PNL-9811
UC-[redacted]
1340

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

M. C. Hoyer
J. P. Hallgren
M. H. Uebel
G. N. Delin
S. J. Eisenreich
R. L. Sterling, Principal Investigator

December 1994

Prepared by
Underground Space Center
Department of Civil and Mineral Engineering
University of Minnesota
500 Pillsbury Dr. S.E.
Minneapolis, MN 55455

for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

MASTER

Pacific Northwest Laboratory
Richland, Washington 99352

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED BS/mp

DISCLAIMER

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 processs. 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 5-10% of the nation's energy, with major contributions in the commercial and industrial sectors and in district heating and cooling applications.

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

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

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

FTF are to: 1) evaluate the technical issues associated with design and operation of a high-temperature (>100°C) ATES system, and 2) obtain data on fundamental geotechnical processes to validate laboratory and bench-scale geochemical testing and geohydrothermal modeling.

W. Kevin Winegardner
Manager, Seasonal Thermal Energy Storage Program

ABSTRACT

The University of Minnesota aquifer thermal energy storage (ATES) system has been operated as a field test facility (FTF) since 1982. The objectives were to design, construct, and operate the facility to study the feasibility of high-temperature ATES in a confined aquifer. Four short-term and two long-term cycles were previously conducted, which provided a greatly increased understanding of the efficiency and geochemical effects of high-temperature aquifer thermal energy storage. The third long-term cycle (LT3) was conducted to operate the ATES system in conjunction with a real heating load and to further study the geochemical impact that heated water storage had on the aquifer. The most critical activities in preparation for LT3 proved to be the applications for the various permits and variances necessary for the third cycle, and matching the ATES system characteristics during heat recovery with a suitable adjacent building thermal load.

For LT3, the source and storage wells were modified so that only the most permeable portion, the Ironton-Galesville part, of the Franconia-Ironton-Galesville aquifer was used for storage. This was expected to improve storage efficiency by reducing the surface area of the heated volume and simplify analysis of water chemistry results by reducing the number of aquifer-related variables which need to be considered.

The first part of LT3 was conducted during the 1989-90 heating season. A second part of LT3 (LT3b), a high-temperature short subcycle, was begun in May 1990. Problems with the storage well pump required factory repair, delayed heat recovery, and limited LT3b's usefulness.

During LT3, a total volume of 63.2×10^3 m^3 of water was injected at a rate of 54.95 m^3/hr into the storage well at a mean temperature of 104.7°C. A total of 6.21 GWh were added to the source water and stored in the aquifer. Of the total, 2.11 GWh were necessary to heat the source water to the useful minimum temperature of 49°C, and 4.10 GWh to heat the water from 49°C to the injection temperature. Tie-in to the reheat system of the nearby Animal Sciences Veterinary Medicine (ASVM) building was completed after injection was completed. A total volume of 66.0×10^3 m^3 of water was recovered at a rate of 44.83 m^3/hr from the storage well at a mean temperature of 76.5°C. The

highest and lowest temperatures of recovered water were 100.0 and 47.8°C, respectively.

Approximately 66 percent (4.13 GWh) of the energy added to the aquifer was recovered. Approximately 50 percent (2.07 GWh) of the energy added to the aquifer above 49°C (33 percent of the total energy stored) was delivered to the ASVM building. Approximately 15 percent (0.64 GWh) of the usable (10 percent of the total) energy stored was actually used in the ASVM building. Operations during heat recovery with the ASVM building's reheat system were trouble-free. Integration into more of the ASVM (or other) building's mechanical systems would have resulted in significantly increasing the proportion of energy used during heat recovery. The cost to connect to other ASVM building systems for this experimental cycle was the main reason for not incorporating other building systems into the FTF.

Water chemistry is critical to the operation of the University of Minnesota ATES field test facility. The ion-exchange water softener reduced the hardness of the source water from 174 mg/L to <5 mg/L as $CaCO_3$ before heating and storage, preventing scaling in the heat exchangers, storage well and aquifer. Recovered water had a hardness of 48 mg/L as $CaCO_3$. Recovered water was saturated with respect to calcite, dolomite, and quartz, meaning that the water picked up dissolved constituents from the ambient ground water. Sodium concentration averaged 19 mg/L in source water, 101 mg/L in injected water, and 87 mg/L in recovered water. Equilibrium modeling can be used to approximate water chemistry behavior. Mixing can explain the changes observed in water chemistry from injection to recovery.

Results from LT3 are consistent with those of the previous cycles. Aquifer characteristics were not observed to have been adversely affected by the cycles. It was demonstrated that high-temperature seasonal aquifer thermal energy storage is a feasible storage technology and can be successfully interfaced with existing, conventional, building systems.

SUMMARY

The objectives in building the University of Minnesota aquifer thermal energy storage (ATES) field test facility (FTF) were to design, construct, and operate the facility for a series of short-term and long-term cycles to study the feasibility of using ATES in a confined aquifer at temperatures up to 150°C. The FTF is located on the St. Paul campus of the University of Minnesota and was designed to inject and recover heat at a rate of 5 MW (thermal) using a well doublet spaced at 255 m, operating at an injection and recovery rate of 18.9 L/sec (68.0 m^3/hr). The wells are completed in the Franconia-Ironton-Galesville (FIG) confined aquifer at a depth of from 182 to 244 m and have static water levels about 55 m below land surface. Heat source for the FTF is the St. Paul campus steam plant.

When the previous four short-term and two long-term cycles had clearly demonstrated that >100°C ATES was feasible, it was determined that additional cycle(s) during which the recovered heat would be used on the campus would be desirable. It was also determined that from a modeling perspective the configuration of the storage and source wells should be simplified. Preparations for, conduct of, and results from long-term cycle 3 (LT3) are the subjects of this report.

LT3 was conducted between October 1989 and March 1990. Objectives of LT3 were to demonstrate that high-temperature ATES could supply a real heating load and to further study water chemistry results. For LT3 the FTF was connected to a nearby campus building to demonstrate the FTF's ability to meet a real heating load. For LT3 the wells were modified so that only the most permeable portions of the Ironton-Galesville aquifer were used to simplify water chemistry comparisons and modeling.

Obtaining new operating and discharge permits, selecting an appropriate heating load in a nearby building, designing and constructing the building connection to the FTF, and modifying the storage and source wells were required for LT3.

Permits from the Minnesota Pollution Control Agency, Minnesota Department of Health, and Minnesota Department of Natural Resources for the

operation of injection wells, discharge of waste water, and appropriation of ground water for two experimental cycles having no more than 90 days of heated water injection were obtained in September 1988. Permit conditions included injection temperatures no higher than 150°C and injection rates no higher than 280 gpm (~17.6 L/sec, 63.4 m^3/hr). Site closeout conditions included stipulations regarding final temperature of the aquifer and sodium concentration of the ground water. Modeling of the planned cycle(s) and well modifications were significant factors in obtaining and setting conditions of the permits.

For LT3 the FTF was connected to a nearby campus building to evaluate the high-temperature ATES FTF's ability to meet a real heating load. Several possible nearby buildings were considered for tie-in. Distance to the building, type of building heating system, heating system capacity and tie-in cost were considerations. The reheat system, a relatively constant load, of the Animal Sciences Veterinary Medicine (ASVM) building was connected to the FTF. The characteristics of an ATES system, with highest temperature water being recovered initially and relatively complicated startup/shutdown and reversal procedures strongly suggested that replacing a base load portion of heating need would interface more simply to the FTF. Replacing peak loads would have required much more extensive, and more costly, modifications to the uFTF. These would probably have included variable-speed pumps and a complicated pumping procedure. No new control systems were required on the aquifer water side of the system; fine control of the reheat system was taken care of by the already existing ASVM building systems. The only modification required, besides installation of the piping and the double-wall heat exchanger, was simply adjusting alarm points on the ASVM reheat system. The tie-in was completed in December 1989, after LT3 had begun.

The storage and source wells were originally completed with two screened intervals in the FIG aquifer, the upper Franconia (UF) and the Ironton-Galesville (IG). Modification of the storage/source wells consisted of removing the UF well screens and replacing them with blank pipes. This left only the IG, the most permeable part of the aquifer, screened to the wells. The capacity of the wells was reduced somewhat. This modification simplified modeling of the aquifer because the UF and IG parts of the aquifer have significantly different mineralogy and permeability. Having the single storage zone simplified the geometry of the heated area around the storage/recovery well, tending to reduce heat loss to the aquifer and adjacent confining beds.

While the wells were being modified, the pumps were inspected. The storage well pump required replacement because of wear from the previous experimental cycles. Considerations for the replacement pump included the capacity reduction of the wells because of removal of the UF screens and the required heating need for the ASVM. The required pumping rate for recovery was determined to be approximately 12.6 L/sec (45.5 m^3/hr) instead of the 18.9 L/sec (68.0 m^3/hr) that was originally installed. The replacement pump in the injection/recovery well was sized for the required recovery rate rather than the original rate.

LT3 was planned to consist of 90 days of injection of 104.4°C water at a rate of 15.8 L/sec (56.7 m^3/hr). Recovery was to be continued until a volume of water equal to that stored was recovered. The recovered water was to be used to supply heat to the ASVM building as long as the water temperature was high enough to be useful.

LT3 was conducted over 155 days between October 1989 and March 1990. Most injection was conducted from October 25 until December 12. Heat recovery was not possible at that time because the ASVM building tie-in was not completed until late December. Heat recovery began on January 2. Unseasonably warm weather hit the area, and on January 5 heat recovery was halted. Injection was restarted to take advantage of the additional warm weather, but problems with the steam system forced a shutdown of injection after a few hours. Recovery was continued; warm weather forced recovery to stop on January 7. Injection was again attempted; however, the source well pump did not operate properly. Inspection and repairs at the source well were undertaken. Partial repair to allow recovery to continue was not completed until late January when seasonably cold weather had returned. Heat recovery was restarted January 31 and continued through March 29

There were 47.2 days of injection. Source water temperatures averaged 20.2°C. A total volume of 63.2×10^3 m^3 of water was injected at a rate of

54.95 m^3/hr into the storage well at a mean temperature of 104.7°C from October through December 1989. A total of 6.21 GWh were added to the source water and stored in the aquifer. Of the total, 2.11 GWh were necessary to raise the water temperature to the useful minimum temperature of 49°C, and 4.10 GWh were necessary to raise the water temperature from 49°C to 104.7°C.

A total volume of 66.0 x 10^3 m^3 of water was recovered at a rate of 44.83 m^3 /hr from the storage well at a mean temperature of 76.5°C. Highest and lowest temperatures of recovered water were 100.0 and 47.8°C, respectively. A total of 4.13 GWh of energy were recovered from the aquifer. The mean return water temperature was 68.1°C.

Chemistry of the ground water is critical to the operation of an ATES system. Ion-exchange water softening was used during injection to prevent scaling of the heat exchangers and the storage well during the cycle. Operation of the softener during injection was nearly trouble-free. The major change to the water was from a calcium-magnesium bicarbonate water to a sodium bicarbonate water. Source water had a hardness of 174 mg/L as $CaCO_3$; the injected water had a hardness of <5 mg/L as $CaCO_3$. Sodium concentration was changed from 19 to 101 mg/L by the water softener. Recovered water had an average hardness of 48 mg/L as $CaCO_3$ and a sodium concentration of 87 mg/L. Mixing (dispersion) can account for the increase of calcium and magnesium and the decrease in sodium in water recovered from storage. Ion-exchange water softening was effective in preventing scaling in the heat exchangers and the storage well.

LT3 did demonstrate that ATES in a confined aquifer at temperatures above 100°C can be effectively tied into a conventional building heating system. In evaluating energy recovery, it must be remembered that the source water was considerably cooler than would be optimal for this system. Approximately 66 percent (4.13 GWh) of all of the energy added to the water was recovered; approximately 50 percent (2.07 GWh) of the energy added to the water above 49°C (33 percent of the total energy stored) was delivered to the ASVM building. Approximately 15 percent (0.64 GWh) of the usable (10 percent of the total) energy stored was actually used in the ASVM building. The remainder of the energy recovered, 3.49 GWh (above 20.2°C) or 1.43 GWh (above 49°C), depending upon the base used, was returned to the source well. The useful minimum temperature for recovered water was 49°C. Operations during heat recovery with the ASVM building's reheat system were trouble-free after adjusting the alarm points on the ASVM reheat system.

The ASVM building was able to use only about one-third of the possible heat supplied. If variable pumping rates had been possible, significantly more of the supplied heat could have been utilized. Integration into more of the ASVM (or other) building's mechanical system would have resulted in a significant increase in the use of the energy supplied during heat recovery. The cost to connect to and modify other ASVM building systems for this experimental cycle was the main reason for not incorporating other building systems into the FTF. The delivery of heat from the storage system to the targeted use is reasonably predictable if the parameters of the aquifer and operating scheme are well characterized. The system as operated for this cycle would not be cost effective during an initial cycle, but with continued cycles and an appropriate building interface, preliminary results indicate that it can be cost effective.

Results from LT3 are consistent with those of previous cycles. Aquifer characteristics were not observed to have been adversely affected by the cycles. It was demonstrated that high-temperature seasonal aquifer thermal energy storage is a feasible storage technology and can be successfully interfaced with existing building systems.

ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy and was conducted 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 L.D. Kannberg, program manager responsible for this project; Everett Jenne, senior scientist with particular interest in rock and water interactions; as well as John Raymond, Lance Vail, Sue Arey, Cheryl Nicola, Bruce Simanton, Sriram Somasundaram, Kevin Winegardner and the other PNL and DOE staff who played an important role in supporting and administering this phase of the operation of the St. Paul aquifer thermal energy storage field test facility. The understanding and cooperation of many individuals and agencies was also essential to the project. Thanks go to Brad Sielaff, John Holck, and Jim Strudell from the Minnesota Pollution Control Agency; Jim Japs from the Minnesota Department of Natural Resources; and Ed Ross and Jim Nye from the Minnesota Department of Health for their willingness to work to resolve permitting questions. Matt Walton, by his efforts, helped ensure the continuation of the ATES experiments after his retirement from Director of the Minnesota Geological Survey. The cooperation and interest of many individuals from the Physical Plant (now Facilities Management) of the University of Minnesota Twin Cities Campus made the ATES experiments possible. Warren Soderberg, University of Minnesota Physical Plant (retired), prepared the initial concepts for linking the ATES system to a campus building; Mike Nagel and Dan Radford provided essential cooperation in supplying steam for LT3; Roger Wegner provided the liaison, design and supervision for the ATES/building interconnection; John Hosfield, Ray Jackson, and Harvey Ramlow provided design and supervisory services for the necessary work on the pumping and monitoring wells. Thanks also go to the students who helped to staff the site during the injection and recovery periods: C. Lee, H. Liu, Y. Park, Y. Sun, and K. You. Operation of LT3 and preparation of this report also would not have been possible without the efforts of Underground Space Center staff members, Sara Hanft Mann and Andrea Spartz who handled administrative, secretarial and bookkeeping responsibilities.

CONTENTS

FIGURES

TABLES

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

1.0 INTRODUCTION

The objectives of the University of Minnesota aquifer thermal energy storage (ATES) project were to design, construct and operate a field test facility (FTF) to study the feasibility of a moderately high-temperature [up to 150°C (302°F)] thermal energy storage system in a confined aquifer. This project, performed via a subcontract with Pacific Northwest Laboratory(a) (PNL), has been part of the U.S. Department of Energy Underground Energy Storage Program since 1980. The FTF is located at the St. Paul campus of the University of Minnesota. It was originally designed to inject and recover heat at a rate of 5 MW (thermal) using a well doublet spaced at 255 m, operating at an injection/recovery rate of 18.9 L/sec (300 gpm) and maximum water temperature of 150°C (302°F). Figure 1.1 presents a schematic view of the ATES system.

A series of four short-term (ST) and two long-term (LT) cycles were conducted at the FTF between 1982 and 1987, which clearly showed the technical feasibility of ATES in a confined aquifer at temperatures above 100°C (see Appendix G; Walton et al. 1991; Hoyer et al. 1991a, 1991b). These results, including the effects of ATES cycles on aquifer water chemistry, encouraged the conduct of a demonstration cycle at the FTF where the ATES system was coupled to a real thermal load so that problems and efficiencies that occur in a commercial ("real") system could be studied. This demonstration cycle, long-term cycle 3 (LT3), was also planned to allow further research to better understand and predict geochemical changes in the aquifer resulting from continued use of the ATES system.

Planning for LT3 comprised the following major components:

- Submission of the necessary permit and variance applications.

(a) Operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RLO 1830.

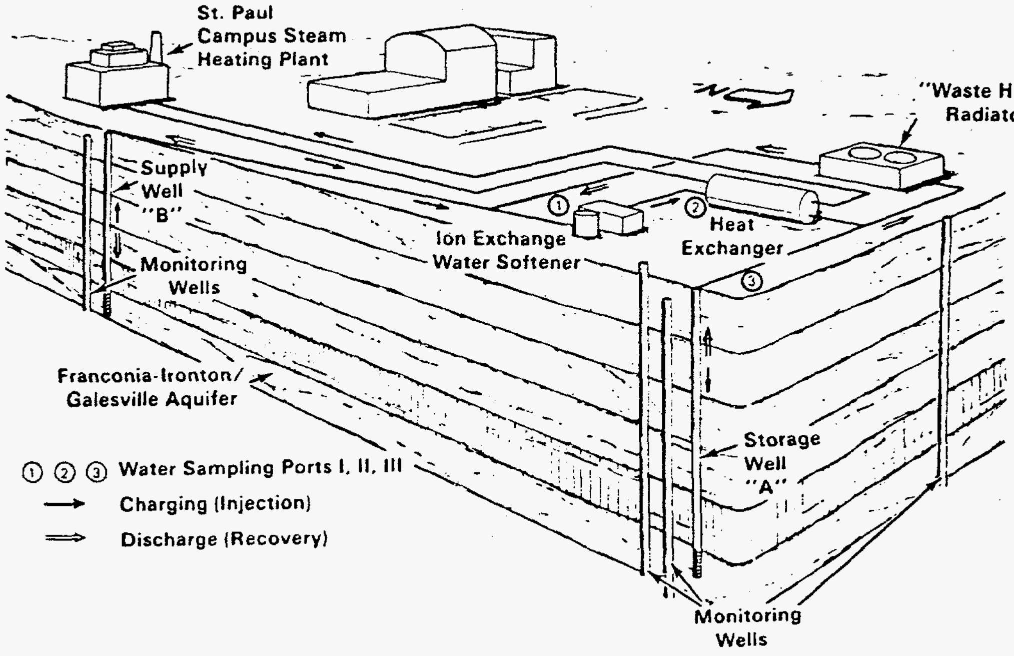


FIGURE 1.1. Conceptual Drawing of the University of Minnesota ATES Field Test Facility

- Modification of the supply and storage wells to limit injection to the Ironton-Galesville portion of the aquifer.
- Design and construction of the necessary piping, heat exchangers and controls to permit the use of aquifer-stored heat in an adjacent campus building.
- Operation of a third long-term test cycle integrated with the heating demand characteristics of a real building.
- An economic analysis of the continued use of the current ATES configuration by the University of Minnesota beyond the planned test cycle.
- An economic analysis of the potential of a new ATES system developed in conjunction with anticipated future changes in the University physical plant system.
- A post-mortem corehole drilled to examine the effects of hot water injection and withdrawal cycles on the fabric, mineralogy and geochemistry of the affected rock formations.

- Computer simulation of the hydraulic, thermal and geochemical activity in the aquifer during the third long-term cycle.

- The necessary monitoring and analysis to support the above activities and to satisfy permit requirements.

As part of the shift of project emphasis towards the actual utilization of the ATES system, the principal responsibility for the project was shifted within the University of Minnesota from the Minnesota Geological Survey to the Underground Space Center, a division of the Department of Civil and Mineral Engineering.

This report details the preparations for and the results of LT3. The field test facility and preparations for LT3 are described in Section 2. The operation of LT3 is described in Section 3. Section 4 summarizes the thermal and hydrologic responses of the aquifer and surrounding rock to the cycle. Water chemistry results for the cycle are presented in Section 5. Discussion of the results and conclusions from LT3 and associated activities are presented in Sections 6 and 7.

A chronology of events related to LT3 is found in Appendix A. A summary of the operating parameters for the various LT3 activities are found in Appendix B. A tabular record of the daily flow and temperature data from the cycle are found in Appendix C. Water chemistry data from the cycle are found in Appendix D. Appendix E provides a record of the pumpout of the heated water from the aquifer following cycle LT2 (required by the permit for the operation of the previous long-term cycles). For completeness, Appendix F provides data from subcycle Long-Term 3b and for the pumpout that followed LT3. Appendix G briefly summarizes all of the cycles conducted at the St. Paul ATES FTF.

2.0 FIELD TEST FACILITY AND PREPARATIONS FOR LONG-TERM CYCLE 3

The field test facility is located on the St. Paul campus of the University of Minnesota (U of M). Plans for LT3 required new permits, connecting the FTF to a nearby building, and modifying the storage and source well configurations.

2.1 FIELD TEST FACILITY

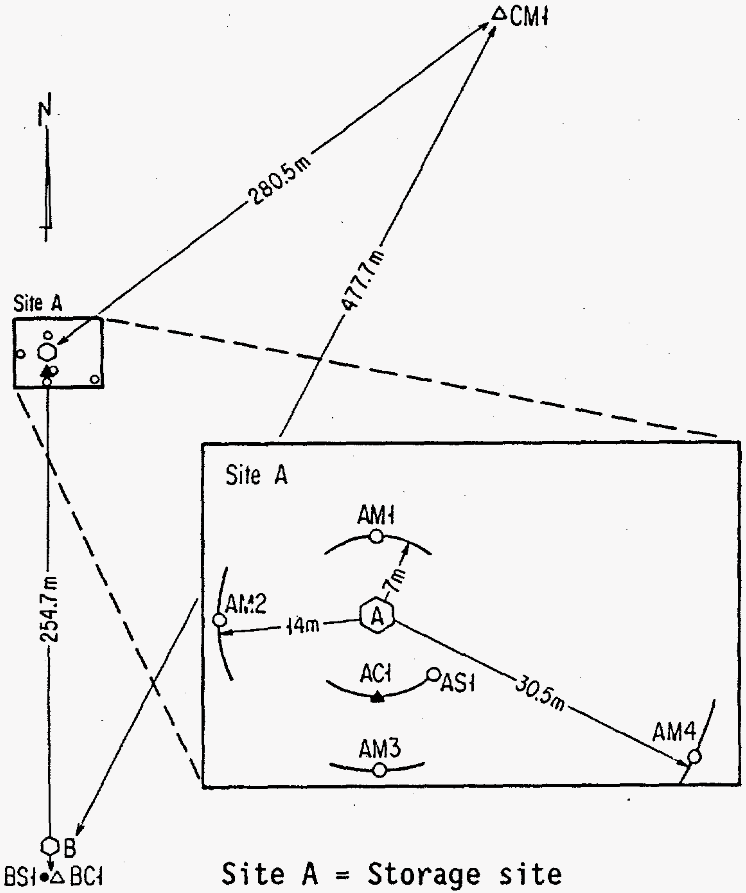
Figure 1.1 presents a conceptual sketch of the FTF on the St. Paul campus. Further details of the site configuration and its modification for LT3 are provided in the section below. An earlier report describes the field test facility and aquifer characterization in detail (Walton et al., 1991).

2.1.1 Site Location and Setting

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

For the previous long-term test cycles, the facility consisted of two pumping/injection (source and storage) wells completed in the FIG aquifer; nine monitoring wells in the FIG aquifer, its confining beds, and the Jordan and Mt. Simon aquifers; connecting piping, heat exchangers, and a water softener between the source and storage wells; and piping to supply steam to the heat exchangers (Figures 2.1, 2.2, and 2.3). Changes made to the site to tie into a nearby building for LT3 are described in Section 2.2.

The FIG aquifer was chosen for this experimental system because it is the least used in the site vicinity. It has the lowest hydraulic conductivity and transmissivity of the aquifers, and its hydraulic gradient at the site is very low (0.004). Environmental concerns about possible effects of the high

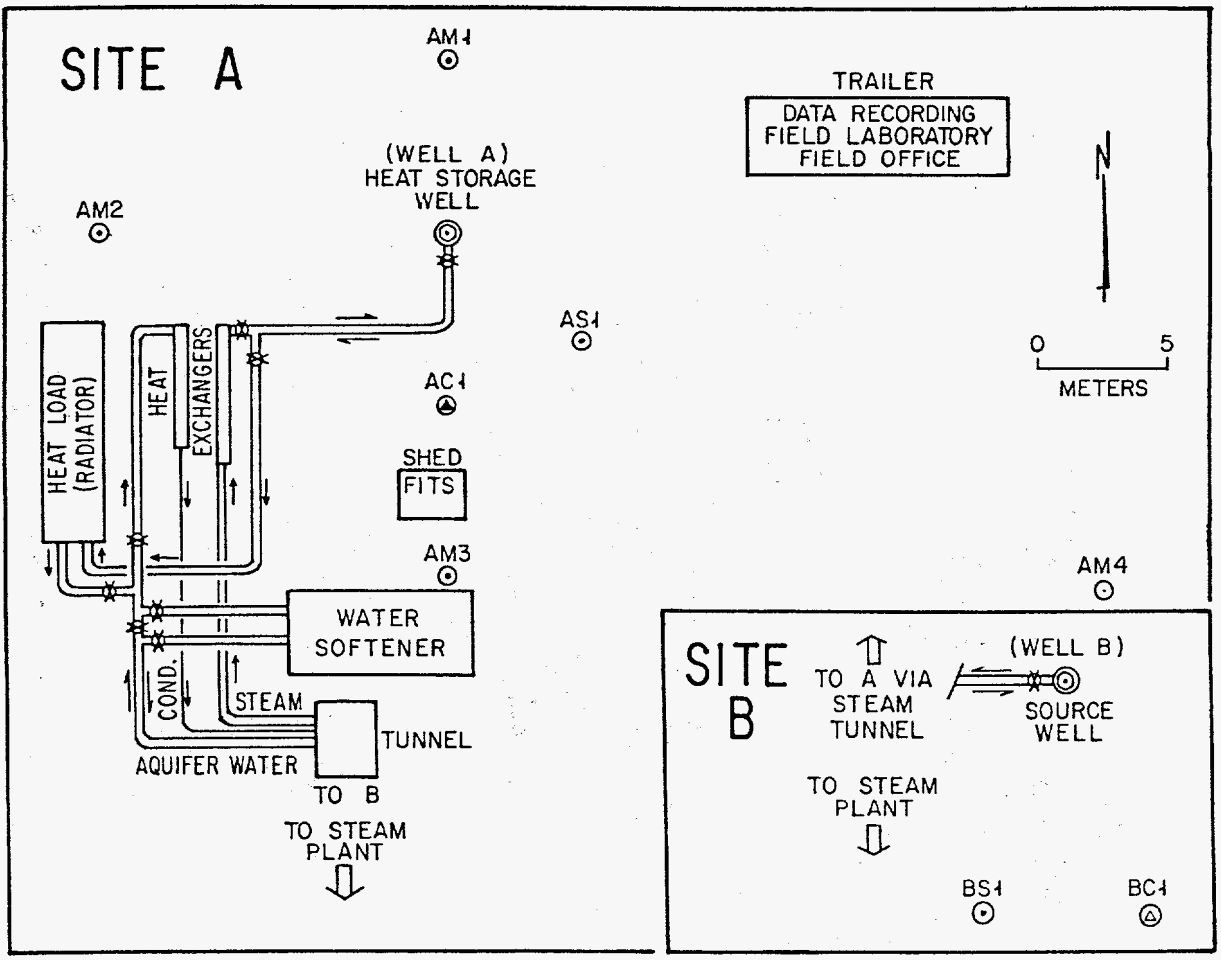


Site A = Storage site
A = Storage well
B = Source well
AC1, BC1 = Core hole monitoring wells
AM1, AM2, AM3, AM4, AS1, BS1, CM2 = Monitoring wells

FIGURE 2.1. Well Plan of University of Minnesota ATES Field Test Facility

temperatures of the ATES tests made selection of a little-used aquifer with a low hydraulic gradient an important siting factor.

Examination of cores, geophysical logs, packer test results, and ambient temperature measurements confirmed that the FIG aquifer comprises interbedded, highly stratified fine- to medium-grained sandstone and thin shale beds. The upper boundary of the FIG aquifer occurs at a depth of about 180 m (600 ft), and the aquifer is approximately 60-m (195-ft) thick at the site. Static water levels for the FIG aquifer are at a depth of about 55 m (180 ft). Hydraulic conductivity ranges from about <0.01 to 1.5 m/day (0.003 to 0.5 ft/day); the horizontal-to-vertical conductivity ratio is about 10:1 in



Site A = Storage site
Site B = Source site
FITS = Field injectivity test stand
AC1, AM1, AM2, AM3, AM4, AS1, BC1, BS1 = Monitoring wells

FIGURE 2.2. Storage and Source Well Sites at the University of Minnesota ATES Field Test Facility for the Long-Term Cycles

permeable horizons and 100:1 in less permeable horizons. The presence of thin strata of low conductivity interbedded with beds of high conductivity greatly reduces thermal convection and thermal stratification when heated water is introduced into the aquifer.

The Ironton-Galesville (IG) and upper Franconia (UF) parts of the aquifer are the two more permeable portions of the aquifer. These have quite

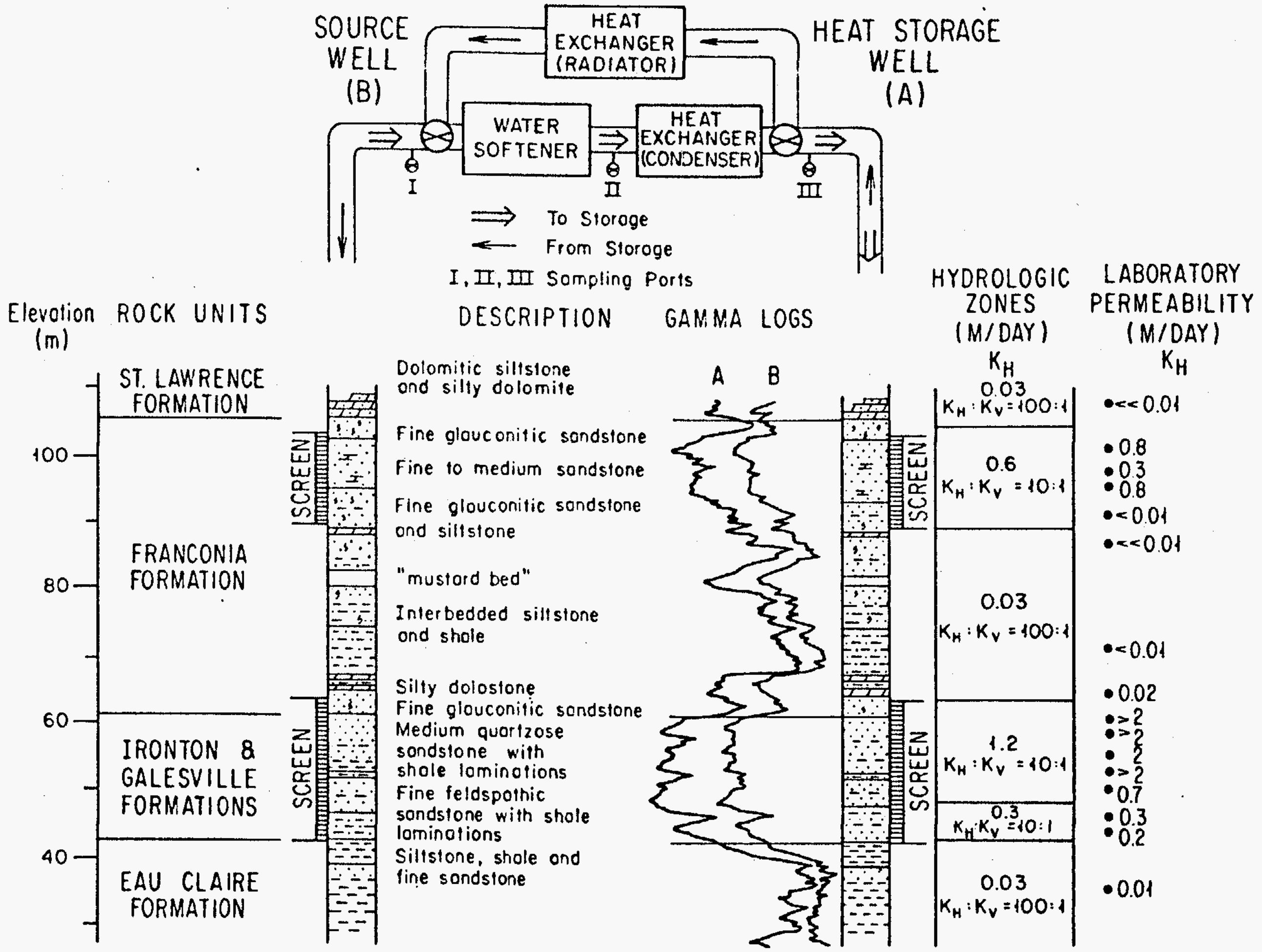


FIGURE 2.3. Stratigraphy and Hydrogeologic Units at the University of Minnesota ATES Field Test Facility with Screened Intervals and Flow Path for Long-Term Cycles LT1 and LT2

different mineralogies (Figure 2.3), which complicated water chemistry modeling during previous cycles.

2.1.2 Source and Storage Wells

The source well (B) and the storage well (A) were each originally completed with two screened intervals in the FIG aquifer (Figure 2.3). The head of Well A is at an altitude of 287 m (941 ft) above mean sea level (msl); the head of Well B is 278 m (912 ft) above msl. The upper 13.7 m (45 ft) section of the 25-slot stainless steel screen, opposite the upper portion of the Franconia formation in the interval between 104 m (341 ft) msl and 90 m (296 ft) msl, was removed from both wells before LT3. The lower 22.9 m (70 ft) section of screen, opposite the entire thickness of the Ironton and Galesville sandstones and small thicknesses of the lowermost Franconia and uppermost Eau Claire formations, was the only screened interval for LT3 (Figure 2.3). Modification of the wells before cycle LT3 is discussed in Section 2.2.3.

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

2.1.3 Monitoring Wells

Nine monitoring wells provide instrumentation for the full stratigraphic interval affected by the system. Parameters measured at monitoring wells are temperature, pressure (water level), and composition of the ground water. Six wells are located at the storage site (Site A), two at the source site (Site B), and one at Site C. Site C is located 280.5 m (920 ft) northeast of the storage well to detect any unexpected far-field effects of heat storage (Figure 2.1).

At the storage site, wells are located 7 m (AC1, AM1, AS1), 14 m (AM2, AM3), and 30.5 m (AM4) from the storage well. Downhole gyroscopic surveys were conducted in Wells AM1, AM2, AM3, and AM4 to determine positions with respect to the storage well at the storage horizons (Figure 2.4). All wells were surveyed when drilled by a plumb bob method. For those surveyed by both

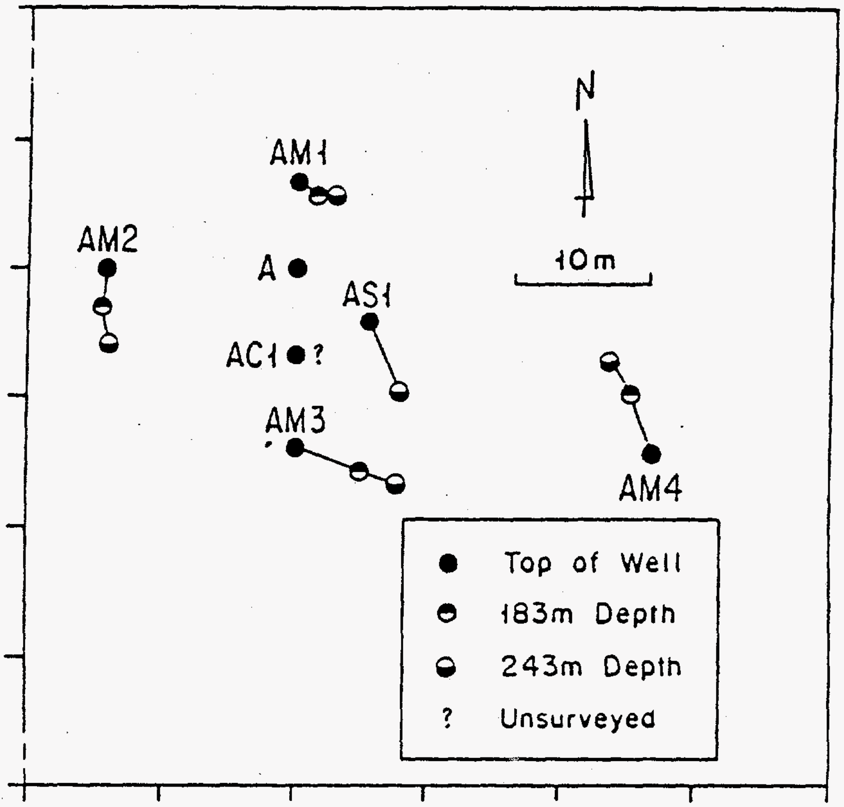


FIGURE 2.4. Plan View of Surface and Downhole Gyroscopic-Surveyed Locations of Wells AM1, AM2, AM3, and AM4

methods, the results were similar. It is believed that the survey results for the plumb bob method suffice for those wells with insufficient pipe diameters to survey with the gyroscopic tool. Table 2.1 compares the results of the methods. Well AM4 was drilled by cable tool and shows a deviation opposite that of all the other surveyed wells, which were drilled by rotary methods.

All wells at the storage site, except AC1 (see next paragraph) have multiple-pair thermocouple strings for monitoring temperatures in the FIG aquifer and the immediately overlying and underlying formations (Figure 2.5). These thermocouple strings are in closed-end pipes except in AM1, which was initially constructed with a direct buried thermocouple string attached to the pipe. This string was replaced before long-term cycle 1 (LT1) because several thermocouples failed, and a replacement string was installed in the AM1 pipe, which is open-ended and extends to the Eau Claire formation.

TABLE 2.1. Comparison Between Downhole-Surveyed Positions of Monitoring Wells at 243-m Depth

	Driller's Survey		Gyroscopic Survey		
Well	Displacement, m	Azimuth	Displacement, m	Azimuth	Difference, m
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

Well AC1 was used for monitoring only during long-term cycle 2 (LT2) (Hoyer et al. 1991b, Appendix D). Special LT3 monitoring plans were prepared for AC1 because of detected leakage at that well. Plans were developed as part of the permitting process for LT3 (see Section 2.2.1) to replace a packer that was used to study the leakage problem during LT2 but that failed during the cycle because of high temperatures. The intention was to replace the packer and its inflation line with equipment that would withstand the temperatures expected during LT3 and attempt to monitor AC1 as was done during LT2. However, when attempting to remove the packer and thermocouples from AC1, the packer and some of the inflation line became firmly wedged in the well pipe at a depth of about 91.5 m (300 ft). Several attempts to remove them proved futile. Special permission was received from the Minnesota Pollution Control Agency to conduct LT3 without the packer installed in Well AC1 provided that following the cycle, the well would be properly abandoned.

At the source site, the surface position of the monitoring wells, that were not gyroscopically surveyed, is 10 m from the source well. The location of the bottom of Well BS1 is known to be immediately adjacent to Well B because during the drilling of Well B, Well BS1 was intersected at a depth of about 206 m (675 ft). Eight different horizons are monitored at the site from the Jordan to the Mt. Simon aquifers. Each monitored interval has a 0.9-m (3 ft) screen installed at the depths indicated in Figure 2.4. The Mt. Simon and Jordan pipes are for providing samples for water analyses as well as for

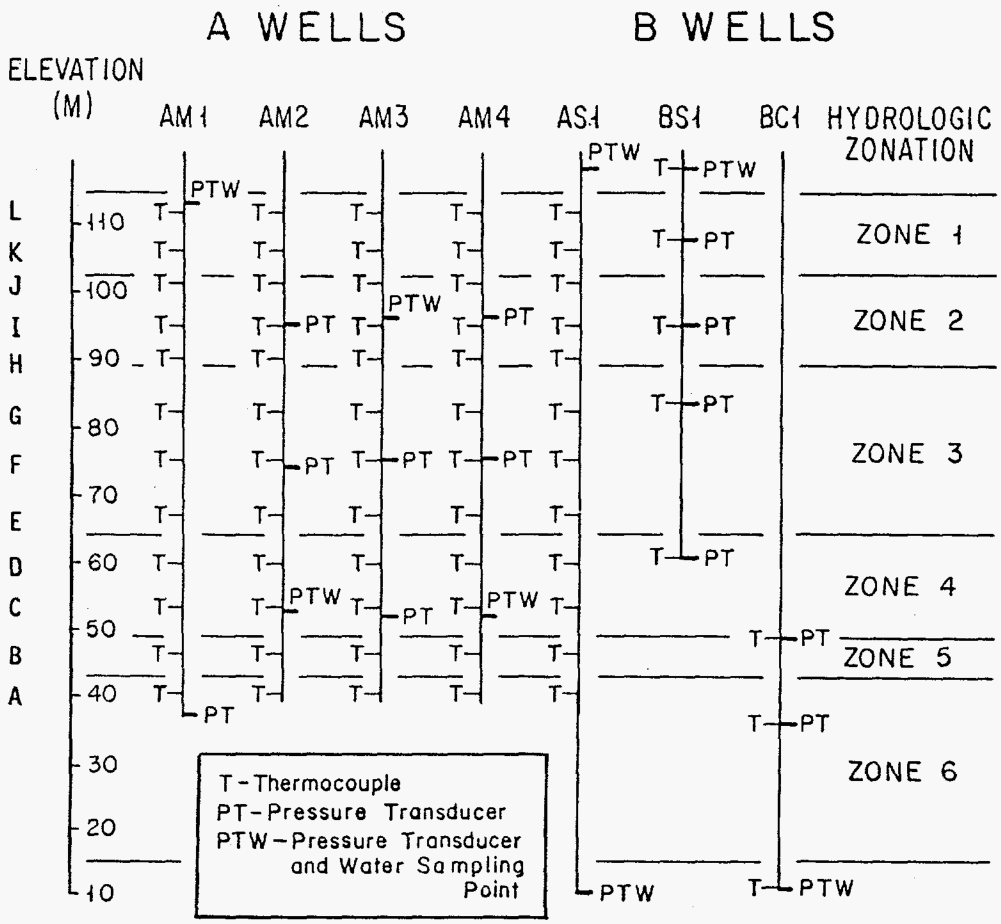


FIGURE 2.5. Monitor Well Instrumentation at Sites A and B. Letters next to the elevation column identify thermocouple locations referenced in Section 4.

observing pressure (water level) and temperature. The remaining pipes are only for monitoring pressure (water level) and temperature.

Water samples were collected from the Jordan, Mt. Simon, and FIG aquifers at Site A before and after each test was conducted. The 1.25-in. (0.03-m) pipes in monitoring Wells AM1, AM2, AS1, BC1, BS1, and CM1 are for sampling and measuring water level (piezometer). Well AM4 has a 2-in. (0.05-m) pipe for sampling and measuring water level. The sampling pipe installed in AM3 was plugged, apparently with grout, and the pipe in the upper Franconia in Well CM1 was accidentally plugged with a pump while attempting to collect samples before the start of testing at the site. (Walton et al. 1991).

