.4	NA	64.1	64.1
pH	6.93	6.93	6.90	6.90	6.98	6.98	NA	6.94	6.94
SC (umho/cm) @ 25 C	490	490	499	499	498	498	NA	481	481
DO (mg/L)	1.5	1.5	0.8	0.8	0.8	0.8	NA	0.8	0.8
Alk (meq/L)	4.58	4.56	4.60	4.57	4.60	4.56	0.02	4.57	4.56
SiO2 (mg/L) as Si	19.91	19.91	18.80	18.80	17.88	18.15	0.00	16.77	17.03
IC Analysis:									
SO4 (mg/L) as S	2.07	2.16	1.96	2.12	2.16	2.20	0.00	2.15	2.15
Cl (mg/L)	20.7	20.9	19.6	20.0	18.6	18.4	0.0	15.8	15.8
F (mg/L)	0.52	0.55	0.55	0.54	0.55	0.55	0.00	0.55	0.55
NO3 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NO2 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PO4 (mg/L) as P	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AA Analysis:									
Ca (mg/L)	11.3	11.3	12.9	12.9	14.8	15.1	0.0	16.9	17.2
Mg (mg/L)	4.0	4.2	4.2	4.1	4.6	4.6	0.0	5.1	5.1
Na (mg/L)	88	88	93	92	87	81	0	85	81
K (mg/L)	10.4	10.8	10.8	11.0	11.0	10.9	0.0	10.9	10.8
Fe (mg/L)	0.29	0.29	0.21	0.21	0.23	0.21	0.00	0.21	0.23
Hardness (mg/L) as CaCO3	44.6	45.4	49.3	49.0	55.7	56.7	0.0	63.0	63.6

TABLE B.2. (continued)

Well	A	A	Field Blank	A	A	A	A	Field Blank	A
Sample Type	III	III		III	III	III	III		III
Date sampled	850506	850506	850506	850509	850509	850513	850513	850513	850516
Time	1315	1315		1210	1210	1330	1330		1230
No. days since start	34	34	34	37	37	41	41	41	44
Cum. vol m^3	53124	53124	53124	57785	57785	64213	64213	64213	68884
Replication	1	2		1	2	1	2		1
Temperature (deg C)	73.1	73.1		71.1	71.1	65.8	65.8		63.1
Temp @ pH deg C	62.6	62.6	NA	60.4	60.4	55.6	55.6	NA	51.2
pH	6.98	6.98	NA	7.00	7.00	6.99	6.99	NA	6.95
SC (umho/cm) @ 25 C	459	459	NA	495	495	480	480	NA	478
DO (mg/L)	0.6	0.6	NA	1.5	1.5	0.6	0.6	NA	0.2
Alk (meq/L)	4.60	4.57	0.01	4.62	4.60	4.63	4.66	0.00	4.63
SiO2 (mg/L) as Si	15.85	15.72	0.00	14.87	15.13	13.43	13.37	0.00	12.52
IC Analysis:									
SO4 (mg/L) as S	2.54	2.63	0.00	2.63	2.63	2.72	2.72	0.00	2.81
Cl (mg/L)	16.8	17.2	0.0	15.3	15.3	13.3	13.3	0.0	12.0
F (mg/L)	0.53	0.56	0.00	0.54	0.53	0.52	0.50	0.00	0.50
NO3 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NO2 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PO4 (mg/L) as P	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AA Analysis:									
Ca (mg/L)	20.1	20.3	0.0	22.5	22.2	24.6	24.6	0.0	27.0
Mg (mg/L)	5.7	5.6	0.0	6.2	6.1	6.9	6.9	0.0	7.4
Na (mg/L)	76	75	0	68	71	67	68	0	63
K (mg/L)	10.8	10.9	0.0	10.7	10.6	10.2	10.2	0.2	9.9
Fe (mg/L)	0.39	0.39	0.00	0.41	0.41	0.39	0.37	0.00	0.39
Hardness (mg/L) as CaCO3	73.5	73.8	0.0	81.4	80.5	89.7	89.7	0.0	97.6

TABLE B.2. (continued)

Well	A	A	A	A	A	Field Blank	A	A	A
Sample Type	III	III	III	III	III		III	III	III
Date sampled	850516	850520	850520	850523	850523	850523	850528	850528	850530
Time	1230	1230	1230	1200	1200		1010	1010	1025
No. days since start	44	48	48	51	51	51	56	56	58
Cum. vol m^3	68884	75184	75184	79861	79861	79861	87596	87596	90735
Replication	2	1	2	1	2		1	2	1
Temperature (deg C)	63.1	58.3	58.3	54.7	54.7		48.9	48.9	46.9
Temp @ pH deg C	51.2	51.0	51.0	46.1	46.1	NA	45.2	45.2	42.2
pH	6.95	6.96	6.96	6.95	6.95	NA	6.97	6.97	7.00
SC (umho/cm) @ 25 C	478	454	454	456	456	NA	443	443	453
DO (mg/L)	0.2	0.2	0.2	0.2	0.2	NA	0.2	0.2	0.2
Alk (meq/L)	4.63	4.64	4.65	4.64	4.63	0.00	4.62	4.61	4.62
SiO2 (mg/L) as Si	13.43	11.21	11.21	10.42	10.42	0.00	9.13	9.13	8.74
IC Analysis:									
SO4 (mg/L) as S	2.81	2.62	2.62	2.66	2.70	0.00	2.71	2.75	2.79
Cl (mg/L)	12.0	9.5	9.5	8.4	8.4	0.0	7.3	7.4	6.7
F (mg/L)	0.50	0.49	0.51	0.49	0.49	0.00	0.46	0.46	0.45
NO3 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NO2 (mg/L) as N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PO4 (mg/L) as P	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AA Analysis:									
Ca (mg/L)	27.0	29.9	29.9	29.1	30.7	0.0	33.2	33.7	36.1
Mg (mg/L)	7.4	8.4	8.4	9.1	9.2	0.0	10.5	10.4	11.1
Na (mg/L)	60	56	56	51	50	0	42	41	41
K (mg/L)	9.8	9.6	9.5	9.2	9.2	0.0	8.8	8.8	9.4
Fe (mg/L)	0.39	0.41	0.41	0.37	0.37	0.00	0.46	0.46	0.55
Hardness (mg/L) as CaCO3	97.6	109.0	109.0	110.0	114.4	0.0	126.2	127.0	135.8

TABLE B.2. (continued)

Well	A	Field Blank
Sample Type	III	
Date sampled	850530	850530
Time	1025	
No. days since start	58	58
Cum. vol m^3	90735	90735
Replication	2	
Temperature (deg C)	46.9	
Temp @ pH deg C	42.2	NA
pH	7.00	NA
SC (umho/cm) @ 25 C	453	NA
DO (mg/L)	0.2	NA
Alk (meq/L)	4.57	0.01
SiO2 (mg/L) as Si	8.74	0.00
IC Analysis:		
SO4 (mg/L) as S	2.79	0.00
Cl (mg/L)	6.8	0.0
F (mg/L)	0.45	0.00
NO3 (mg/L) as N	0.00	0.00
NO2 (mg/L) as N	0.00	0.00
PO4 (mg/L) as P	0.00	0.00
AA Analysis:		
Ca (mg/L)	36.2	0.0
Mg (mg/L)	10.7	0.0
Na (mg/L)	39	0
K (mg/L)	9.3	0.0
Fe (mg/L)	0.55	0.00
Hardness (mg/L) as CaCO3	134.2	0.0

TABLE B.3. Water Analyses, Well AM1 - St. Lawrence, January 1982 to December 1985

Date	2-1-82	8-30-83	11-3-83	1-17-84	6-12-84	9-10-84	6-24-85	9-16-85	9-16-85	12-9-85
Replication	1	1	1	1	1	1	1	1	1	1
pH Temp C	NA	23.0	21.9	16.8	25.0	20.0	19.5	17.3	17.3	12.1
pH	7.69	7.78	8.22	7.58	7.28	7.44	6.43	7.00	7.00	5.92
SC (umho/cm)	351	466	460	NA	493	299	437	450	465	449
DO (mg/L)	NA	0.1	NA	0.1	0.4	1.5	0.4	7.5	0.5	7.0
Alk (meq/L)	5.37	5.17	5.19	5.21	NA	5.44	5.25	5.03	5.20	5.26
SiO2 (mg/L) as Si	NA	3.92	3.82	4.58	NA	4.16	7.07	6.46	6.74	5.80
DIC (mg/L) as C										
IC Analysis										
SO4 (mg/L) as S	NA	5.49	5.26	5.48	NA	5.24	5.22	2.14	5.37	5.80
Cl (mg/L)	NA	1.03	1.10	0.87	NA	0.89	2.63	2.36	2.43	1.81
F (mg/L)	NA	0.66	0.24	0.23	NA	0.28	0.34	0.35	0.35	0.36
NO3 (mg/L) as N	NA	ND	ND	ND	NA	ND	ND	ND	ND	ND
NO2 (mg/L) as N	NA	ND	ND	ND	NA	ND	ND	ND	ND	ND
PO4 (mg/L) as P	NA	ND	ND	ND	NA	ND	ND	ND	ND	ND
AA Analysis										
Ca (mg/L)	1.32	63.30	65.70	66.10	73.90	72.32	53.71	57.80	57.10	63.00
Mg (mg/L)	11.20	23.10	21.30	21.30	0.44	23.94	18.11	20.60	20.10	20.85
Na (mg/L)	5.29	4.83	5.24	4.96	5.06	5.51	44.14	10.38	10.89	8.12
K (mg/L)	5.08	5.86	5.75	5.90	6.33	6.57	7.82	6.73	6.73	6.52
Fe (mg/L)	NA	0.59	NA	9.55	4.20	2.16	2.14	0.49	1.61	ND
Mn (mg/L)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hardness (mg/L) as CaCO3	49.42	253.19	251.77	252.77	186.34	279.17	208.69	229.16	225.35	243.17

TABLE B.4. Water Analyses, Well AM2 - Ironton-Galesville, January 1982 to December 1985

Date	2-4-82	2-18-82	3-12-82	8-30-82	2-15-83	2-22-83	2-22-83	8-31-83	8-31-83	11-2-83	11-2-83
Replication	1	1	1	1	1	1	2	1	2	1	2
pH Temp C	NA	NA	NA	NA	20.0	21.6	21.6	21.0	21.0	22.7	22.7
pH	7.83	7.83	7.72	7.27	7.32	7.28	7.28	7.18	7.18	7.25	7.25
SC (umho/cm)	321	321	NA	305	401	415	415	392	392	575	575
DO (mg/L)	NA	NA	NA	0	NA	NA	NA	1	1	NA	NA
Alk (meq/L)	4.65	4.65	4.47	4.35	4.29	4.16	4.52	4.45	4.46	4.08	4.41
SiO2 (mg/L) as Si	2.83	NA	2.66	6.23	4.57	4.65	4.91	5.34	5.29	7.19	6.06
DIC (mg/L) as C											
IC Analysis											
SO4 (mg/L) as S	5.59	NA	6.20	2.09	2.52	2.52	2.55	2.60	2.55	2.49	2.42
Cl (mg/L)	0.28	NA	1.52	0.10	0.92	0.88	0.88	1.11	1.07	1.40	1.57
F (mg/L)	0.36	NA	0.99	0.32	0.35	0.35	NA	0.34	0.39	0.36	0.41
NO3 (mg/L) as N	NA	NA	ND	ND	ND	ND	ND	ND	ND	ND	ND
NO2 (mg/L) as N	NA	NA	ND	2.07	ND	ND	ND	ND	ND	ND	ND
PO4 (mg/L) as P	NA	NA	ND	ND	ND	ND	ND	ND	ND	ND	ND
AA Analysis											
Ca (mg/L)	NA	1.56	NA	46.37	51.06	50.18	51.06	56.51	56.51	47.29	NA
Mg (mg/L)	NA	10.45	8.51	15.56	17.28	23.56	17.16	18.72	18.72	16.85	NA
Na (mg/L)	NA	5.52	6.67	7.61	5.98	4.92	5.47	4.83	4.83	5.24	NA
K (mg/L)	NA	6.65	5.08	11.30	8.33	8.60	8.60	8.21	8.21	9.15	NA
Fe (mg/L)	NA	NA	NA	NA	NA	NA	NA	3.08	2.86	NA	NA
Mn (mg/L)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hardness (mg/L) as CaCO3	NA	46.95	NA	179.86	198.68	222.31	198.18	218.20	218.20	187.47	NA

TABLE B.4. (continued)

Date	1-18-84	1-18-84	6-13-84	6-13-84	9-11-84	9-11-84	6-25-85	9-17-85	9-17-85	12-12-85	12-12-85
Replication	1	2	1	2	1	2	1	1	2	1	2
pH Temp C	18.3	18.3	22.3	22.3	20.2	20.2	26.8	20.9	22.3	15.1	15.1
pH	7.44	7.44	7.31	7.31	7.15	7.15	6.85	6.90	6.90	6.71	6.71
SC (umho/cm)	311	311	431	431	384	384	407	419	429	433	433
DO (mg/L)	0	0	>1	>1	3	3	1	7	1	7	7
Alk (meq/L)	4.31	NA	4.42	NA	4.37	4.78	4.73	4.66	4.77	4.84	4.84
SiO2 (mg/L) as Si	8.39	8.05	8.00	8.03	6.19	6.43	9.37	9.55	9.55	8.83	8.80
DIC (mg/L) as C											
IC Analysis											
SO4 (mg/L) as S	2.21	2.01	3.79	3.85	3.41	3.62	2.24	2.49	2.42	3.13	3.19
Cl (mg/L)	2.29	2.24	2.15	2.14	1.73	1.78	5.12	6.71	6.71	8.86	8.86
F (mg/L)	0.45	0.41	0.21	0.51	0.47	0.48	0.58	0.58	0.58	0.63	0.63
NO3 (mg/L) as N	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
NO2 (mg/L) as N	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
PO4 (mg/L) as P	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
AA Analysis											
Ca (mg/L)	53.31	NA	54.71	54.51	58.68	57.39	32.87	33.20	34.90	41.20	41.50
Mg (mg/L)	16.56	NA	20.39	NA	22.88	22.17	6.27	11.70	11.80	13.32	13.32
Na (mg/L)	5.68	NA	5.77	6.30	5.54	5.26	38.62	40.83	41.83	38.31	39.57
K (mg/L)	10.01	NA	11.30	11.38	9.21	9.13	7.86	7.14	7.14	7.87	7.98
Fe (mg/L)	8.60	NA	NA	4.10	15.40	2.32	1.30	0.12	1.08	0.04	0.07
Mn (mg/L)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hardness (mg/L) as CaCO3	201.28	NA	220.57	NA	240.74	234.60	107.89	131.08	135.74	157.73	158.48