2.1.4 Piping, Heat Exchangers, and Water Softener

2.1.4.1 Piping and Heat Exchangers. Piping connecting Sites A and B, and from the campus steam plant to Site B, is routed through an existing steam and utilities tunnel that passes under Sites A and B. A provision for sending water from the wells to waste via the existing storm sewer was added so the system could be flushed before beginning injection or recovery, and the heated and softened water could be pumped out and discharged to waste. The water softener has an outlet to the sanitary sewer so brine and final rinse water could be routed to waste. Six-in. lines (150 mm) (Schedule 40 steel with 3-in. thick (75 mm) fiberglass insulation) are used for steam and connective piping. The condensate return line is a 2-in. (50 mm) line (Schedule 80, 2-in. fiberglass insulation), and lines to waste are 4-in. (100 mm) lines (Schedule 40, uninsulated).

The aquifer water is heated in a tube-and-shell subcooler and a tube-and-shell condenser connected in series. The aquifer water is on the tube side, and the 150 psia (1034 kPa) steam and condensate are on the shell side. Both exchangers are two-pass on the tube side and single-pass on the shell side. The temperature of the aquifer water is regulated during injection by a self-operated valve controlled by a temperature sensor in the aquifer water line downstream of the condenser.

A fan-cooled, water-to-air heat exchanger (radiator) was the simulated heating load for previous experimental cycles. A water-to-water plate heat exchanger on the reheat system of a nearby campus building was the heating load during LT3 (see Section 2.2.2 and 2.2.3).

The radiator used in the previous cycles was only used during pumpout following LT3 to reduce the temperature of the aquifer water before discharge to the storm sewer.

2.1.4.2 Water Softener. An ion-exchange water softener was installed for the long-term cycles to allow virtually uninterrupted operation during the injection phase of the cycles. The softener removes the hardness from the ground water before heating by substituting sodium ions for calcium ions. The effect of the softener is to change the ground water from a calcium-magnesium bicarbonate water to a sodium-bicarbonate water.

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

The softener malfunctioned several times forcing system shutdowns during LT1 (Hoyer et al. 1991a). During LT2 and LT3, the softener worked with few malfunctions, none of which required shutting down the system for repair (Hoyer et al. 1991b).

During LT1, the water softener used approximately 684 kg (1500 lb) of salt (NaCl) per day during the injection phase. During LT2, because the source water was warmer and therefore not as hard, only approximately 500 kg (1100 lb) of salt per day were required. During LT3, the flow rate was less than previous cycles and the source water temperature was low again because of the pumpout following LT2. Approximately 500 kg (1100 lb) of salt per day were required. Chapters 3 and 5 discuss the operation and effects of the softener replacing calcium and magnesium with sodium in the stored water.

2.2 PREPARATIONS FOR LONG-TERM CYCLE 3

Preparations for LT3 included obtaining renewed permits/variances to operate the FTF, selecting an appropriate heating load for the FTF to supply energy to a nearby building, designing and constructing the connection of the building to the ATES FTF, and modifying the storage and source wells to simplify the geochemical characterisitcs of the aquifer system. Appendix A provides a chronology of steps for LT3.

---

[a] Manufactured by Matt-Son, Inc., Streamwood, Illinois.

2.2.1 Permits and Variances

Four permits and/or variances from State rules or regulations issued by three State departments or agencies were required for the operation of the ATES system in Minnesota. The departments' jurisdictions do overlap; however, each was the lead agency on only some issues. The primary regulatory issues and lead agencies are:

- Water appropriation/use - Minnesota Department of Natural Resources
- Water well construction/operation - Minnesota Department of Health
- Injection of heated water/monitoring/water discharge - Minnesota Pollution Control Agency

The three departments worked together on the permits/variances; meetings and discussions were held with staff members of each agency. If the primary department/agency approved of plans in their primary area, the others approved the plan.

The most critical variance requested was from Minnesota Rules Chapter 7060, which prohibits discharge into the zone of saturation by injection wells and prohibits the long-term storage of pollutants (including heat) underground. The original variance, for the short-term cycles, was issued by the Minnesota Pollution Control Agency (MPCA) in 1980 after a contested case hearing. A revised variance, for the first two long-term cycles, was issued by the MPCA in 1984 after a public informational meeting was held. The expiration date for the reissued variance was July 31, 1988.

The new variance request was received by the agency on February 5, 1988. Principal differences in this variance request from the previous ones included:

1) an injection period of 120 days
2) modification of the injection/recovery wells so that only the Ironton-Galesville portion of the aquifer was used for heat storage
3) reduction of the maximum heated water injection/withdrawal rate to 17.3 L/sec (275 gpm).

Several meetings were held between MPCA staff and project staff to review the proposed variance request and to request further information. A principal concern of MPCA staff was that not all the heat or volume of water injected would necessarily be recovered between cycles leading to a gradual spread of the areal influence of the ATES system on the aquifer. A further concern was that limiting the storage zone to the Ironton-Galesville portion of the aquifer would also increase the areal extent of the influence of the ATES system. The proposed increased injection period (120 days versus 60 days in prior long-term cycles), the application of the recovered heat to a real load, and the restriction of the storage zone to just the thickness of the Ironton-Galesville portion of the aquifer were the cause of the concerns.

Modeling the proposed cycle using the ATESSS code developed at PNL (Vail 1989) was a significant factor in this permitting process. Various scenarios for the cycle using U of M ATES FTF site parameters and planned flows and temperatures were used to determine expected thermal front positions for injection periods of 60, 90, and 120 days.

The agency considered requiring an additional monitoring well at a greater distance from the injection well to monitor these effects, but this requirement was dropped for the third cycle when the proposed injection period was reduced to 90 days. Other injection limitations were 0.39 MGD (17.3 L/sec, 275 gpm) as a maximum flow rate, 150°C (300°F) as a maximum injection temperature and 180 mg/L as a maximum concentration of dissolved sodium in the FIG water. The possibility for two complete cycles was approved under this variance, but a requirement was added that volume of water equal to that injected in the first cycle (LT3) be pumped out before a second cycle (LT3b) could commence. The variance was approved, as modified, by the MPCA Board on September 27, 1988. The new variance request was uncontested and extended until July 31, 1993.

The MPCA also has approval authority for the "National Pollutant Discharge Elimination System And State Disposal System Permit" (NPDES/SDS). The existing NPDES/SDS permit MN 0051632 was reissued by the agency in conjunction with the variance discussed above.

A variance from the Minnesota Well Construction Code is required for the ATES system. An extension of the existing variance was requested from the Minnesota Department of Health on October 5, 1988, after the MPCA permit approval, and was granted on October 25, 1988.

The final permit required was that authorizing the appropriation of the ground water used in the ATES cycle and withdrawn during pumpout before site closeout. An extension to the existing permit (#80-6201) was requested from the Minnesota Department of Natural Resources on August 12, 1988 and was issued on December 20, 1988.

2.2.2 Selection of Building Heating Load

The original concept for interfacing the ATES system with a real building load was to connect the system to Peters Hall, a campus building immediately to the east of the FTF storage site. The building already had a heating system designed to operate from a hot water supply rather than steam (which is the norm for the campus system) and was very close to the FTF. In addition, the size of the load at Peters Hall was small enough so that the ATES system could meet the full heating demand of the building. From a readiness standpoint coupled with the low cost of piping to connect the building to the ATES system and the potential demonstration that ATES could handle the full heating load for a campus building, the choice appeared a suitable one. The design of the piping and controls for connection to Peters Hall was initiated early in 1988. As the design progressed, several major drawbacks to Peters Hall as an end use for the heat became apparent and several significant limitations on how ATES heat could be withdrawn from the existing well and pump configuration also became clear.

The most obvious problem was that while the peak load of Peters Hall was a reasonable match for the thermal withdrawal rate of the ATES system, the load was too small during warmer weather to make effective use of ATES heat as it would be withdrawn. The flow rate of the ATES system during heat recovery is controlled on the high side by the capacity of the pump in Well A pumping against the head of water represented by the elevation difference from the piezometric surface to the highest point in the system plus the head loss in the piping, heat exchangers, etc. On the low flow side, the system is controlled by the need to return water to the aquifer via Well B without aeration (i.e., sufficient flow must be maintained to keep the drop pipe in Well B flowing full) and by a minimum flow requirement for pump cooling. A further limiting condition resulting from system design was that the pump bearings in Well B had not been designed to handle water temperatures as high as those in Well A. The maximum return temperature to Well B was thus limited to 85°C to remain within pump specifications.

During preliminary design, the change to a variable-speed pump in Well A was considered but not pursued because of concerns about reliability, control and cost. A dual-speed pump coupled with a bypass pipe was considered more reliable and easier to control when trying to match the heating demand in the building. The use of a pair of smaller drop pipes in Well B was planned to allow a minimum flow rate of 4.7 L/sec (75 gpm). Flow rates below this level were not considered practical with the current ATES system configuration. Back pressure in the piping system by partially closing valves also can be used to control flow rates within certain limits but will increase the power requirements for pumping.

The initial water temperature recovered from the aquifer was expected to be potentially as high as 105°C requiring that the heat exchanger in the building effect a minimum temperature drop of 20°C to permit reinjection at 85°C or below. The other alternative would be to pass the water through an additional heat exchanger, wasting the heat, to lower the temperature prior to injection.

A second major problem was that the temperature of the hot water heating system in Peters Hall is reset progressively from 82°C at -29°C exterior temperature to 43°C at 10°C exterior temperature. Thus, the minimum useable temperature is higher than 82°C when the exterior temperature is less than -29°C. During warmer weather, the ATES water would be useable down to 43°C at 10°C outside temperature.

Because of the progressively falling temperature of recovered water from the ATES system during recovery (Figure 2.6) and the need to drop the temperature of the ATES water by the greatest amount early in the recovery period (to permit reinjection), the recovery period for the heat stored would be best initiated at the beginning of the period of maximum heat demand (Figure 2.6). At this time, the recovered water temperature is above the set point value for the coldest weather and the load is sufficient to drop the ATES water temperature to below 85°C. This scenario does, however, limit the total amount of ATES-stored energy that can be utilized in the building over

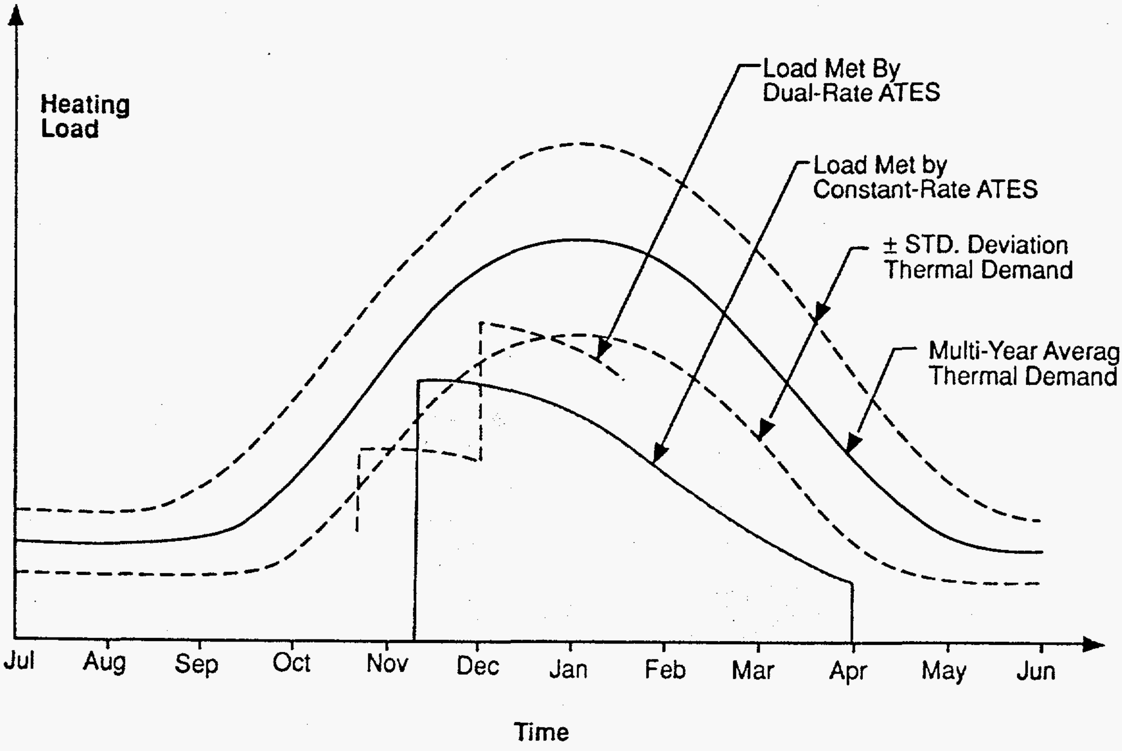


FIGURE 2.6. Typical Seasonal Heating Demand and ATES System Output

the winter season because the system is not operational during the early portion of the winter. Furthermore, this mode of operation either extends the storage period before heat is recovered (when heat is injected during the summer months) or encourages injection during the late fall and early winter to limit the storage period. Neither of these options is particularly desirable.

As the preliminary design for the interface to Peters Hall progressed, it became increasingly clear that the relatively small peak load of Peters Hall and its major dependence on outdoor temperature exacerbated the limitations on ATES operation described above. The delay in permit approval (see Section 2.2.1) essentially precluded long-term cycle 3 from being conducted during the winter of 1988-89 and it was decided to reexamine other options for the utilization of ATES heat on the St. Paul campus.

Other nearby buildings considered for connection to the ATES system for LT3 included the Earle Brown Center, the Biological Sciences Building, the Veterinary Diagnostic Labs, and the Animal Sciences/Veterinary Medicine (ASVM) buildings. The heating and process heat use loads/capacities for the buildings are given in Table 2.2.

An issue that became very clear during the search for a heating load to match the FTF capability was that, although the total thermal load history for a particular building was generally available from University records, the individual systems that would be utilized for connection to ATES-supplied heat were not separately monitored. Furthermore, the design capacity of the equipment may be very misleading as to the magnitude and variation of the thermal load, especially when process water heat is involved.

As a result of the limitations of the building loads available in the vicinity of the St. Paul campus ATES site, an ideal interaction for LT3 could not be found, but it was felt that the investigation, design and operation of an applied cycle would prove very valuable to the design of future commercial systems.

A final decision was reached to provide the reheat system of the ASVM building with heat recovered from storage during LT3. The characteristics of an ATES system, with highest temperature water being recovered initially and relatively complicated startup/shutdown and reversal procedures strongly suggested that replacing a base load portion of heating need would interface

TABLE 2.2. Design Capacities of Potential Building Loads, in Megawatts

	Radiation	Preheat	Reheat	Hot Water
Peters Hall	0.44	..	..	0.52
Earle Brown Center	0.26	..	..	0.40
Lewis Animal Hospital	0.21	..	*	1.64
Animal Sciences/Vet. Med.	0.10	#	1.21	1.64
Biological Sciences	#	5.27	0.38	0.40

.. Not applicable
* Included with radiation
\# Not considered

more simply to the FTF. Matching peak load capacity would have required much more extensive, and more costly, modification to the FTF. These would probably have included variable-speed pumps and a complicated pumping procedure. Replacing a relatively constant demand part of the heating system allowed a nearly constant speed operation and a relatively simple tie-in. No new control systems were required on the water side of the system. The fine control of the reheat system was taken care of by the already existing ASVM building systems.

2.2.3 ATES FTF/Building Connection - Design and Construction

The ASVM building was connected to the FTF. The aquifer water lines connecting the FTF and ASVM were routed through existing steam tunnels. The aquifer lines between the source and storage wells were cut and valved so that the aquifer water could be routed from a pumping FTF well to the ASVM building heat exchanger, and to the injecting (receiving) well. Normally this would be from the storage well, through the heat exchanger in the building, and to the source well. The FTF was tied into the building system upstream of the building's reheat condensers. Figure 2.7 is a diagram of the flow path for LT3.

Two plate heat exchangers were installed in the ASVM building, one having aquifer water heating intermediate-loop water, the other having the intermediate-loop water heating the ASVM reheat water, were installed in the ASVM building. This provided isolation of the aquifer water from the circulating building water (i.e., a double-wall heat exchanger). A double-wall heat exchanger was desired to provide isolation of the building system water from the aquifer water.

The only modification required on the building side besides piping to the FTF and installing the double-wall heat exchanger, was adjusting alarm points on the ASVM reheat system. Temperatures of incoming and outgoing water on each side of the exchangers were measured; a flowmeter was installed in the building on the aquifer line side. Aquifer water temperatures and flow measurement data were transmitted back to the FTF site trailer. The tie-in was completed in December 1989, after the storage portion of LT3 had begun. Section 3 presents some discussion of the ASVM-FTF tie-in.

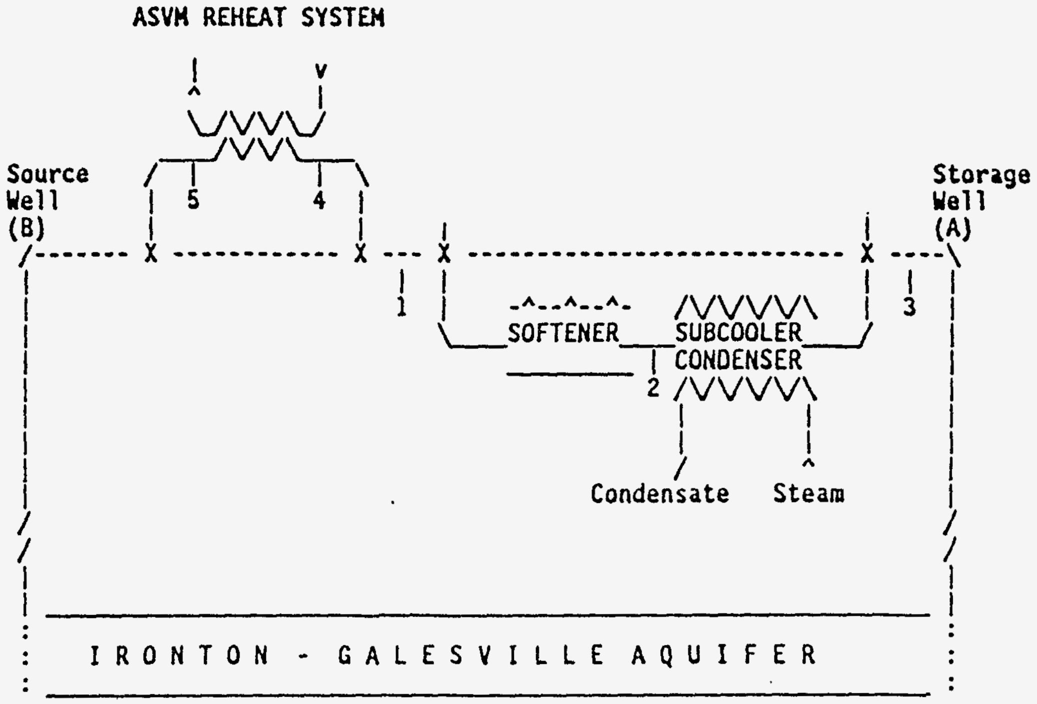


FIGURE 2.7. Flow Path During Long-Term Cycle 3

2.2.4 Storage and Source Well Modification

The storage and source wells were originally completed with two screened intervals in the FIG aquifer, the upper Franconia (UF) and the Ironton-Galesville (IG). The original purpose in having the two screened intervals was to ensure that the wells had enough capacity for the 18.9 L/sec (300 gpm) goal of the early cycles. However, during the previous cycles, it was found that the decision to inject the water into the two permeable zones of the FIG aquifer -- the upper Franconia and the Ironton-Galesville -- had some negative aspects. These were: a loss of efficiency caused by the thermal convection in the upper Franconia, the downhole flow in the wells, and the high surface area of the two heat storage zones; and more diverse geochemical conditions because the two permeable zones have substantially different mineralogies (Figure 2.3). These conditions complicated interpretation of thermal and water chemistry results. The temperature of the water recovered represented a composite temperature of the water entering the storage well from the two screened intervals, which could, and likely did, have different temperatures. Dissolved constituents have different saturations at different temperatures for the same concentrations. Water at different temperatures would have different chemical equilibria with the dissolved constituents. The partitioning ratio of water stored or recovered from the aquifer at the two screened intervals could be estimated from the observed behavior at monitoring wells, but the degree of certainty was not high. Water in contact with different minerals would also have different chemical equilibrium points, in part a function of the solids in contact with the water.

The wells were modified so that only the Ironton-Galesville interval was screened. This is the most permeable part of the aquifer and the permeable portion having the simpler mineralogy. Modification of the injection/recovery wells consisted of removing the UF well screens and replacing them with blank pipes (Figure 2.8). The modification to each of the wells was done by cutting the riser pipe below the UF screen, pulling the riser pipe and UF well screen from the hole, replacing the riser pipe and well screen with a blank riser pipe, and cementing this riser pipe in place. This procedure allowed the original gravel pack at the IG well screen to remain in place during the entire well modification. After the riser pipe had been cut, a TV camera was lowered into the well to allow inspection of the riser pipe left in the well. The riser pipe was centered in the well borehole.

Removal of the upper well screen reduced the capacity of the wells. The well capacity remained about equal to what the revised permits and variance would allow.

The storage well modification for Well A began in June 1988, while the source well (Well B) was still being pumped out following the previous cycle LT2. The well modification work for Well B started after pumpout from LT2 was completed in July 1988.

While modification of the wells was taking place, the pumps in the wells were removed and inspected. The pumps were inspected by representatives from the manufacturer's servicing agent and by personnel from the St. Anthony Falls Hydraulic Laboratory at the University of Minnesota. The bowls, impellers and bearings of the storage well pump (Well A) showed significant wear. Cost to

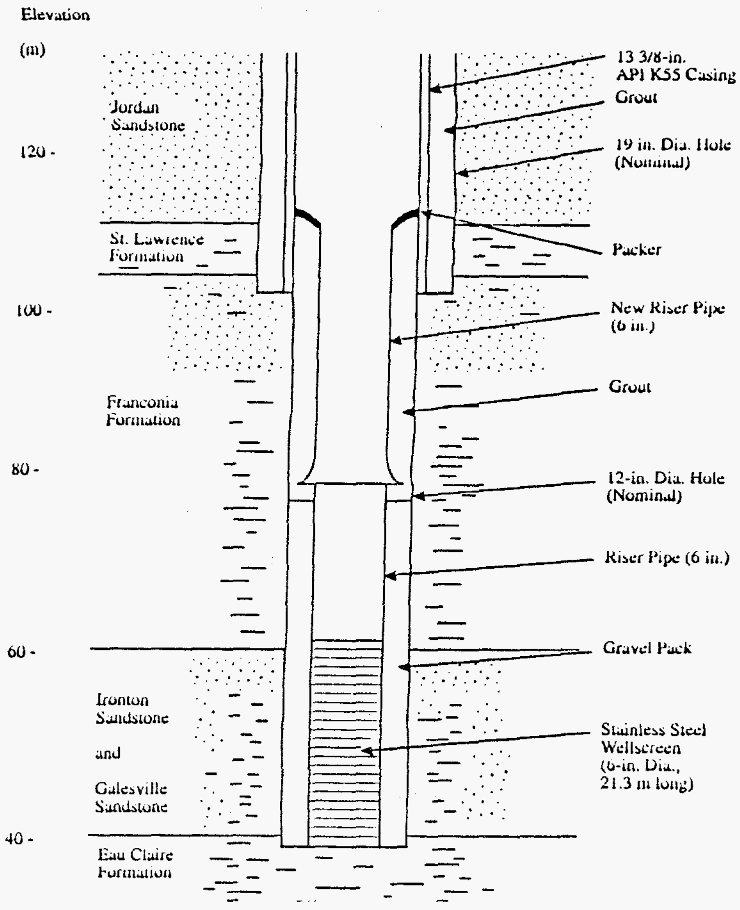


FIGURE 2.8. Lower Portion of Storage Well (Well A) After Modification. The source well (Well B) was modified in the same way.

repair the pump would have exceeded the cost for a replacement pump. Inspection of the source well pump (Well B) revealed minor wear, and the pump was considered to be in suitable condition for continued use. The wear in the storage well pump was caused in part by the very large temperature range (10°C to 104°C) at which the pump operated during the cycles. The pump had been designed with extra adjustment capability because of the anticipated changes in shaft and column length caused by changes in temperature. However, it is probable that the frequency of impeller adjustment as water temperature changed during recovery phases of the earlier cycles and pumpout had not been sufficient. This may have contributed significantly to the excessive pump wear. This should be considered a critical item for maintenance in high-temperature ATES cycles in deep aquifers.

When the pump was reinstalled in the source well (Well B), drop pipes to accommodate flow rates as low as 4.7 L/sec (75 gpm) were installed to allow the potential for low flow rate operation. Drop pipes, 1-in. and 2-in., were installed to a depth of 61 m (200 ft) and secured to the column pipe. However, a header to tie the upper end of the pipes to the above ground piping was not installed. Decisions regarding the flow rates had not, as yet, been made when the pump was reinstalled. No connection has been made because the flow rates chosen later did not require use of the drop pipes. The pipes remain in the source well. Well screen modification to the wells and source well pump installation was completed in January 1989.

Storage well pump replacement considerations included the capacity reduction of the wells caused by removal of the UF screens and the required heating needed for the ASVM building. The required pumping rate for recovery was determined to be approximately 12.6 L/sec (45.5 m^3/hr, 200 gpm) instead of the 18.9 L/sec (68.0 m^3/hr, 300 gpm) originally installed. The replacement pump in the injection/recovery well was sized for the needed recovery rate rather than the original rate and was rated for 12.6 L/sec (200 gpm) at a total dynamic head of 186 m (610 ft). The replacement pump was ordered from the manufacturer of the original pump in April 1989 after the ASVM building was chosen as the target building. The pump was installed in September 1989.

2.2.5 Computer Simulation of Long-Term Cycle 3

The cooperative research program with the United States Geological Survey (USGS), active on previous stages of the project, was continued. The USGS responsibility was simulation of the injection, storage and retrieval of heated water in the aquifer (Miller 1984, 1985, 1986; Miller and Delin 1993; Miller and Voss 1986). Simulation results and methodology also were used for comparison with the geochemical and system simulation work underway at PNL (Vail 1989). The USGS also participated in the site data acquisition and analysis process. For LT3, the USGS supplied Campbell CR10 data loggers and a personal computer to serve as the data acquisition system for aquifer and confining bed temperatures. Temperatures at the wellhead of the storage well were also recorded by the data loggers.

Simulation work was curtailed because of budget restrictions on LT3. It was considered that there was less additional understanding to be gained from extending the successful simulation of the prior cycles than from the other aspects of the LT3 research. The decision was also influenced by the change in the ground-water-flow modeling code supported by the USGS from the SWIP code used in the prior cycles to the HST3D code, which had not yet been adequately tested for nonisothermal, anisotropic conditions. Code development was neither in the scope of work nor in the budget.

3.0 LONG-TERM CYCLE 3 OPERATION

Long-term cycle 3 was planned to consist of 90 days of injection of 104.4°C (220°F) water at a rate of 15.8 L/sec (56.7 m^3/hr, 251 gpm). Heated water recovery was planned to be at a flow rate of 12.6 L/sec (45.4 m^3/hr, 200 gpm) and to continue until all the water stored had been recovered. The recovered water was to be used to supply heat to the ASVM building as long as the water temperature was high enough to be useful. If conditions caused an interruption in the heated water injection period before the planned 90-day injection period was completed, another period of injection, after some heat recovery had been completed, was possible. This chapter chronicles the cycle.

LT3 began at 1018 on October 25, 1989 when injection of heated water was started into the storage well. The cycle ended 155 days later with the completion of heat recovery at 0900 on March 29, 1990. Figure 3.1 presents daily flows and temperatures for the cycle. Table 3.1 summarizes flows and temperatures for the main injection recovery cycle. Appendix B presents operating parameters for the cycle. Appendix C presents flows, temperatures, energy data, and related cycle information. Water levels and temperatures observed at monitoring wells in the aquifer are presented in Section 4. Section 5 presents complete water chemistry results for the cycle; Appendix D presents analytical results on water samples collected. Table 3.2 presents summary water chemistry results on selected parameters.

A high-temperature extension to the cycle was requested by PNL in April 1990 to examine some questions about silica deposition in heat exchangers during heat recovery at high temperatures. This extension was possible because of the shortened injection period (only ~47 days of a permitted 90 days) of the original LT3. The injected water was to be heated to as close to 150°C as possible. This high-temperature extension was scheduled as a short cycle having 7 days each of injection, storage, and recovery. This extension, termed LT3b, began on May 31 and finally ended following several problems with the storage well pump, on November 23, 1990. LT3b is discussed in Section 3.5 and Appendix F.

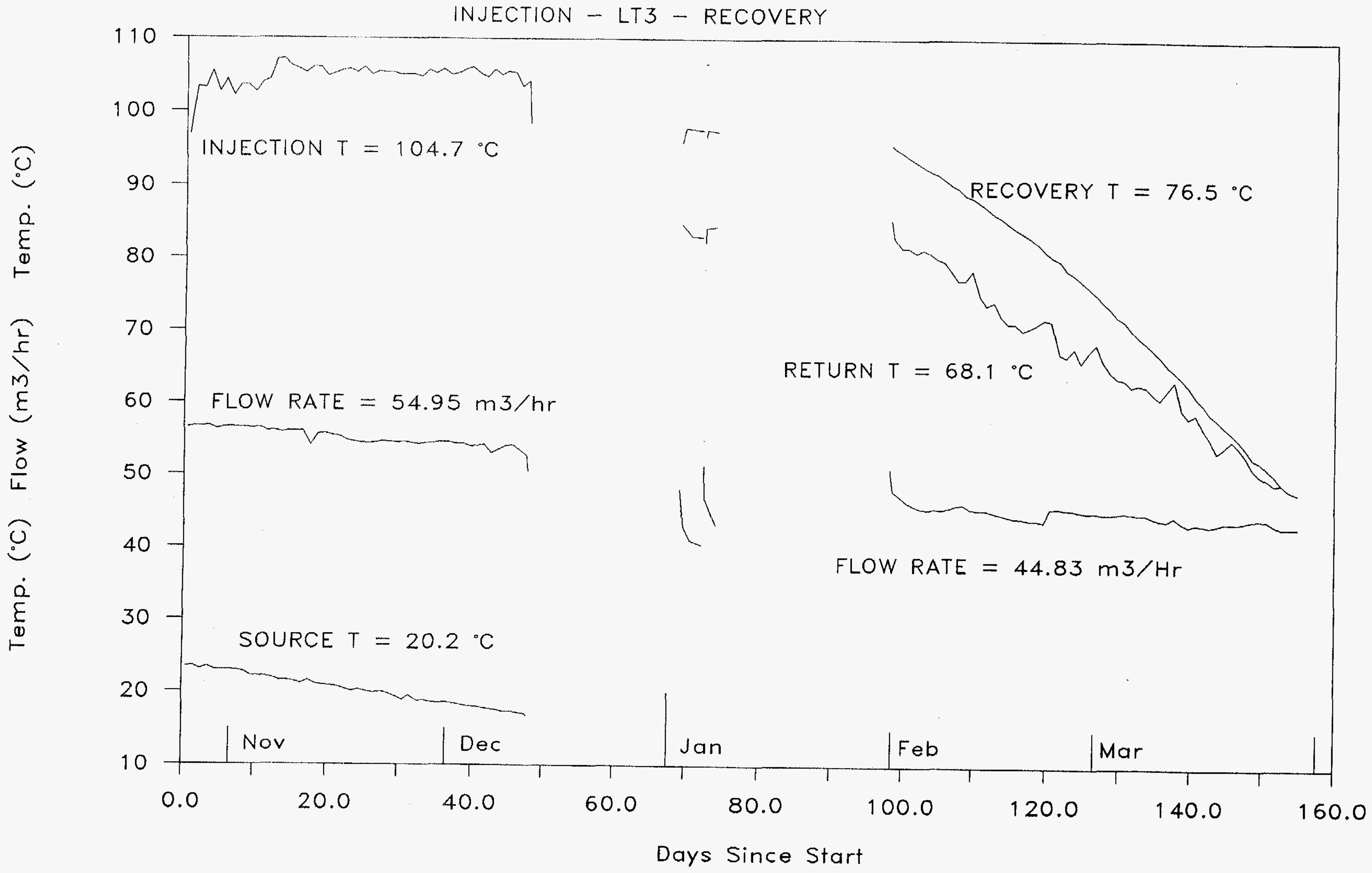


FIGURE 3.1. Flows and Temperatures Plotted Versus Time for Long-Term Cycle 3

TABLE 3.1. Summary of Long-Term Cycle 3

	Duration, days	Average Temperature, °C	Average Flow Rate, L/sec	Volume, $10^3 m^3$	Energy, GWh
Injection	47.2[a]	104.7	15.3	63.2	6.21
Storage	21.4				
Recovery	61.2[b]	76.5	12.5	66.0	4.13

Energy Recovery Factor -- See Explanation in Text
(using 20.2°C source water) 0.67
(using ambient 11.0°C source water) 0.70

---

[a] Over 47.8 days
[b] Over 85.8 days

TABLE 3.2. Typical Water Chemistry of Some Major Constituents During Long-Term Cycle 3

Water Analysed	Alkalinity, meq/L	Ca, mg/L	Mg, mg/L	Na, mg/L	SiO_2 (as Si), mg/L
Source	4.48	46.41	14.14	19.32	6.42
Softened	4.61	0.83	0.37	101.9	6.43
Injected [a]	4.52	0.89	0.46	101.5	6.43
Recovered	4.53	12.95	3.81	88.94	16.58
Returned	4.58	13.38	3.96	87.96	16.27

---

[a] Softened and heated.

3.1 INJECTION PHASE

The injection phase of LT3 began at 1018 on October 25, 1989. Earlier in October, problems with the steam controller and leaks in the above ground piping thwarted initial attempts to begin the cycle. The unsuccessful attempts to start the cycle allowed thorough testing of the water softener and flushing of system piping. Injection began before completion of the hookup to the ASVM building. Injection continued until 0535 on December 12, 1989, when the source well pump shut off just as the water softener began regeneration of a unit. The pressure overload switch at the source well turned the system off. The overload was caused by ice blockage of the water trap in the water softener's pneumatic control system. The valves of the water softener all closed when the pneumatic control system lost air pressure. The extremely low temperature when the shutdown occurred [-17.7°C (0°F)], and a forecast for even colder weather to follow, did not allow injection to be resumed. [It should be noted that December 1989 was the coldest December on record in St. Paul; temperatures were below -17.7°C (0°F) continuously for 116 hours.]

Flow during injection averaged 15.3 L/s (54.95 m^3/hr, 242.3 gpm). Temperature of the injected (stored) water averaged 104.7°C (220.5°F). Temperature of the source water averaged 20.2°C (68.4°F). The average temperature increase before injection (Delta T) was 84.5°C (152.1°F). Highest injected water temperature during LT3 was 112.2°C (234°F). Average steam consumption during the cycle was 8.28 tonnes/hr (18.25 x 10^3 lb/hr) to heat the water. Approximately 9,500 tonnes of steam (10,500 tons) were supplied to heat the water during the cycle. Energy supplied by the steam totaled 6.77 GWh (23.1 x 10^9 Btu). A total of 6.21 GWh (21.2 x 10^9 Btu) were added to the water and stored in the aquifer. The remaining 0.56 GWh (1.9 x 10^3 Btu) represented energy losses in the heat exchanger.

Injection was interrupted for repairs to the steam controller three times during the first several days of injection. The steam controller was turning on full, then completely off, in a very short time. Temperatures would vary by more than 5°C (9°F) in minutes; steam pressures would jump from 30 psi to 60 psi (210 kPa to 420 kPa) in seconds. On October 31, in an attempt to solve the problem, a replacement thermal sensor was installed on the steam controller. For a short time the system settled down, then the erratic temperature/steam fluctuations resumed, worse than before. On November 2, the original sensor and a pressure pilot valve were installed. Immediately, the steam controller operated smoothly, giving close temperature control on the injected water through the rest of the injection period. During these steam controller repairs, the source well remained on; injection was interrupted by diverting the water to waste.

The source well pump was turned off by power "bumps" on three occasions. The system steam safety shutoff turned the steam off immediately. These shutoffs required a complete system restart. This was accomplished as soon as possible after the shutoff took place.

Scheduled campus steam system repair on required turning off the source well and interrupting injection for about 8 hours on November 4. Injection was restarted following completion of the campus steam repair.

Ion-exchange water softening was used during injection to prevent scaling and blocking of the heat exchangers and the storage well during the cycle. Operation of the softener during injection was nearly troublefree. Malfunctions, including sticking valves and some improper cycling, occurred about six times during injection. Injection continued while the malfunctions were corrected. Softener regenerations were initiated manually during part of the injection phase because the lower flow rate of LT3 did not always keep the water softener control timer running. A field kit was used to measure hardness of water leaving the water softener 6 to 12 times per day to provide nearly real time checks on the performance of the softener. Average hardness of the source water was 174 mg/L as $CaCO_3$; hardness of the softened, injected water was <5 mg/L as $CaCO_3$. Sodium concentration changed from 19 mg/L to 101 mg/L. Recovered water had an average hardness of 48 mg/L as $CaCO_3$ and a sodium concentration of 88 mg/L. The softener regenerated 228 times using approximately 24,000 kg of salt during the injection period. Salt consumption was approximately 500 kg/day (1100 lb/day).

3.2 STORAGE PHASE

Storage began with the end of injection on December 12, 1989. Plans were for recovery to begin whenever there was significant heat demand on the campus, not after some preset period of storage. However, because the hookup to the ASVM building was not yet completed, it was not possible to begin heat recovery during the very cold spell in December.

When the ASVM building hookup was first completed, initial pressure testing on December 21, of the intermediate-loop lines between the two plate heat exchangers in the building revealed that the exchangers had been cross-connected. Repiping of the exchangers and rewiring of the instrumentation required 5 days. The repiped and rewired building system was pressure tested successfully on December 27. Temperature and flow signals from the ASVM building to the FTF system above-ground system recorder in the site trailer required correction; corrections were completed on December 28. Final testing of the aquifer lines and flow and temperature transmitters in the ASVM building was completed on December 29, 1989. With the completion of the ASVM/FTF hookup, LT3 recovery could have been started at any time; but with the New Year's holiday imminent, the start of recovery was scheduled for January 2, 1990. At the end of December, the very cold winter weather ended.

3.3 RECOVERY PHASE

A total volume of 66.0 x 10^3 m^3 of water was recovered from the storage well at a rate of 44.83 m^3/hr and at a mean temperature of 76.5°C from January through March 1990. Highest and lowest temperatures of recovered water were 100.0 and 47.8°C, respectively. A total of 4.13 GWh was recovered from the aquifer. The mean return water temperature was 68.1°C.

LT3 was to be an applied cycle with the recovered heat being used in the ASVM building. Thus, it was anticipated that the recovery phase would include several periods of time when storage or injection would take place. Recovery was halted when the weather was too warm to use the heat and to maintain conditions at the storage well that would keep temperatures at the source well within specifications (85°C or less).

Flow was targeted to be 12.6 L/sec (45.4 m^3/hr, 200 gpm). Temperature drop across the ASVM heat exchanger on the aquifer side was approximately 15°C (27°F) when the air temperature was below freezing. Reheat water was warmed by 30°C (54°F). Flow on the building side was approximately 6.3 L/sec (100 gpm).

Early in recovery when the weather was relatively mild and the recovered water was very close to 100°C, it became apparent that to have the reheat system take as much heat from the aquifer as possible, the alarm point needed to be reset above 96.1°C (205°F). Later, as the recovered water temperature went down, the low-temperature alarm point needed to be reset to 49°C (120°F) to allow as much heat as possible to be accepted by the ASVM reheat system.

Recovery was started on January 2, 1990, assuming that the weather would be close to normal. [January is normally the coldest month of the year.] The initial recovered water temperature was 100°C (212°F). Unseasonably mild January weather presented a problem because the highest acceptable temperature at the source well of 85°C (185°F) required a temperature difference across the heat exchanger on the aquifer side of 15°C. To allow the maximum temperature difference possible, the flow on the aquifer side was reduced to the minimum permitted by the pressures in the piping at the storage well. When the reheat side of the ASVM building was not taking enough heat, recovery had to be halted on January 5. The ATES system was then switched over to resume injecting heated water. The switch was accomplished in 2 hours and heated water injection was started. When attempting to return condensate to the steam plant, it was discovered that the steam condensate return line was frozen, forcing an end to injection. This injection period lasted for 4.1 hours. Temperature of the source water for the 4.1 hours of injection was 79.4°C (175°F), and required only 2.2 tonnes (4.8×10^3 lb) of steam per hour to heat the water to 104°C. Continuation of this operation would have demonstrated a capability to superimpose short storage-recovery cycles on top of a seasonal cycle. Such short storage-recovery cycles have the advantage of improving the energy recovery because of the short storage times and more effective use of the heating plant with short- as well as long-term storage cycles. Equipment problems and the unusual weather patterns interfered with this plan.

The switchover back to heat recovery mode was made in less than 2 hours. Heat recovery continued until 1036 on January 7, when the continued very mild weather again required shutdown because the recovered water was not being cooled to 85°C.

At this time, the condensate line was thawed and an attempt to restart heated water injection was made on January 9. After only a short time, the source well pump was not producing the expected flow for the pressure conditions. The pump was surging, vibrating, and making excessive noise; it was immediately turned off. An investigation into the problems with the source well was begun. A series of discussions with the pump manufacturer, check of impeller setting, and examination of the top assembly by the pump installer followed. Several attempts to repair and run the source well pump proved futile. The pump ran smoothly until the system was pressurized. The upper assembly of the pump was removed and examined. While replacing the upper assembly, the tension nut was stripped. This did not allow either recovery or injection to continue until the parts were replaced in late January. Replacement parts, allowing partial repair, were delivered and installed. Early on January 31, the source well pump was reassembled and run. The pump did not operate properly; however, the well could receive water, allowing heat recovery to continue. The mild weather had continued through most of the month.

Heat recovery resumed at 1457 on January 31, and continued without interruption until 0900 on March 29. The recovered water temperature started at 97.2°C (207°F) and declined to a temperature of 47.8°C (118°F), just below the lower limiting temperature for the ASVM reheat system of 49°C (120°F) (Figure 3.1).

Temperature drop on the aquifer side of the heat exchangers in the ASVM building averaged 8.4°C, with a maximum drop of 14.7°C. The building reheat side had a temperature rise of approximately double the aquifer side temperature drop. When the heat demand was low and when the recovered water temperature was approaching the lower limiting temperature, the temperature drop was less. During February, when the FTF supplied the ASVM building with all heat added to the reheat system, the temperature of the recovered water started the month at 91.7°C (197°F) and slowly cooled to 76.1°C (169°F) at the end of the month. Flow averaged 12.7 L/sec (201 gpm) during the month. Temperature drop across the ASVM heat exchanger averaged 11.7°C (21°F). The maximum temperature increase on the building side was 28°C (50°F), occurring when the drop on the aquifer side was approximately 14°C (25°F).