TABLE B.5. Water Analyses, Well AM4 - Ironton-Galesville, July 1984 to December 1985

Date	7-20-84	7-20-84	7-20-84	7-20-84	11-1-84	6-26-85	6-26-85	9-17-85	9-17-85	9-17-85	12-11-85
Replication	1	2	3	4	1	1	2	1	1	2	1
pH Temp C	15	18	20	17	NA	18.9	NA	17.2	15.2	NA	10.7
pH	7.32	7.33	7.35	7.35	NA	6.41	NA	6.50	6.50	NA	6.71
SC (umho/cm)	NA	NA	NA	NA	NA	394	NA	NA	363	NA	420
DO (mg/L)	0.2	0.1	0.2	ND	NA	0.5	NA	8	0.3	NA	7
Alk (meq/L)	5.16	5.14	5.16	5.19	NA	4.40	4.40	NA	4.20	4.19	4.71
SiO2 (mg/L) as S	7.85	6.49	7.66	7.71	7.28	5.06	5.12	NA	5.25	5.39	7.54
DIC (mg/L) as C											
IC Analysis											
SO4 (mg/L) as S	1.12	1.34	1.12	1.17	NA	1.84	1.91	NA	2.89	2.53	3.94
Cl (mg/L)	3.04	2.75	2.91	2.84	NA	4.35	4.65	5.01	4.58	4.59	6.87
F (mg/L)	0.21	0.25	0.21	0.21	NA	0.34	0.36	0.32	0.36	0.38	0.49
NO3 (mg/L) as N	ND	ND	ND	ND	NA	ND	ND	ND	ND	ND	ND
NO2 (mg/L) as N	ND	ND	ND	ND	NA	ND	ND	ND	ND	ND	ND
PO4 (mg/L) as P	ND	ND	ND	ND	NA	ND	ND	ND	ND	ND	ND
AA Analysis											
Ca (mg/L)	65.60	65.20	65.00	65.40	NA	35.67	34.47	NA	29.50	28.60	40.20
Mg (mg/L)	23.95	22.24	23.78	23.78	NA	13.27	12.86	10.60	13.80	13.90	13.13
Na (mg/L)	4.76	4.92	5.22	4.81	NA	29.66	28.28	31.01	30.51	30.26	39.06
K (mg/L)	2.04	5.36	2.90	2.52	NA	7.86	7.98	7.04	7.25	7.14	7.14
Fe (mg/L)	1.30	1.00	0.50	0.80	NA	1.01	1.01	0.10	0.54	0.57	0.07
Mn (mg/L)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hardness (mg/L) as CaCO3	262.43	254.39	260.23	261.23	NA	143.73	139.03	NA	130.49	128.65	154.45

TABLE B.6. Water Analyses, Well AS1 - Jordan, January 1982 to December 1985

Date	2-18-82	8-31-82	8-31-82	2-16-83	9-2-83	11-3-83	1-19-84	6-14-84	9-10-84	6-25-85	9-17-85
Replication	1	1	2	1	1	1	1	1	1	1	1
pH Temp C	NA	NA	NA	22	22	15.7	19.8	20.8	21	23	16.7
pH	8.55	8.50	NA	9.06	8.39	8.28	7.74	8.04	7.82	6.56	6.70
SC (umho/cm)	313	283	NA	259	327	399	383	410	360	441	415
DO (mg/L)	NA	NA	NA	NA	0.1	NA	0.1	0.5	4	0.7	7
Alk (meq/L)	4.06	3.60	3.56	1.75	3.04	4.17	4.57	3.85	4.82	5.08	4.61
SiO2 (mg/L) as Si	NA	2.78	2.73	3.48	2.25	2.66	2.87	3.04	3.45	4.39	4.21
DIC (mg/L) as C											
IC Analysis											
SO4 (mg/L) as S	NA	11.50	11.50	11.30	9.74	8.80	8.57	8.57	6.71	7.40	8.22
Cl (mg/L)	NA	1.42	1.23	1.31	2.65	1.27	1.02	1.19	0.99	1.37	1.26
F (mg/L)	NA	0.14	0.21	0.22	0.17	0.23	0.22	0.17	0.21	0.20	0.21
NO3 (mg/L) as N	NA	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
NO2 (mg/L) as N	NA	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
PO4 (mg/L) as P	NA	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
AA Analysis											
Ca (mg/L)	1.72	38.36	39.52	16.03	34.47	48.10	53.71	50.70	64.13	64.13	52.60
Mg (mg/L)	10.94	18.79	18.26	12.18	16.77	19.13	21.05	17.75	22.36	18.35	19.00
Na (mg/L)	8.28	10.21	9.66	9.66	9.89	9.43	8.62	8.99	9.99	8.97	9.29
K (mg/L)	11.34	12.47	11.89	11.73	10.95	10.40	8.92	10.79	9.76	9.78	8.92
Fe (mg/L)	NA	NA	NA	NA	0.19	NA	2.28		1.09	0.84	0.09
Mn (mg/L)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hardness (mg/L) as CaCO3	49.35	173.16	173.86	90.19	155.14	198.88	220.80	199.68	252.21	235.71	209.58

TABLE B.6. (continued)

Date	9-17-85	12-12-85
Replication	1	1
pH Temp C	16.1	10.8
pH	6.70	6.41
SC (umho/cm)	458	429
DO (mg/L)	0.5	7
Alk (meq/L)	5.13	4.77
SiO2 (mg/L) as Si	4.69	3.85
DIC (mg/L) as C		
IC Analysis		
SO4 (mg/L) as S	8.01	8.47
Cl (mg/L)	1.26	1.35
F (mg/L)	0.21	0.20
NO3 (mg/L) as N	ND	ND
NO2 (mg/L) as N	ND	ND
PO4 (mg/L) as P	ND	ND
AA Analysis		
Ca (mg/L)	61.40	56.40
Mg (mg/L)	20.40	19.69
Na (mg/L)	9.29	9.19
K (mg/L)	8.71	8.92
Fe (mg/L)	0.86	ND
Mn (mg/L)	NA	NA
Hardness (mg/L) as CaCO3	237.32	221.91

TABLE B.7. Water Analyses, Well AS1 - Mt. Simon, January 1982 to December 1985

Date	1-21-82	2-17-82	9-1-82	2-16-83	8-31-83	6-14-84	9-11-84	9-17-85	9-17-85	12-12-85
Replication	1	1	1	1	1	1	1	1	1	1
pH Temp C	NA	NA	NA	20.9	22.3	21.8	19.0	18.7	29.8	11.1
pH	11.16	8.77	8.42	8.64	8.23	7.78	7.14	6.70	6.90	6.36
SC (umho/cm)	222	NA	182	248	310	399	280	412	458	387
DO (mg/L)	NA	NA	0	NA	0	0	3	8	0	8
Alk (meq/L)	0.84	2.41	2.15	1.43	2.46	3.46	4.14	4.21	4.74	4.11
SiO2 (mg/L) as Si	NA	NA	0.56	2.90	1.88	2.94	7.21	9.13	11.07	8.22
DIC (mg/L) as C										
IC Analysis										
SO4 (mg/L) as S	NA	NA	27.04	13.59	14.59	10.50	7.27	4.83	4.93	3.91
Cl (mg/L)	NA	NA	6.43	3.44	3.09	2.39	2.31	8.96	8.83	7.87
F (mg/L)	NA	NA	0.53	0.25	0.20	0.24	0.33	0.46	0.41	0.49
NO3 (mg/L) as N	NA	NA	0.15	0.16	0.18	ND	0.11	ND	ND	ND
NO2 (mg/L) as N	NA	NA	ND	ND	ND	ND	ND	ND	ND	ND
PO4 (mg/L) as P	NA	NA	ND	ND	ND	ND	ND	ND	ND	ND
AA Analysis										
Ca (mg/L)	2.48	2.40	14.31	16.03	30.86	55.51	58.79	36.11	45.00	34.70
Mg (mg/L)	3.40	8.51	9.63	9.85	14.59	16.04	17.08	10.10	10.40	10.62
Na (mg/L)	11.04	9.20	10.25	8.74	7.36	6.87	7.24	34.24	34.34	31.12
K (mg/L)	14.47	12.12	14.59	13.26	14.86	15.60	14.03	11.52	11.52	11.00
Fe (mg/L)	NA	NA	NA	NA	ND	2.00	2.60	0.07	1.05	0.07
Mn (mg/L)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hardness (mg/L) as CaCO3	20.22	41.04	75.37	80.58	137.13	204.68	217.13	131.76	155.19	130.38

TABLE B.8. Water Analyses, Well BC1 - Mt. Simon, January 1982 to December 1985

Date	2-23-82	9-3-82	2-19-83	6-20-84	9-12-84	6-27-85	6-27-85	9-18-85	9-18-85	12-10-85
Replication	1	1	1	1	1	1	2	1	2	1
pH Temp C	NA	NA	19.3	NA	26.0	25.7	15.8	18.7	26.9	9.0
pH	9.82	11.42	9.58	NA	7.62	6.76	6.30	6.60	6.70	5.70
SC (umho/cm)	NA	269	156	NA	196	387	374	393	411	NA
DO (mg/L)	NA	NA	NA	NA	5	1	9	8	1	8
Alk (meq/L)	0.09	1.45	0.65	3.75	4.20	4.22	4.28	4.38	4.36	NA
SiO2 (mg/L) as Si	NA	3.29	6.85	2.11	5.62	6.92	6.55	5.64	5.93	NA
DIC (mg/L) as C										
IC Analysis										
SO4 (mg/L) as S	NA	15.42	11.78	2.80	9.02	7.48	7.26	8.15	8.33	NA
Cl (mg/L)	NA	3.56	2.62	2.23	1.98	2.01	1.93	2.08	2.11	2.18
F (mg/L)	NA	0.96	0.32	0.36	0.48	0.30	0.34	0.35	0.35	0.35
NO3 (mg/L) as N	NA	ND	ND	ND	0.79	ND	ND	ND	ND	ND
NO2 (mg/L) as N	NA	ND	ND	ND	ND	ND	ND	ND	ND	ND
PO4 (mg/L) as P	NA	ND	ND	ND	ND	ND	ND	ND	ND	ND
AA Analysis										
Ca (mg/L)	2.28	37.23	19.24	41.68	53.48	47.29	47.21	55.20	54.50	NA
Mg (mg/L)	3.16	ND	2.97	18.85	18.33	16.36	16.97	17.90	17.40	13.90
Na (mg/L)	7.59	7.31	6.85	12.07	7.33	1.17	5.52	6.17	5.96	5.96
K (mg/L)	9.78	9.19	7.78	5.63	7.56	8.60	8.76	7.66	7.56	7.77
Fe (mg/L)	NA	NA	NA	0.10	0.18	0.03	ND	0.09	0.09	0.07
Mn (mg/L)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hardness (mg/L) as CaCO3	18.72	92.97	60.25	181.71	209.02	185.47	187.77	211.55	207.74	NA

TABLE B.9. Water Analyses, Well BS1 - Jordan, January 1982 to December 1985

Date	2-22-82	9-3-82	2-19-83	6-20-84	9-12-84	6-27-85	6-27-85	9-18-85	9-18-85	12-10-85
Replication	1	1	1	1	1	1	1	1	1	1
pH Temp C	NA	NA	NA	23.2	24.0	17.9	15.7	20.2	18.8	9.1
pH	8.13	8.14	8.04	8.06	7.52	6.06	6.42	6.80	6.80	6.14
SC (umho/cm)	NA	321	356	374	343	386	382	380	373	369
DO (mg/L)	NA	0	NA	0	2	1	10	1	9	7
Alk (meq/L)	0.29	4.41	3.46	2.93	3.96	4.51	4.52	4.28	4.31	4.24
SiO2 (mg/L) as Si	NA	2.97	2.61	1.47	4.53	6.53	6.68	6.29	6.38	5.42
DIC (mg/L) as C										
IC Analysis										
SO4 (mg/L) as S	NA	27.02	6.24	7.31	2.71	1.61	1.61	2.32	2.28	2.07
Cl (mg/L)	NA	NA	2.62	2.19	1.78	5.30	5.29	4.19	4.18	2.86
F (mg/L)	NA	0.50	0.35	0.20	0.56	0.38	0.38	0.40	0.39	0.43
NO3 (mg/L) as N	NA	ND	ND	ND	ND	ND	ND	ND	ND	ND
NO2 (mg/L) as N	NA	ND	ND	ND	ND	ND	ND	ND	ND	ND
PO4 (mg/L) as P	NA	ND	ND	ND	ND	ND	ND	ND	ND	ND
AA Analysis										
Ca (mg/L)	2.12	51.54	35.47	36.59	44.51	39.28	39.40	43.90	43.30	44.80
Mg (mg/L)	9.72	23.63	17.55	16.17	18.71	16.46	16.46	16.50	16.80	17.37
Na (mg/L)	13.33	16.67	12.09	9.66	12.28	18.99	18.53	16.13	15.93	13.21
K (mg/L)	9.38	8.45	7.16	9.54	4.50	5.55	5.67	3.91	3.91	3.29
Fe (mg/L)	NA	NA	NA	0.20	0.67	0.03	ND	0.07	0.10	ND
Mn (mg/L)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hardness (mg/L) as CaCO3	45.35	226.01	160.85	157.96	188.19	165.85	166.15	177.57	177.30	183.40

TABLE B.10. Water Analyses, Well CM1 - Ironton-Galesville, January 1982 to December 1985