Flow during recovery averaged 12.5 L/sec (45.0 m^3/hr, 198.1 gpm); highest water temperature was 100°C; temperature of the last water supplying heat to ASVM was 49°C. Average temperature of the recovered water was 76.5°C (170°F). The aquifer water gave up 0.64 GWh of thermal energy to the reheat system of the ASVM building. The ATES system supplied all of the reheat energy for the entire month of February (see Section 3.4).

The only adjustment that had to be made to the ASVM building heating system was resetting of alarm points on the reheat system. At the beginning of recovery, the high-temperature alarm point had to be set higher than normal (to ~99°C); toward the end of recovery, the low-temperature alarm point had to be set lower than normal (~49°C).

Recovery continued until 0900 on March 29. Temperature of the recovered water had fallen to 47.8°C (118°F) when recovery ended. During the final 2.5 days of recovery, none of the recovered heat was used in the ASVM building because the water temperature was too low. A total of 1.04 volumes of stored water were recovered during recovery (1.00 volumes when heat supplying ended), making the cycle approximately mass balanced, as were all the previous cycles.

3.4 ENERGY BALANCE FOR LT3

Table 3.3 presents a summary of the energy balances for LT3. A total of 6.21 GWh (21.2 x 10^9 Btu) were added to the aquifer. This was from a total of 6.77 GWh (23.1 x 10^9 Btu) that were supplied to the storage site by steam.

The energy values presented in Table 3.3 for different parts of the cycle are explained below. Energy added to the aquifer above 20.2°C is the total energy added to the water above the source water temperature (20.2°C) for the cycle. Energy added to the aquifer above 49°C is the energy added to the aquifer at temperatures useful for the ASVM reheat system. Energy recovered from the aquifer above 20.2°C is the energy added to the aquifer that was recovered. Energy recovered from the aquifer above 49°C is the total potentially usable energy supplied to the ASVM building. Energy used in the

TABLE 3.3. Energy Summary of Long-Term Cycle 3

	Energy added to aquifer	Energy recovered from aquifer	%
Energy -			
above 20.2°C --	6.21 GWh	4.13 GWh	66.5
above 49°C --	4.10 GWh	2.07 GWh	50.5
Energy used in ASVM building - - -		0.64 GWh	
Energy used in ASVM / Total energy added - - - -			10.3
Energy used in ASVM / Energy added >49°C - - - -			15.6
Energy supplied ASVM >49°C / Total energy added - -			33.3
Total energy supplied ASVM / Energy added >49°C - -			50.5

ASVM building is the total energy actually removed from the aquifer water by the building heat exchangers.

Energy balances are presented as percentages of the various energy values stored and recovered from different appropriate values, as given in Table 3.3. In reviewing the energy recovery, it must be remembered that the source water was considerably cooler than would be optimal, or than would be likely after other cycles, for this system. Approximately 66 percent (4.13 GWh) of all of the energy added to the water was recovered; approximately 50 percent (2.07 GWh) of the energy added to the water above 49°C (33 percent of the total energy stored) was delivered to the ASVM building. Approximately 15 percent (0.64 GWh) of the usable (and 10 percent of the total) energy stored was actually used in the ASVM building. The remainder of the energy recovered [3.49 GWh (above 20.2°C) or 1.43 GWh (above 49°C), depending upon the base used] was returned to the source well. The useful minimum temperature for recovered water was 49°C.

Temperature drop on the aquifer side of the heat exchangers in the ASVM building averaged 8.4°C, with a maximum drop of 14.7°C. The building reheat side had a temperature rise of approximately double the aquifer side temperature drop. When the heat demand was low and when the recovered water temperature was approaching the lower limiting temperature, the temperature drop was less (Figure 3.1).

The ASVM building was able to use only about one-third of the possible heat supplied. If variable pumping rates had been possible, significantly more of the supplied heat could have been utilized. Integration into more of the ASVM (or other) building's mechanical system would have resulted in a significant increase in the use of the energy supplied during heat recovery. The cost to connect to and modify other ASVM building systems for this experimental cycle was the main reason for not incorporating other building systems into the FTF.

3.5 HIGH-TEMPERATURE PHASE - LT3b

An extension to the cycle was requested by PNL in April to examine some questions about silica deposition in heat exchangers during heat recovery at high temperatures. This extension was possible because of the shortened injection period of the original LT3. Plans were for the water to be heated to as close to 150°C as possible. The recovered water was to be routed through the radiator and cooled to approximately 54°C; the heat exchanger was to be examined for silica scale. In preparation for this, several rods were installed in radiator tubes on the site to serve as precipitation surfaces and several thermal wells were installed in adjacent radiator tubes to provide temperature data for these surfaces. This extension to LT3, the high-temperature phase (LT3b), began with a 7-day injection phase from May 31 to June 7, 1990 with the injected water heated to 132°C. When heat recovery was begun on June 20, 1990, the storage well pump would not pump the hot (up to 115.6°C) water. Following a series of attempts to recover the heated water, the pump was pulled, examined, and sent to the factory for detailed examination. The factory examination discovered that the clearances on the impellers in the bowls did meet specifications at low (<80°C) temperatures, but did not meet specifications at high temperatures (>90°C). The pump was repaired, returned, and reinstalled. Heat recovery finally began on November 16, 1990. The long delay in beginning recovery seriously affected the LT3b results. The water temperature at the beginning of recovery was only 86.9°C, not nearly high enough to be of interest regarding potential silica precipitation in the heat exchanger. Thus, LT3b did not fulfill the purposes of the extension; however, storage and recovery information did result from this effort. Appendix F presents a discussion of LT3b, the data from LT3b, and the pumpout of the aquifer.

4.0 THERMAL AND HYDROLOGIC RESPONSES TO LONG-TERM CYCLE 3

Responses to LT3 were measured at the FTF monitoring wells. Type T thermocouples in the storage site monitoring wells responded to temperature changes in the FIG aquifer. Water levels were measured in the Jordan, FIG, and Mt. Simon aquifers, and the St. Lawrence and Eau Claire confining beds. The observed responses reflected the pattern of pumping/injection, the nature of the FIG aquifer, the storage well configuration, and the monitoring well configurations.

Temperatures recorded in the Ironton-Galesville, opposite the storage well screen, rose and fell quite rapidly when the thermal front reached the monitoring wells. Temperatures above the screened interval, in the Franconia formation, the less permeable part of the aquifer, responded quite slowly to the injection and withdrawal of heat. Monitoring well sampling showed up as spikes in the thermal data.

Water levels in the Ironton-Galesville responded immediately to pumping, injection, and well shutoff. These changes in water level were superimposed upon the seasonal changes throughout the cycle. Upper Franconia, Mt. Simon and Jordan water levels showed expected seasonal changes and seasonal basin pumping influences.

4.1 THERMAL RESPONSES

Temperatures measured in the storage site monitoring wells through all of LT3 are presented in Figures 4.1 through 4.5. Thermocouple locations are given in Figure 2.5. The thermocouples located in Ironton-Galesville aquifer, hydrologic zones 4 and 5 (Figures 2.3 and 2.5) opposite the injection/recovery zone are thermocouples B, C, and D in the wells. Temperatures were recorded at least hourly during the injection and recovery phases of LT3 and twice daily during storage phases. Highest temperatures recorded were 105°C during the injection phase. Thermal responses were not uniform throughout the aquifer, reflecting the distances to the monitoring wells, hydraulic conductivities and porosities of the units, the storage well configuration, and configuration of the monitoring wells.

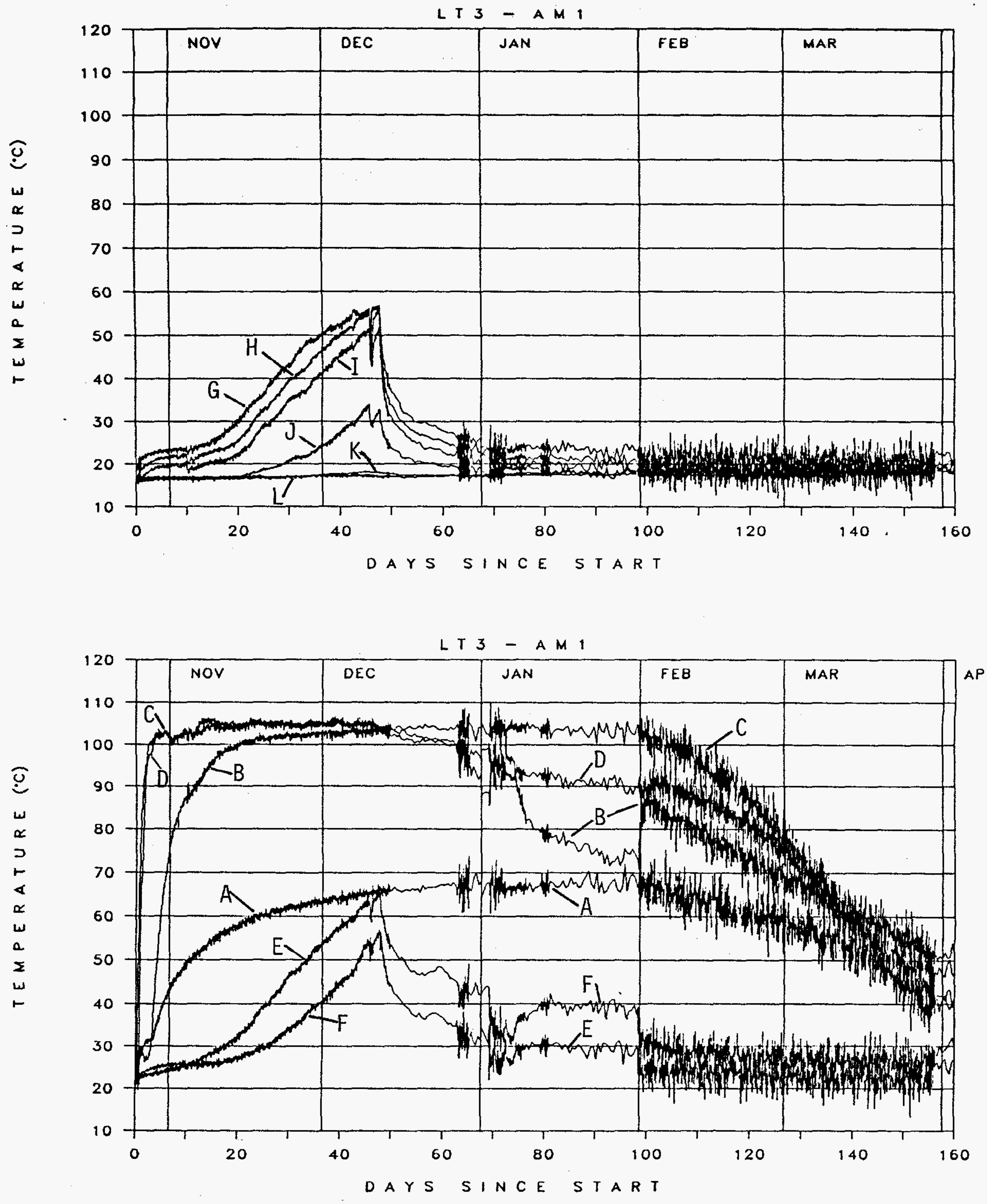


FIGURE 4.1. Temperatures in Well AM1 During Long-Term Cycle 3. Upper Diagram Includes Thermocouples G Through L. Lower Diagram Includes Thermocouples A Through F. Thermocouple Locations as in Figure 2.5.

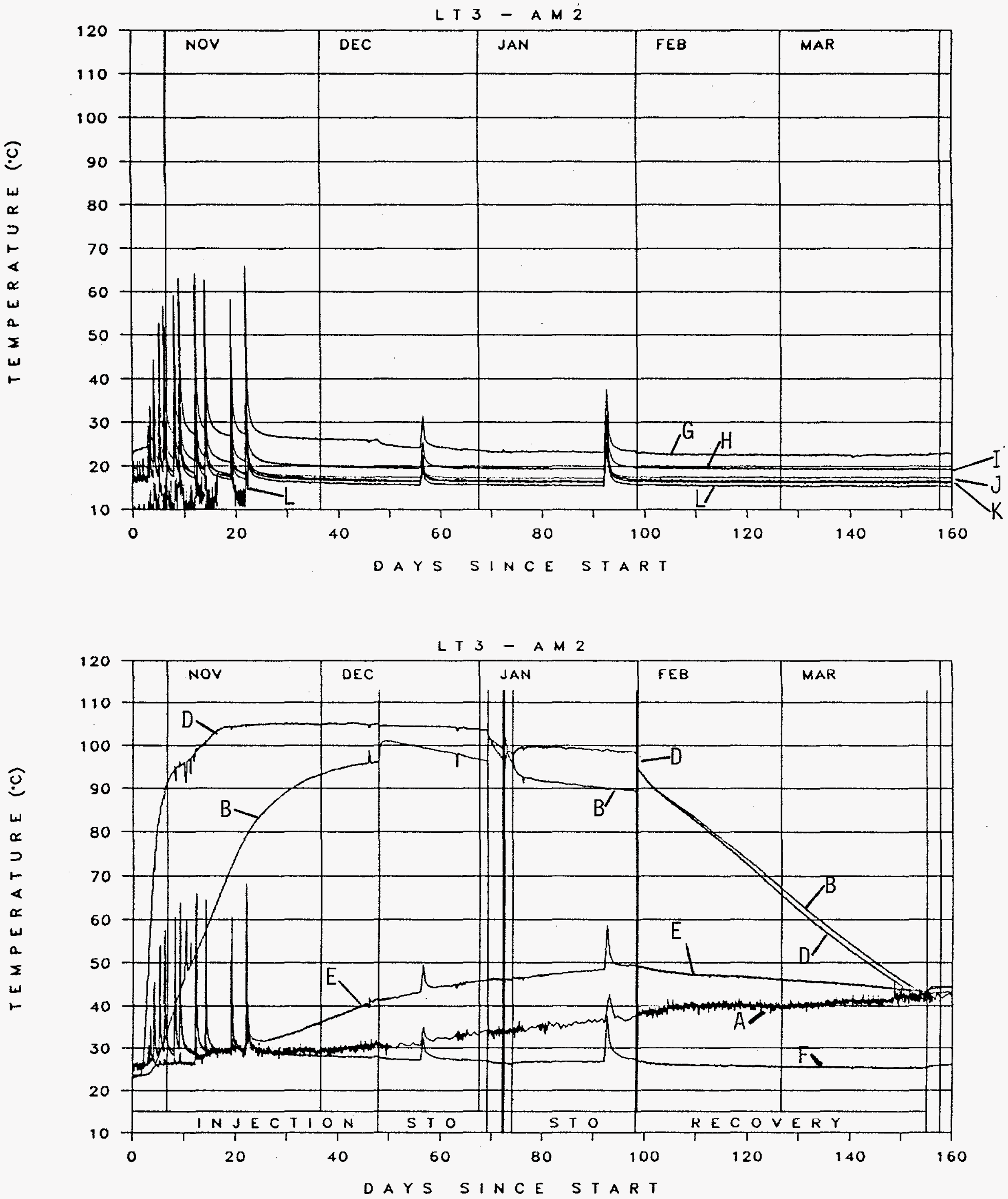


FIGURE 4.2. Temperatures in Well AM2 During Long-Term Cycle 3. Upper Diagram Includes Thermocouples G Through L. Lower Diagram Includes Thermocouples A Through F. Thermocouple C failed and is not plotted. Thermocouple Locations as in Figure 2.5.

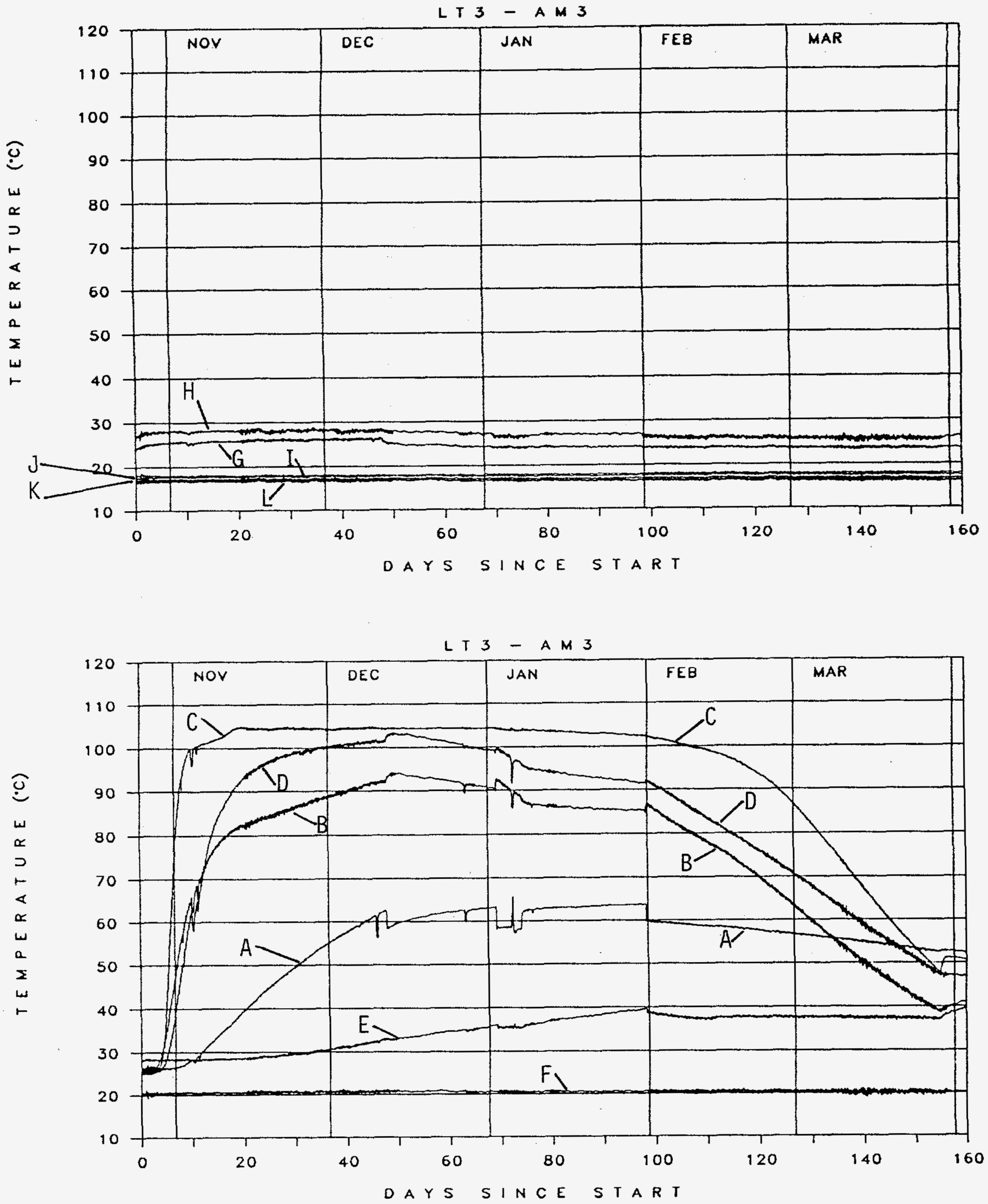


FIGURE 4.3. Temperatures in Well AM3 During Long-Term Cycle 3. Upper Diagram Includes Thermocouples G Through L. Lower Diagram Includes Thermocouples A Through F. Thermocouple Locations as in Figure 2.5.

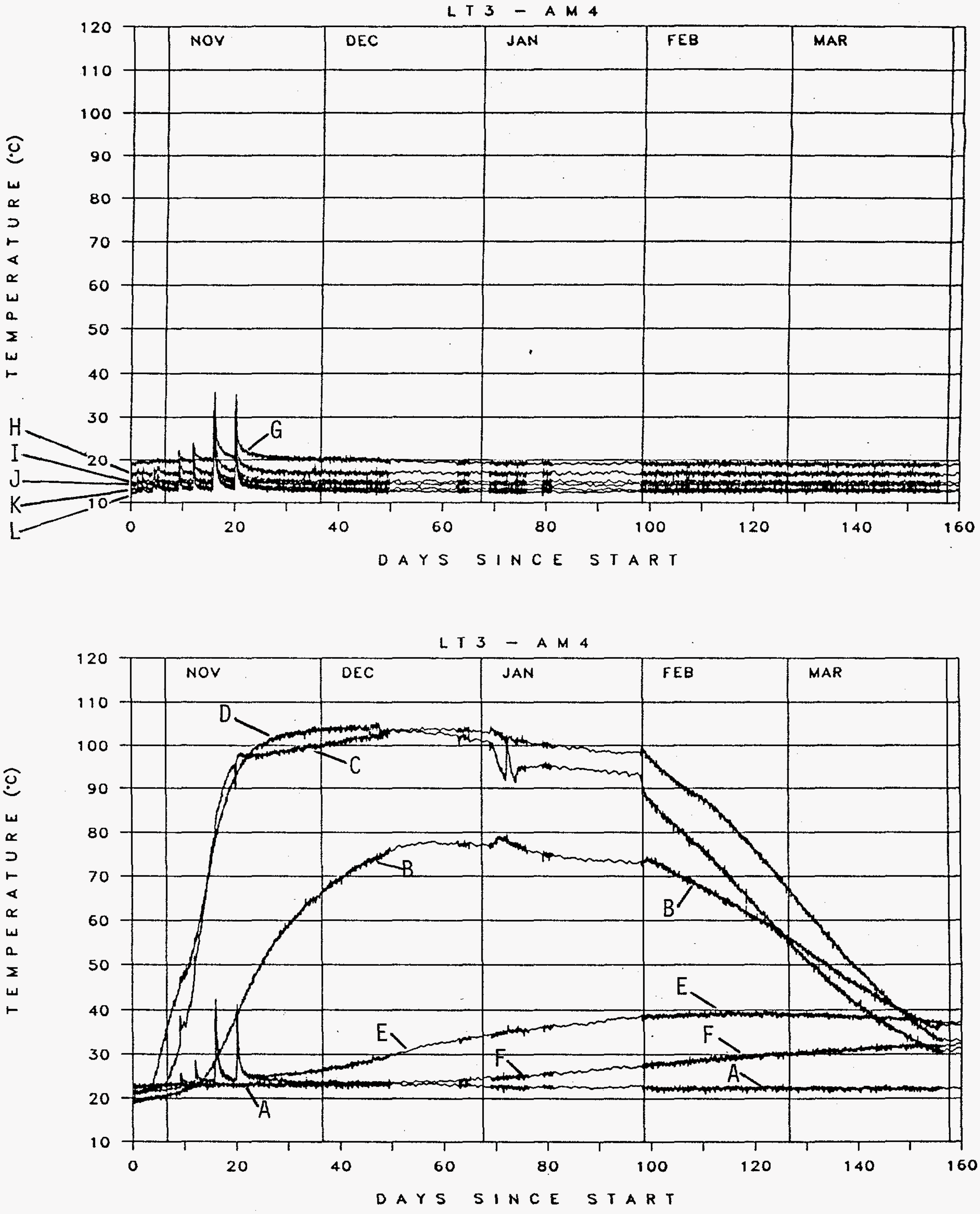


FIGURE 4.4. Temperatures in Well AM4 During Long-Term Cycle 3. Upper Diagram Includes Thermocouples G Through L. Lower Diagram Includes Thermocouples A Through F. Thermocouple Locations as in Figure 2.5.

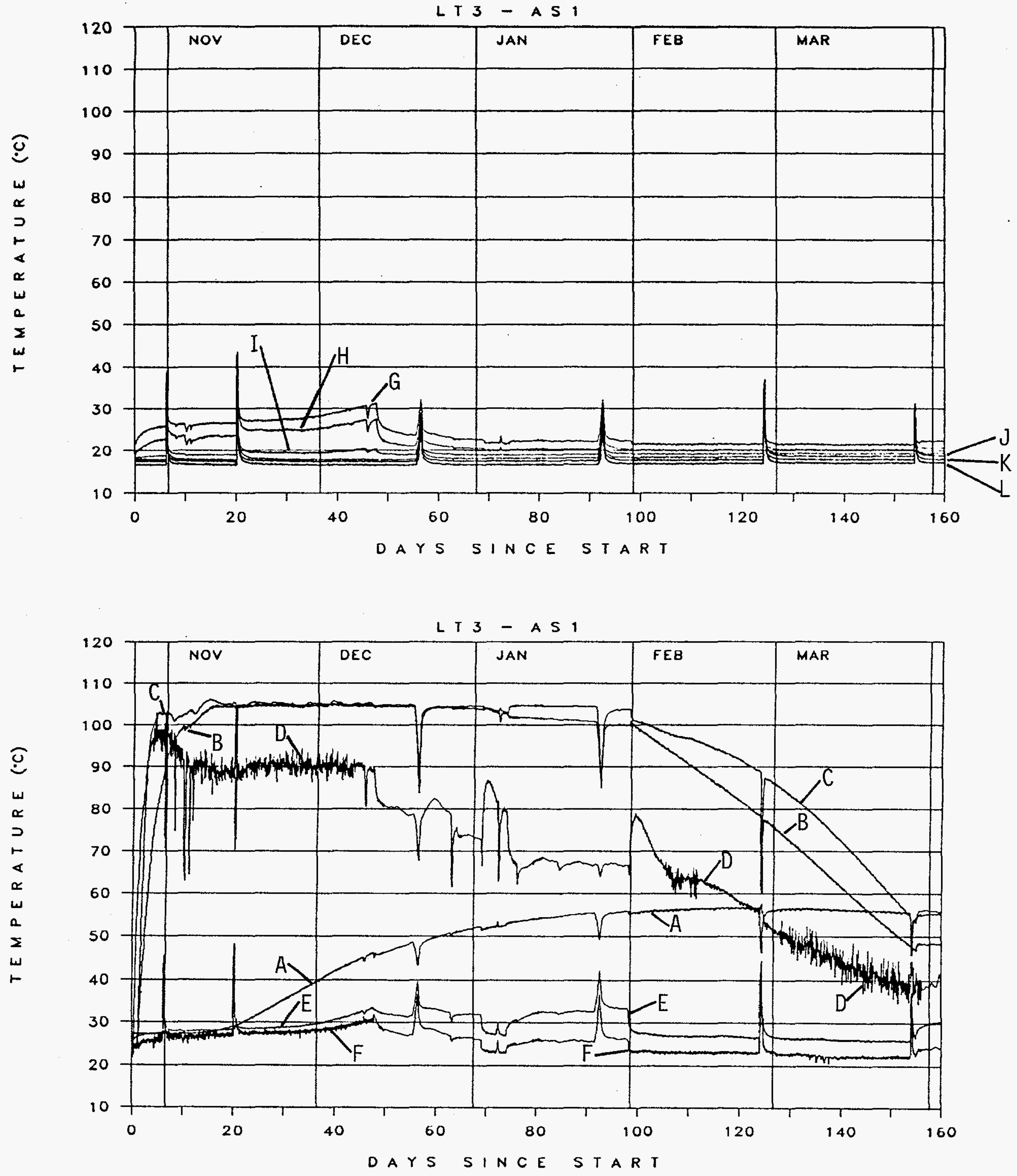


FIGURE 4.5. Temperatures in Well AS1 During Long-Term Cycle 3. Upper Diagram Includes Thermocouples G Through L. Lower Diagram Includes Thermocouples A Through F. Thermocouple Locations as in Figure 2.5.

Figures 4.6 through 4.10 present thermal profiles of the monitoring wells at different times during LT3. The Ironton-Galesville hydrologic zones are those opposite the storage well screen where the water was injected and recovered.

Temperatures measured in the Ironton-Galesville (IG) portion of the aquifer at the start of LT3 were from 19 to 26°C (thermocouples B, C, and D in Figures 4.1 through 4.10). Elevated temperatures were recorded in the monitoring wells located 7 m from the storage well (AM1 and AS1) at the IG horizons less than 1 day after the start of injection (Figures 4.1 and 4.5). Measured temperatures in the Ironton portion of the FIG aquifer reached 80°C at Well AM1 after less than 1 day of injection and at Well AS1 after less than 2 days of injection. Temperatures reached 100°C at Well AM1 after less than 3 days of injection, and at Well AS1 after less than 4 days of injection. First high-temperature arrivals were at the uppermost thermocouple in the Ironton-Galesville unit (hydrologic zone 4) -- the most permeable part of the aquifer. Without closely-spaced thermocouples, precise tracking of the thermal effects is somewhat limited. The IG temperatures primarily reflect the advection transport of the heated water during the heated water injection phase.

Temperatures in the Franconia rose slowly through the injection phase. This rise was greatest just above the IG part of the aquifer, and least at the thermocouples farthest from the heat storage zone. Wells AM2, AM3, and AS1 (Figures 4.2, 4.3, and 4.5) show this most clearly. Highest temperatures were approximately 40°C. The measured temperature rise in the Franconia is the result of conduction of heat in the well pipe enclosing the thermocouples and the conduction of heat into the formation.

Well AM1 shows a much greater rise in temperature, to between 50 and 60°C in the Franconia formation during the injection phase (Figure 4.1). This temperature rise in AM1 during injection is followed by a very rapid decline in temperature following injection. The possible cause for this greater rise in temperature is flow of water in the pipe containing the thermocouple string during the cycle. Unlike the other monitoring wells, the thermocouple string in AM1 is installed in an open-end pipe, not a closed-end pipe. The open-end pipe allows flow up or down the pipe during head changes. The rapid drop in temperature in the AM1 upper thermocouples at the end of the heated water

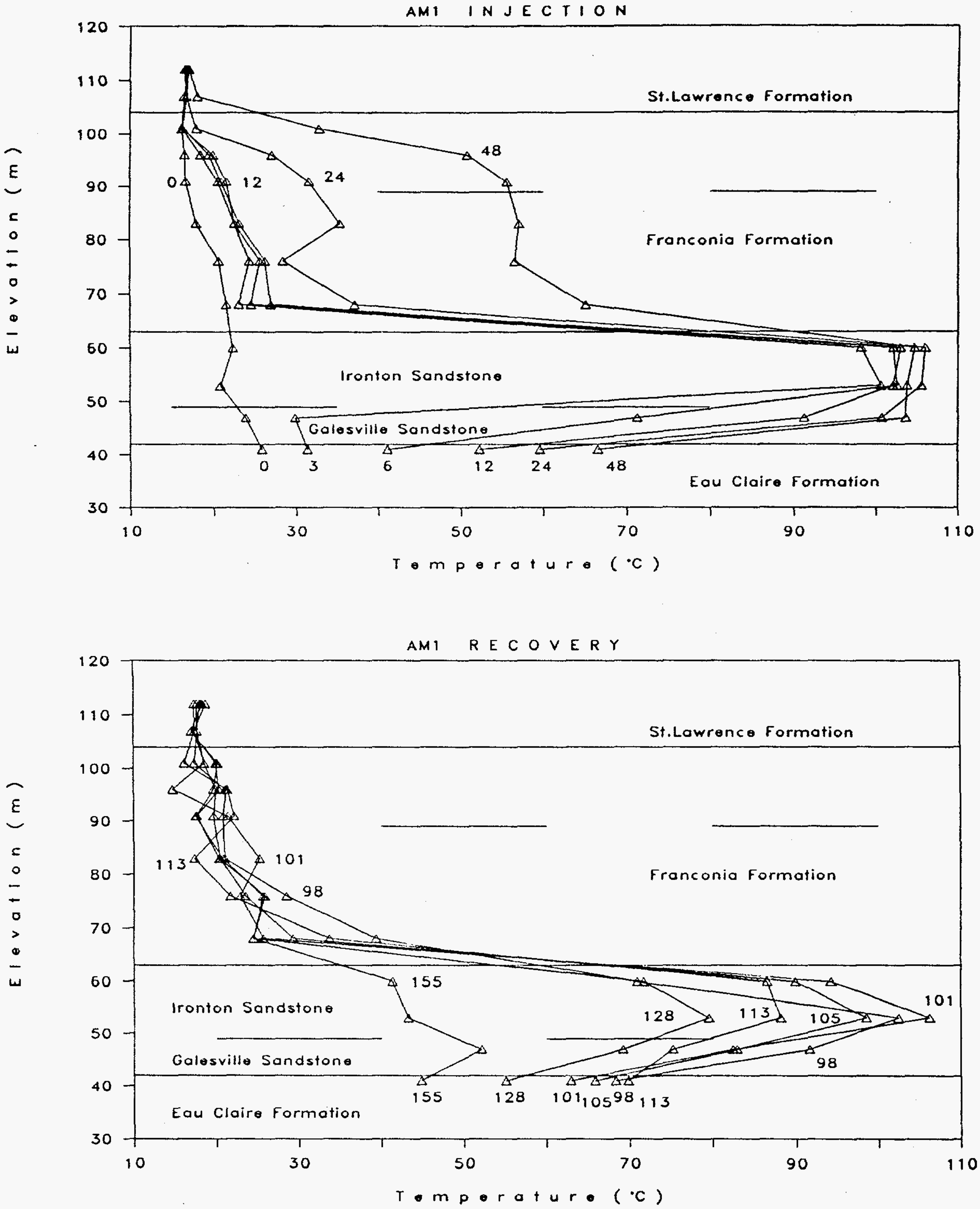


FIGURE 4.6. Temperature Profiles in Well AM1 During Long-Term Cycle 3 Injection and Recovery. Numbers on graph indicate days since start of cycle.

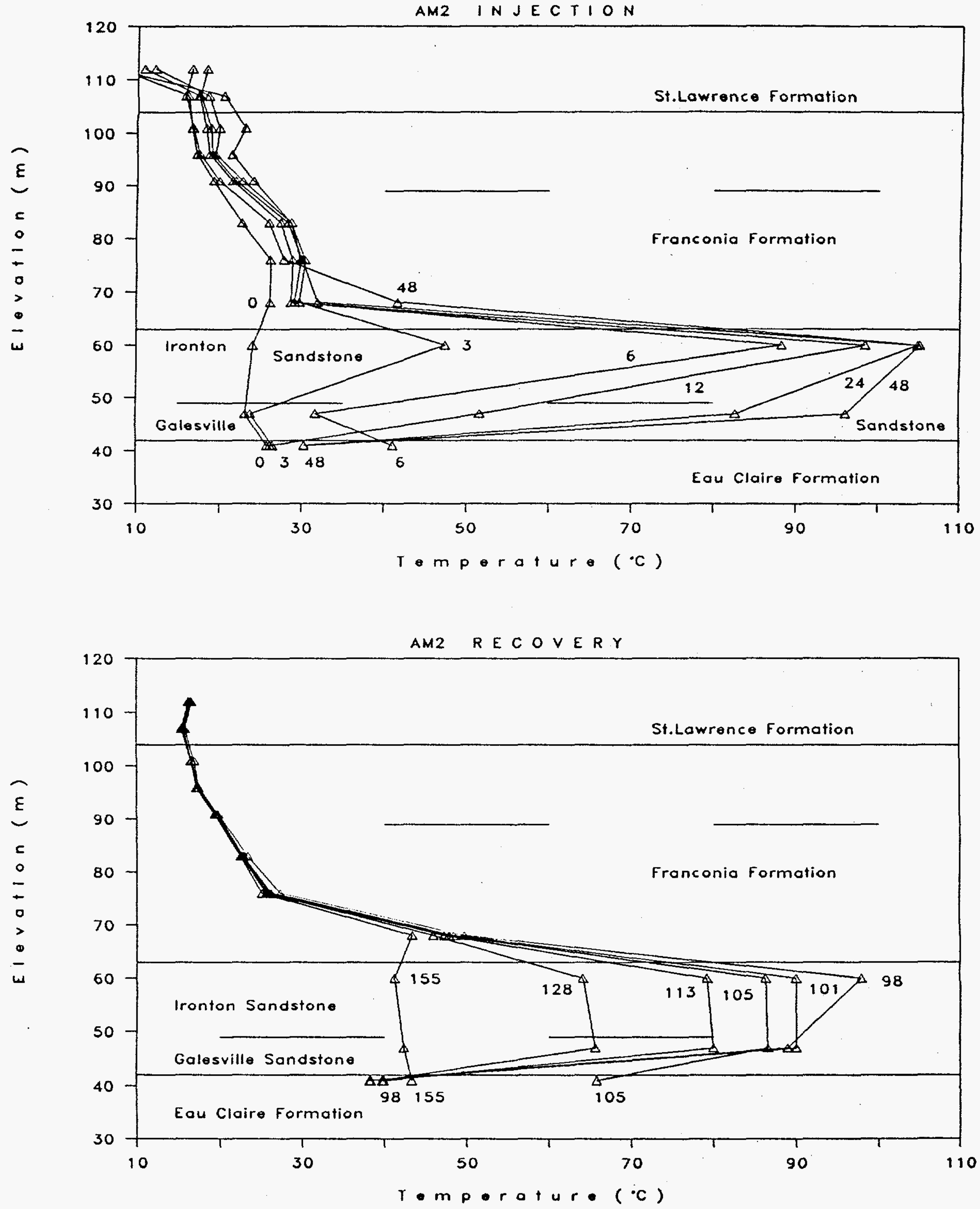


FIGURE 4.7. Temperature Profiles in Well AM2 During Long-Term Cycle 3 Injection and Recovery. Numbers on graph indicate days since start of cycle.

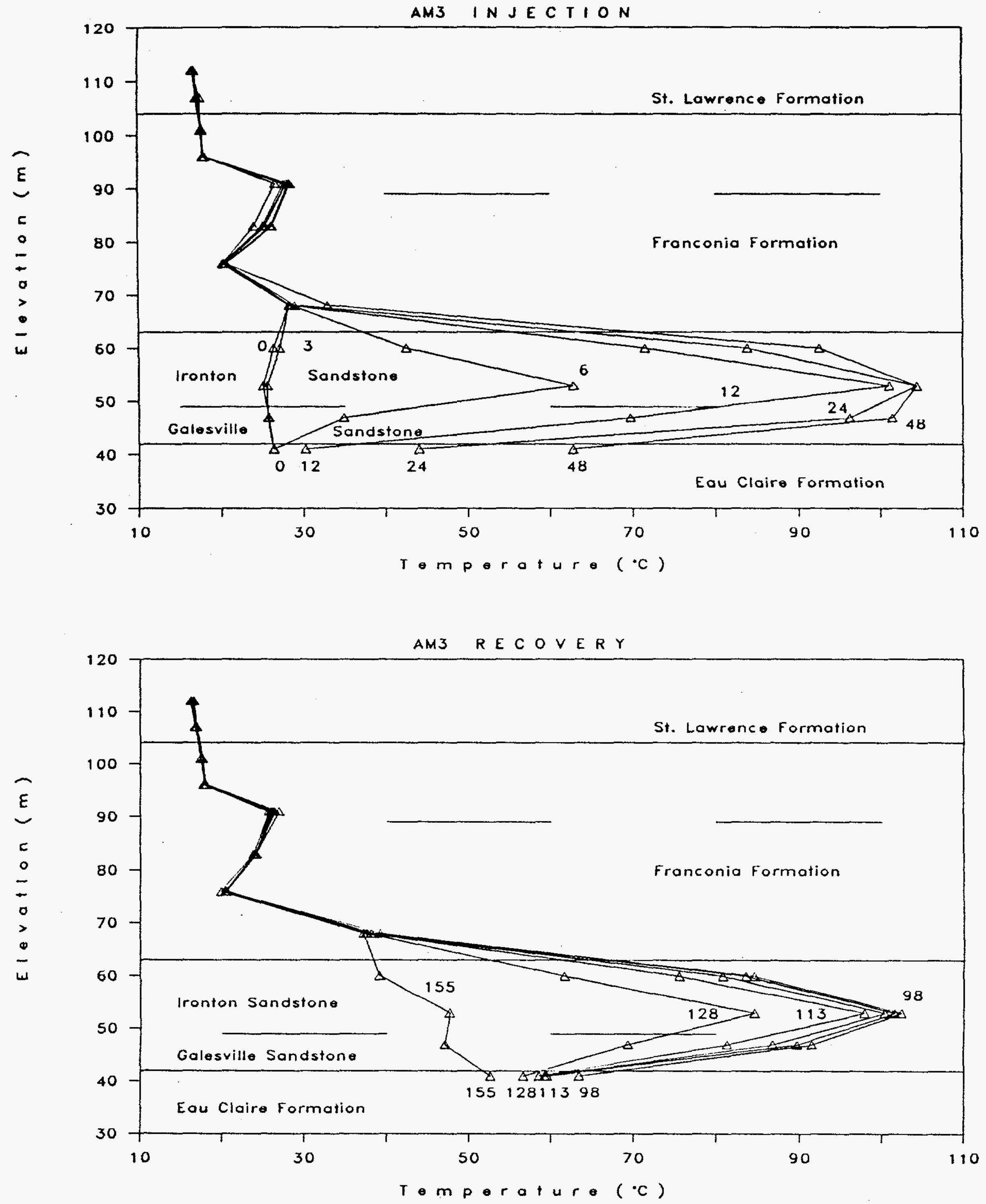


FIGURE 4.8. Temperature Profiles in Well AM3 During Long-Term Cycle 3 Injection and Recovery. Numbers on graph indicate days since start of cycle.

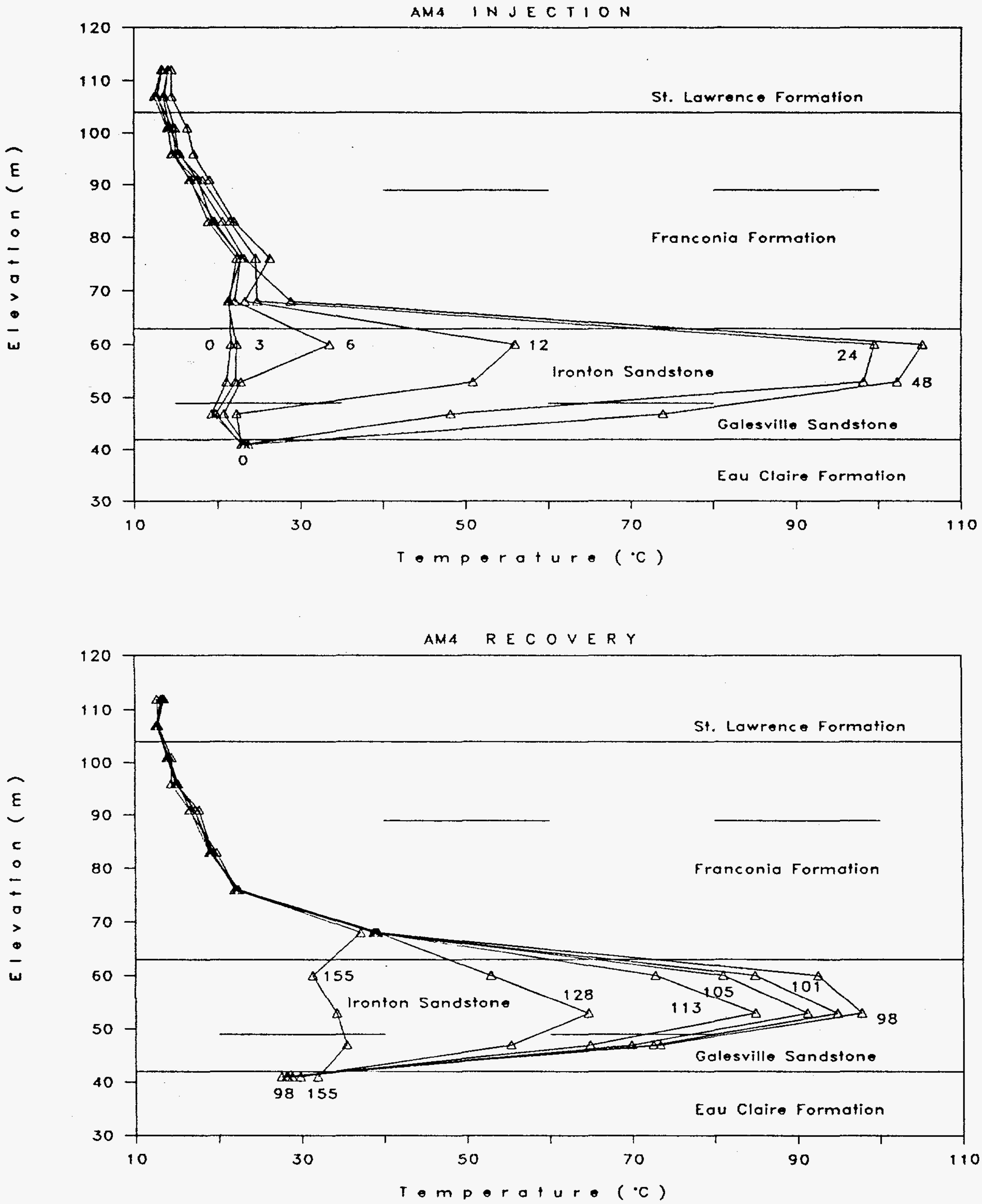


FIGURE 4.9. Temperature Profiles in Well AM4 During Long-Term Cycle 3 Injection and Recovery. Numbers on graph indicate days since start of cycle.