Date	3-11-82	9-2-82	2-18-83	9-2-83	6-19-84	9-13-84	6-28-85	9-18-85	9-18-85	12-10-85
Replication	1	1	1	1	1	1	1	1	2	1
pH Temp C	NA	NA	22.0	22.0	24.2	21.0	14.7	19.1	20.2	7.3
pH	8.10	8.14	7.46	7.52	7.58	7.20	6.29	6.90	6.90	6.16
SC (umho/cm)	NA	214	372	375	423	299	356	369	373	363
DO (mg/L)	NA	0	NA	1	>1	1	1	10	1	7
Alk (meq/L)	2.87	3.41	4.03	4.15	4.28	3.98	4.36	4.32	4.36	4.32
SiO2 (mg/L) as Si	1.62	2.73	3.70	3.93	3.54	3.40	3.93	4.10	3.85	3.49
DIC (mg/L) as C										
IC Analysis										
SO4 (mg/L) as S	6.97	2.23	1.60	1.40	1.10	1.24	1.01	0.92	0.87	1.00
Cl (mg/L)	2.03	1.16	0.93	0.91	1.03	0.89	0.87	1.02	0.98	1.18
F (mg/L)	0.30	0.23	0.34	0.25	0.27	0.49	0.30	0.32	0.32	0.32
NO3 (mg/L) as N	ND	ND	ND	0.01	ND	ND	ND	ND	ND	ND
NO2 (mg/L) as N	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
PO4 (mg/L) as P	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
AA Analysis										
Ca (mg/L)	NA	38.36	44.05	49.70	53.71	52.67	46.61	50.80	49.70	50.50
Mg (mg/L)	8.02	15.29	14.71	17.02	16.68	18.02	15.66	16.10	16.10	16.02
Na (mg/L)	6.67	7.43	7.22	6.67	6.81	7.46	6.00	6.97	7.17	6.57
K (mg/L)	4.69	7.86	8.25	6.65	7.23	6.66	6.69	5.89	6.00	6.00
Fe (mg/L)	NA	NA	NA	2.21	3.40	0.18	0.06	ND	0.29	0.07
Mn (mg/L)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hardness (mg/L) as CaCO3	NA	158.74	170.55	194.17	202.80	205.72	180.86	193.15	190.40	192.07

TABLE B.11. Factors to Convert Between mmol/L and mg/L

Parameter	mmol/L to mg/L multiply mmol/L by:	mg/L to mmol/L multiply mg/L by:
SiO_2 as Si	28.08	0.03561
DIC as C	12.01	0.08326
SO_4 as S	32.06	0.3119
Cl	35.45	0.2821
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

APPENDIX C

OPERATING PARAMETERS, LONG-TERM CYCLE 1

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OPERATING PARAMETERS, LONG-TERM CYCLE 1

Flow, temperature, pressure, and water hardness conditions are all factors that affected operations.

Rates of pumping for injecting the ground water during LT1 are limited by permit to no more than 18.9 L/s (300 gpm). Water flow from the pumping well is controlled by adjusting the system flow control valve, which adjusts the backpressure against which the constant speed turbine pumps must work. The source well pump (B) delivers about 18.9 L/s when the pressure at the entry point to site A (ahead of water softener) is 1035 kPa (150 psi). The storage well pump (A) delivers about 18.9 L/s when the pressure at the wellhead is 860 kPa (125 psi).

Maximum temperature for injected water is 150°C (302°F) by permit. This is also a physical limitation of the heat source, 930 kPa (135 psi) saturated steam. The design delta T for the system is 66°C (119°F). All cycles, long and short, exceeded this delta T; however, the temperature never exceeded 150°C. The source water temperature always was less than the 85°C (105°F), which the design engineers assumed. Pressures inside the piping between the condenser and the storage well always were maintained higher than 345 kPa (50 psi); 395 kPa (357 psi) is required to prevent flashing to steam at 150°C (300°F). (NOTE: Lowest pressures were 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 changes observed in monitoring wells always maintained more than 88 m (290 ft) of head above the FIG aquifer (860 kPa), more than two times than that necessary to prevent flashing to steam in the aquifer.

Hardness of the source water during LT1 averaged 195 mg/L as $CaCO_3$, slightly less than the 200 to 210 mg/L of the ambient FIG ground water. As noted in Sections 4 and 5, the softeners did not regenerate properly as initially configured. Following the installation of the proper brine-feed orifice and addition of more media to the resin tanks, each tank could serve for the 8 hours as specified.

When a pump was running during injection and recovery phases, the site was staffed continuously. Reading of pressure gauges and thermometers on the piping were taken at least hourly. The flow records of water and steam were recorded hourly as well. The datalogger was checked several times daily to be sure it was operating.

During injection, when steam was flowing (~20,000 lb/hr), two persons were at the site.

Records of the readings were entered into files on a microcomputer for compilation and reduction. The datalogger records were written to magnetic tape and read at the University of Minnesota computer center.

During storage, the site was visited periodically three to four times per week, to check on the datalogger.

APPENDIX D

FIELD INJECTIVITY STUDIES DURING LONG-TERM CYCLE 1

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FIELD INJECTIVITY STUDIES DURING LONG-TERM CYCLE 1

This appendix describes field studies performed by researchers from PNL (S. Blair and P. Mitchell) and MGS (M. Hoyer) during LT1 to characterize ground-water injectability at the ATES FTF located on the St. Paul campus of the University of Minnesota. Characterization of the injectability was undertaken to augment standard geochemical and water quality studies. These studies were necessary because earlier laboratory investigations (Blair 1985) indicated considerable disaggregation of representative core materials when subjected to flow of hot ground waters. Permeability reduction of laboratory test samples was observed and attributed to core plugging caused by release of fine particles generated during disaggregation. On-site field tests to assess release of fine particles and subsequent potential for plugging of the aquifer near the injection well was essential to establishing the usefulness of laboratory tests to estimate field behavior as well as determine the potential for well plugging at the test site.

Field studies conducted during injection and withdrawal pumping periods of LT1 included membrane filter tests to anticipate well impairment by particle plugging. These tests monitored suspended solids content and other injectability parameters of the heated ground water. On-site core flooding tests were also conducted to aid in determining response of the aquifer formation to the injected fluid.

D.1 INSTRUMENTATION AND METHODOLOGY

A portable field injectivity test stand (FITS) was used to characterize suspended solids and injectability parameters of fluid streams. The FITS was used to divert a portion of the fluid stream through a reservoir analog such as a membrane filter or a core sample and was configured to enable sampling at several locations in the ATES facility. The FITS provides the capability to measure permeability of a reservoir analog under conditions of constant differential pressure or constant flow rate. Also, the reservoir analog can be maintained at process stream temperature during flow tests. All components of the FITS are constructed of Inconel or 316 stainless steel to reduce the possibility of chemical or physical contamination caused by degradation of the apparatus by heated fluids.

Filters of various pore sizes were employed during testing of the process fluids. Total suspended solids in the fluid stream were determined from flow through 0.4-μm and 0.45-μm membrane filters. The pore size of the injection formation was previously estimated by Blair, Deutsch, and Mitchell (1985) to be 12 μm using the methods of Champlin, Thomas, and Brownlow (1976); 10-μm filters were used along with core samples to simulate the receiving formation. Filtration data were plotted as cumulative filter throughput (volume) versus $\sqrt{\text{time}}$ from start of test, after the methods of Barkman and Davidson (1972). All filtration tests were conducted at the temperature of the injection stream and with differential pressure held constant. Differential pressure for most filters was held at 0.14 MPa (20 psi).

Core flooding tests were conducted at the temperature of the injection stream and with the flow rate held constant. Stacked core samples of the Franconia-Ironton-Galesville (FIG) aquifer were used as reservoir analogs. Permeability (K) of the core samples was calculated using Darcy's equation.

$$K = \frac{Qml}{A\ P}$$

where Q = flow rate (mL/s)
m = viscosity (centipoise)
l = sample length (cm)
A = cross-sectional area of sample (cm^2)
P = differential pressure (atm).

Filters and core samples were examined using standard scanning electron microscopy (SEM) and energy dispersive x-ray (EDX) techniques to identify major minerals.

D.2 FIELD TEST RESULTS

D.2.1 Membrane Filter Tests

Membrane filter tests were used to characterize the heated ground-water injection and withdrawal/reinjection fluids of the first long-term heat storage test. Cumulative flow data for 10-μm membrane filter tests, which sampled these fluids at the wellhead, fall in the envelope illustrated in Figure D.1. Cumulative flow data for 0.4- and 0.45-μm filter tests fall in the envelope illustrated in Figure D.2. These data indicate that the overall injectability of this fluid is quite good.

The suspended solids content determined by filtration tests with 0.4- and 0.45-μm filters range from 0.04 to 0.09 ppm for heat injection and from 0.01 to 0.06 for heat recovery.

Observation of scanning electron photomicrographs show particles ranging from 1 to 40 μm in size for both heat injection and recovery. The metallic components of particles collected during filtration tests, as determined by SEM and EDX, are primarily iron for large particles (greater than 3-μm diameter) and silica, calcium, chromium, and nickel for the smaller particles (less than 3-μm diameter). Calcium carbonate is present as aragonite. The silica and calcium carbonate are from the ground water. The iron, chromium, and nickel are probably from the piping of the FTF and the FITS.

D.2.2 Core Flooding Tests

Three sets of stacked samples from the injection formation were tested in the FITS during LT1. The flow rate through the samples was held at approximately 0.2 L/min (0.007 cfm) for all core flooding tests. One set was tested during heat injection; while the other two were tested during heat recovery. The first set of two stacked core samples used during the 37th day of injection pumping were from the 785-ft depth and are labeled 785-AC-1 and 785-AC-2. The constant flow rate through these samples resulted in a differential pressure between 0.093 and 0.175 MPa (13.5 and 25.4 psi). Core flooding tests during heat recovery were done with two sets of stacked core samples. The first set, tested on the 2nd day of recovery pumping, consisted of four stacked core samples from the 787-ft depth and are labeled 787-1, 787-2, 787-3, and 787-4. The differential pressure observed across these

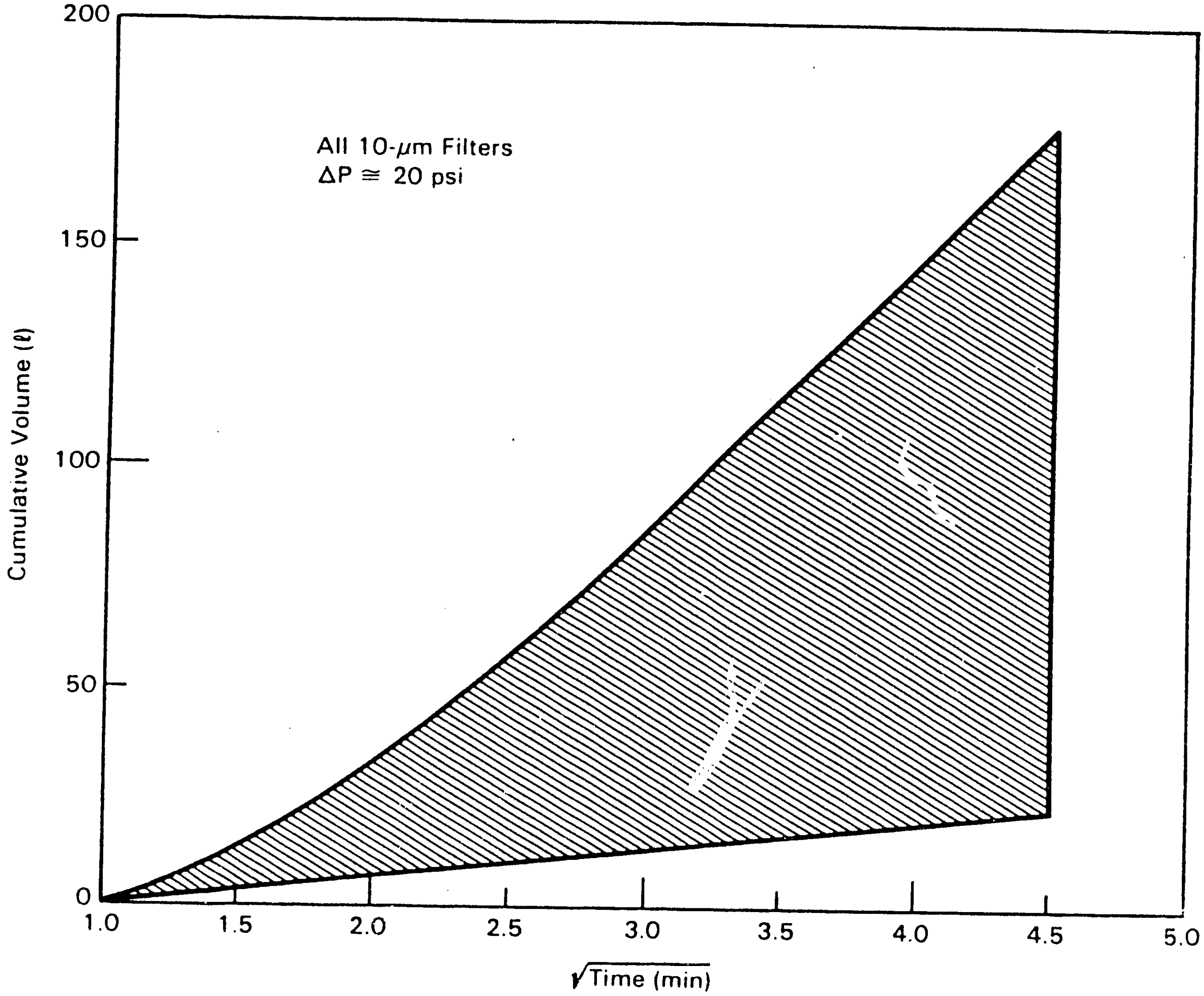

FIGURE D.1. Cumulative Throughput Versus $\sqrt{\text{Time}}$ for 10-μm Filter Tests of Fluids During LT1

samples ranged between 0.029 and 0.152 MPa (4.15 and 22 psi). The second set, tested on the 49th day of recovery pumping, consisted of three stacked core samples from the 748-ft depth and are labeled 748-2, 748-4, and 748-6. The differential pressure observed across these samples ranged from 0.207 to 0.276 MPa (30 to 40 psi). Calculated permeabilities versus cumulative pore volumes passed through the core samples are shown in Figure D.3. The dates and fluid temperatures for each test are also listed in Figure D.3. The permeabilities calculated for all three tests were close to 0.01 darcies, with no marked difference caused by temperature, pressure, or cycle phase.