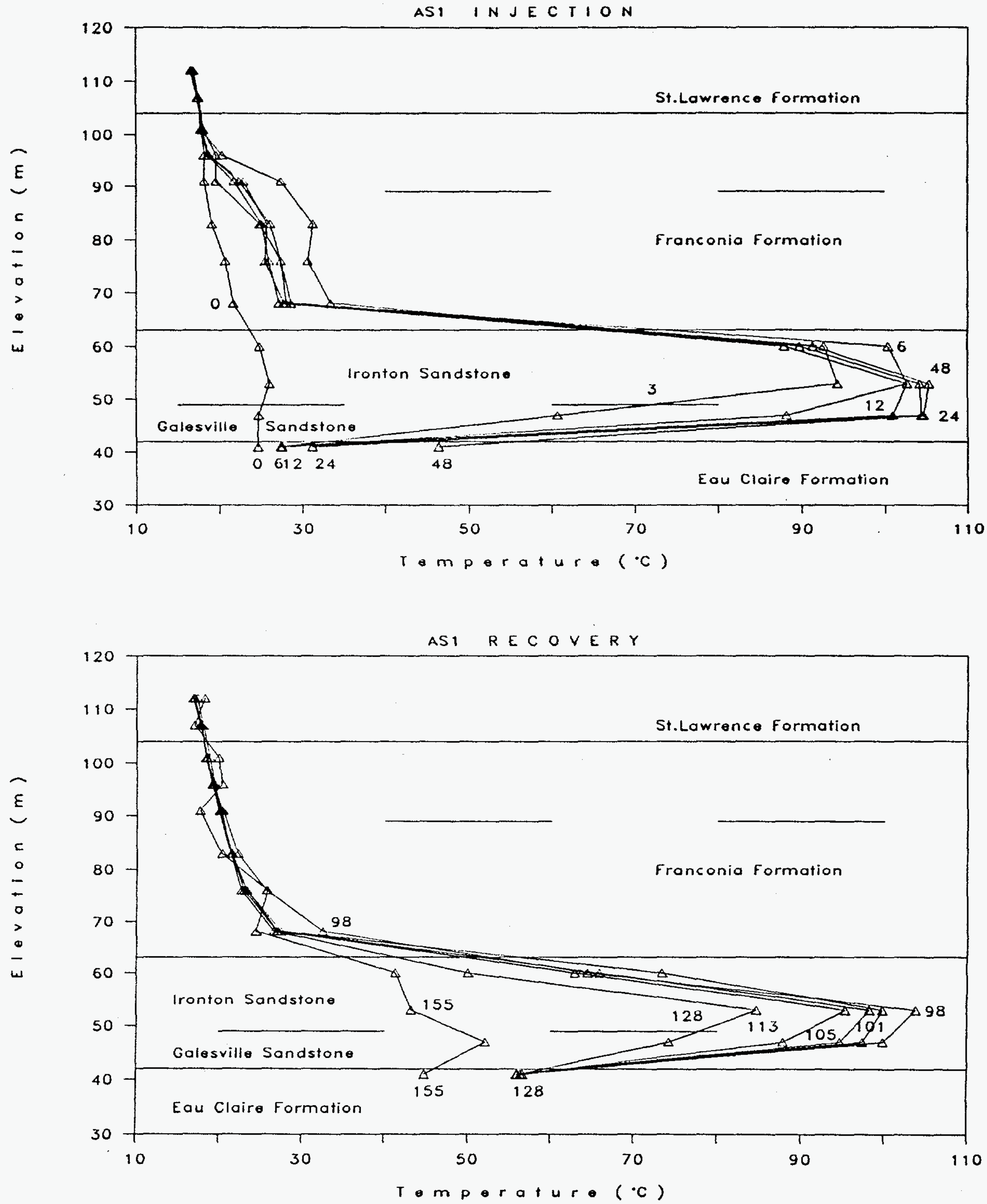


FIGURE 4.10. Temperature Profiles in Well AS1 During Long-Term Cycle 3 Injection and Recovery. Numbers on graph indicate days since start of cycle.

injection is the result of the rapid fall in head in the pipe. The AM1 thermocouple string is enclosed in the Eau Claire pipe (AM1EC), which has been suspected of having a break at a depth of about 190 m (624 ft), in the upper Franconia; the data support the existence of such a break.

Temperatures at the upper Eau Claire, the deepest thermocouple (thermocouple A in the monitoring wells) increased through the heat injection and storage phases of LT3. This reflects heat conduction from the adjacent heat storage zone to the upper part of the Eau Claire formation. Temperatures decreased in the upper Eau Claire during the recovery phase, as heat was removed from the overlying storage zone.

Monitoring Wells AM2, AM4, and AS1 during LT3 have distinct temperature spikes during water sampling of these wells. These temperature spikes were caused by pumping water having a different temperature past the thermocouples in an adjacent pipe during sampling. The temperature spikes dissipate in a few hours. Well AM2 was sampled the most frequently in an attempt to catch the arrival of the softened water at that well (see Figure 4.2 and discussion in Section 5).

Thermal responses were not uniform throughout the aquifer, but reflected the hydraulic conductivities and porosities of the hydrologic zones within the Ironton-Galesville (Figure 2.3). The response in the upper Franconia was much different than during the previous cycles because of the removal of the upper screen from the injection/storage well (Figure 2.4). Temperatures recorded in monitoring wells at Site A increased during the injection phase of the cycle. The temperature pattern was a relatively rapid increase in the more permeable Ironton-Galesville and a low increase in the less permeable and unscreened zones and the confining beds. The confining beds and low permeability beds of the lower Franconia formation showed a temperature increase throughout the period of storage, and at some wells, through the entire cycle.

The removal of the upper well screen in the storage well (Well A) eliminated the slow down well flow from the upper Franconia to the Ironton-Galesville parts of the FIG.

Hot water reached all storage site (Site A) monitoring wells at the Ironton-Galesville. Temperatures between 100 and 105°C were recorded in all storage site wells in zone 4, the upper two-thirds of the Ironton-Galesville. The highest temperatures in zone 5, the Galesville part of the IG, were between 100 and 105°C at the 7 m wells (AS1 and AM1), between 90 and 100°C at the 14 m wells (AM2 and AM3), and 77°C at the 30.5 m well (AM4).

Within the Ironton-Galesville, temperatures at the start of the cycles averaged approximately 23°C (73°F), slightly warmer than the 20°C (68°F) temperature following pumpout after LT2, which was completed more than 14 months before the start of LT3. Residual heat in the adjacent confining layers had slightly warmed the aquifer.

Thermal profiles (Figures 4.6 through 4.10) of monitoring wells at Site A immediately before, during, and immediately after LT3 show the high temperatures reached in the permeable Ironton-Galesville screened interval. The hourglass-shape of the temperature profiles of previous cycles did not appear because of the change in well screen configuration. Injection was only taking place in the Ironton-Galesville, not the upper Franconia as well. Temperatures measured in the Franconia reflected conduction from the Ironton-Galesville. Temperatures measured in the Ironton-Galesville increased and decreased in temperature by about 80°C (144°F) during the cycle.

As during the previous cycles (Hoyer et al. 1985, 1991a, 1991b; Walton et al. 1991), heat arrived in permeable zones after less than 2 days of injection and was recorded by thermocouples in monitoring wells located 7 m and 14 m from the storage well. Thermal responses were not uniform throughout the aquifer, but reflected the hydraulic conductivities and porosities of the aquifer zones being monitored. Figures 4.1 through 4.5 plot temperatures in Wells AM1, AM2, AM3, AM4, and AS1 during the injection, storage, and recovery phases of LT3. Heat arrival is not uniform and the response to pump shutoff varies with location in the aquifer.

Highest temperatures in the permeable parts of the Ironton-Galesville portion of the FIG aquifer were reached in Well AM1 after about 2 days. The temperatures then followed the trend of the injected water temperature (compare Figures 3.1 and 4.1).

When injection was interrupted, temperatures at some horizons dropped and others increased. This rapid temperature change likely resulted from the head change in an adjacent piezometer pipe causing water that had been at a different level, and temperature, to pass by the thermocouple(s) that recorded the temperature. This same effect was seen when water samples were collected from monitoring wells AM2 (Figure 4.2), AM4 (Figure 4.4), and AS1 (Figure 4.6).

Temperatures recorded at monitoring wells in the heat storage zone of the aquifer declined from as high as 105°C to as low as 39°C during recovery (for example, see Figures 4.1 through 4.10). The shapes of the recovery temperature curves in the Ironton-Galesville are convex up or nearly straight (curves B, C, and D). Recovery temperatures at horizons above the well screen remained approximately constant or slowly declined. The recovered water temperature curve nearly matches the Ironton-Galesville curves.

No thermal effects were recorded at Well CM1 located 280 m (920 ft) from the storage site, as expected.

4.2 HYDROLOGIC RESPONSES

Hydrologic response to injection and recovery was monitored by measuring water levels with a steel tape. The repeated failure of pressure transducers during earlier operations resulted in the decision to measure the water levels by periodic hand measurements. Measurements in monitoring wells at the storage site were made daily during injection and recovery, and twice per week during storage. Wells BC1MS and CM1 were measured at least weekly during the cycle. Figures 4.11 through 4.15 present the water levels measured at the storage site.

The seasonal trends of the piezometric surfaces of the aquifers at the site near the center of the Twin Cities Basin are for a gradual rise in late fall through early spring, and for a decline in late spring through early fall. FIG aquifer static water levels measured during storage and at the end of the cycle are somewhat higher than static levels at the beginning of the cycle (Figures 4.11 through 4.15) showing the seasonal trends. Water levels measured in the overlying upper Franconia part of the FIG (Figure 4.14) and Jordan, and underlying Mt. Simon aquifers show just the seasonal trends through the entire cycle (Figure 4.12). The lower Franconia water levels show

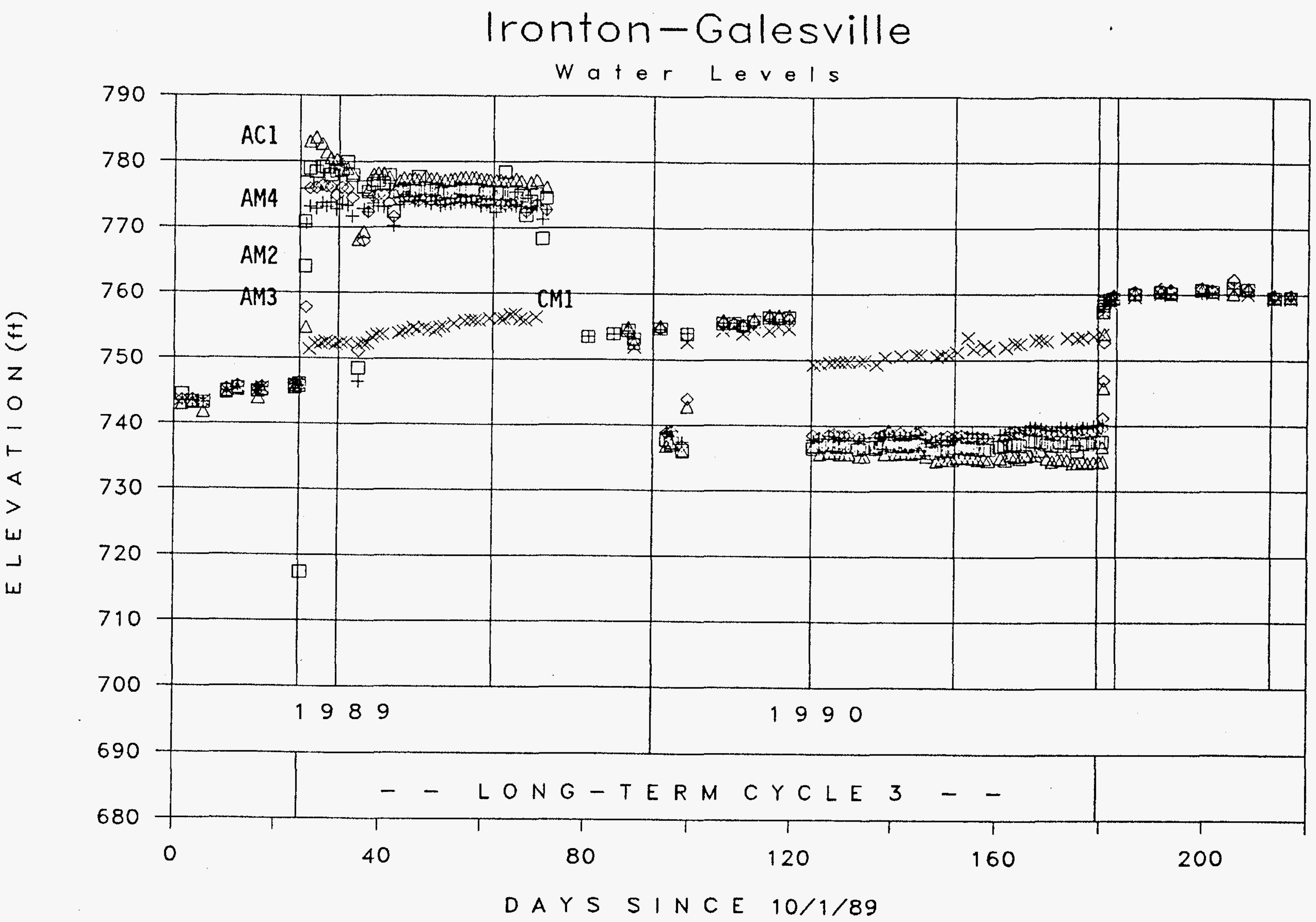


FIGURE 4.11. Ironton-Galesville Aquifer Water Levels at Wells AM2, AM3, AM4, AC1, and CM1 During Long-Term Cycle 3

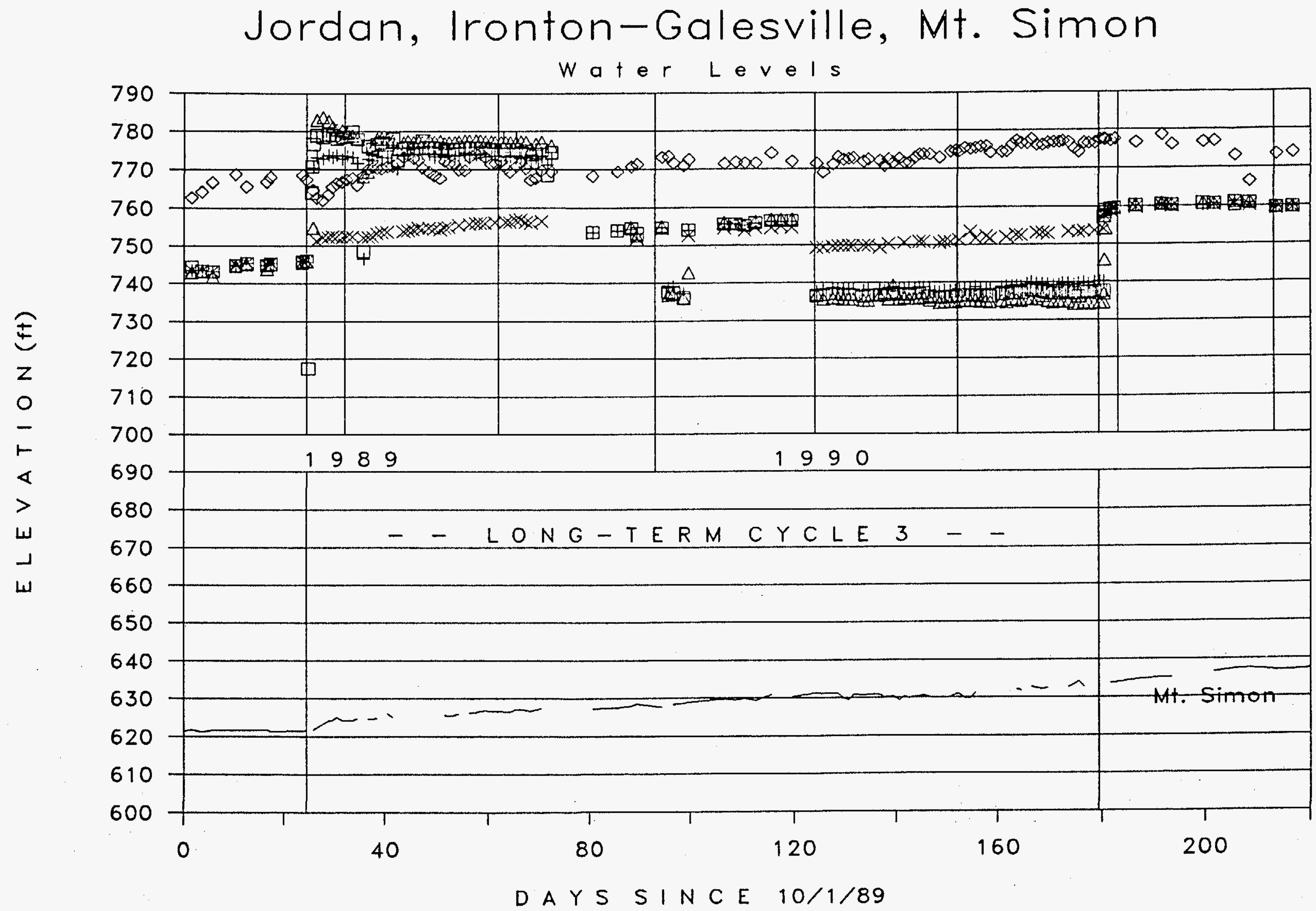


FIGURE 4.12. Jordan Aquifer and Mt. Simon Aquifer Water Levels at Well AS1 During Long-Term Cycle 3. The Ironton-Galesville water levels from Figure 4.11 are plotted for comparison.

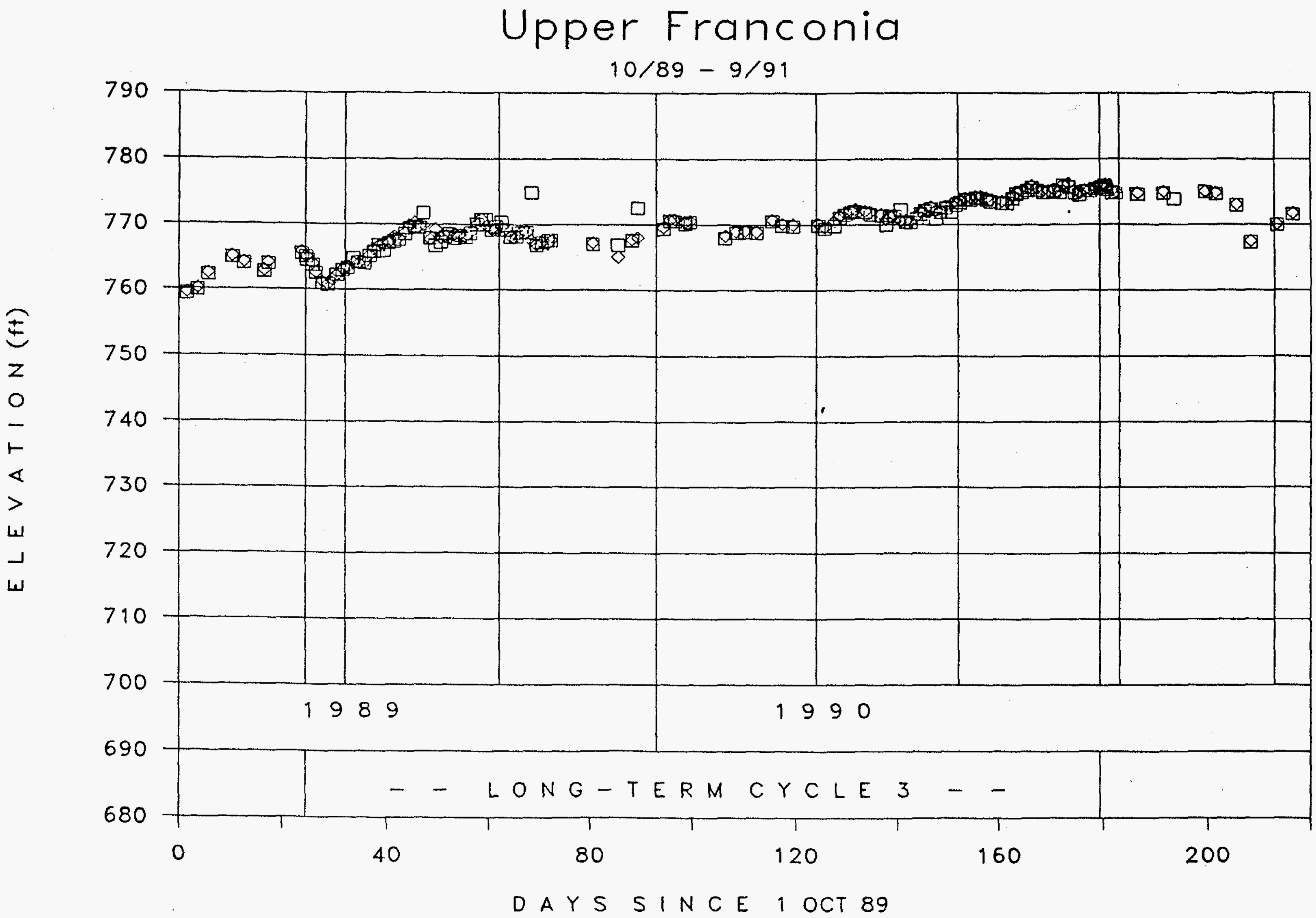


FIGURE 4.13. Upper Franconia Aquifer Water Levels at Wells AM2 and AM4 During Long-Term Cycle 3

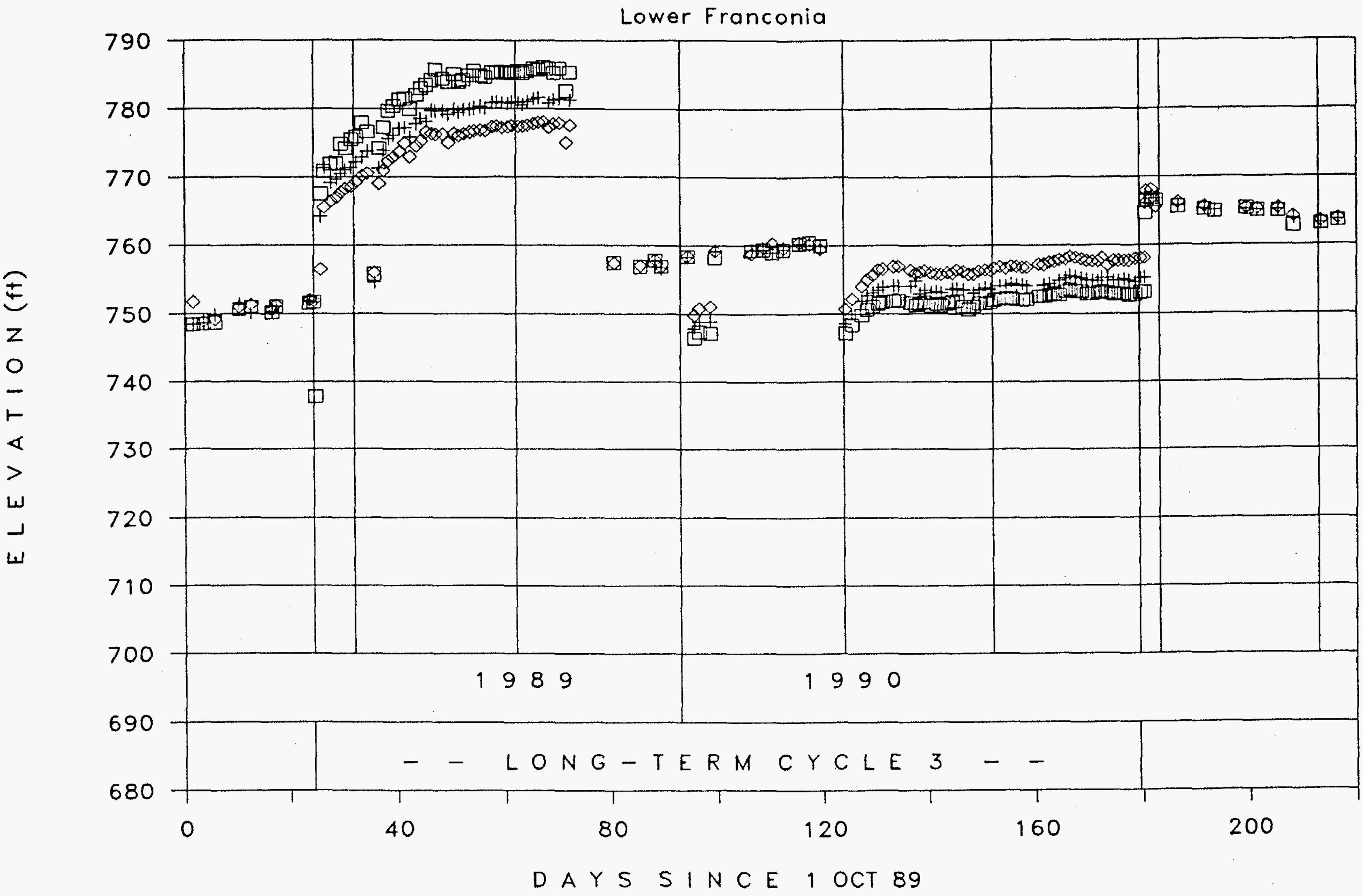


FIGURE 4.14. Lower Franconia Confining Bed Water Levels at Wells AM2, AM3, and AM4 During Long-Term Cycle 3

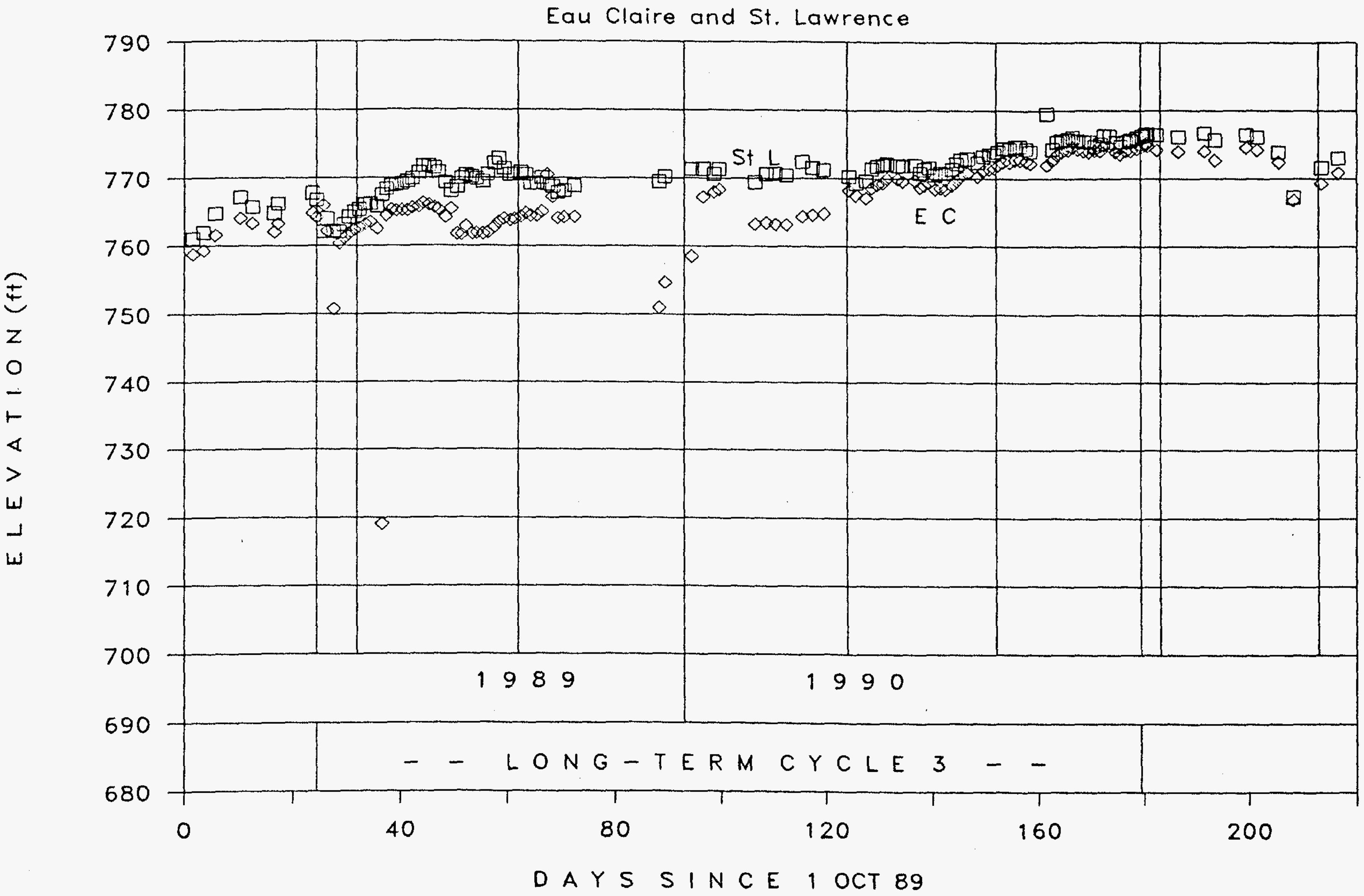


FIGURE 4.15. Eau Claire Confining Bed and St. Lawrence Confining Bed Water Levels at Well AM1 During Long-Term Cycle 3

the influence of the cycle, as expected in the confining bed adjacent to the affected aquifer (Figure 4.14). The Eau Claire water levels are a bit erratic. This is likely caused by the lack of a well screen in the pipe and a possible break in the pipe (see Sections 2.1.3 and 4.1).

Static water levels in the IG were about 227 m (746 ft) above mean sea level (msl) prior to the start of LT3. During the injection phase, the water levels rose rapidly at the storage site with the maximum being 11.3 m (37 ft). This change in water levels represents a pressure difference of approximately 110 kPa (~16 psi). Following injection, IG water levels quickly declined during storage to a static level of about 230 m (755 ft) asl. During recovery, the IG water levels at the storage site dropped by no more than 6.4 m (21 ft) as pumping from the storage site progressed. This change represents a pressure reduction of 63 kPa (9 psi). Following LT3, the IG water levels returned to 232 m (760 ft) above msl. Static water levels measured during storage and at the end of the cycle were somewhat higher than static levels at the beginning of the cycle, reflecting the normal seasonal trend.

Responses of the upper Franconia (UF), lower Franconia (LF), and Ironton-Galesville piezometers were not uniform, reflecting the different hydrologic properties of the different zones of the FIG aquifer. The LF portion of the FIG aquifer shows a significant response to injection or pumping from the aquifer at the site (Figure 4.15).

Water levels in the upper Franconia part of the FIG aquifer, the Jordan, and the Mt. Simon aquifers at the site were essentially unaffected by the injection and recovery phases of the cycle (Figure 4.12). The Jordan water levels follow both a weekly cycle (caused by weekly pumping elsewhere in the basin) and the seasonal trend. The Mt. Simon water levels show primarily the seasonal upward trend.

Figure 4.16 presents the water levels from October 1989 to the end of September 1991 for the IG completion of Well AM2 and for both the Jordan and Mt. Simon completions of Well AS1. This figure includes both LT3 and the pumpout from the storage and source wells, which followed LT3. The effect of the cycle and the pumpout is clearly shown for the Ironton-Galesville levels, but not seen in the water levels for the Jordan and Mt. Simon.

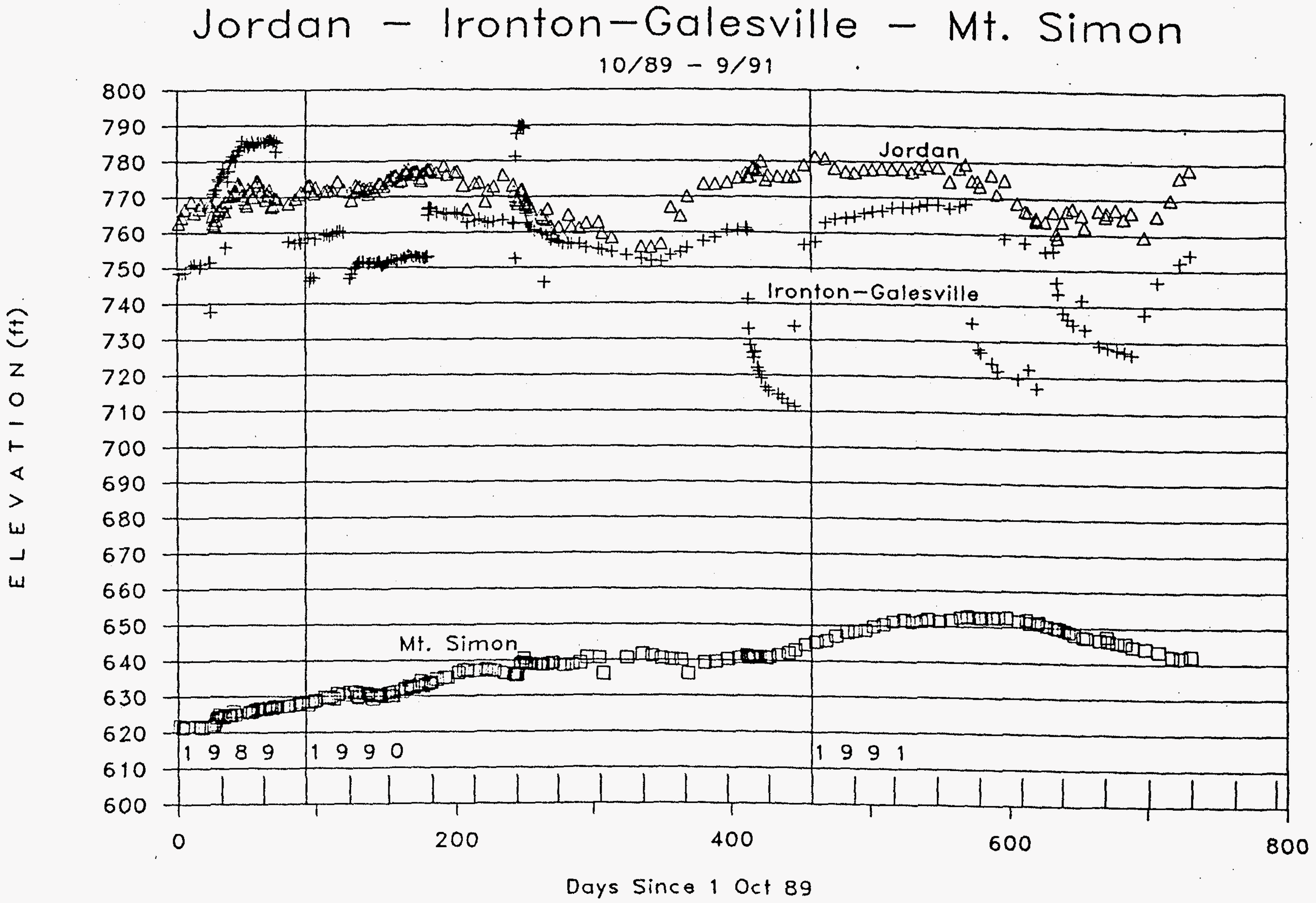


FIGURE 4.16. Jordan Aquifer, Ironton-Galesville Aquifer, and Mt. Simon Aquifer Water Levels from October 1, 1989 to September 30, 1991 at the ATES FTF

4.3 DISCUSSION

The thermal and hydrologic behavior observed during LT3 is consistent with what was observed during all previous cycles, taking into consideration the reconfiguration of the storage well. This suggests that no significant changes took place in the hydraulic or thermal characteristics of the aquifer.

Within the Ironton-Galesville, temperature averaged approximately 23°C (73°F), slightly warmer than the 20°C (68°F) that was the temperature following pumpout after LT2, which was completed more than 14 months before the start of LT3. Residual heat in the adjacent confining layers had slightly warmed the aquifer.

A few thermocouples failed during the cycle. These were identified by recorded temperatures well beyond the range of possible temperatures (<10°C to >125°C), or a sudden shift of the recorded temperatures to unreasonable values. Several temperature curves show spikes, most of which are real and can be related either to sampling water from the well, or to pumping/injection shutdown. The jagged nature of some of the temperature curves (see Figure 4.1) is caused by electronic noise of the data logger on some channels for some periods of time.

The Ironton-Galesville, which has many thin interbedded shale layers, has the highest hydraulic conductivity. High-temperature water reached all of the Site A wells at these horizons. Highest temperatures were approximately equal to the injected water temperature (105°C). During recovery, the temperatures went down to approximately 40°C.

A slight amount of convective tilting of the thermocline or interface between injected and ambient water occurred in these layers. However, large-scale convection was inhibited by the many thin interbeds of shale.

The lower Franconia is essentially a confining bed effectively dividing the FIG aquifer into two aquifers. Strata in this zone showed a constant or slow increase in temperature during the cycle, comparable to the thermal response in the overlying and underlying confining beds.

Water levels indicate good separation of the Jordan and Mt. Simon aquifers from the Ironton-Galesville aquifer. The upper Franconia water levels mimic the Jordan levels indicating good separation from the Ironton-Galesville aquifer. Separation between the Ironton-Galesville levels and the upper Franconia levels is greater than during previous cycles when the storage and source wells were completed at both levels. This change is consistent with stoppage of leakage down the wellbore between the two levels, which occurred during the previous cycles.

5.0 WATER CHEMISTRY DURING LONG-TERM CYCLE 3

The aqueous geochemistry of ATES has been a major part of the monitoring and experimental plan since the initiation of the project. Water samples have been collected during the four short-term tests and the three long-term tests and analyzed for major ions. The geochemical results of the short-term, first long-term, and second long-term test cycles have been reported in Holm et al. (1987), Perlinger et al. (1987), Walton et al. (1991), and Hoyer et al. (1991a, 1991b).

This chapter presents a summary of the water chemistry of LT3. The methods used in collecting and analyzing water samples are described first. The results of water analyses are then presented, followed by characterization of ambient ground water. Concentrations, concentration trends, and mass balances of dissolved chemicals from LT3 are presented and compared with results from LT1 and LT2. Analytical results from LT3 and monitoring well samples are presented in Appendix D. Analytical results from samples collected during pumpout following LT2 are presented in Appendix E.

5.1 METHODS

Sampling methods, analytical techniques, and quality control measures are described below.

5.1.1 Sampling During Long-Term Cycle 3

Samples of the pumped water were taken three times per week (Monday, Wednesday, Friday) throughout the injection phase. On each sampling day, ground water was collected from each of three ports on the system (Figure 5.1): Port I yielded source water (Well B) before it was softened; Port II yielded water passed through the softening units before it was heated; and Port III yielded the heated water before it was injected into the ground at the injection well (Well A). To minimize the chances of sampling the short-term fluctuation caused by the softening unit changeover (see Hoyer et al. 1991b and Section 5.2.4), all injection samples were collected before or at least 1 hour after the softener changeover. During the recovery phase, samples were collected from Ports III, IV and V every other day for the first

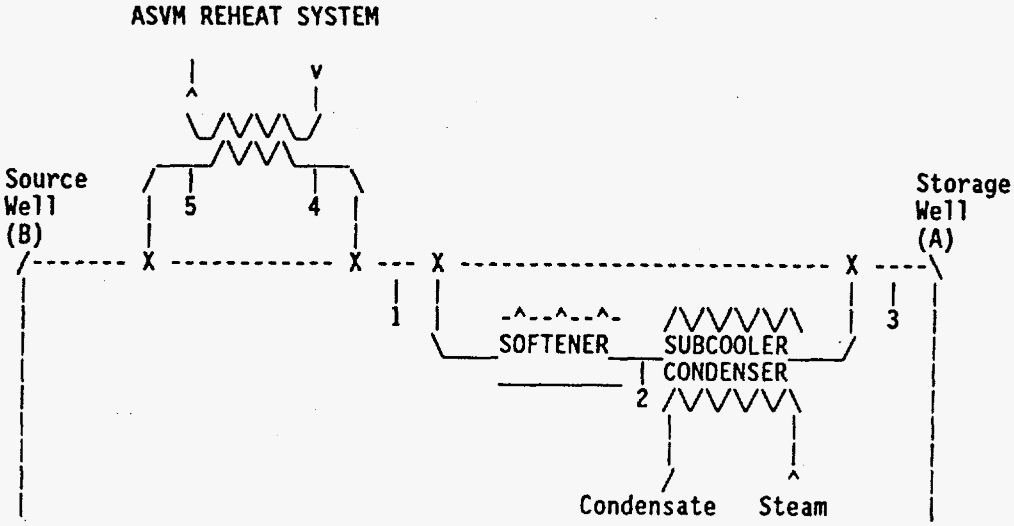


FIGURE 5.1. ATES System Piping for Long-Term Cycle 3

2 weeks and twice per week on Tuesdays and Thursdays for the remaining time. Port III samples are representative of the hot water recovered from storage; this port samples water directly out of Well A. Port IV taps the system immediately before the radiator; Port V taps the system after the Animal Science Veterinary Medicine (ASVM) building heat exchanger, yielding cooled recovered water that is returned to Well B (Figure 5.1). Samples from monitoring wells AM2 and AM4 were taken during the first 4 weeks of injection and occasionally during storage and recovery (see Section 5.1.2). Well AS1MS was sampled monthly throughout the cycle. Sampling methods are presented in Section 5.1.2.

For each sample, dissolved oxygen was analyzed directly at the port using a CHEMetrics®[a] field kit. An unfiltered sample was collected at Ports I and II, and taken inside the field trailer for pH and conductivity readings. At Ports III, IV and V, an in-line pH cell having a temperature-resistant pH probe was used to provide an accurate pH reading at a temperature close to the actual water temperature. Because pressurization of the system

---

[a] CHEMetrics, Inc., Calverton, Virginia.

allowed the injection temperature of the water to be greater than 100°C, Port III samples were passed through a cooling coil prior to sampling, lowering the temperature into the 90°C to 95°C range. No cooling was used on the Port IV and Port V samples. Filtered samples for use in laboratory analyses were collected directly at each port using a 0.45-μm Millipore®[a] membrane filter.

Filtered samples from each port were placed in three polyethylene bottles, a 250-ml bottle (full, not acid washed) for anion, silica, dissolved inorganic carbon (DIC) and alkalinity analyses; and a 1000-ml bottle (half-full, acid washed) for cation analyses; and a 60-ml bottle (full, acid washed) for aluminum analysis. The 250-ml samples were taken by placing the filling hose in the bottom of the bottles and allowing the water to overflow three to four volumes before collecting the final sample. This procedure was used to minimize possible addition of CO_2 to the sample from the initial filling of the bottle. The cation samples were acidified in the field to about 2 percent by volume with HCl to lower the sample pH to below 2. Reagent grade HCl was used for the cation samples and a high purity HCl was used for the aluminum sample. The anion sample was refrigerated upon arrival in the laboratory (within 1 to 3 hours). Field blanks were collected each sampling day by passing deionized water through the filter apparatus into separate bottles for anion and cation analyses, and then processed as samples.

5.1.2 Sampling Monitoring Wells

Monitor wells were sampled quarterly, except when the ATES system was in operation. Wells AM2, AM4, and AS1MS were sampled during LT3 by the methods described below. For each well, an air hose was lowered about 60 m below the water level, and the well was purged of about three well volumes of water by air-lift pumping. Samples collected in this way are altered in dissolved oxygen and carbon dioxide content. The dissolved oxygen for the air-lifted monitoring well samples ranged from 6 to 8 mg/L, compared to less than 1 mg/L for the injected and recovered water.

---

[a] Millipore Corporation, Bedford, Massachusetts.

At each well an unfiltered sample was immediately analyzed for oxygen content, pH, and specific conductance. A 1-L bottle was filled at the well site and then taken back to the field trailer where the water was filtered through a 0.45-µm Millipore® membrane filter using a hand-pressurized system. Blanks and filtered samples were treated in the same manner as water samples taken from the ports during the cycle.

5.1.3 Analysis

As mentioned above, dissolved oxygen was quantified in the field with a kit from CHEMetrics®. All pH readings were obtained on a Beckman Model Phi-11 meter with an automatic temperature compensating (ATC) probe and an Orion Ross combination pH 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.

Alkalinity was determined via a Gran-method titration on a 20-ml sample using 0.02 N H_2SO_4 (Stumm and Morgan 1981). Soluble reactive silica was measured colorimetrically using a reduced silicomolybdic acid method (Strickland and Parsons 1972). Anion analysis was performed by ion chromatography (O'Dell et al. 1984; ASTM 1984) on a Dionex Model 10 or Dionex Model DX-100 instrument. The six anions determined were fluoride, chloride, nitrate, nitrite, phosphate, and sulfate. However, only fluoride, chloride, and sulfate were observed regularly. Dissolved inorganic carbon was determined using a Dohrman Model DC-80 carbon analyzer. Cations were quantified using atomic absorption flame spectrophotometry (Varian AA175) and included calcium, magnesium, sodium, potassium, total iron, and manganese. Hardness was calculated directly as the sum of calcium and magnesium. Aluminum was determined by ICP-AES for selected samples at PNL.

5.1.4 Quality Control

To ensure quality control, a system of field replicates, laboratory replicates, field blanks, field spikes, and U.S. Environmental Protection

Agency (EPA) quality assurance samples was established. During the cycle, each Port III sample was collected in replicate; i.e., over 10 percent of all samples collected represented field replicates. One field replicate was collected each time the monitor wells were sampled, usually from Well AM2 or AM4. For each analysis, laboratory replicates were run. These laboratory replicates comprise over 10 percent of the analyses. Standard deviations for sample values were calculated for each of the field and laboratory replicate data sets. These values are reported in Table 5.1 for each parameter.

The percent error of the injection and recovery laboratory replicates are below 6 percent, except where concentrations are near detection limits. The percent error is greater for both the injection and recovery field replicates than in the laboratory replicates because replicate samples were taken sequentially as the water flowed, rather than from a single well-mixed

TABLE 5.1. Concentration Ranges and Standard Deviations of Laboratory and Field Replicates During Long-Term Cycle 3

		Laboratory Replicates			Field Replicates		
		Range	Standard Deviation	(N)	Range	Standard Deviation	(N)
Injection							
Alk	(meq/L)	4.29-4.66	0.011	9	4.41-4.67	0.024	18
SiO_2	(mmol/L)	0.21-0.25	0.00072	9	0.21-0.25	0.0010	18
DIC	(mmol/L)	4.29-4.66	0.0082	9	4.29-4.66	0.022	17
SO_4	(mmol/L)	0.04-0.09	0.00029	9	0.04-0.09	0.0006	18
Cl	(mmol/L)	0.10-0.17	0.0013	9	0.10-0.22	0.0025	18
F	(mmol/L)	0.01-0.02	0.00074	9	0.01-0.02	0.00037	18
Ca	(mmol/L)	0.00-0.09	0.00085	9	0.00-0.23	0.0031	18
Mg	(mmol/L)	0.00-0.01	0.00013	9	0.00-0.37	0.0062	18
Na	(mmol/L)	4.27-4.85	0.0069	9	2.06-4.84	0.019	18
K	(mmol/L)	0.02-0.10	0.0012	9	0.00-1.51	0.0076	18
Recovery							
Alk	(meq/L)	4.42-4.73	0.020	4	3.86-4.83	0.10	18
SiO_2	(mmol/L)	0.37-0.76	0.0036	4	0.35-0.78	0.013	18
DIC	(mmol/L)	4.55-4.96	0.023	4	4.49-4.93	0.13	14
SO_4	(mmol/L)	0.04-0.05	0.00043	4	0.04-0.05	0.00060	18
Cl	(mmol/L)	0.52-0.80	0.0036	4	0.49-0.89	0.015	18
F	(mmol/L)	0.01-0.04	0.0061	4	0.01-0.03	0.0027	18
Ca	(mmol/L)	0.07-0.65	0.0021	4	0.07-0.68	0.019	18
Mg	(mmol/L)	0.04-0.32	0.00056	4	0.04-0.34	0.0017	18
Na	(mmol/L)	2.71-4.60	0.011	4	2.59-4.67	0.014	18
K	(mmol/L)	0.13-0.22	0.00090	4	0.12-0.22	0.0012	18

volume. Short-term fluctuations are discussed in Section 5.2.2. The percent error for the injection field replicates is higher than that for recovery samples because of short-term fluctuations caused by the water softener.

Field blanks showed no identifiable contamination of the samples from sampling and filtering techniques. Any chemical species found in the field blanks were at or below the detection limits for those compounds.

To check the accuracy of the laboratory techniques, a series of EPA quality assurance samples were run with every sample batch during routine laboratory analysis. In general, results agreed with concentration values supplied by the EPA (Table 5.2).

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

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

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

TABLE 5.2. Analysis of EPA Quality Assurance Standards

Parameter	Error, %	Standard Deviation, %	Samples, No.
Sulfate	3.7	4.5	17
Chloride	5.2	3.7	12
Fluoride	10.5	6.8	14
Calcium	3.9	2.3	18
Magnesium	3.5	4.0	23
Sodium	5.1	4.9	14
Potassium	4.1	3.3	18

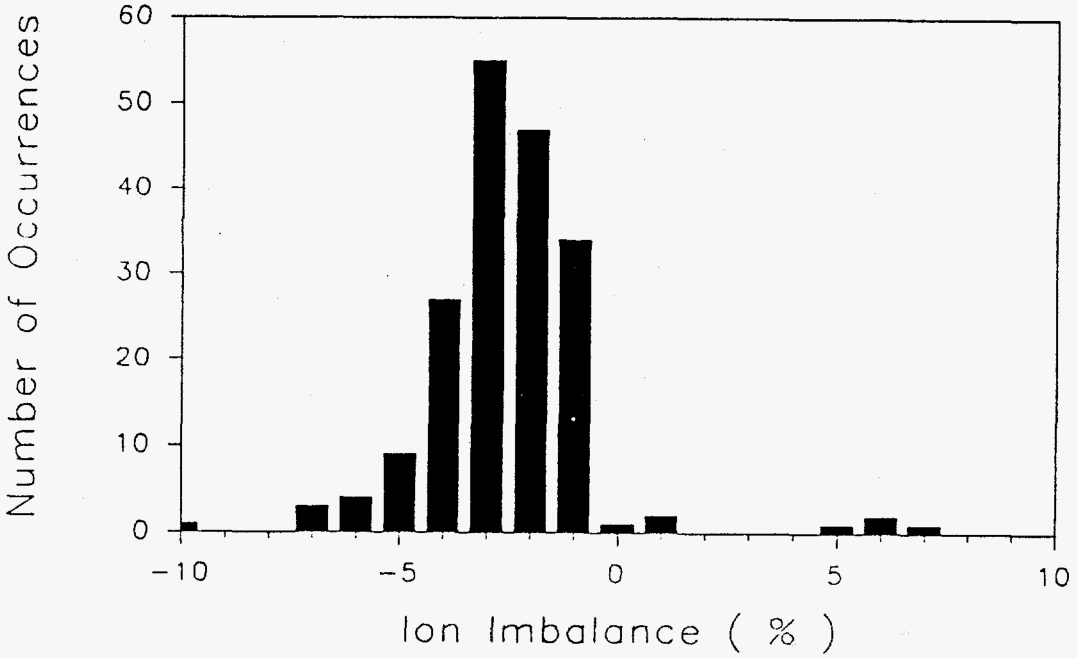


FIGURE 5.2. Frequency Histogram of Percent Ion Imbalance

5.2 WATER CHEMISTRY RESULTS

Source ground water from the start of LT3 is compared to cold (ambient) ground water analyses performed before the thermal testing began (Section 5.2.1). Trends in chemical concentrations during LT3 are described in Section 5.2.2. The effects of softening, heating, and storage are quantified through the mass balance method in Section 5.2.3. Finally, Section 5.2.4 compares water chemistry in the three long-term cycles by examining water temperatures, alkalinity, and elemental concentrations.

5.2.1 Ambient Ground-Water Characteristics

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

Early in 1982 the system was run with cold (ambient temperature) water to test the pumping and plumbing systems. Water collected at that time may be considered ambient for most parameters (Table 5.3), the exception being an anomalous high value for potassium. Analysis of subsequent samples collected near the end of the injection phase of LT1 after more than 90,000 m^3 had been pumped through the system suggests a better potassium value of 0.19 mmol/L. In general, the water from the FIG aquifer is a calcium and magnesium bicarbonate water in equilibrium with calcite and quartz at 11°C (Holm et al. 1987).

Table 5.3 shows the 1982 ambient ground-water characteristics and the average concentrations of chemical species in LT2 and LT3 source water.

5.2.2 Long-Term Cycle 3 Concentration Trends

Temperatures of water sampled during LT2 are shown in Figure 5.3. Figures 5.4 through 5.14 present analytical results for many chemical species plotted against a function of cumulative volume of water pumped (injected or recovered). No graphs of iron, manganese, aluminum, phosphate, nitrite, or nitrate are presented because all samples were at or near the detection limits of methods used. Dissolved oxygen is not graphed because all values are very low.

The layout of Figures 5.3 through 5.14 requires explanation. The upper plots depict concentration trends observed in all port samples -- that is, samples taken directly from the ATES plumbing system. Lower plots depict trends observed in aquifer-derived samples; Port III recovery samples are

TABLE 5.3. Comparison of FIG Water Chemistry from Well B Collected Before ATES Cycles, During Long-Term Cycle 2, and Long-Term Cycle 3

Parameter		Cold Water Test 1982	Long-Term Cycle 2 1986	Long-Term Cycle 3 1989
Temperature	(°C)	12	32	21
pH		7.46	6.75	7.14
Alkalinity	(meq/L)	4.87	4.88	4.49
Sulfate	(mmol/L)	0.10	0.08	0.046
Chloride	(mmol/L)	0.26	0.12	0.09
Fluoride	(mmol/L)	0.01	0.01	0.02
Nitrate		not detected	not detected	not detected
Calcium	(mmol/L)	1.19	1.42	1.16
Magnesium	(mmol/L)	0.87	0.81	0.58
Potassium	(mmol/L)	0.69[a]	0.18	0.21
Sodium	(mmol/L)	0.24	1.18	0.84
Silica	(mmol/L)	0.15	0.27	0.23
Iron	(mmol/l)	0.03	0.03	not detected

---

[a] Value is high; average Well B potassium concentration is 0.19 mmol/L.

included here (as well as in upper plots) because they were essentially obtained directly from Well A, the storage well.

The labeling of the abscissa in Figures 5.3 through 5.14 also requires explanation. All the data are plotted as a function of cumulative volume of water pumped. The injection data are plotted above the negative x axis; the volume of -64,348 m^3 corresponds to the start of injection and -40,000 m^3 corresponds to 24,348 m^3 of water injected into Well A. The zero (0) denotes the end of injection, the 45-day storage period, and the beginning of the recovery phase. This method of labeling allows easy comparison of the change in the chemistry of a particular parcel of water over the period of time of storage, assuming no mixing in the aquifer. For example, in the absence of mixing, the parcel of water injected at -40,000 m^3 (after 24,348 m^3 had been injected) should be the same parcel of water recovered at +40,000 m^3.

The temperature and chemistry of the source water from Well B for LT3 (sampling Port I) were influenced very little by previous cycles. Pumpout of Well B following LT2 brought water quality close to that of ambient water in terms of both temperature and composition (Table 5.3).

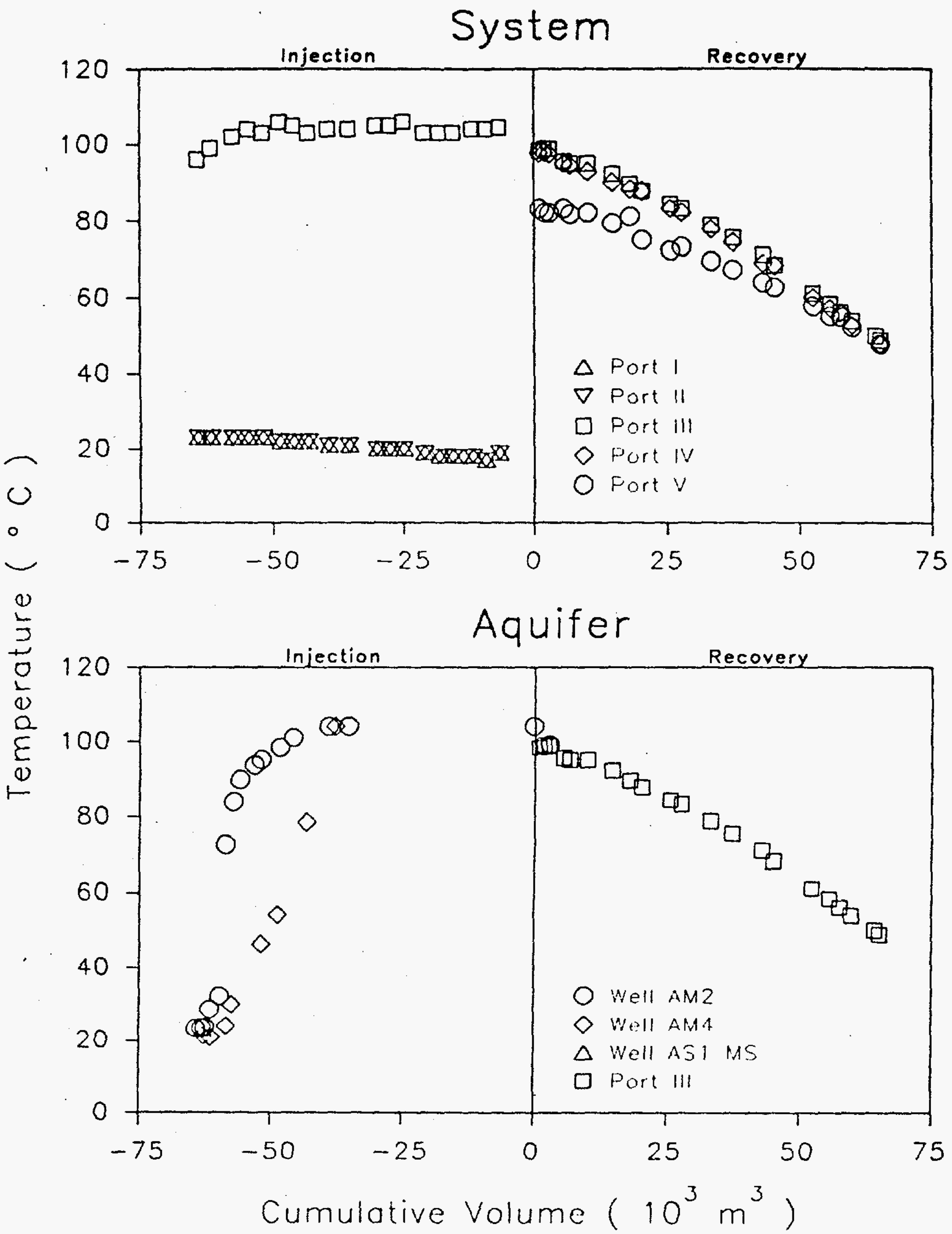


FIGURE 5.3. Water Temperatures at Long-Term Cycle 3 Sampling Times

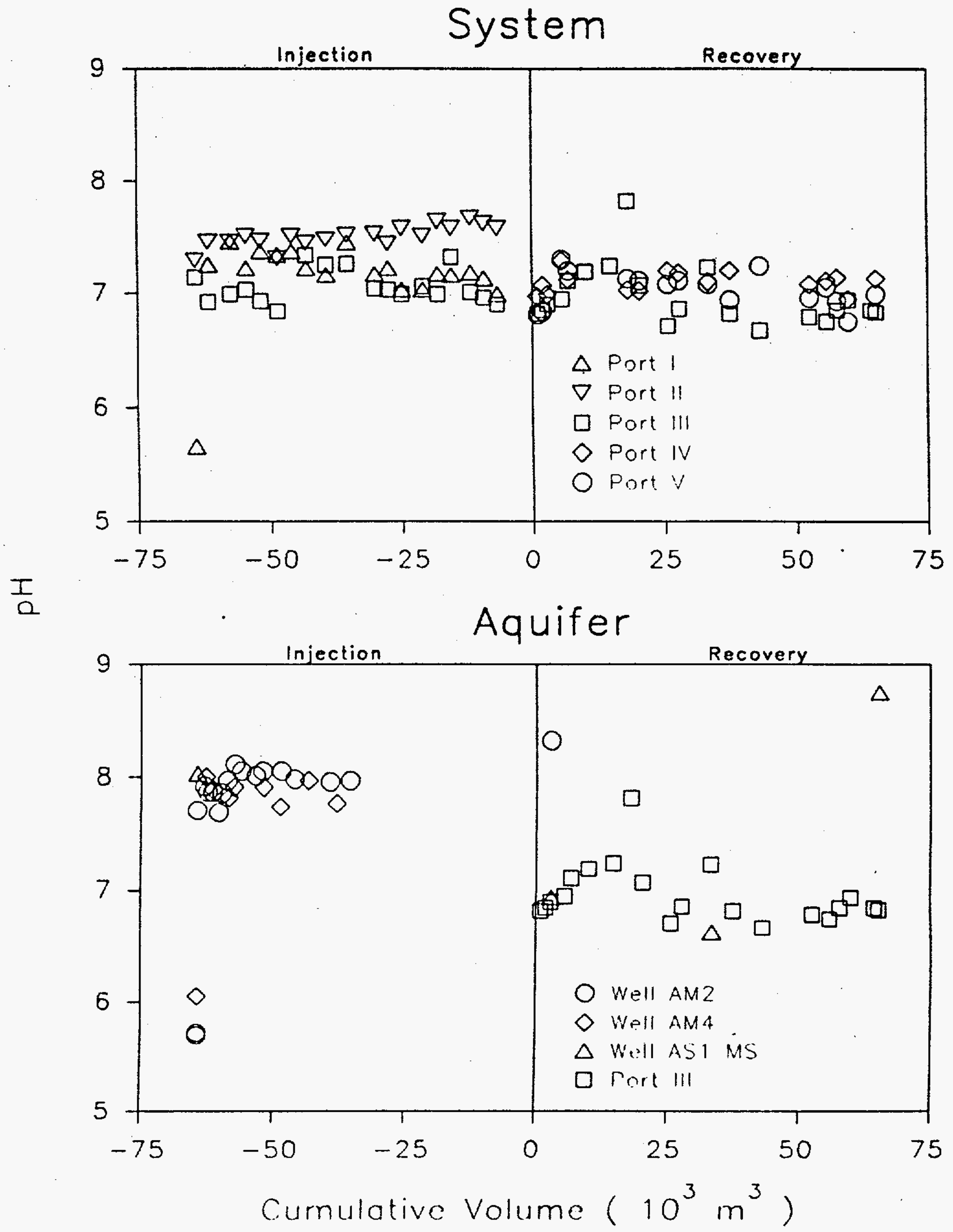


FIGURE 5.4. pH of Long-Term Cycle 3 Water Samples

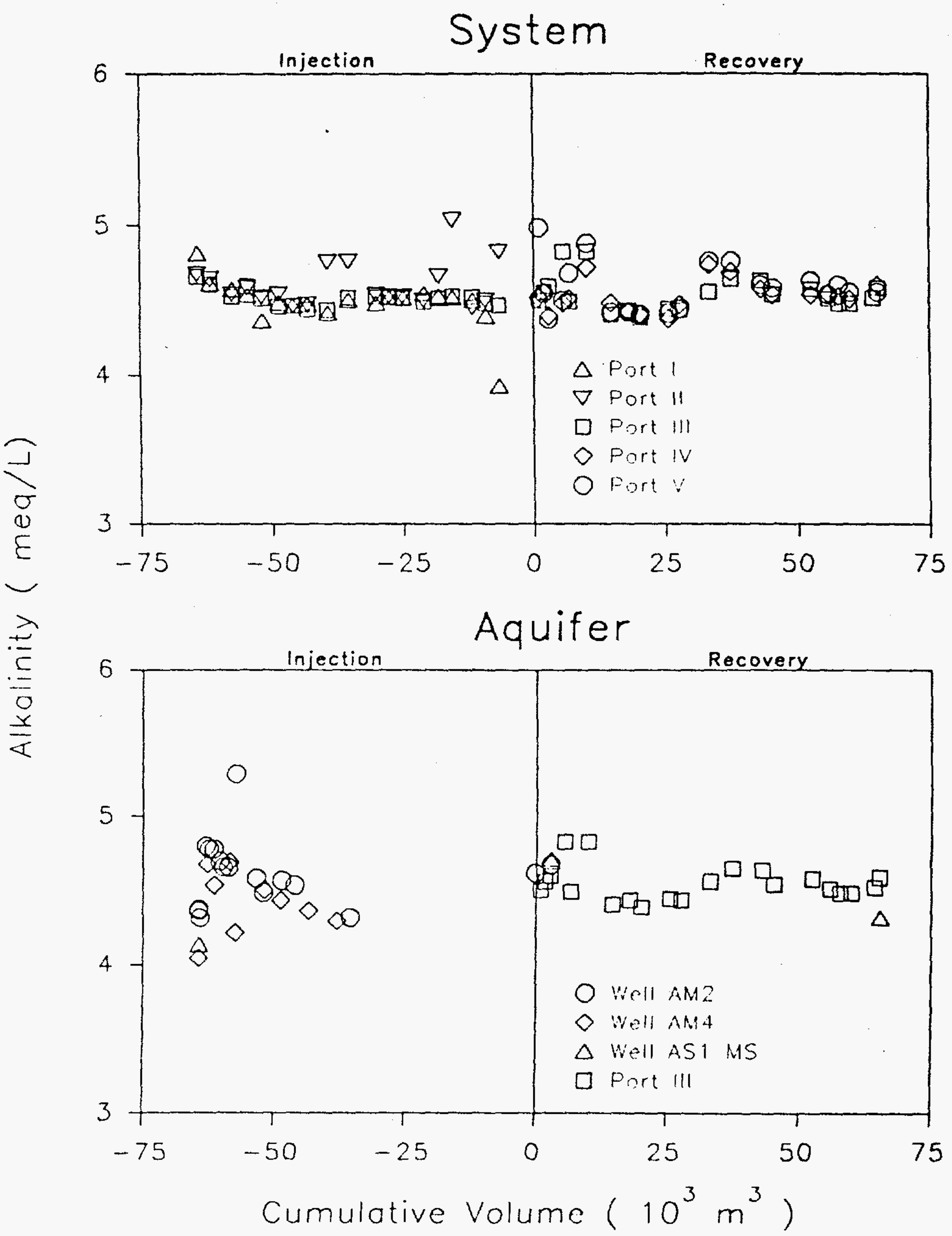


FIGURE 5.5. Alkalinity of Long-Term Cycle 3 Water Samples

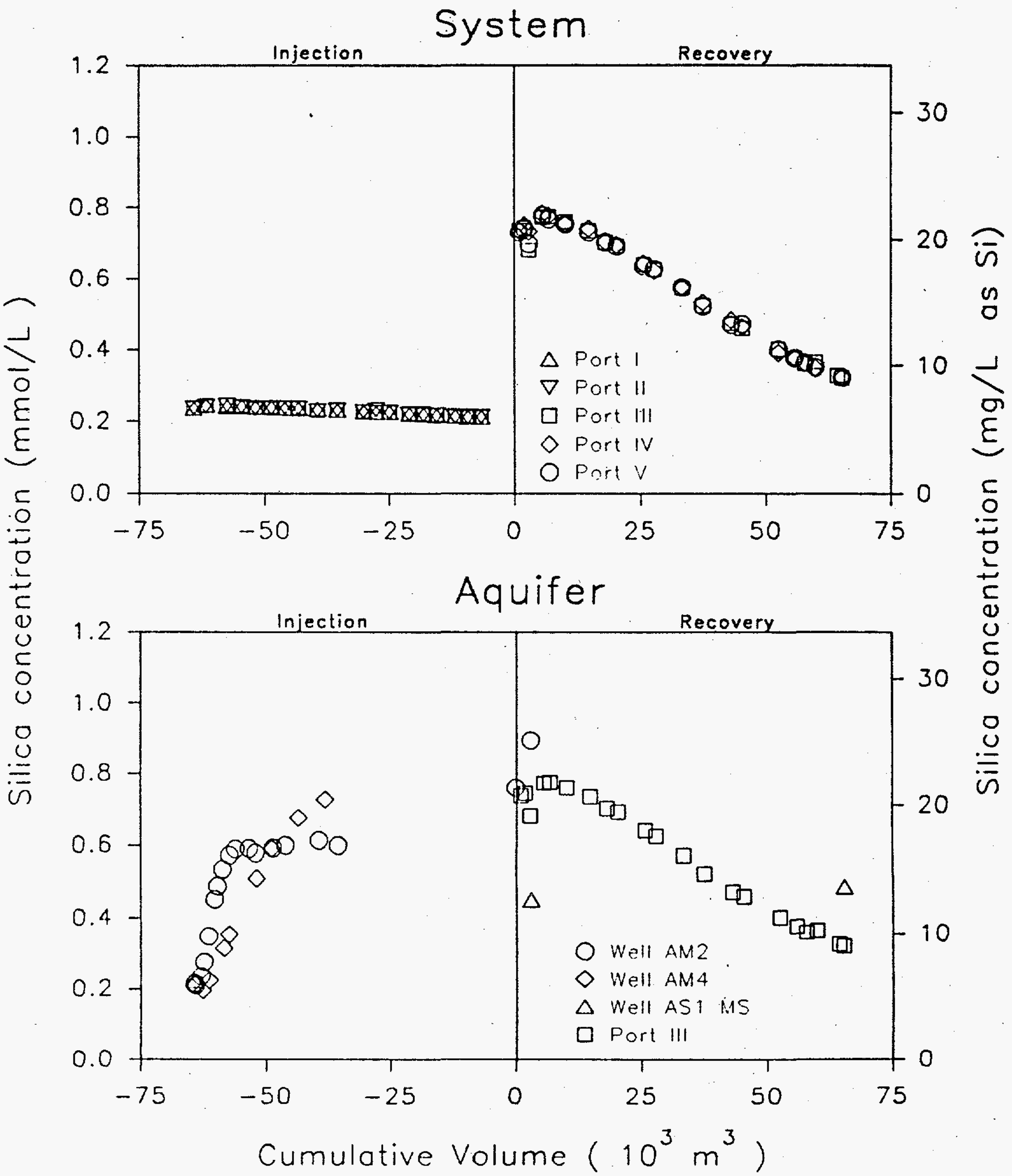


FIGURE 5.6. Silica (as Si) Concentration of Long-Term Cycle 3 Water Samples

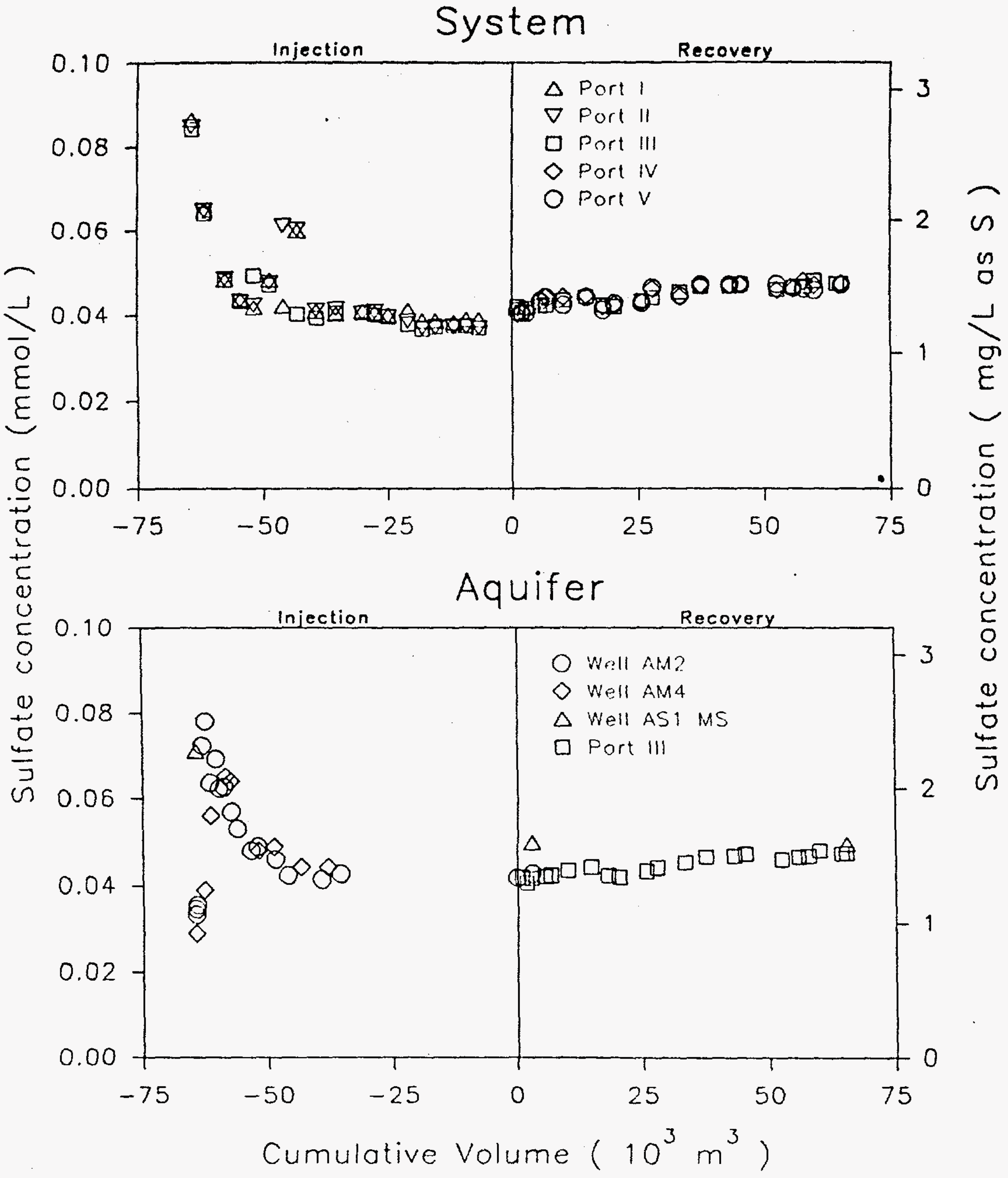
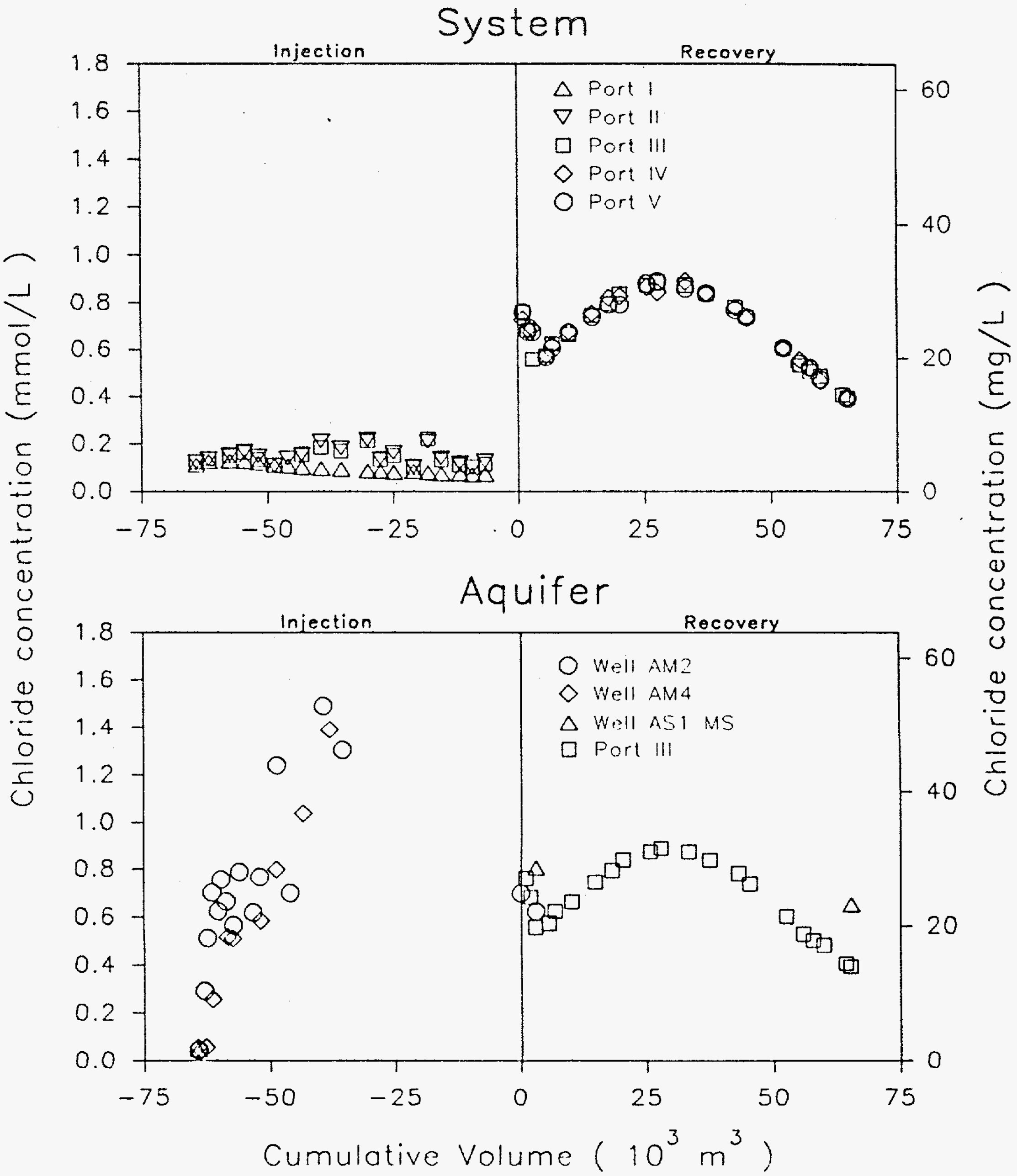