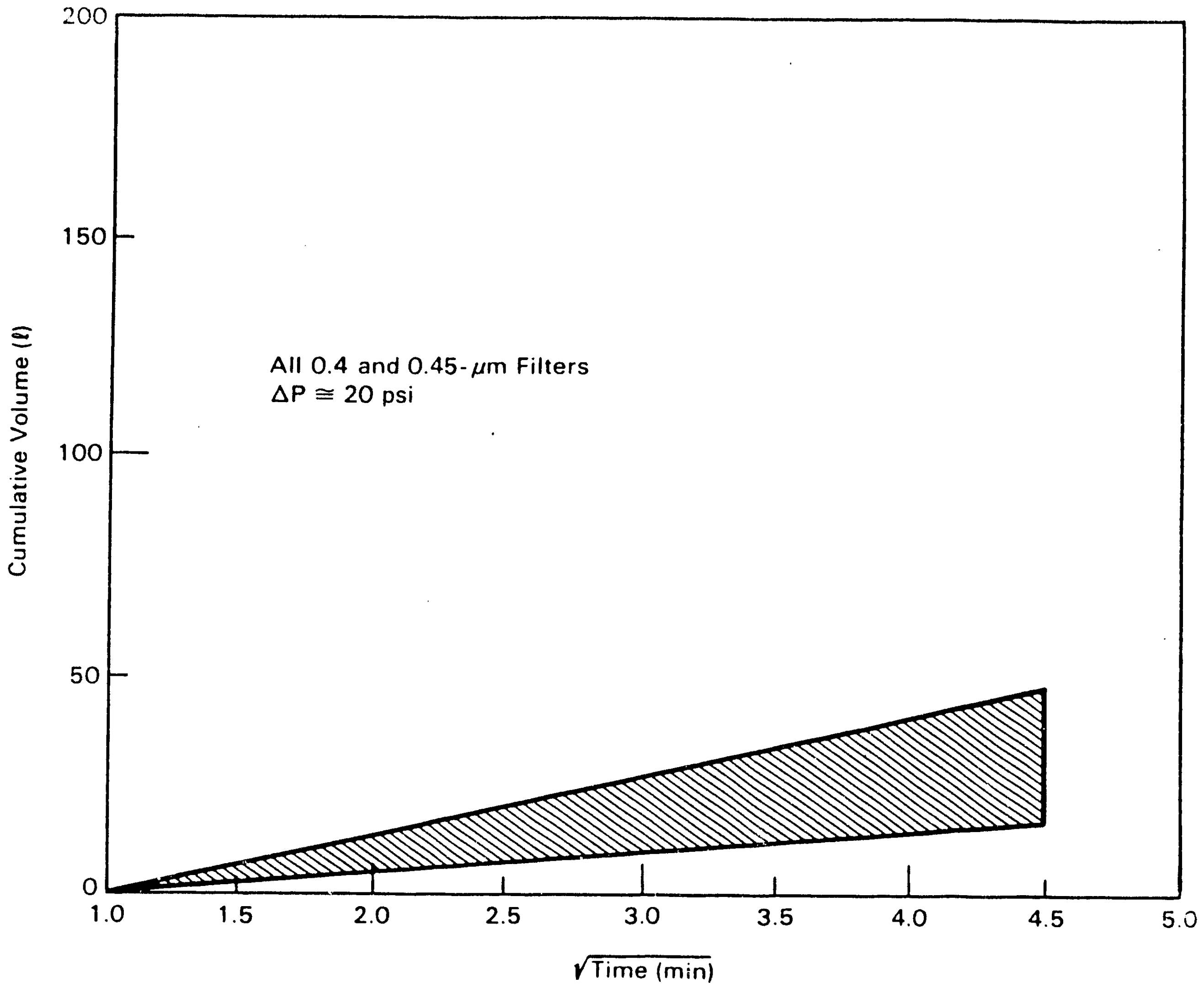

FIGURE D.2. Cumulative Throughput Versus $\sqrt{\text{Time}}$ for 0.4- and 0.45-μm Filter Tests of Fluids During LT1

Scanning electron and energy dispersive x-ray microscope analyses were done on the inlet (upstream) face of each core sample. All the general area scans showed silica as the dominant constituent with minor amounts of aluminum, potassium, and iron. Iron particles were almost absent just below the inlet face of the upstream sample (785-AC-2) tested during injection. A photomicrograph of the inside of this core toward the downstream end showed a much cleaner matrix (i.e., dissolution of cementing materials or absence of filter cake). Visual evaluation of all core samples along a lengthwise cut (parallel to flow direction) showed varying lengths of filter cake infiltration. The upstream sample (785-AC-2) tested during injection showed discoloration to a depth of about 0.85 mm. The downstream sample of this stacked-core sample set showed none. The first set of core samples tested

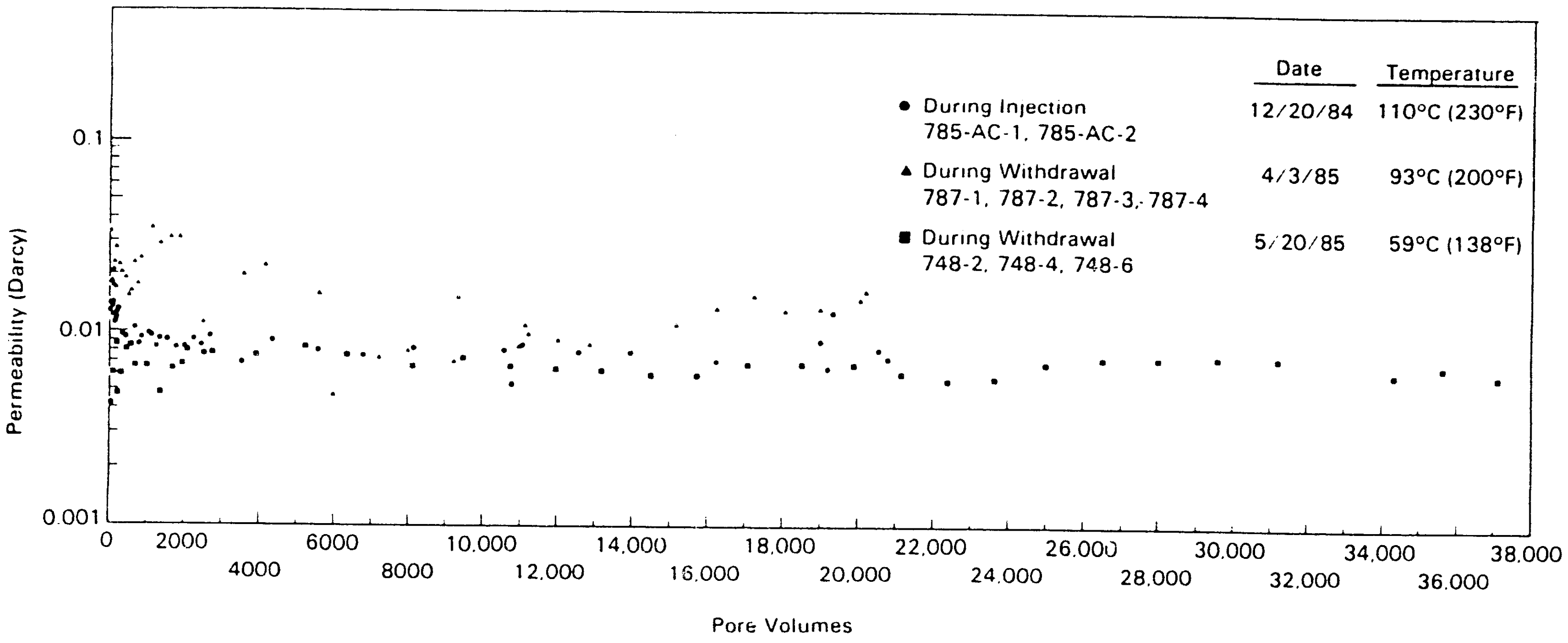

FIGURE D.3. Permeability of Core Samples Plotted Versus Pore Volumes for Core Flood Tests Conducted During Heat Injection and Recovery, LT1 during heat recovery showed discoloration to a depth of 0.85 mm on the upstream sample (787-1) and no discoloration on the other samples (787-2, 787-3, and 787-4). The second set of core samples tested during heat recovery showed discoloration to a depth of about 4.25 mm on the upstream sample (748-2) while the middle and downstream samples (748-4 and 748-6) showed a color change to a depth of 0.85 mm. The color changes most likely indicate the removal of cementing agents downstream from the filter cake.