FIGURE 5.7. Sulfate Concentration of Long-Term Cycle 3 Water Samples



<u>FIGURE 5.8</u>. Chloride Concentration of Long-Term Cycle 3 Water Samples

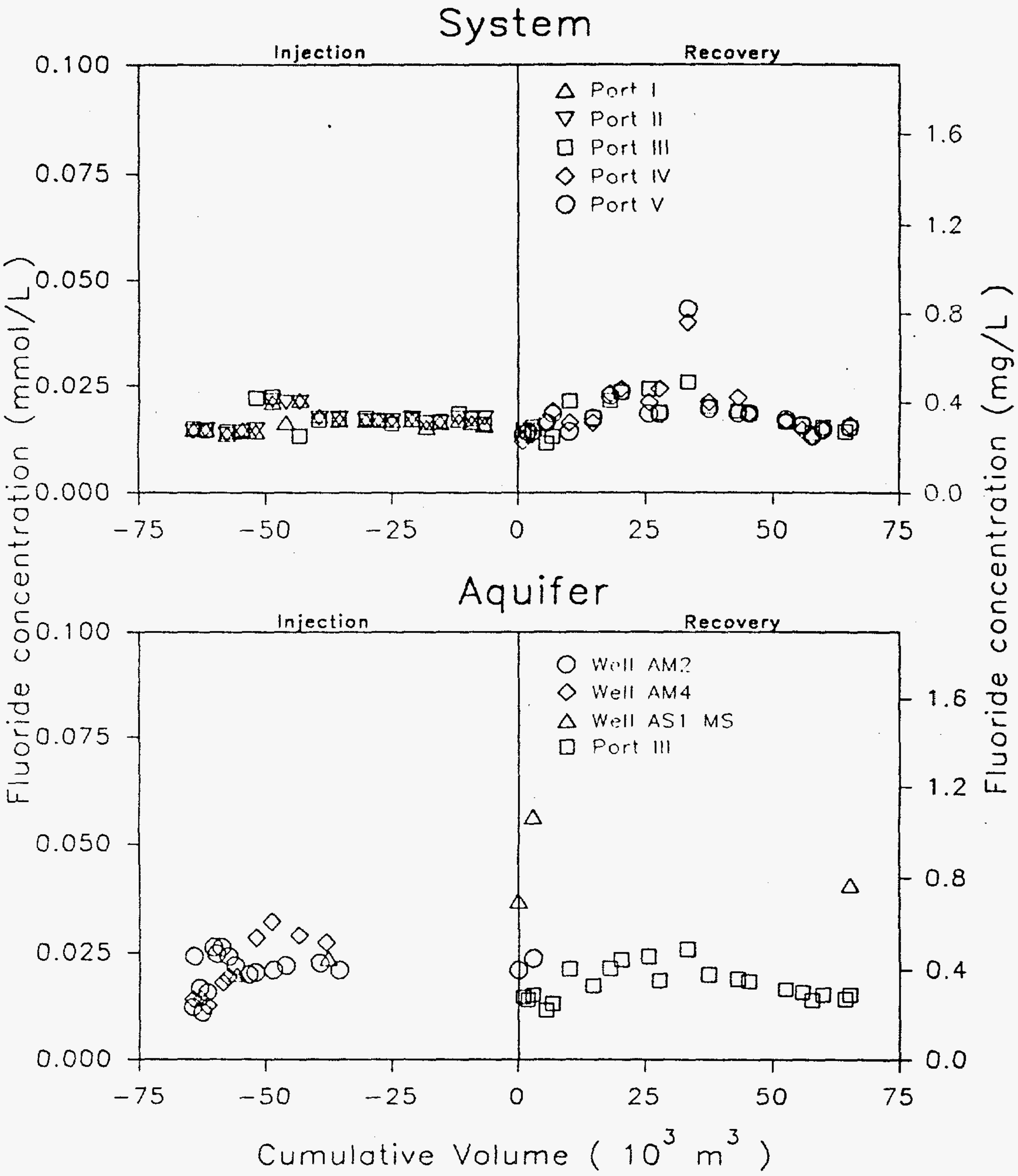


FIGURE 5.9. Fluoride Concentration of Long-Term Cycle 3 Water Samples

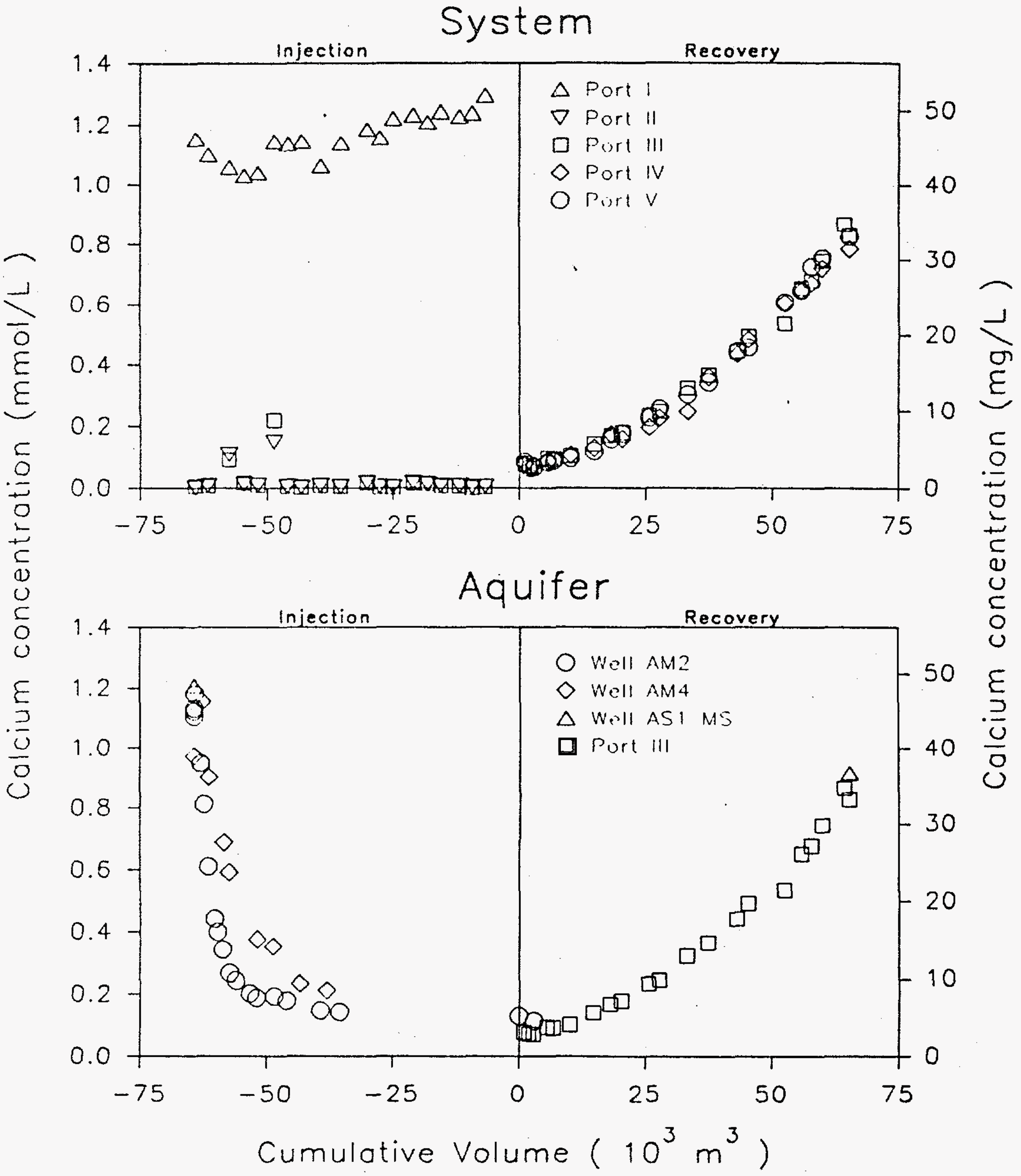


FIGURE 5.10. Calcium Concentration of Long-Term Cycle 3 Water Samples

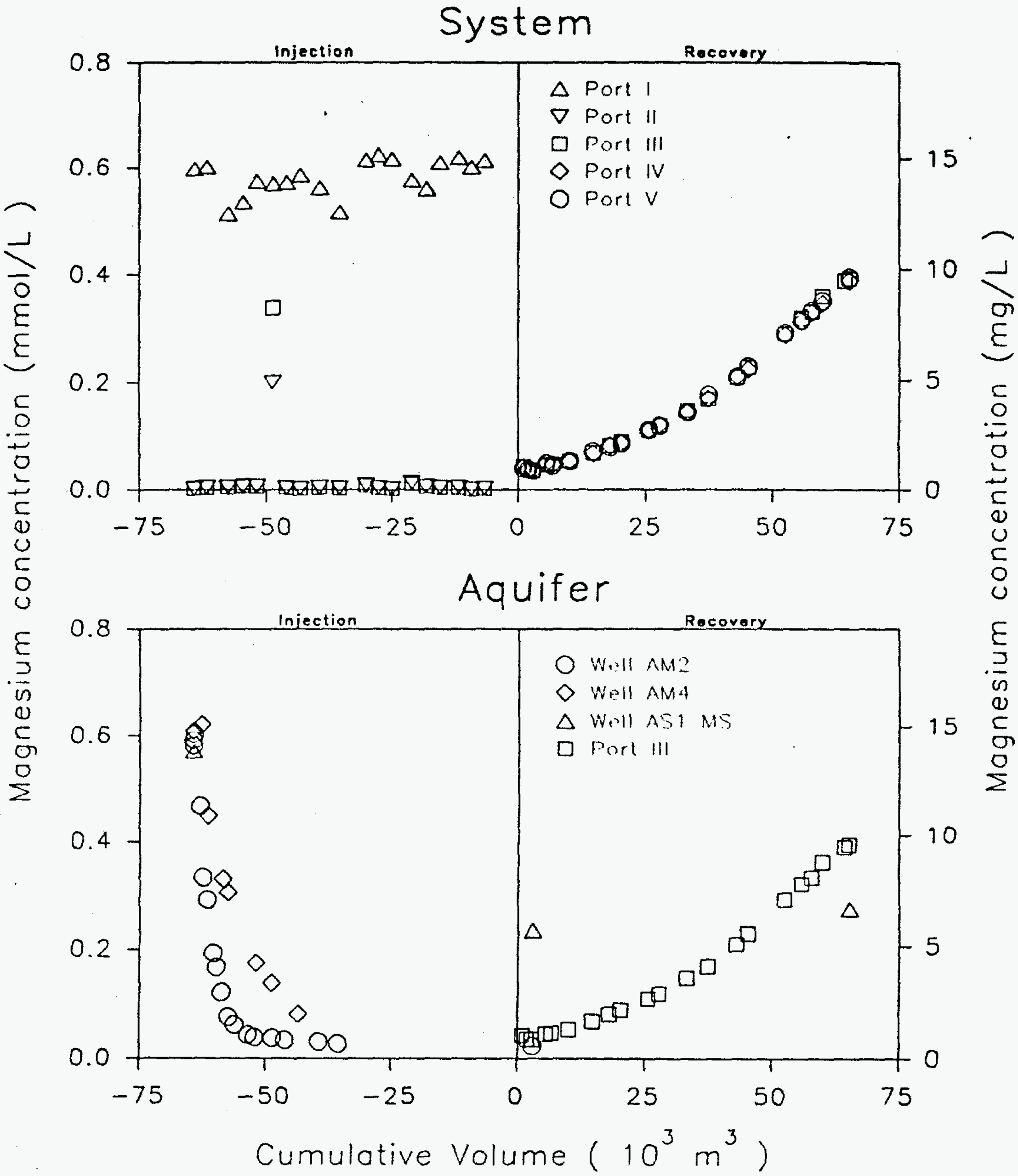


FIGURE 5.11. Magnesium Concentration of Long-Term Cycle 3 Water Samples

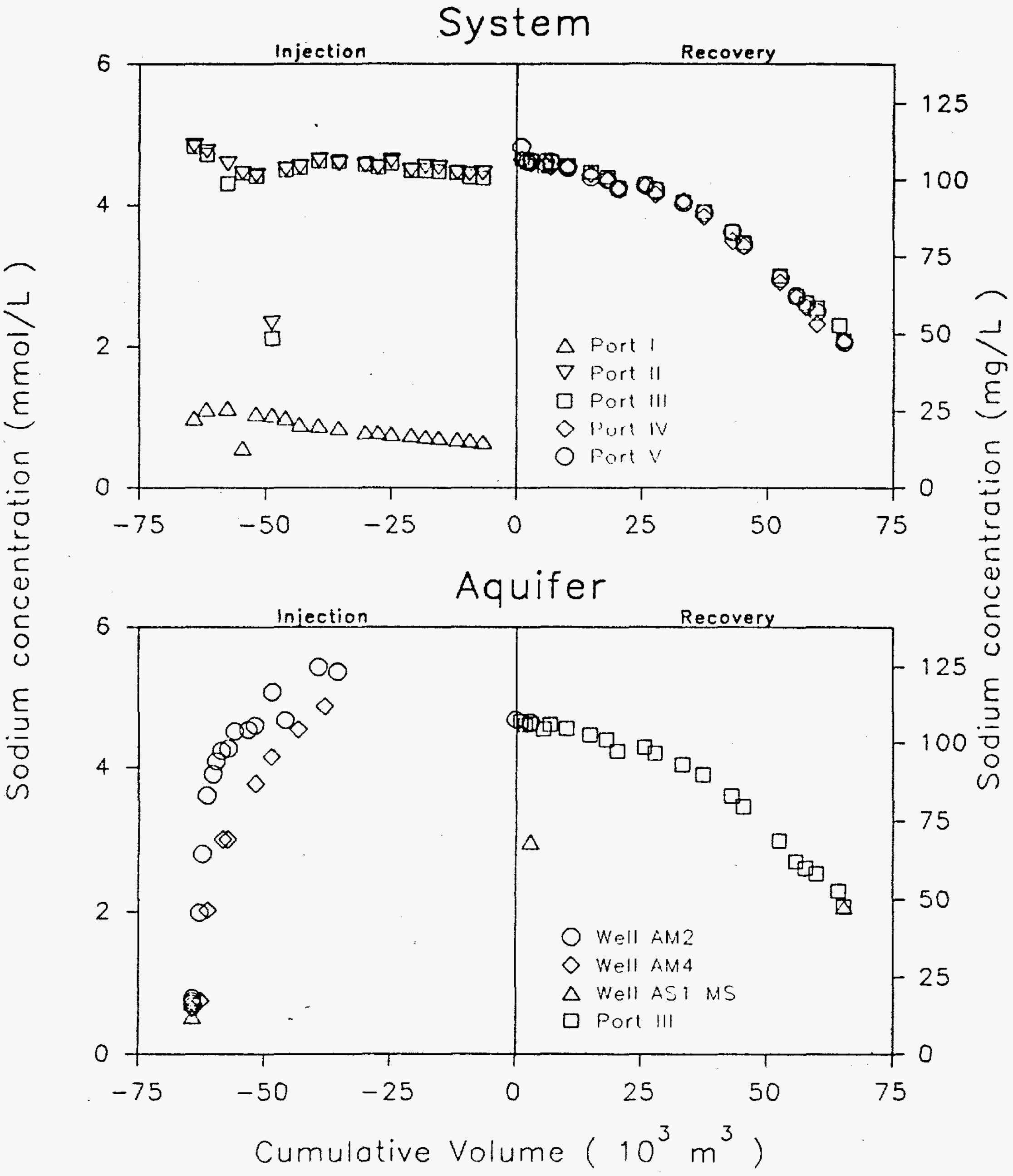


FIGURE 5.12. Sodium Concentration of Long-Term Cycle 3 Water Samples

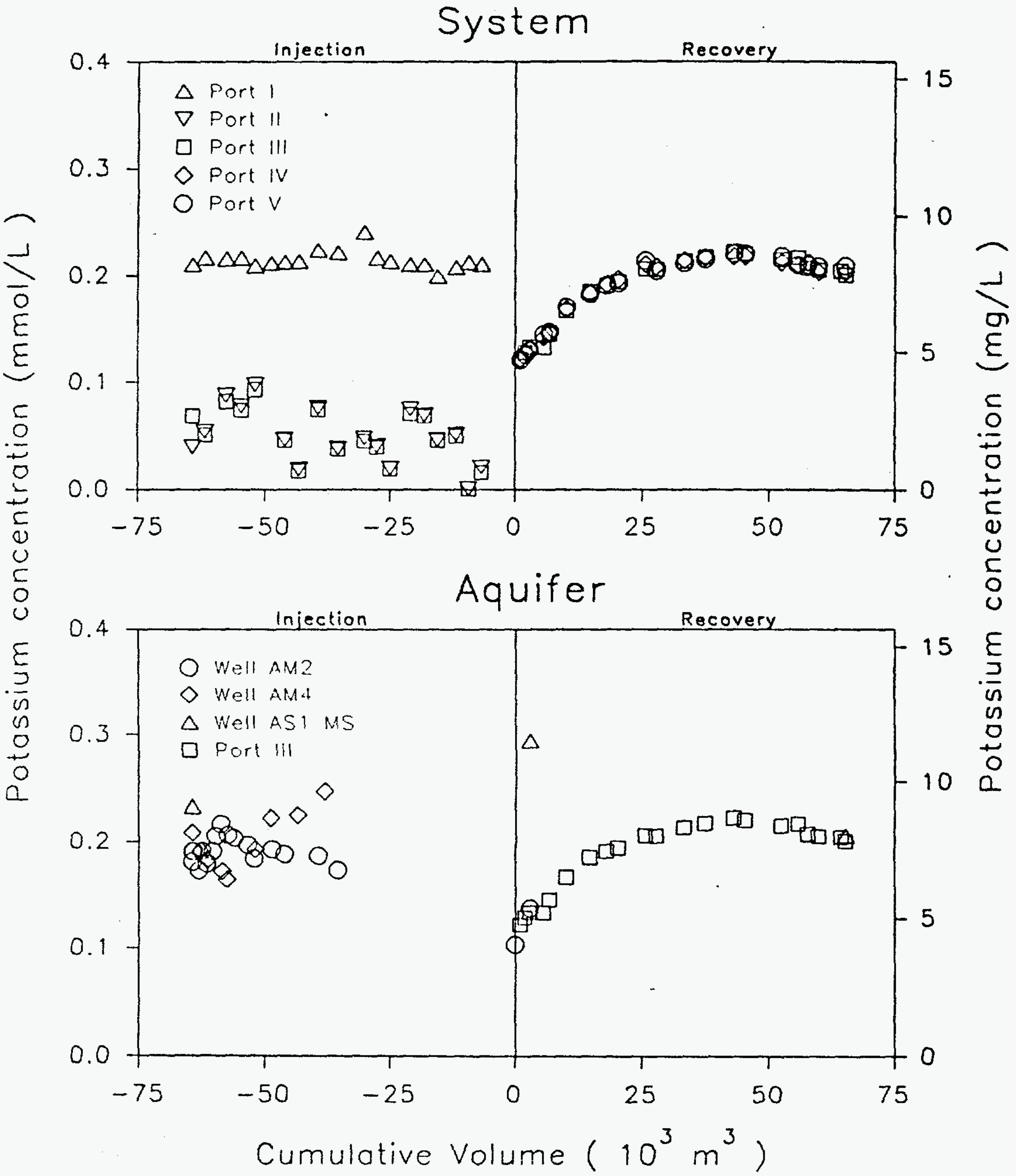


FIGURE 5.13. Potassium Concentration of Long-Term Cycle 3 Water Samples

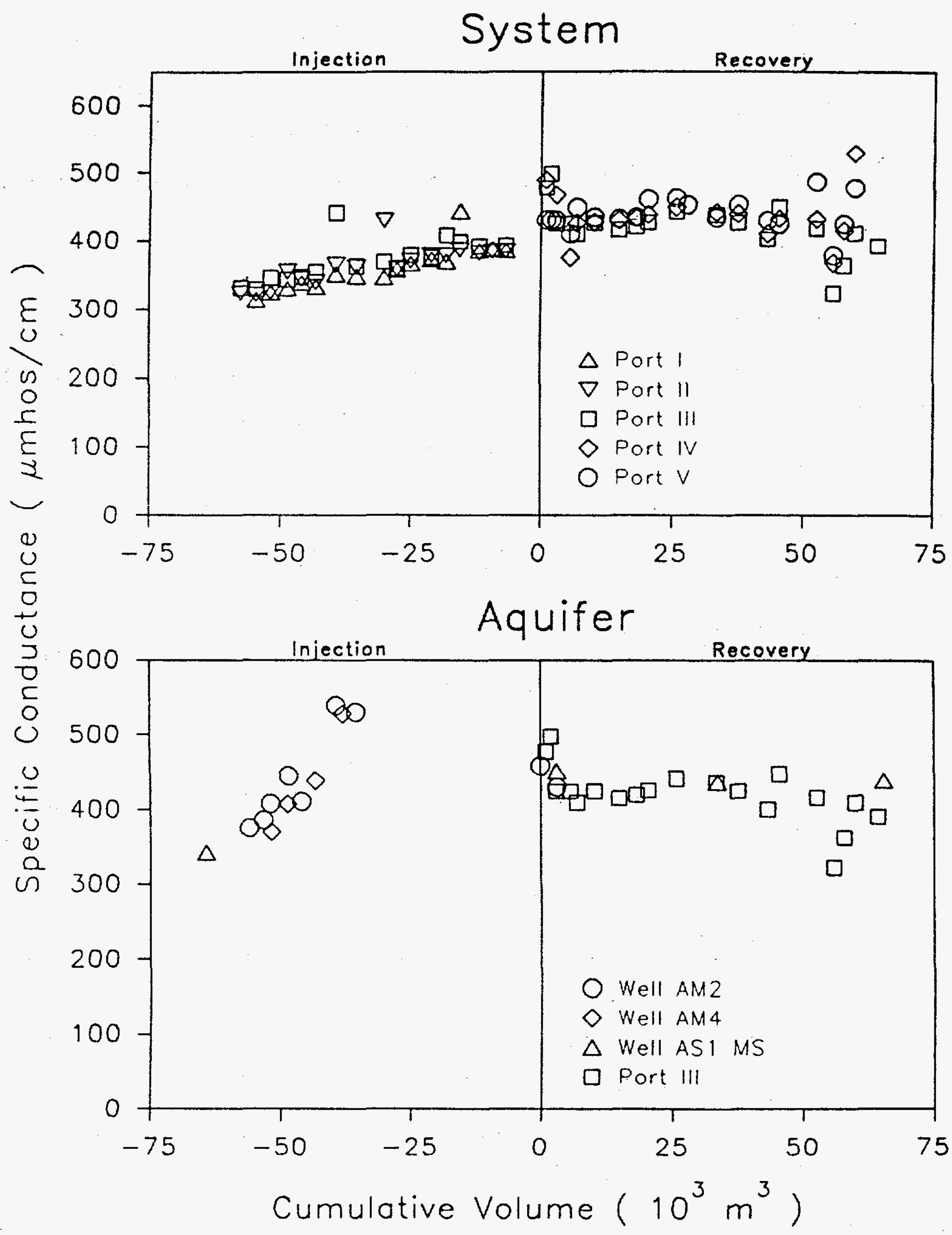


FIGURE 5.14. Specific Conductance of Long-Term Cycle 3 Water Samples

The injection temperatures of 96°C to 106°C were reflected in recovery temperatures, which reached a high of about 100°C early in recovery and declined to nearly 49°C at the end of the cycle. The pH of the source, injection, and recovery waters was in the vicinity of 7.0 (Figure 5.4). Alkalinity values of injection and recovery waters were about 4.4 to 4.8 meq/L (Figure 5.5).

Silica in injection water was nearly constant at about 0.22 mmol/L (Figure 5.6). The variation of silica in the recovery phase followed the water temperature, ranging from 0.78 (hottest) to 0.32 mmol/L (coolest). Silica concentrations of samples from Well AM2 during recover also followed the water temperature. During injection, samples from AM2 showed a silica peak of 0.90 mmol/L, reflecting the higher temperature of the water stored than recovered. Silica-rich water reached the monitoring well before highest temperatures were recorded at the well. These relationships were expected given the temperature solubility relationship of quartz.

Sulfate (Figure 5.7) and fluoride (Figure 5.9) did not exhibit significant changes during LT3. Chloride (Figure 5.8) first increased, then decreased, during the recovery phase, exhibiting a maximum of 0.89 mmol/L at about 25,700 m^3.

Calcium concentrations (Figure 5.10) exhibited trends in line with the temperature solubility relationship of calcite. The calcium concentrations in source water reflected previous test activity, and the low concentrations in Port III injection water resulted from softening in the ion exchanger. The calcium levels in the recovery water samples varied inversely with temperature, ranging from 0.071 mmol/L near the start of recovery (T = 99°C) to 0.865 mmol/L at the end of recovery (T = 49°C). Magnesium levels generally mimicked the calcium fluctuations, reflecting the solubility controls of carbonate phases (Figure 5.11).

Sodium concentrations in the source water of Well B (Figure 5.12) averaged about 0.8 mmol/L (18.4 mg/L), a value approximately twice the "ambient" concentration, reflecting previous test cycles and pumpout. After passing the ion-exchange softener, sodium concentrations increased to between 4.3 and 4.9 mmol/L (99 and 120 mg/L). Sodium in recovery water peaked at the initiation of the recovery phase at 4.7 mmol/L (108 mg/L) and decreased to about 2.1 mmol/L (48 mg/L). The decreasing sodium concentration is attributed to mixing (or dilution) of ATES warm water with low-sodium ambient water at the fringe of the warm water plume (Perlinger et al. 1987).

Potassium concentrations (Figure 5.13) increased throughout the first 43,000 m^3 of recovery and then underwent a slow decline, finally reaching a value lower than that of the source water. Specific conductance (Figure 5.14) was about 450 to 525 µmhos/cm in source and injection water and 325 to 525 µmhos/cm in recovery water. Specific conductance was dominated by the sodium-bicarbonate pair in the recovery phase.

5.2.3 Chemical and Mass Balance of Long-Term Cycle 3

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

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

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

In calculating the total mass, a final injection volume of 64,348 m^3 was used for V_{n+1} for both the injection and recovery phases. The effects of softening, heating, and storage are best illustrated by constructing a mass balance around each process (Tables 5.6, 5.7). Negative values indicate a loss of mass through that process, and positive values indicate a gain.

The statistical significance of the total mass and mass balance values has been estimated using a propagation of errors method (Shoemaker et al.

TABLE 5.4. Cumulative Mass of Dissolved Species in Source, Softened, Injected, and Recovered Water for Long-Term Cycle 3. Kiloequivalents, except as noted. See note for explanation.

	Source	Softened	Injected	Recovered
Alkalinity	285.46 ±0.33	297.93 ±0.34	290.14 ±0.34	297.26 ±2.10
Silica (kmol)	14.64 ±0.01	14.66 ±0.02	14.68 ±0.02	37.23 ±0.27
Sulfate	5.71 ±0.03	5.74 ±0.02	5.51 ±0.02	5.93 ±0.03
Chloride	5.94 ±0.04	9.75 ±0.04	9.25 ±0.04	46.53 ±0.31
Fluoride	1.06 ±0.01	1.10 ±0.01	1.08 ±0.01	1.22 ±0.09
Calcium	150.18 ±0.09	2.58 ±0.09	3.44 ±0.09	47.47 ±0.78
Magnesium	74.91 ±0.17	1.75 ±0.18	3.49 ±0.18	22.99 ±0.07
Sodium	53.12 ±0.27	285.62 ±0.28	279.53 ±0.28	249.24 ±0.29
Potassium	13.83 ±0.11	7.70 ±0.11	9.20 ±0.11	12.93 ±0.03
Hardness as $CaCO_3$	225.09 ±0.19	4.33 ±0.20	6.93 ±0.20	70.47 ±0.79
Anions, total	298.20 +0.34	314.52 +0.35	305.97 +0.35	350.95 +2.10
Cations, total	292.03 +0.34	297.65 +0.36	295.65 +0.36	332.63 +0.84

Note: Source: Port I
Softened: Port II
Injected: Port III(I)
Recovered: Port III(R)

TABLE 5.5. Cumulative Mass of Dissolved Species in Source, Softened, Injected, and Recovered Water, Long-Term Cycle 3. Kilograms. See note on Table 5.4 for explanation.

	Source	Softened	Injected	Recovered
Alkalinity, as HCO_3^-	17418 ±20	18180 ±21	17704 ±21	18139 ±128
Silica as Si	411.0 ±0.4	411.7 ±0.4	412.2 ±0.4	1045 ±8
Sulfate as S	91.48 ±0.48	92.03 ±0.27	88.30 ±0.27	95.10 ±0.40
Chloride	210.6 ±1.2	345.5 ±1.3	327.9 ±1.3	1650 ±11
Fluoride	20.20 ±0.19	20.90 ±0.19	20.46 ±0.20	23.20 ±1.8
Calcium	3010 ±2	51.7 ±1.7	68.9 ±1.7	951 ±16
Magnesium	910.3 ±2.1	21.3 ±2.1	42.4 ±2.1	279.5 ±0.8
Sodium	1221 ±6	6566 ±6	6426 ±6.4	5730 ±7
Potassium	540.6 ±4.1	300.9 ±4.3	359.7 ±4.3	505.6 ±1.0
Hardness, as $CaCO_3$	11265 ±10	217 ±10	347 ±10	3526 ±39

TABLE 5.6. Mass Balance Across the Water Softener, Heat Exchanger, Aquifer Storage, and Total Cycle for Long-Term Cycle 3. Kiloequivalents, except as Noted. See note for explanation

	Water Softener	Heat Exchanger	Aquifer Storage	Total Cycle
Alkalinity	12.48 ±0.48	-7.80 ±0.49	7.13 ±2.10	11.8 ±2.10
Silica (Kmol)	0.02 ±0.02	0.02 ±0.02	22.55 ±0.27	22.60 ±0.27
Sulfate	0.03 ±0.03	-0.23 ±0.02	0.42 ±0.03	0.23 ±0.04
Chloride	3.80 ±0.05	-0.50 ±0.05	37.28 ±0.31	40.60 ±0.31
Fluoride	0.03 ±0.01	-0.02 ±0.02	0.14 ±0.10	0.16 ±0.10
Calcium	-147.60 ±0.12	0.86 ±0.12	44.00 ±0.79	-102.70 ±0.79
Magnesium	-73.16 ±0.25	1.74 ±0.25	19.50 ±0.19	-51.90 ±0.18
Sodium	232.50 ±0.39	-6.10 ±0.39	-30.30 ±0.40	196.10 ±0.39
Potassium	-6.13 ±0.15	1.50 ±0.15	3.70 ±0.11	-0.89 ±0.11
Hardness as $CaCO_3$	-220.80 ±0.27	2.60 ±0.28	63.50 ±0.81	-154.60 ±0.81
Total Anions	16.35 ±0.48	-8.55 ±0.49	44.98±2.10	52.80 ±2.10
Total Cations	5.62 ±0.50	-2.00 ±0.51	36.98±0.91	40.60 ±0.91

Note: Softener: Chemical added (+)/ removed (-) in the water softener
Port II - Port I
Exchanger: Chemical added (+)/ removed (-) in the heat exchanger
Port III(I) - Port II
Storage: Chemical added (+)/ removed (-) during aquifer storage
Port III(R) - Port III(I)
Cycle: Chemical added (+)/ removed (-) during ATES test cycle
Port III(R) - Port I

TABLE 5.7. Mass Balance Across the Water Softener, Heat Exchanger, Aquifer Storage, and Total Cycle for Long-Term Cycle 3. Kilograms. See note on Table 5.6 for explanation.

	Water Softener	Heat Exchanger	Aquifer Storage	Total Cycle
Alkalinity, as HCO_3^-	761 ±29	-475 ±30	435 ±129	720 ±129
Silica as Si	0.70 ±0.57	0.49 ±0.58	633 ±8	635 ±8
Sulfate as S	0.55 ±0.55	-3.70 ±0.39	6.78 ±0.48	3.60 ±0.62
Chloride	134.9 ±1.8	-17.6 ±1.8	1322 ±11	1439 ±11
Fluoride	0.65 ±0.27	-0.40 ±0.28	2.8 ±1.8	3.0 ±1.8
Calcium	-2958 ±2	17.2 ±2.5	882 ±16	-2058 ±16
Magnesium	-889 ±3	21.1 ±3.0	237 ±2	-631 ±2.2
Sodium	5345 ±9	-140 ±9	-696 ±9	4509 ±9
Potassium	-239.7 ±5.9	58.7 ±6.0	146.0 ±4.4	-35.0 ±4.2
Hardness, as $CaCO_3$	-11048 ±14	130 ±14	3180 ±41	-7738 ±40

1981). Through the use of partial differential equations, the error of each concentration and volume measurement is propagated to give a standard deviation for the mass (Tables 5.4, 5.5). The general equation is:

$$S^2_{(F)} = \left(\frac{dF}{dx}\right)^2 S^2_{(x)} + \left(\frac{dF}{dy}\right)^2 S^2_{(y)} + \ldots \qquad (3)$$

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

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

The mass charge balances of the cations and the anions for each sampling point have differences of 1.0 to 4.0 percent (Figure 5.15). These percent differences compare very well to the ion imbalances (Figure 5.2) calculated for the individual samples.

The water softener [Port II - Port I] removed 227 keq of calcium, magnesium, and potassium from the source water (Figure 5.16). Sodium, the exchange ion, was added during the softening process to the extent of 233 keq. There was an addition of 5.6 keq of sodium above the amount needed for the softening process. The amount of chloride also increased by 3.8 keq during softening (Figure 5.16). The excess of sodium and chloride can be attributed to the incomplete rinsing of the water softener following regeneration.

The only significant mass changes across the heat exchanger [Port II - Port III(I)] are the loss of 7.8 keq of alkalinity and 6.1 keq sodium.

Heated ATES water stored for 45 days resulted in some dissolution and recovery of aquifer minerals. Silica, which had not changed during softening and heating, gained 22.6 kmol during storage. The increase of silica is caused by dissolution of quartz in the aquifer at the elevated temperature of the injected water. The levels of calcium, magnesium, and potassium also increased by 44 keq, 19.5 keq, and 3.7 keq, respectively (Figure 5.17). The increase in recovery of chemical mass in the storage cycle has been attributed to a combination of mineral dissolution and mixing of stored water with surrounding, ambient ground water. Sodium was lost during storage (30.3 keq). Eighty-nine percent of the injected sodium from the water softening step was recovered, and the 11 percent lost is believed to be the result of mixing. Thirty-seven kiloequivalents of chloride, and small amounts of other anions, were also gained during storage (Figure 5.17).

No important chemical changes occurred as the recovered water passed through the ASVM building heat exchanger (Tables 5.8, 5.9).

5.2.4 Comparison of Long-Term Cycle Water Chemistry

Figures 5.18 through 5.29 present analytical results from recovery water samples for selected chemical species during the recovery phases of the three long-term cycles plotted against cumulative volume. The most obvious differences between the results from LT3 and the previous long-term cycles are the steeper slopes of the temperature, silica, calcium, magnesium, and sodium (Figures 5.18 through 5.22). This quicker approach to ambient conditions is the result of the smaller injected volume for LT3 (~60,000 m^3) than LT1 and LT2 (~90,000 m^3). The smaller injection volume and the changed injection zone would also tend toward more rapid changes in these parameters, when plotted against total volume pumped. More rapid mixing, an alternative explanation for the steeper trends in LT3, is unlikely. The single injection zone, the Ironton-Galesville, used would tend to reduce mixing rather than increase it. Use of a mixing model, using sodium as a conservative tracer, indicated that less mixing occurred in LT3 than in the previous long-term cycles (Uebel, 1992).

Alkalinity and pH (Figures 5.23, 5.24) were approximately constant throughout recovery in all three cycles. Sulfate (Figure 5.25) was lower in

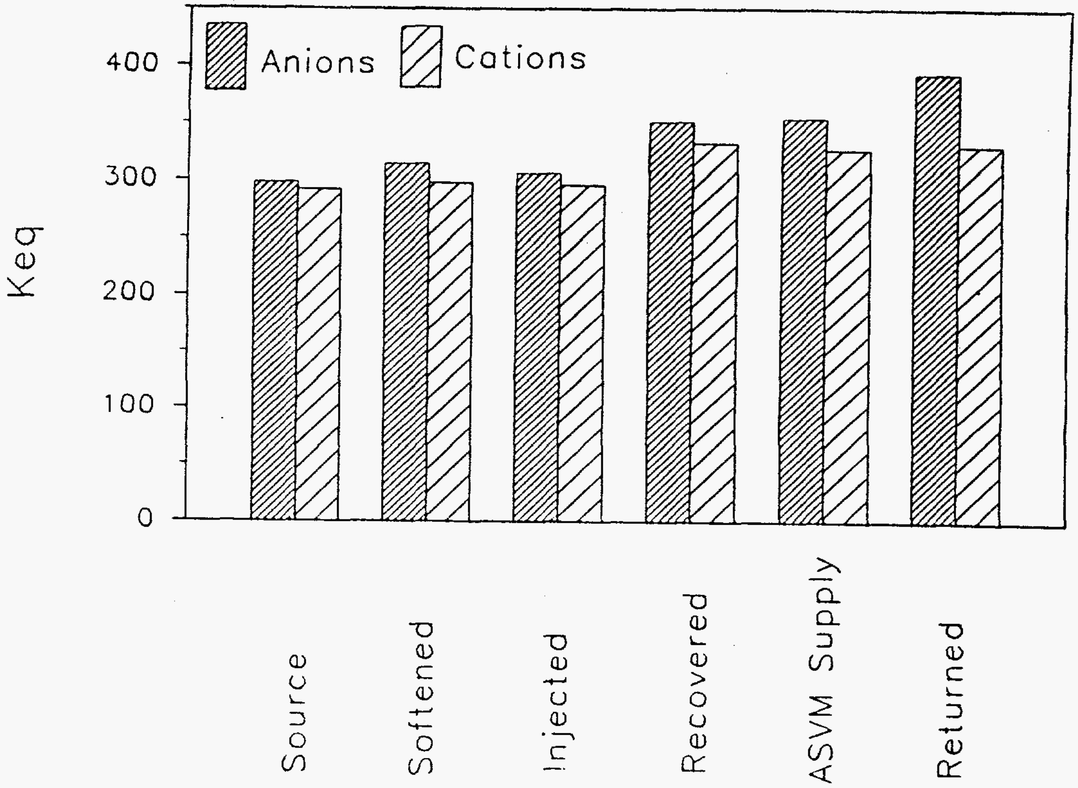


FIGURE 5.15. Anion and Cation Charge Balance of Source, Softened, Injected, Recovered, ASVM Supply, and Returned Water for Long-Term Cycle 3

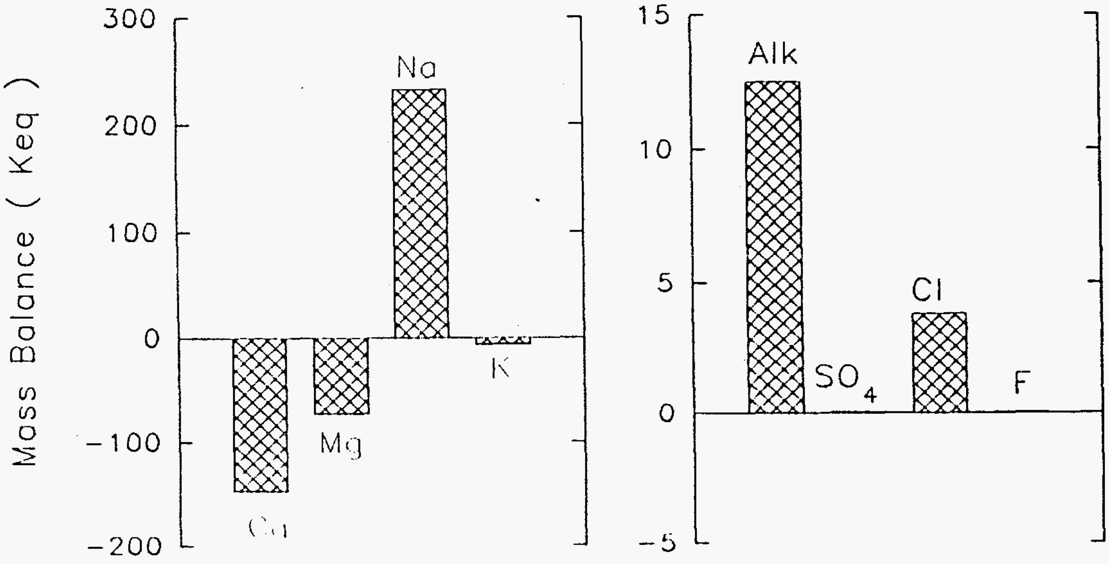


FIGURE 5.16. Mass Balance Across Water Softener for Long-Term Cycle 3

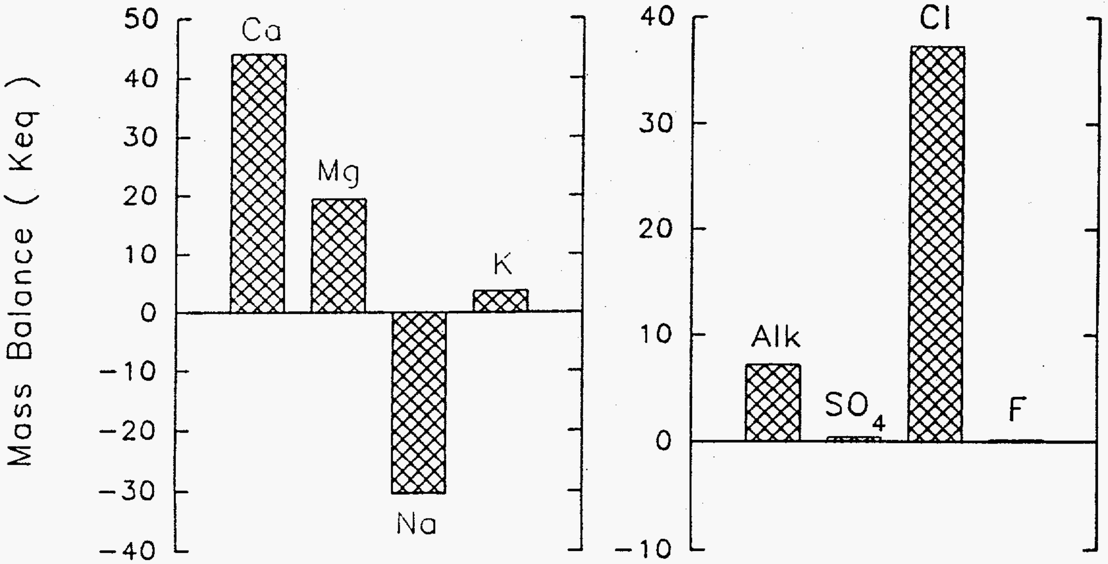


FIGURE 5.17. Mass Balance Across Aquifer Storage for Long-Term Cycle 3

LT3 than in LT1 and LT2. Possibly sulfate-bearing minerals are being depleted; such minerals are not common in the storage aquifer (Section 2.2).

Chloride concentration (Figure 5.26) increased to well above levels of the previous cycles for the first half of LT3 and subsequently decreased to near ambient concentration. This trend was not observed during LT1 or LT2; however, it was observed during the short-term cycles (Walton et al. 1991). Possible explanations include anion exchange reactions and the presence in the storage aquifer of fluid inclusions containing high chloride concentrations.

The potassium trend for LT3 is analogous to those in the first two cycles, but concentrations are lower throughout recovery (Figure 5.27). Potassium concentrations are apparently controlled neither by temperature nor by mixing--an irreverence which thus far defies explanation. Cation exchange may account for the trend, but ion exchange is a difficult phenomenon to model (Holm et al. 1987) and so support for this hypothesis is wanting. Fluoride concentrations and specific conductance (Figures 5.28 and 5.29) are similar in all three cycles.

Long-term cycle 3 results might have proven more useful for determining the effects of consecutive cycles on ground-water chemistry, had not the

TABLE 5.8. Mass Balance Across the System Piping and ASVM Heat Exchanger for Long-Term Cycle 3 Recovery. Kiloequivalents, except as noted.

	System Piping [Port IV-Port III(R)]	ASVM Heat Exchanger [Port V-Port IV]
Alkalinity	2.6 ±2.9	2.9 ±2.9
Silica (Kmol)	0.13 ±0.38	-0.18 ±0.37
Sulfate	0.02 ±0.03	-0.02 ±0.03
Chloride	0.23 ±0.43	-0.33 ±0.43
Fluoride	0.10 ±0.13	-0.04 ±0.13
Calcium	-1.8 ±1.1	1.3 ±1.1
Magnesium	-0.25 ±0.10	0.21 ±0.10
Sodium	-3.82 ±0.40	2.28 ±0.39
Potassium	0.01 ±0.04	0.05 ±0.03
Hardness as $CaCO_3$	-2.1 ±1.1	1.5 ±1.1

TABLE 5.9. Mass Balance Across the System Piping and ASVM Heat Exchanger for Long-Term Cycle 3 Recovery. Kilograms, except as noted.

	System Piping (Port IV-Port III[R])	ASVM Heat Exchanger (Port V-Port IV)
Alkalinity as HCO_3^-	157 ±178	176 ±175
Silica as Si	3 ±11	-5 ±10
Sulfate as S	0.30 ±0.55	-0.34 ±0.54
Chloride	8 ±15	-12 ±15
Fluoride	1.9 ±2.5	-0.8 ±2.5
Calcium	-37 ±22	26 ±22
Magnesium	-3.0 ±1.2	2.6 ±1.2
Sodium	-87.8 ±9.2	52.3 ±9.1
Potassium	0.3 ±1.4	1.9 ±1.4
Hardness as $CaCO_3$	-104 ±56	75 ±56

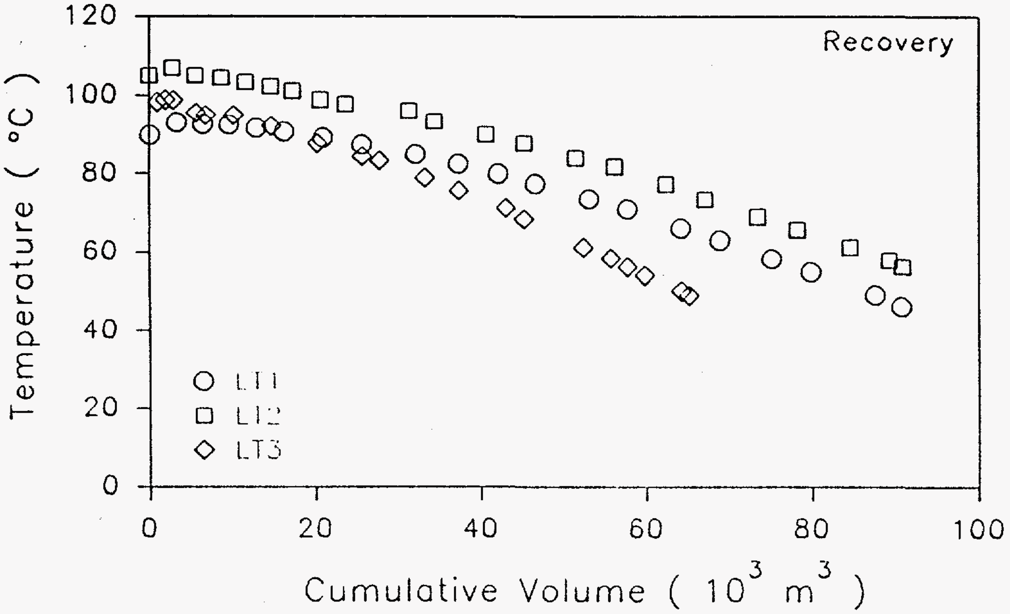


FIGURE 5.18. Temperature of Recovery Water Samples From Long-Term Cycles (LT1, LT2, and LT3)

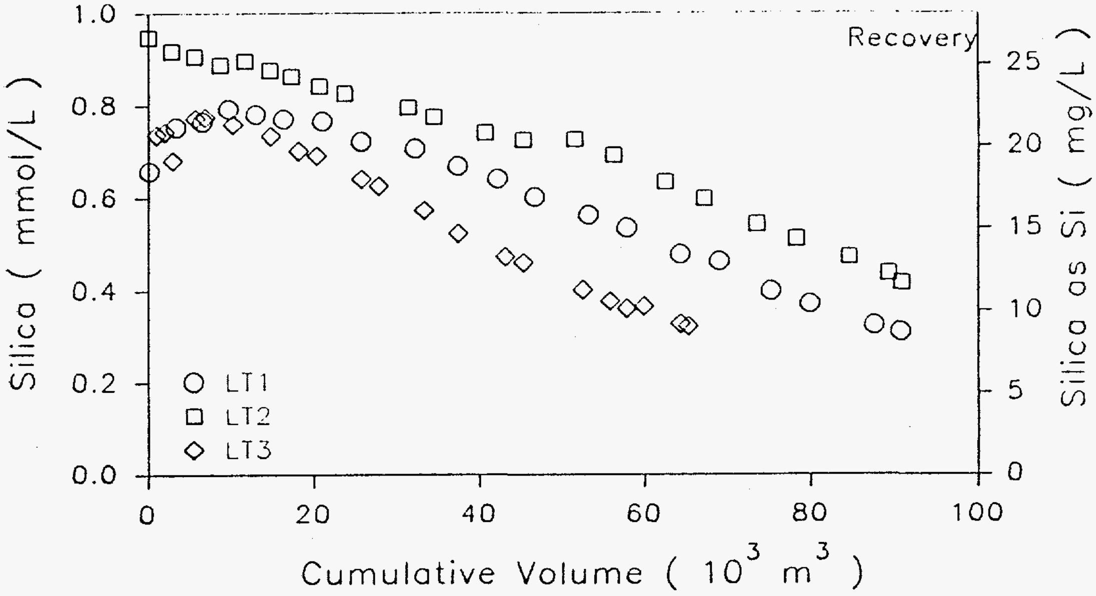


FIGURE 5.19. Silica (as Si) Concentrations of Recovery Water Samples From Long-Term Cycles (LT1, LT2, and LT3)

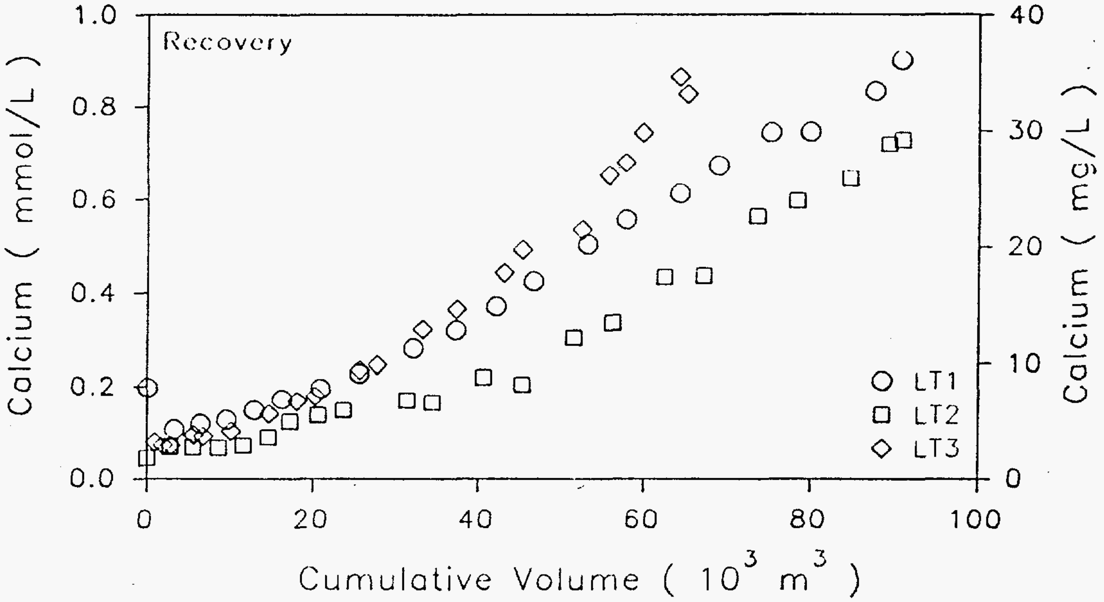


FIGURE 5.20. Calcium Concentrations of Recovery Water Samples From Long-Term Cycles (LT1, LT2, and LT3)

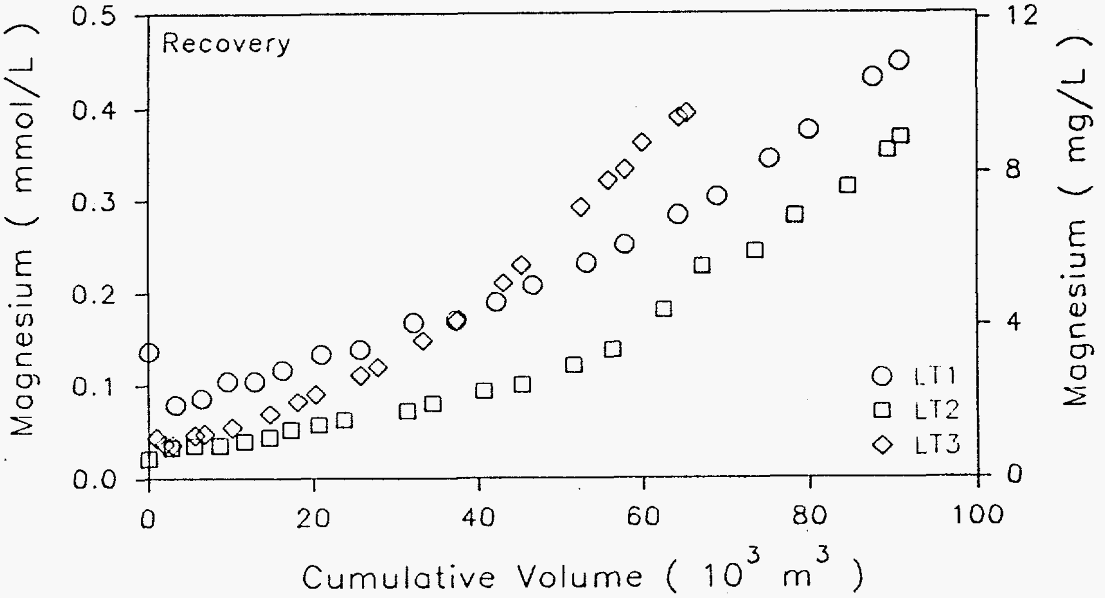


FIGURE 5.21. Magnesium Concentrations of Recovery Water Samples From Long-Term Cycles (LT1, LT2, and LT3)

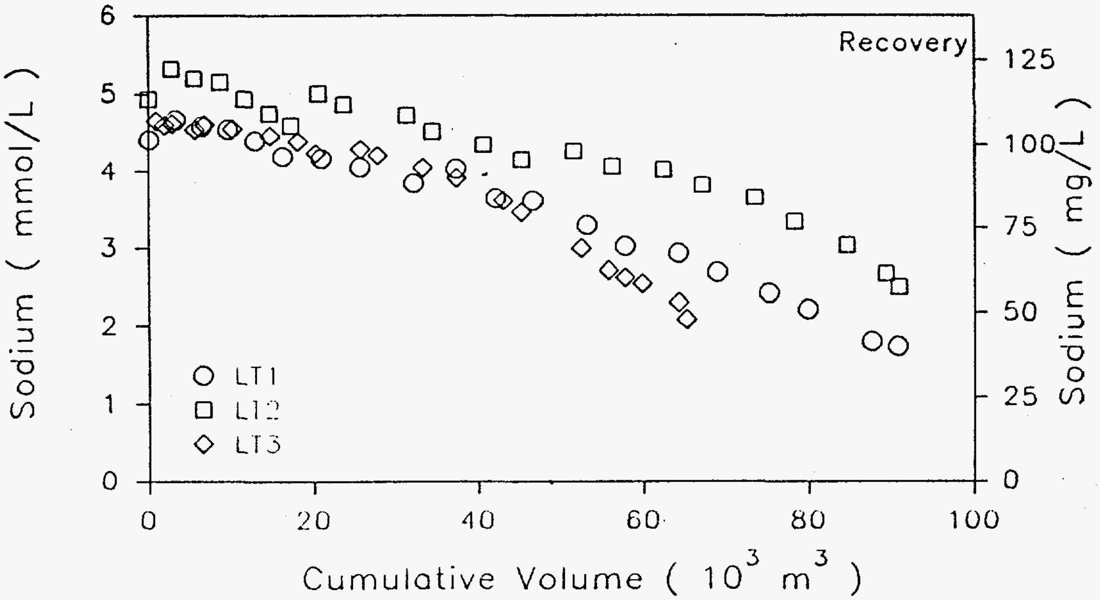


FIGURE 5.22. Sodium Concentrations of Recovery Water Samples From Long-Term Cycles (LT1, LT2, and LT3)

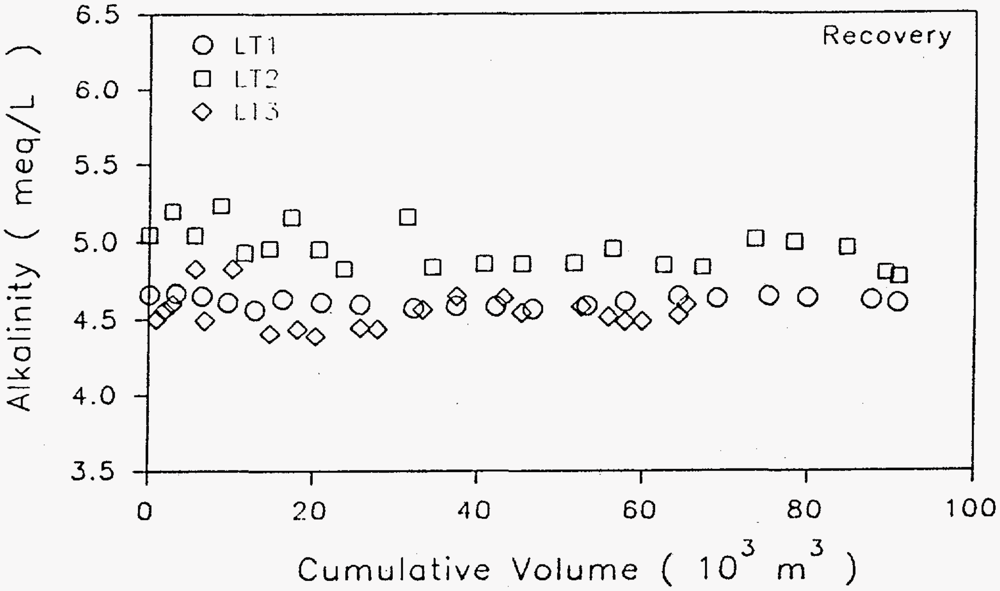


FIGURE 5.23. Alkalinity of Recovery Water Samples From Long-Term Cycles (LT1, LT2, and LT3)

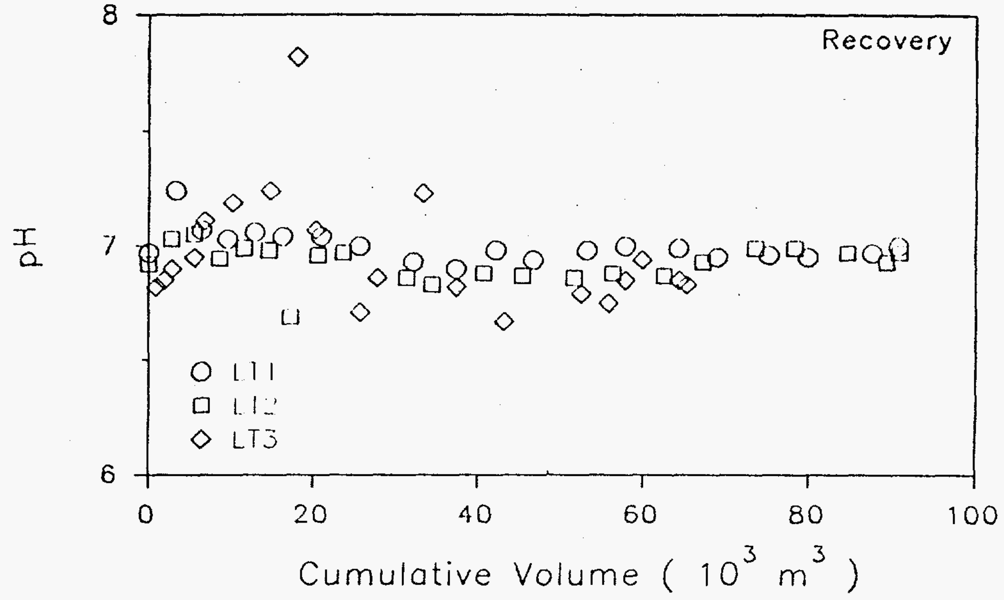


FIGURE 5.24. pH of Recovery Water Samples From Long-Term Cycles (LT1, LT2, and LT3)

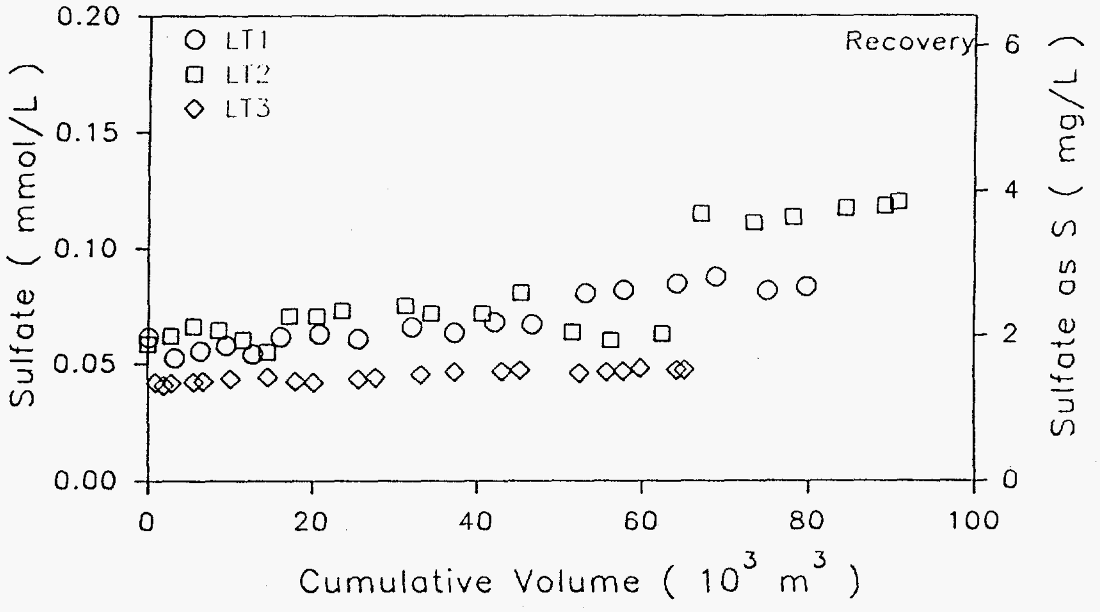


FIGURE 5.25. Sulfate Concentrations of Recovery Water Samples From Long-Term Cycles (LT1, LT2, and LT3)

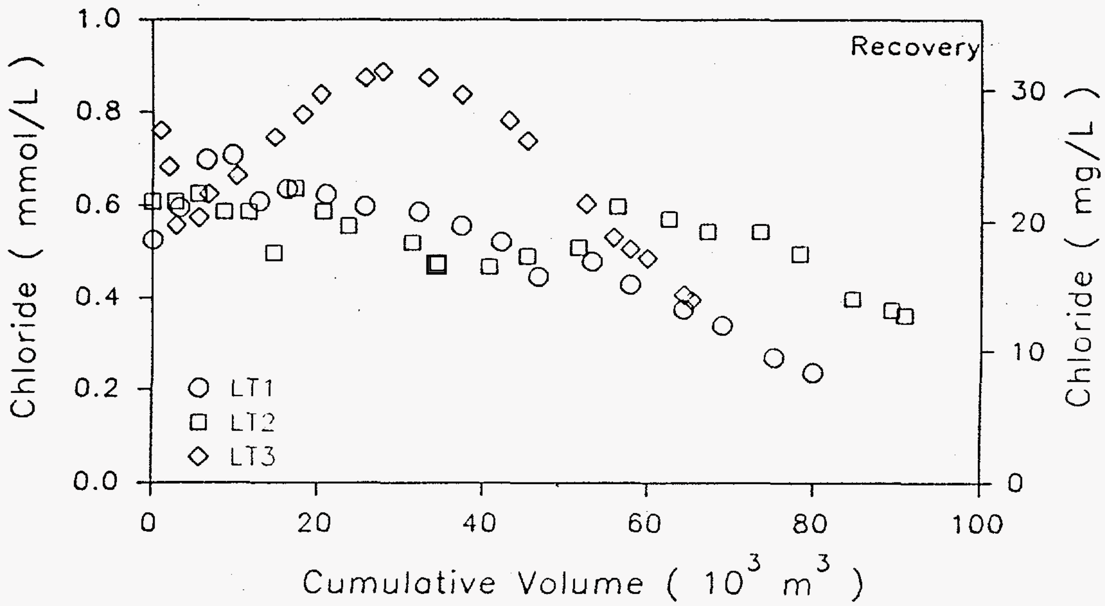


FIGURE 5.26. Chloride Concentrations of Recovery Water Samples From Long-Term Cycles (LT1, LT2, and LT3)

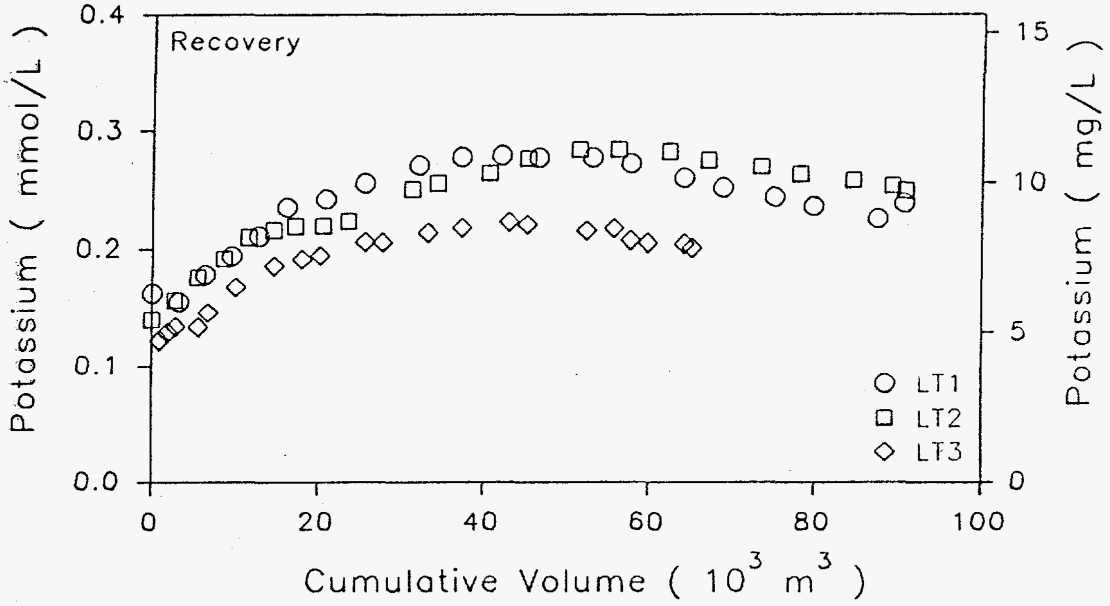


FIGURE 5.27. Potassium Concentrations of Recovery Water Samples From Long-Term Cycles (LT1, LT2, and LT3)

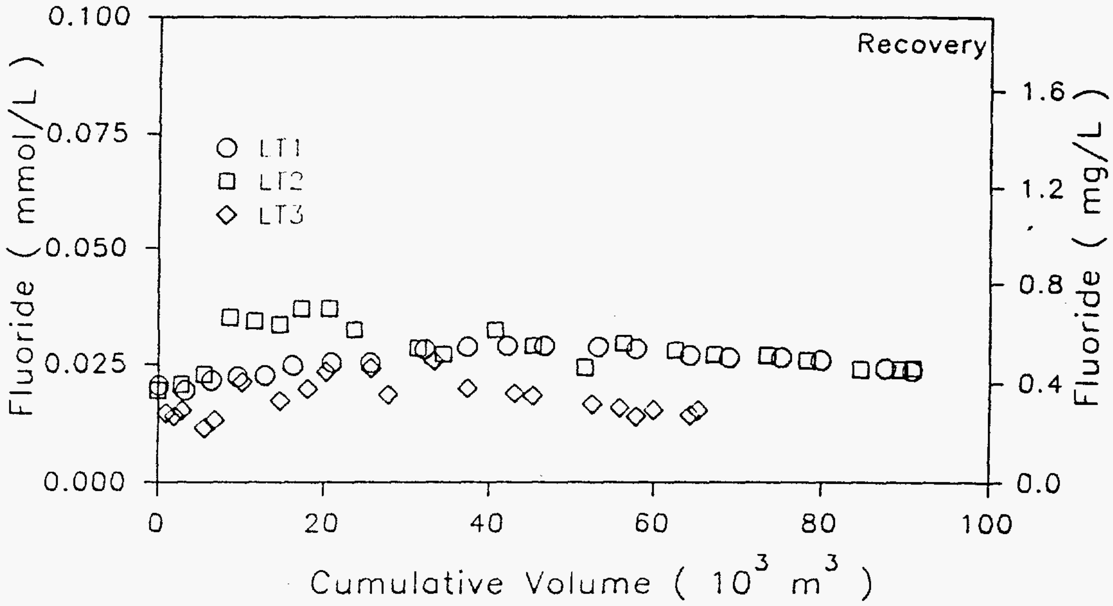


FIGURE 5.28. Fluoride Concentrations of Recovery Water Samples From Long-Term Cycles (LT1, LT2, and LT3)

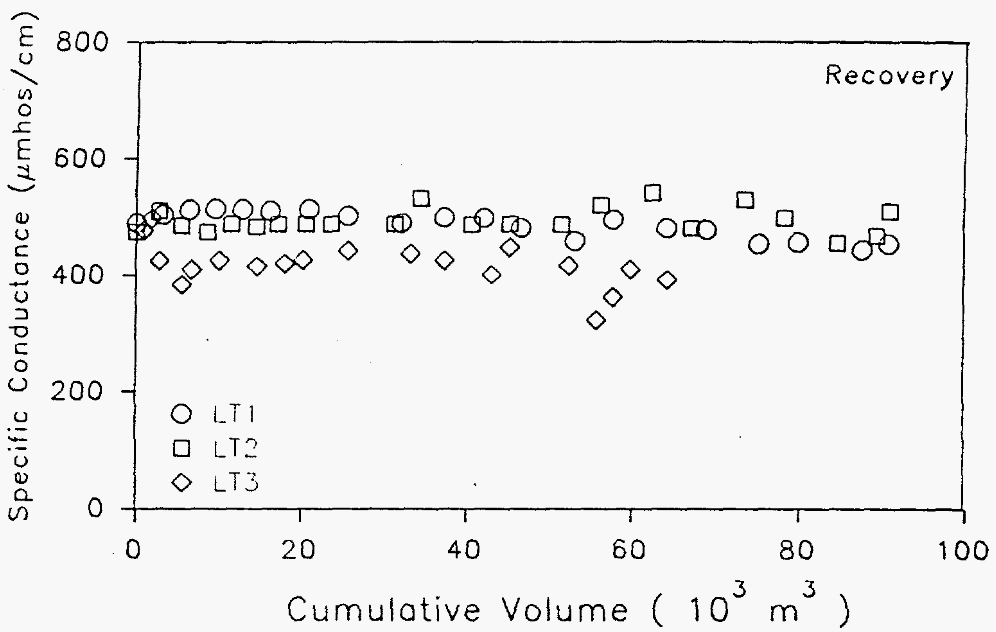


FIGURE 5.29. Specific Conductances of Recovery Water Samples From Long-Term Cycles (LT1, LT2, and LT3)

pumpout of Well A taken place between LT2 and LT3. However, nothing in the LT3 data disagrees with the contention, supported by previous cycles, that additional cycles would continue to heat the rock of the aquifer, maintaining higher ambient temperatures and lowering hardness, thus resulting in lower softening requirements in consecutive cycles. The silica data from LT3 were also consistent with results from the previous cycles. Quartz apparently controls dissolved silica concentrations in both storage and source wells; amorphous silica precipitation (which could plug the source aquifer as the "spent" ATES water cools) therefore poses no danger. Indications are that ATES is a sustainable technology.

5.3 SUMMARY

Ground-water geochemistry was monitored during long-term cycle 3 to evaluate the feasibility of ATES. From the source well, about 64,300 m^3 of ground water was pumped from the FIG aquifer, heated to about 105°C, and injected into the FIG aquifer which consists primarily of quartz sandstone with lesser amounts of dolomite, feldspar, and clay minerals. Softening the ground water prior to heating effectively prevented mineral precipitation in the heat exchanger and injection well.

Mass balances of major ions contained in the ground water at different parts of LT3 clearly showed the effects of ion-exchange water softening. Mass balances also showed the combined effects of mixing of stored water with surrounding "native" ground water and of reaction between the stored water and the aquifer during storage.

Calculations performed for the recovery phases of the three long-term test cycles indicated saturation with respect to quartz, dolomite, and calcite; thus, indicating some mineral dissolution during hot water storage. Loss of sodium during storage is attributed to mixing of ambient ground water with heated ATES water. Predictions (Perlinger et al. 1987) for subsequent test cycles indicated softening requirements would decrease, and less mineral dissolution would be expected to occur during aquifer storage. Test data from both LT2 and LT3 were consistent with this prediction.

5.4 PUMPOUT OF WELL A AND WELL B FOLLOWING LT2

Both source and storage wells were pumped out following the second long-term cycle to bring aquifer and ground-water conditions more in line with those of the ambient aquifer/ground-water system, in compliance with state regulations. Pumpout of the storage well (Well A) was started on October 7, 1987, and completed December 16, after about 120,000 m^3 had been pumped out. Source well (Well B) pumpout began on April 1, 1988 and continued until July 28, 1988; 178,490 m^3 were pumped out. Chemical composition of the water was monitored throughout pumpout of both wells. Data from both the storage well (Figures 5.30 to 5.42) and the source well (Figures 5.43 to 5.54) indicate a steady return toward ambient conditions. The plots were constructed with LT2 recovery concentrations comprising the left half to demonstrate that pumpout concentration trends were merely a continuation of recovery trends. Thus, the abscissa in Well A pumpout plots represents cumulative volume of water pumped from the storage well since the beginning of LT2 recovery. The abscissa in Well B plots represents cumulative volume of water pumped out from the source well following LT2. Negative values on the left half of the plots represent injection of LT2 recovery water into Well B. The left half of Well B plots are thus identical to those of Well A plots, except for abscissa values; the same 93,000 m^3 of water is represented, except that it undergoes a different process in Well B plots (injection into Well B) from that depicted in Well A plots (recovery from Well A).

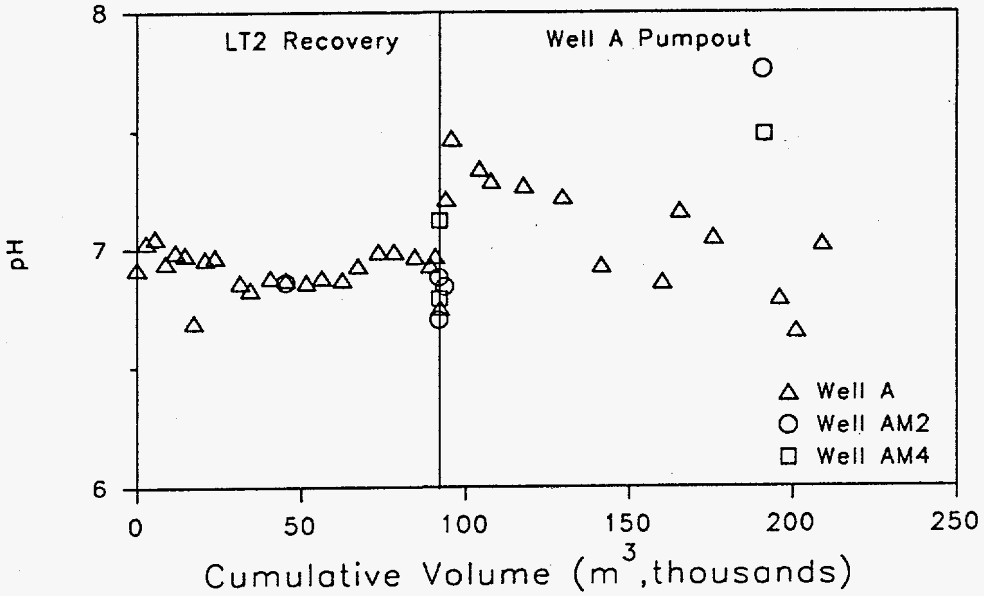


FIGURE 5.30. pH of Water Samples From Long-Term Cycle 2 Recovery and Storage Well Pumpout. Cumulative volume from beginning of recovery.

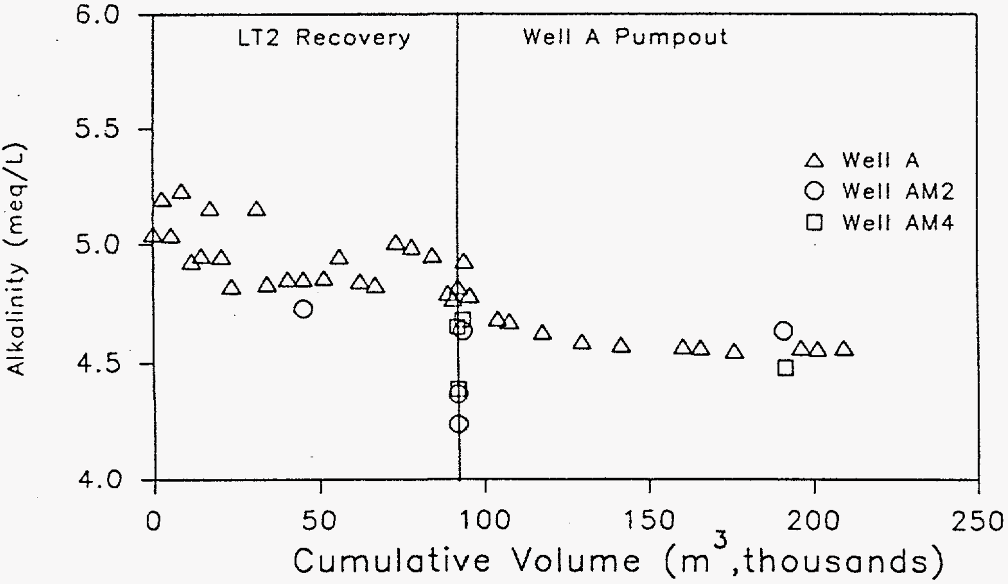


FIGURE 5.31. Alkalinity of Water Samples From Long-Term Cycle 2 Recovery and Storage Well Pumpout. Cumulative volume from beginning of recovery.

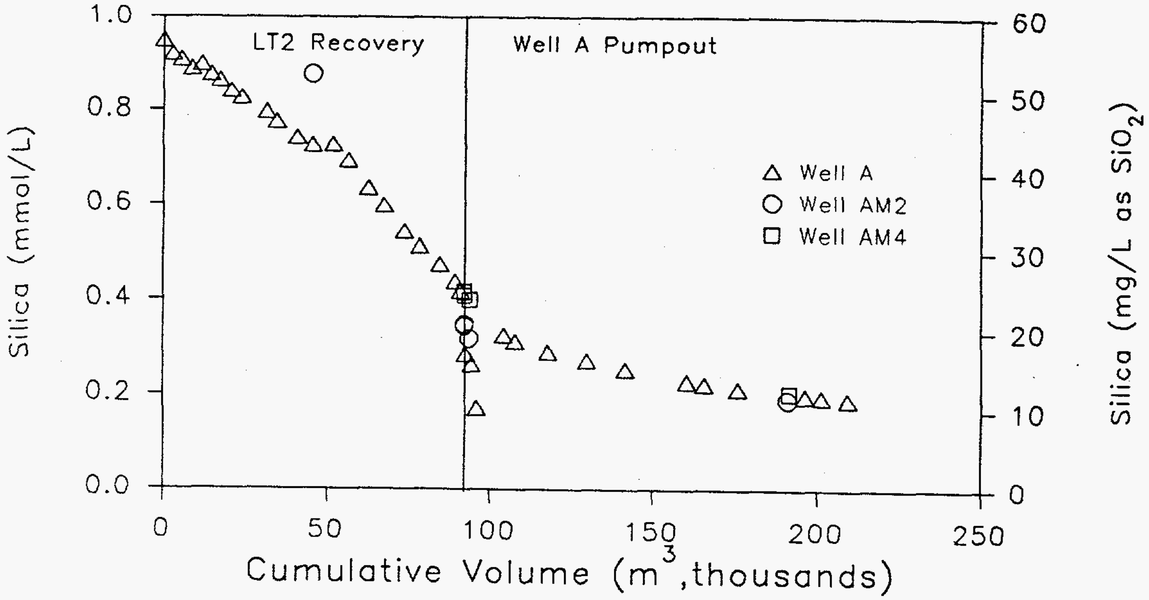


FIGURE 5.32. Silica (as SiO_2) Concentration of Water Samples From Long-Term Cycle 2 Recovery and Storage Well Pumpout. Cumulative volume from beginning of recovery.

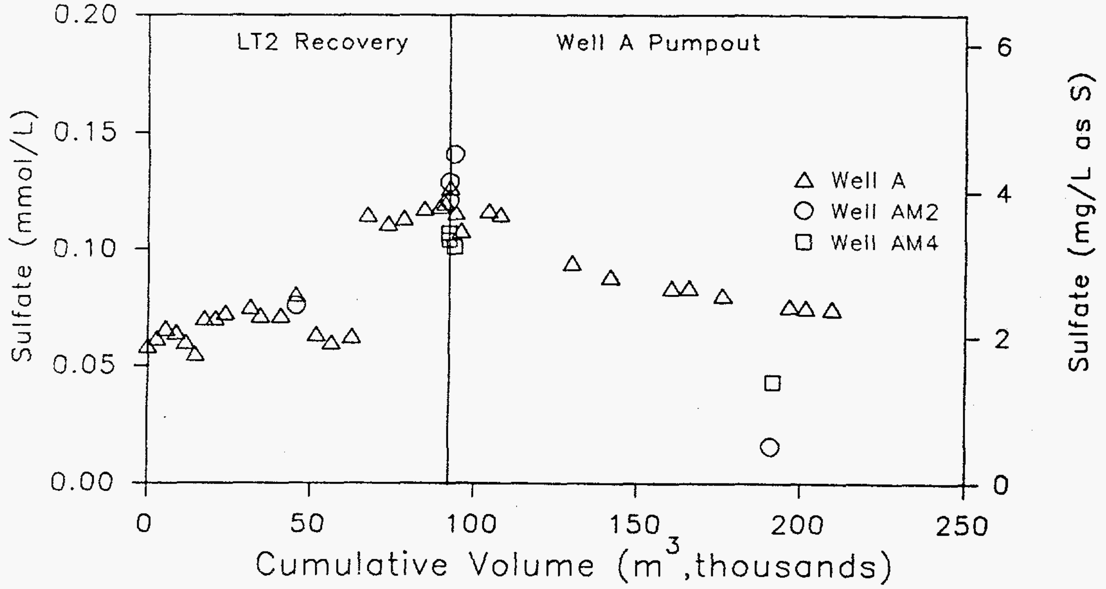


FIGURE 5.33. Sulfate (as S) Concentration of Water Samples From Long-Term Cycle 2 Recovery and Storage Well Pumpout. Cumulative volume from beginning of recovery.

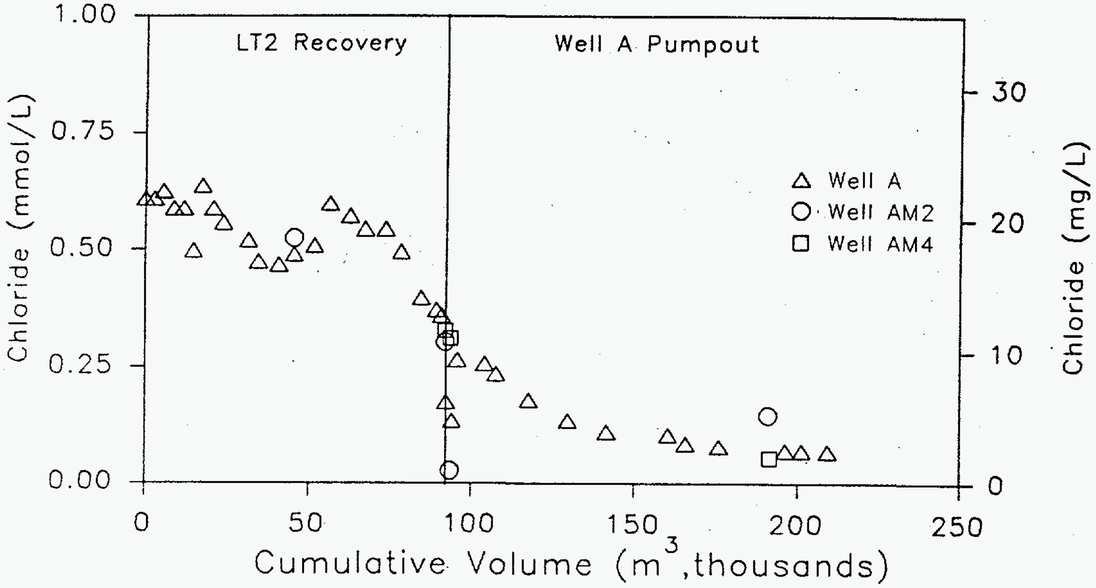


FIGURE 5.34. Chloride Concentration of Water Samples From Long-Term Cycle 2 Recovery and Storage Well Pumpout. Cumulative volume from beginning of recovery.

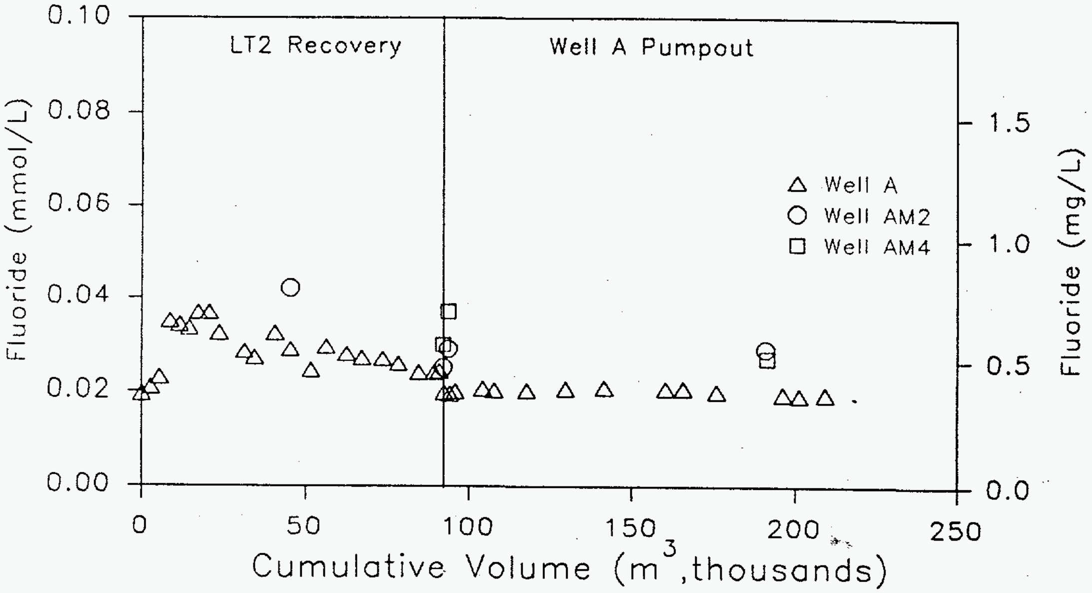


FIGURE 5.35. Fluoride Concentration of Water Samples From Long-Term Cycle 2 Recovery and Storage Well Pumpout. Cumulative volume from beginning of recovery.

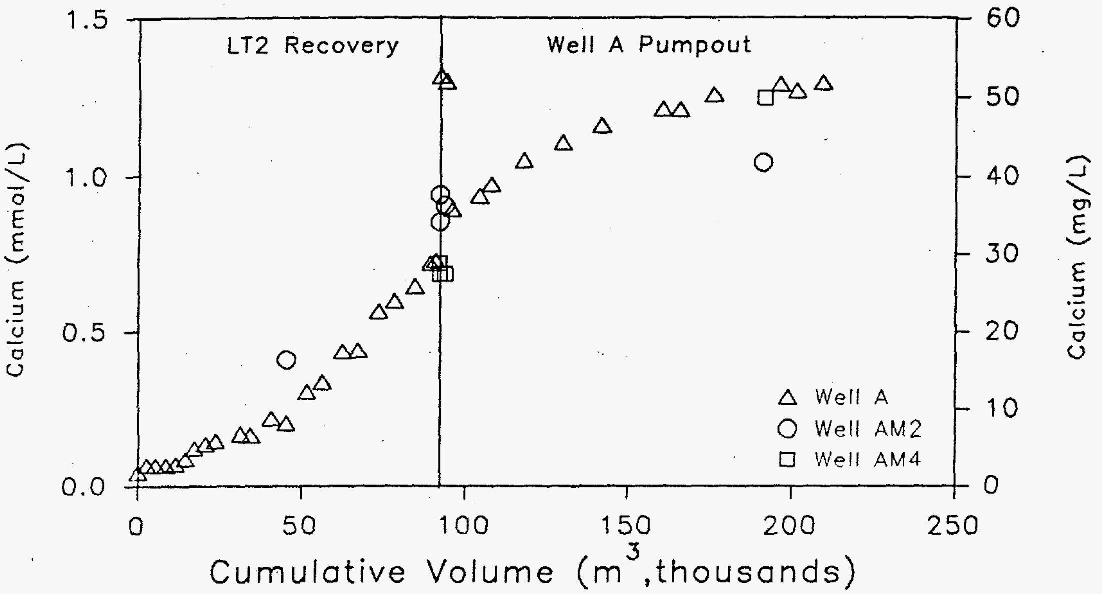


FIGURE 5.36. Calcium Concentration of Water Samples From Long-Term Cycle 2 Recovery and Storage Well Pumpout. Cumulative volume from beginning of recovery.

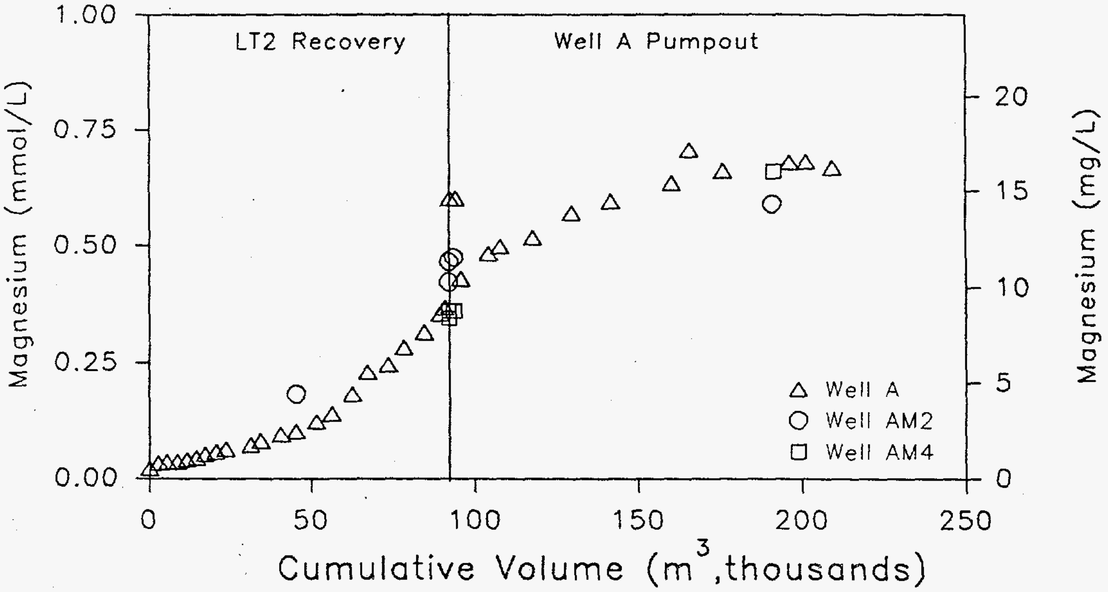


FIGURE 5.37. Magnesium Concentration of Water Samples From Long-Term Cycle 2 Recovery and Storage Well Pumpout. Cumulative volume from beginning of recovery.