D.2.3 Water Chemistry Studies

Evaluation of water chemistry results by University of Minnesota personnel has been completed for the injection and recovery phases of the LT1. The major changes in the withdrawn water are the higher dissolved silica and increased calcium levels above that of the injected water. It appears that silica, calcium, and bicarbonate concentrations are at equilibrium levels in the withdrawn water, even as the temperature declined.

Statements have been made by the University of Minnesota personnel about the trends in component concentrations, which increase or decrease with temperature changes. A typical example of a solute that increases in concentration with increasing temperature is soluble reactive Si (DRSi). In the recovery phase, DRSi concentrations are about 22.5 mg/L as Si on day 4 to 6 of pumping at a temperature of about 93°C and decreasing monotonically to about 9 mg/L as Si on day 48 of pumping at a water temperature of about 46°C. These values are very close to concentrations of DRSi in equilibrium with quartz at those temperatures.

A typical example of a solute that increases in concentration with decreasing temperature is dissolved Ca. In this case, Ca concentrations at day 4 to 6 are about 4 to 5 mg/L at a water temperature of about 93°C, and increase monotonically to about 37 mg/L at day 58 at a water temperature of about 46°C. These values are also very close to the concentrations of dissolved Ca in equilibrium with $CaCO_3$ (aragonite) at those temperatures.

D.3 COMPARISON OF RESULTS WITH PREVIOUS WORK

Laboratory tests conducted in past years produced two results that are significant to ATES (Blair 1985; Blair, Deutsch and Mitchell 1985). The first is that on the time scale of these tests (days), substantial changes in petrofabric were observed in the samples. These changes include loss of cementing agents, an increase in intergranular porosity, and loss of mechanical strength. Past results on changes in pore fluid chemistry indicated increased silica content after residence of pore fluid in the core for a few hours (overnight) at elevated temperature. This result is important to ATES as it shows that the time scale of chemical reactions occurring in aquifers used for ATES is on the order of a few days or less and possibly a few hours.

A second result from laboratory studies was that initial heating of samples caused significant reduction in permeability and the amount of reduction was proportional to the rise in temperature. This is important to heat injection operations because it indicates that permeability reduction may occur in the receiving formation when the temperature of the injection stream is increased.

As of December 1983, four short-term heat storage cycles had been performed at the St. Paul site. These are summarized in Table D.1. The initial heat injection attempt, prior to Cycle 1, was terminated because of well impairment by calcium carbonate precipitation after 50 hours of injection. Following well rehabilitation and installation of precipitating filters (Walton et al. 1991), the cycles shown on Table D.1 were conducted. Heat recovery portions of Cycles 1 and 2 were each delayed by pump bearing failures caused by heated fluids. Cycles 3 and 4 were completed without incident. Results of the short-term tests indicated the fabric of the FIG aquifer rocks that form the host aquifer for the St. Paul FTF are probably being changed by operation of the ATES facility. It was apparent from the success of the short-term tests that these changes in the rock fabric do not impact the hydrologic performance of the aquifer formation. The first long-term cycle is also included in Table D.1 for comparison purposes. This cycle was conducted without well plugging. Only two interruptions lasting more than 2 days occurred during injection pumping (59.1 days of pumping over the 74.7-day period) and one during recovery pumping (58.0 days of pumping

TABLE D.1. Key Parameters for the Short-Term and Long-Term Cycles at the University of Minnesota ATES Field Test Facility

	Flow Rate (L/s)	Mean Temperature (°C)	Volume Pumped (10^3 m^3)	Duration Days	Energy Recovery Factor(a)
Short-Term					
Cycle 1					
Injection	18.4	89.4	8.3	5.2(b)	
Storage				13	0.59
Recovery	18.1	59.3	8.1	5.2/6	0.59(c)
Cycle 2					
Injection	17.6	97.4	12.2	8(b)	
Storage				90	0.46
Recovery	17.8	55.2	12.3	8	0.52(c)
Cycle 3					
Injection	18.3	106.1	12.2	7.7(b)	
Storage				9.7	0.62
Recovery	17.8	81.1	11.8	7.7	0.71(c)
Cycle 4					
Injection	17.9	114.8	11.9	7.7(b)	
Storage				10.1	0.58
Recovery	17.8	89.1	11.9	7.7	0.75(c)
Long-Term Cycle 1					
Injection	18.0	108.5	92.09	59.1(b)	
Storage				64.04	0.62
Recovery	18.4	74.7	92.24	58.0	0.65(c)

(a) Thermal energy recovered above supply well temperatures divided by heat added during injection.
(b) Net injection time (i.e., periods of maintenance not included).
(c) Calculated as heat injected relative to natural ground-water temperature (11°C) divided by heat recovered relative to ground-water temperature.

during the 58.8-day period). The hydrologic performance of the aquifer, based on thermal response, appeared to decrease slightly after the long-term storage cycle. However, the decrease in permeability cannot be quantified without aquifer pumping tests.

The suspended solids data for previous cycles, as well as the long-term cycle is summarized in Table D.2. Particle sizes were estimated by measuring particles in the photomicrographs. As is shown in Table D.2, the suspended solids contents for the long-term cycle are less and the particle size is smaller than that observed during the short-term cycles.

Filtration tests conducted during previous cycles resulted in 30 to 100 liters of flow through 10-μm filters, whereas during LT1, filtration tests showed up to 178 liters for injection and up to 192 liters for withdrawal during the 20 minute tests at a differential pressure of 0.14 MPa (20 psi).

Core flooding tests with single core pieces were done during previous heat injection cycles after the precipitator was added to the system. Two of the samples showed no loss of permeability, which remained around 1.0 darcies, after passing several thousand pore volumes. One sample showed a slight decrease in permeability after 2,500 pore volumes, and a substantial decrease

TABLE D.2. Summary of Suspended Solids Data

Water Type	Suspended Solids (0.4 μm) ppm	Particle Size μm	Filtration Properties
In situ ground water	0.01 - 0.13	<5	Excellent
Short-Term Cycles			
Heat injection	0.20 - 0.70	10 - 100	Very good
Heat recovery			
Cycle 1, 2	0.20 - 0.90	10 - 100	Good
Cycle 3, 4		<10	Very good
Long-Term Cycle 1			
Heat injection	0.04 - 0.09	1 - 40	Good
Heat recovery	0.01 - 0.06	1 - 40	Good

after 15,000 pore volumes from 0.1 darcies to just above 0.01 darcies. This decrease was attributed to the formation of an iron-rich filter cake on the core surface. The permeabilities of around 0.01 darcies calculated for core flooding tests concluded during the first long-term heat storage test did not decrease after passing over 20,000 pore volumes.

D.4 CONCLUSIONS

Results of membrane filter tests indicate that fluids injected during heat injection and heat recovery had very low suspended solids. Overall, the filter test results indicate that, at temperatures to 115°C (238°F), well impairment caused by suspended solids is not a problem. Results of core flooding tests demonstrate that over twenty-thousand pore volumes of fluid in the 93 to 110°C (200 to 230°F) temperature range can be passed through representative core samples with no significant loss in permeability.

It is concluded from the success of the long-term heat storage experiment that the quality of the water (as treated by the water softening system) was very good for heat injection. The water quality during heat recovery was also good. Any changes in rock fabric that may have been experienced in the aquifer formations did not significantly affect hydrologic performance.

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