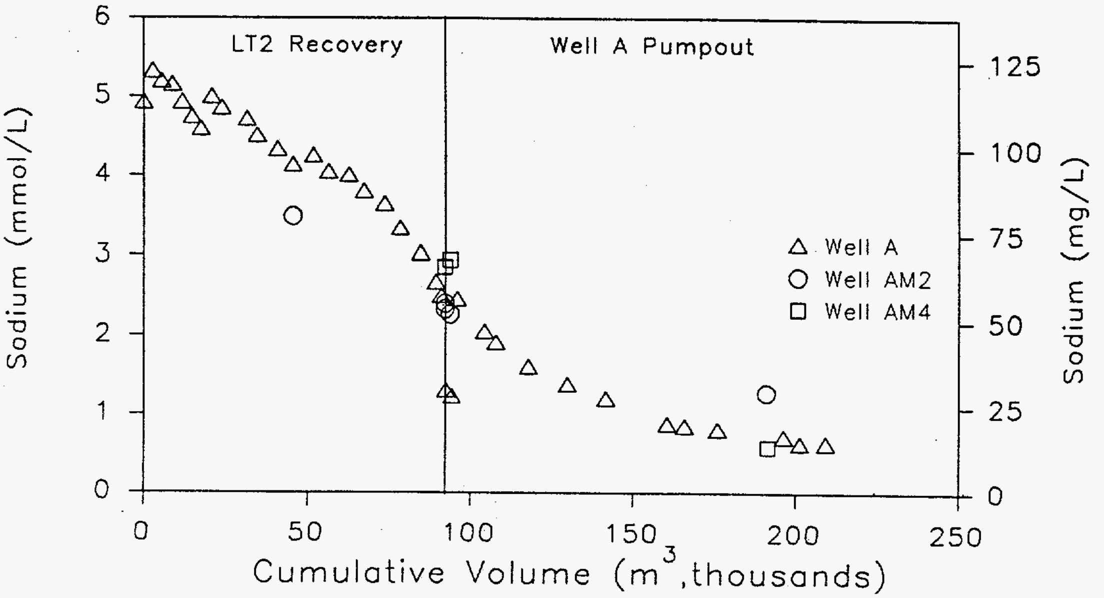


FIGURE 5.38. Sodium Concentration of Water Samples From Long-Term Cycle 2 Recovery and Storage Well Pumpout. Cumulative volume from beginning of recovery.

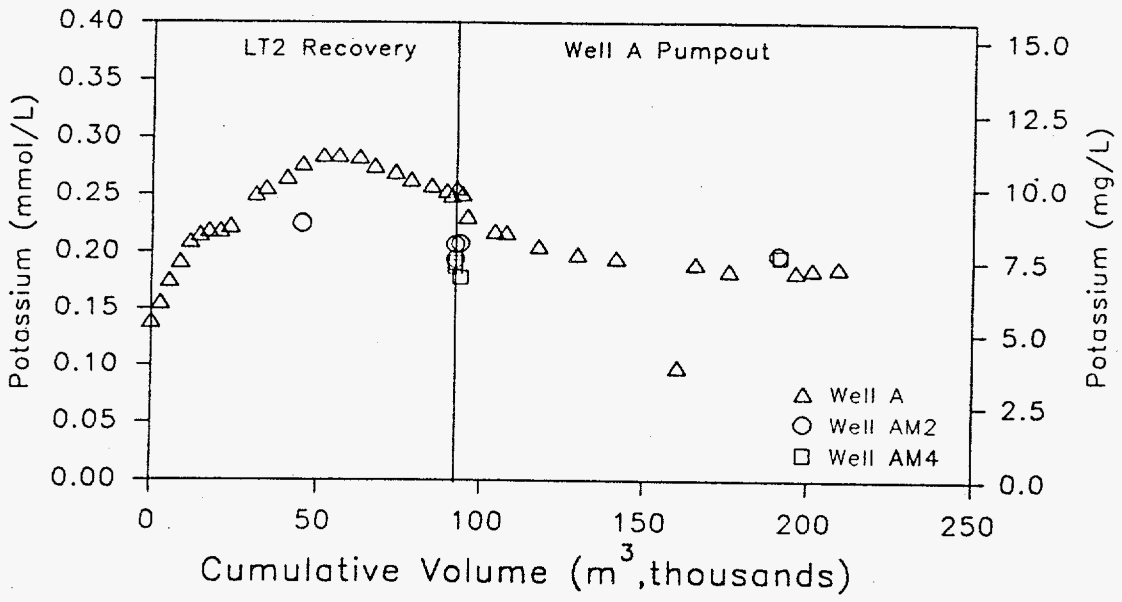


FIGURE 5.39. Potassium Concentration of Water Samples From Long-Term Cycle 2 Recovery and Storage Well Pumpout. Cumulative volume from beginning of recovery.

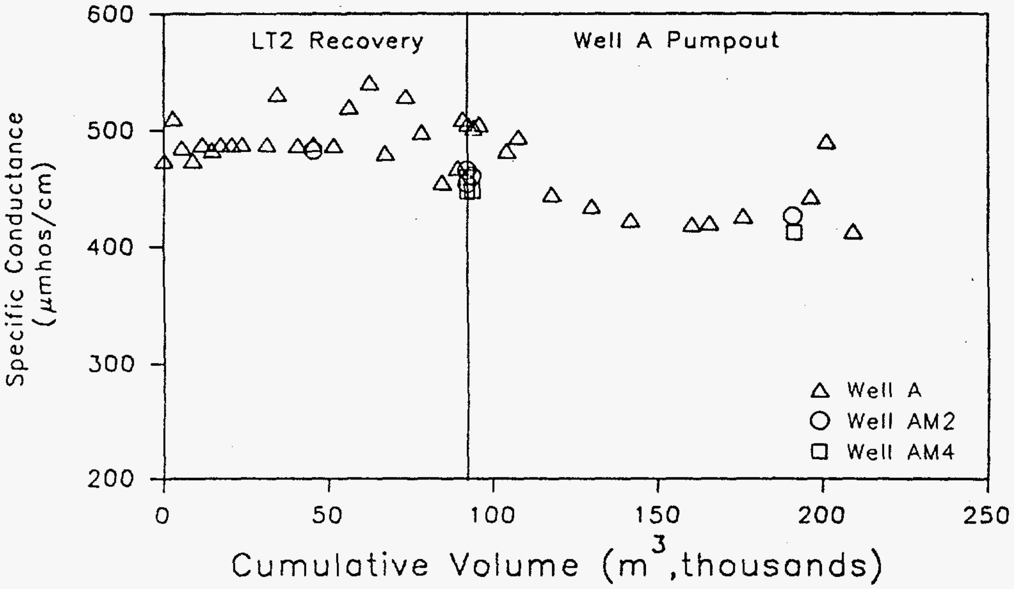


FIGURE 5.40. Specific Conductance of Water Samples From Long-Term Cycle 2 Recovery and Storage Well Pumpout. Cumulative volume from beginning of recovery.

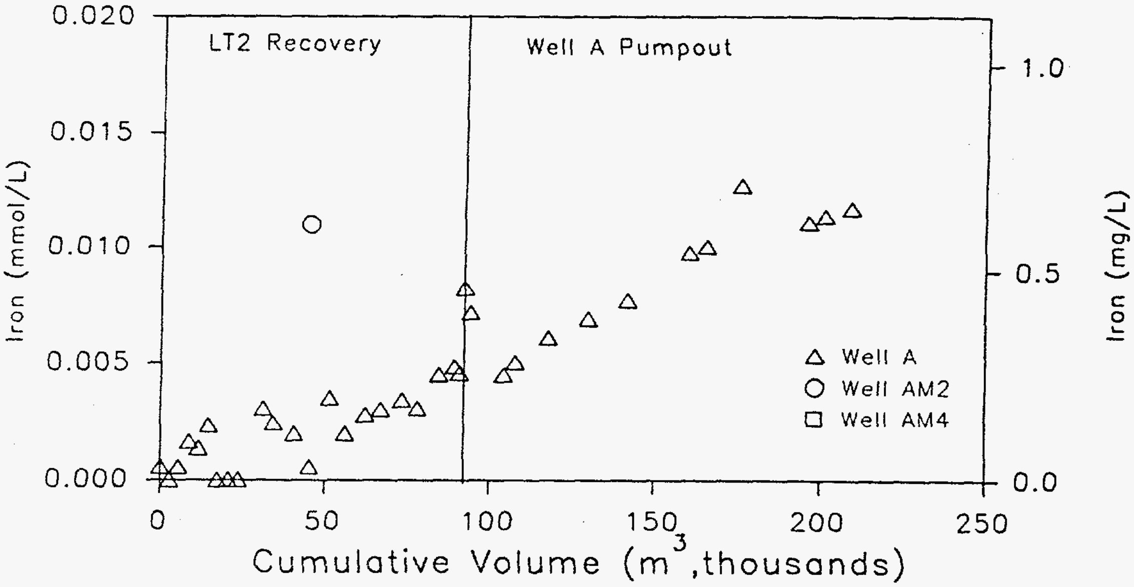


FIGURE 5.41. Iron Concentration of Water Samples From Long-Term Cycle 2 Recovery and Storage Well Pumpout. Cumulative volume from beginning of recovery.

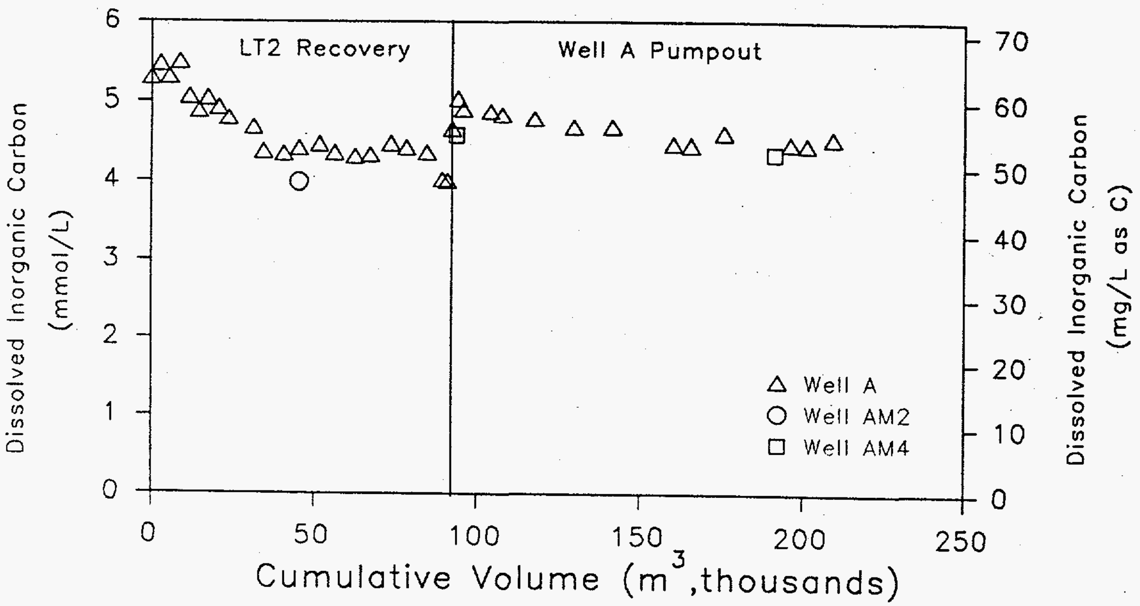


FIGURE 5.42. Dissolved Inorganic Carbon Content of Water Samples From Long-Term Cycle 2 Recovery and Storage Well Pumpout. Cumulative volume from beginning of recovery.

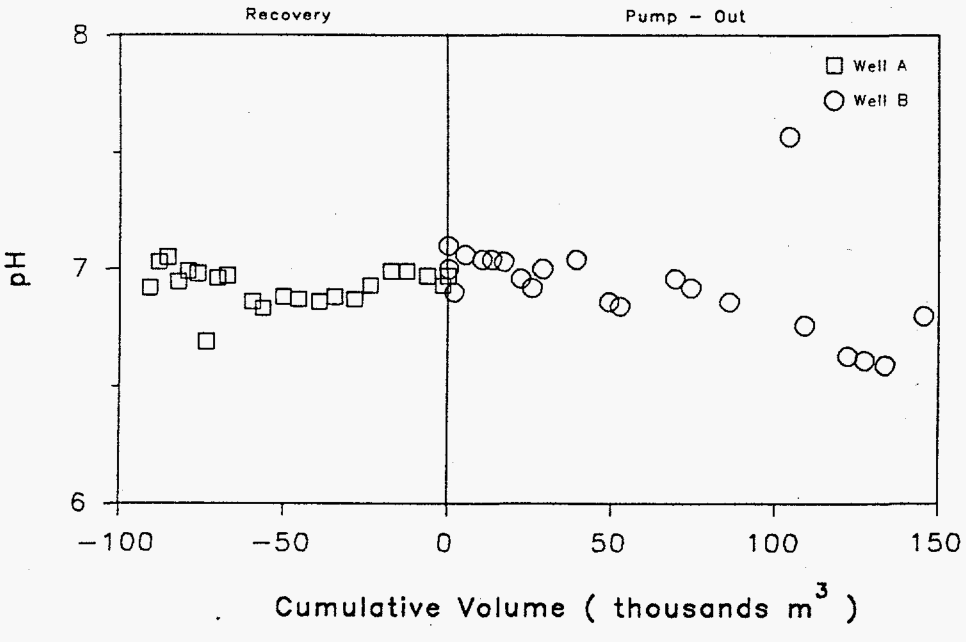


FIGURE 5.43. pH of Water Samples From Long-Term Cycle 2 Recovery and Source Well Pumpout. Cumulative volume from beginning of recovery.

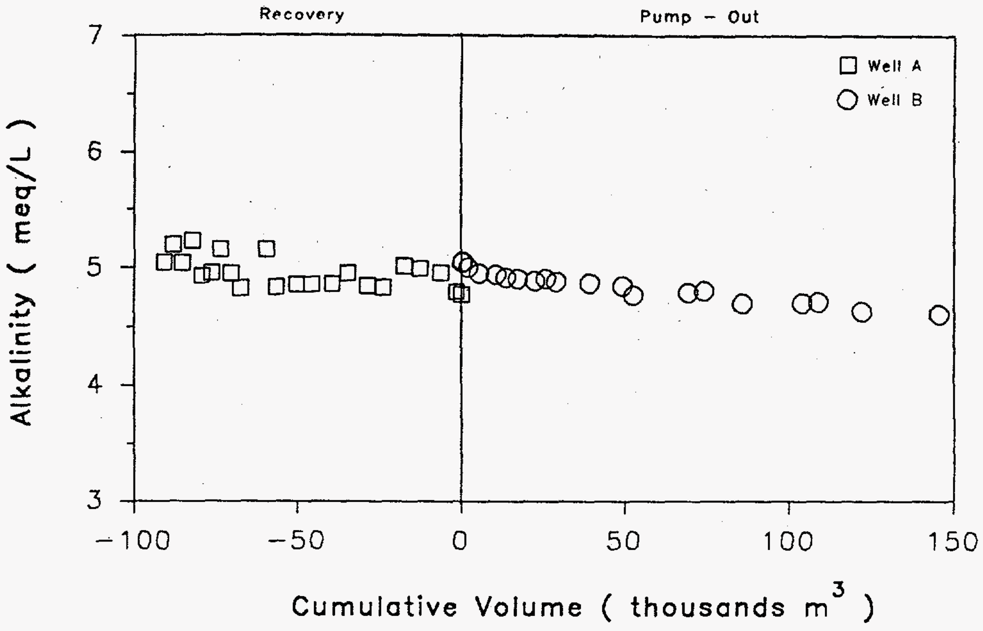


FIGURE 5.44. Alkalinity of Water Samples From Long-Term Cycle 2 Recovery and Source Well Pumpout. Cumulative volume from beginning of recovery.

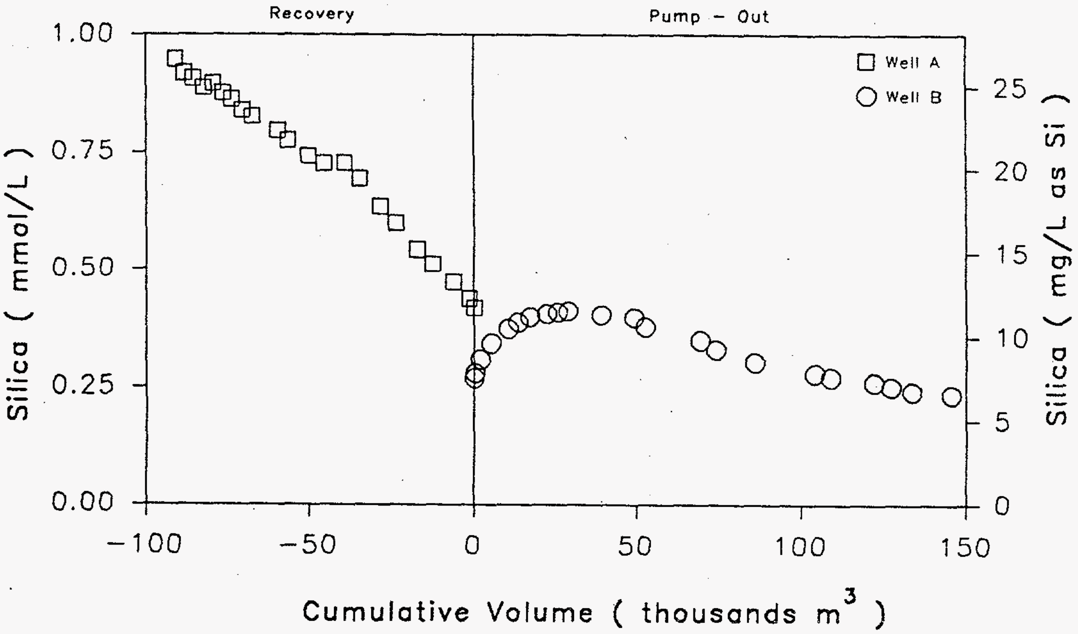


FIGURE 5.45. Silica (as Si) Concentration of Water Samples From Long-Term Cycle 2 Recovery and Source Well Pumpout. Cumulative volume from beginning of recovery.

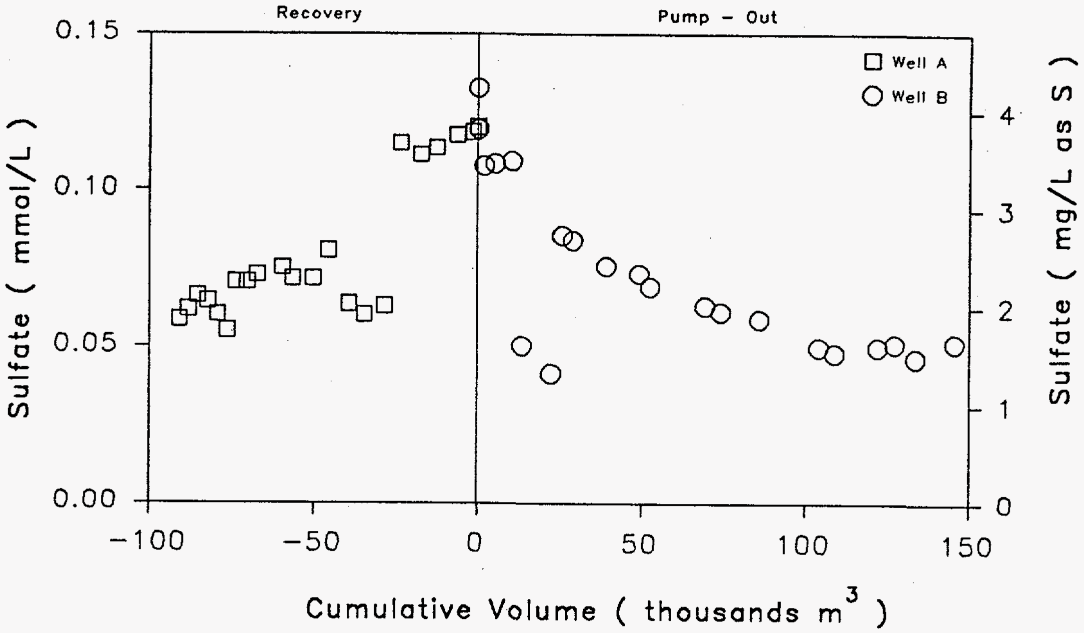


FIGURE 5.46. Sulfate (as S) Concentration of Water Samples From Long-Term Cycle 2 Recovery and Source Well Pumpout. Cumulative volume from beginning of recovery.

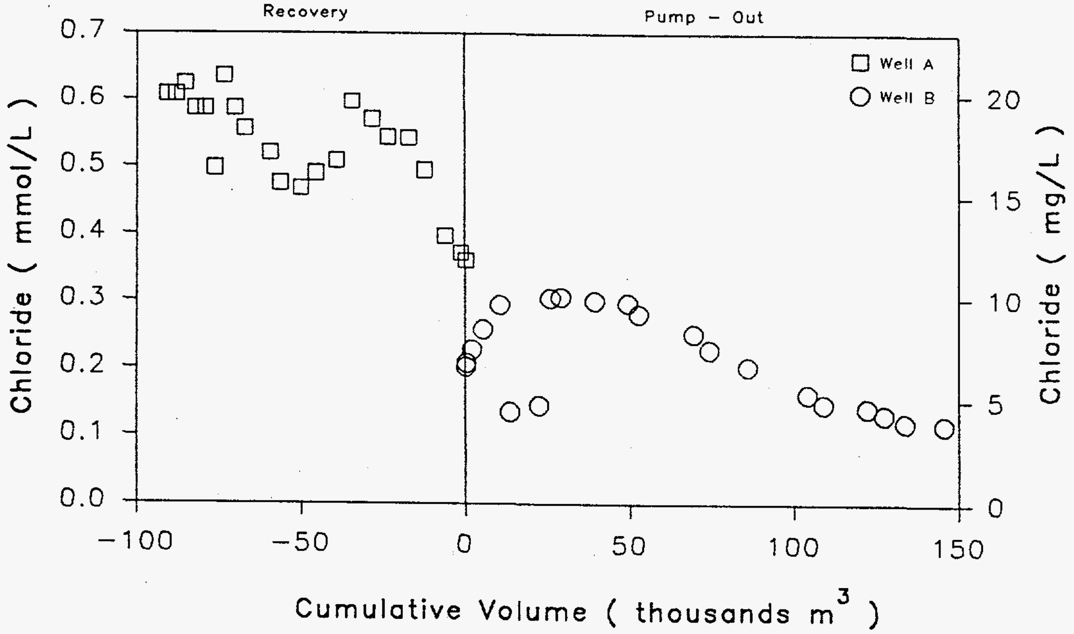


FIGURE 5.47. Chloride Concentration of Water Samples From Long-Term Cycle 2 Recovery and Source Well Pumpout. Cumulative volume from beginning of recovery.

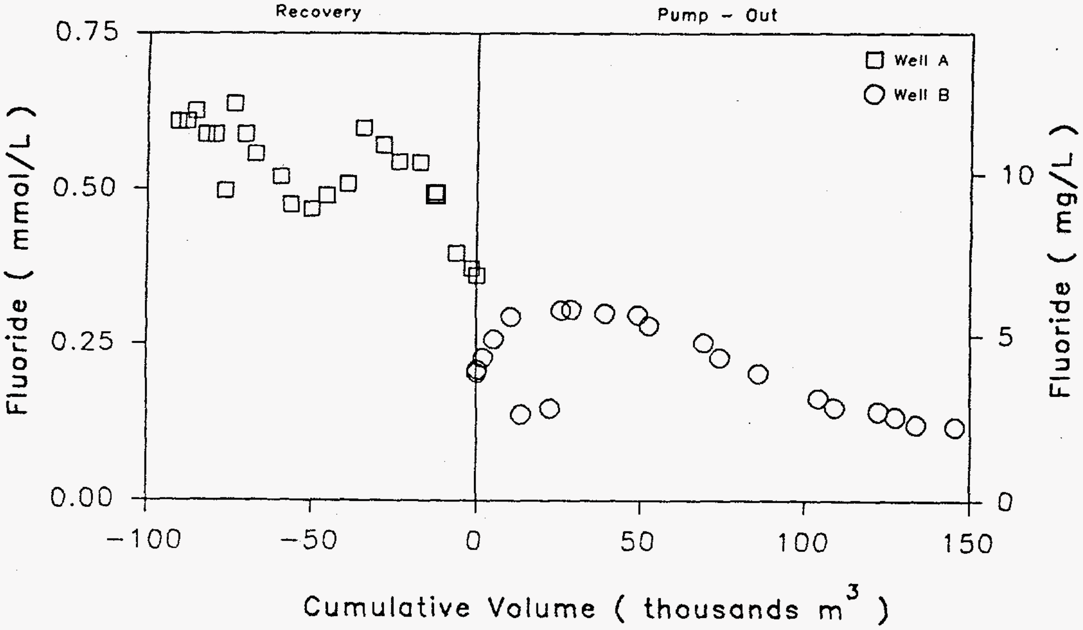


FIGURE 5.48. Fluoride Concentration of Water Samples From Long-Term Cycle 2 Recovery and Source Well Pumpout. Cumulative volume from beginning of recovery.

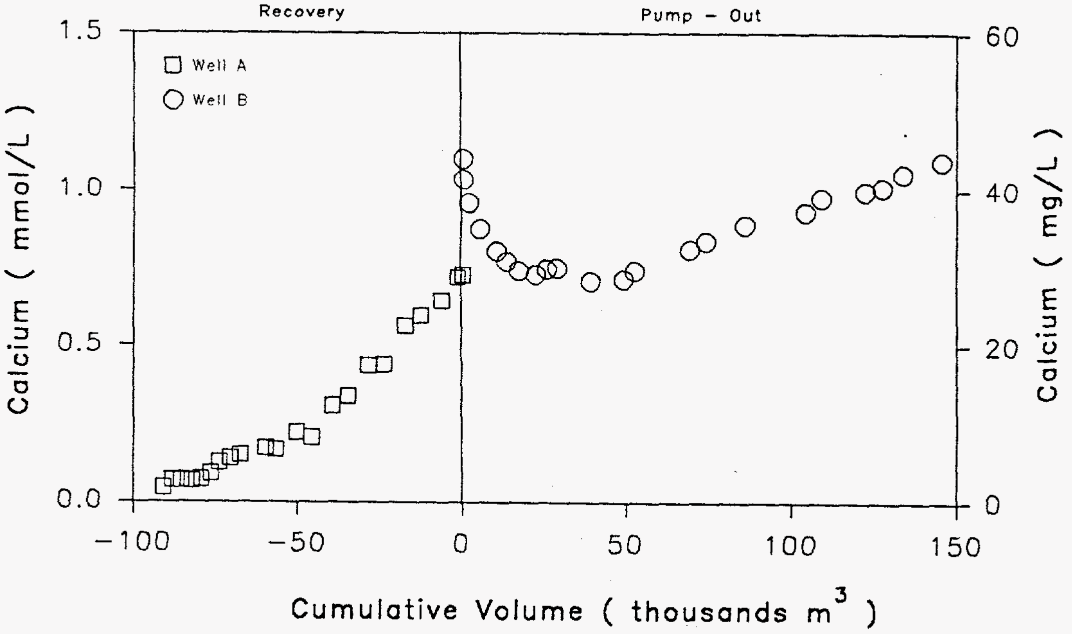


FIGURE 5.49. Calcium Concentration of Water Samples From Long-Term Cycle 2 Recovery and Source Well Pumpout. Cumulative volume from beginning of recovery.

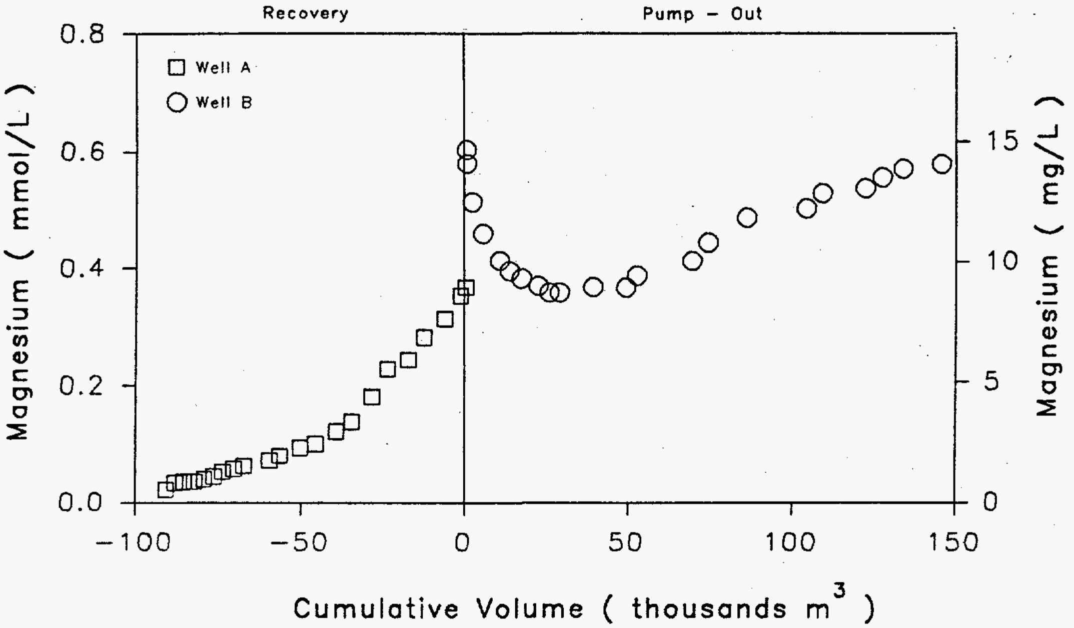


FIGURE 5.50. Magnesium Concentration of Water Samples From Long-Term Cycle 2 Recovery and Source Well Pumpout. Cumulative volume from beginning of recovery.

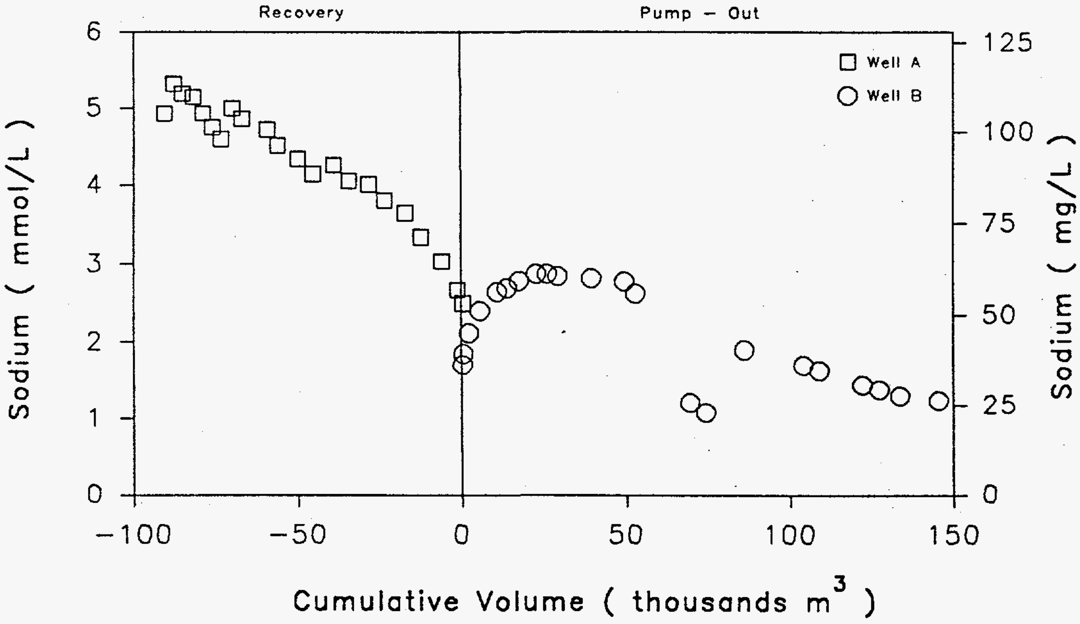


FIGURE 5.51. Sodium Concentration of Water Samples From Long-Term Cycle 2 Recovery and Source Well Pumpout. Cumulative volume from beginning of recovery.

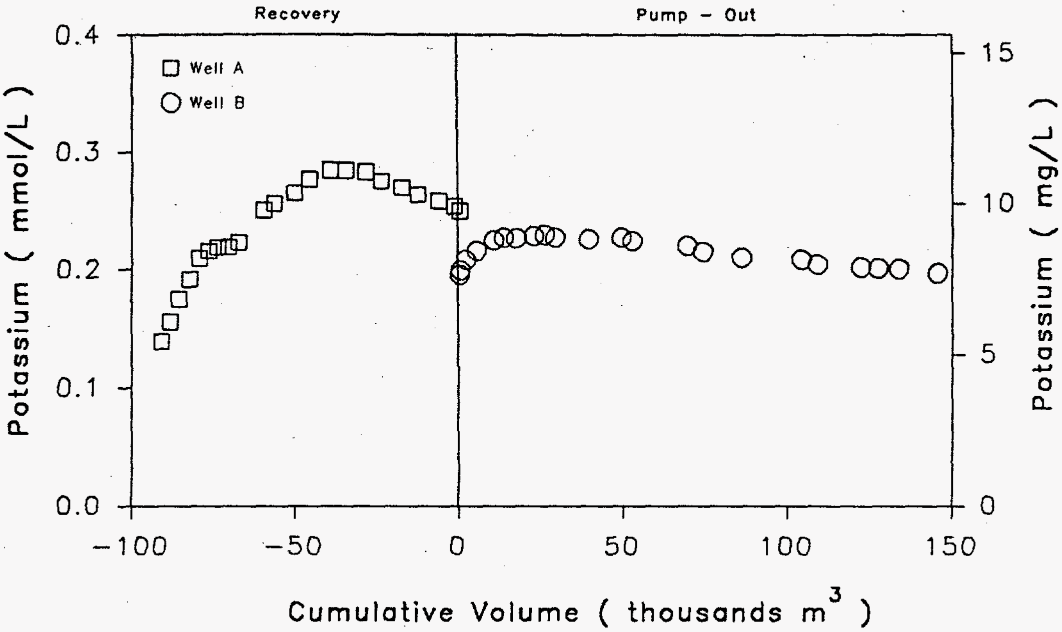


FIGURE 5.52. Potassium Concentration of Water Samples From Long-Term Cycle 2 Recovery and Source Well Pumpout. Cumulative volume from beginning of recovery.

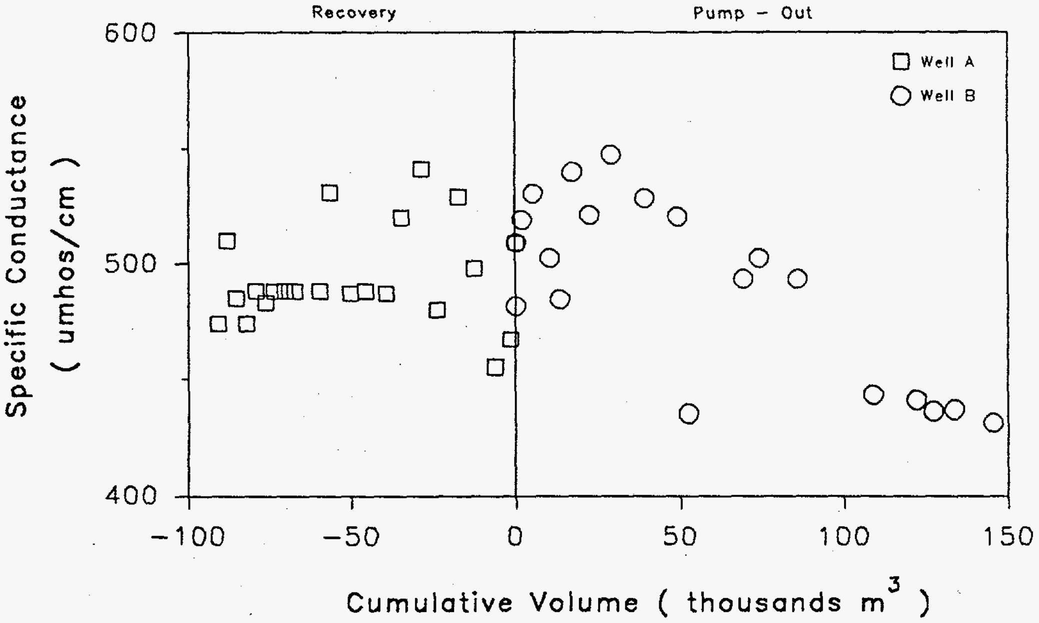


FIGURE 5.53. Specific Conductance of Water Samples From Long-Term Cycle 2 Recovery and Source Well Pumpout. Cumulative volume from beginning of recovery.

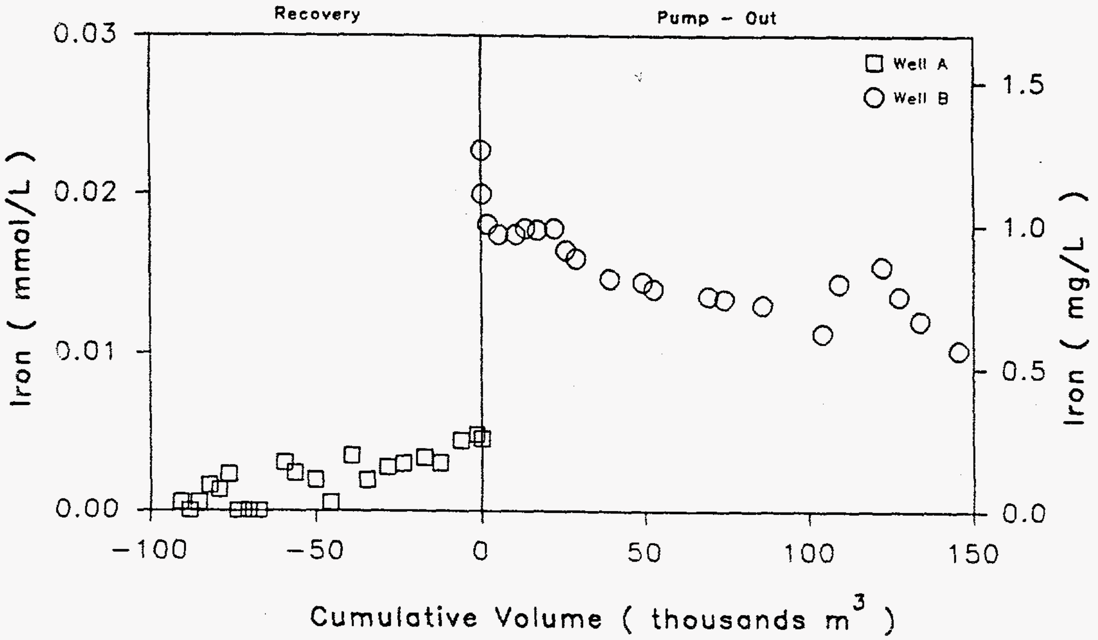


FIGURE 5.54. Iron Concentration of Water Samples From Long-Term Cycle 2 Recovery and Source Well Pumpout. Cumulative volume from beginning of recovery.

6.0 REVIEW AND DISCUSSION

The third long-term ATES cycle (LT3) was conducted between October 1989 and March 1990 to demonstrate that high-temperature ATES could meet the requirements of a real heating load. For LT3, the U of M ATES FTF was connected to the nearby ASVM building. The source and storage wells were modified so only the Ironton-Galesville part of the FIG aquifer was used. Modification of the wells resulted in a single storage zone having relatively simple and consistent mineralogy and geometry to simplify water chemistry comparisons and modeling, and minimize heat losses. The campus steam plant supplied the heat stored during LT3.

6.1 PERMITTING ISSUES

As discussed in Section 2, permitting is a vital issue. ATES requires returning the heated (or cooled) ground water to the aquifer following the addition (or subtraction) of thermal energy for storage. This storing of water in the natural container, the aquifer, requires a significant number of permits, or variances. Though ATES is a nearly nonconsumptive use of ground water, the perception by some is that water used by an ATES system is lost as a resource. This perception must be recognized as a strong influence on the permitting process. Use by an ATES system changes the temperature of the ground water which may affect some potential uses of that ground water. Where the temperature change would cause serious scaling problems, as at the U of M ATES FTF, standard water softening (or other treatment) can effectively prevent the operational problems and maintain high quality ground water. Changes in temperature and water chemistry must be predictable and monitored. Most uses of the water remain possible following use in an ATES system.

In Minnesota, the specific prohibition of injection or reinjection of water into an aquifer makes establishment of ATES on a continuing basis difficult. Protecting ground water from the introduction of contaminants is the rationale for prohibiting injection wells in Minnesota. Essentially all ground water in Minnesota is potable; protection of the ground water to maintain that status is extremely important. Monitoring of the chemistry of the injected and recovered water was critical to the project. The changes in water chemistry measured during the project did not affect the potability of the FIG ground water. The temperature changes temporarily affected the potential uses of the FIG ground water.

Conflicting water use is a significant issue as well. The U of M ATES FTF used the Franconia-Ironton-Galesville aquifer, which is not used as a water source in the vicinity of the site. This was a significant factor during permitting.

The volume of the aquifer affected and the volume of ground water affected by the ATES cycles is also a permitting issue. Knowledge of the aquifer's characteristics and hydrologic setting, so that simulations of the effect can reasonably be expected to approximate the actual conditions, would be especially important in development for an ongoing ATES system. The cycles conducted at this site were, in part, to provide field data and results that could be compared against modeled results.

The fact that the source and supply wells could be used to pump out affected ground water following the test cycles was a significant factor in the permitting process. This ability to pump ground water from the affected aquifer until the water withdrawn approached ambient conditions had been demonstrated following LT2.

6.2 LOAD SELECTION

The ATES FTF supplied heat to a relatively constant load, the ASVM reheat system during LT3. No additional controls were required in the building. The only requirement was adjusting some alarm points as the ATES supplied water changed temperature.

Although the investigation of the optimum utilization of heat in the University of Minnesota ATES system proved difficult, it has suggested some general design guidelines for systems intended for commercial operation. Considerations for an ATES system similar to that at the University of Minnesota FTF, which is designed for constant-flow operation, are:

1. A high-temperature ATES system is simpler to operate at a relatively constant pumping rate.
2. An ATES system has a falling energy recovery rate during the recovery period when the pumping rate is constant.

3. An ATES system has both a minimum and maximum pumping rate depending on wellhead arrangements (drop pipes, foot valves), water levels, and pumping head.

The above characteristics imply that an ideal use of such an ATES system may not be as a system designed to operate to meet peak loads or rapidly changing load variations. A preferable scenario is the use of the ATES system at a constant pumping rate throughout the period when such operation would allow full utilization of the recovered heat, i.e., as a base load. The ATES system would still be used to reduce peak load demand on the rest of the energy plant, and load demand matching is left to systems that can already accommodate this requirement. If a larger peak load reduction is desired, a larger ATES system with a dual-speed pump could greatly improve load matching, even if switched on a calendar schedule (see Figure 2.6).

Systems with variable-flow rates on the aquifer side could be used to provide nearly constant energy output rates over a considerable period of time or to meet changing output needs for short-term needs. The geohydrologic setting has a significant effect upon possible variations. The U of M ATES FTF is located where static water levels are quite deep, approximately 60 m. In order to maintain full piping, this places significant constraints upon operating parameters.

6.3 CYCLE OPERATIONS

Operations during heat recovery with the ASVM building's reheat system were troublefree and required only minor changes to the building system's operation. Integration into more of the ASVM (or another) building's mechanical systems or use of a variable-speed pump would have resulted in significantly increasing the proportion of energy used during heat recovery. The costs to connect other ASVM building systems or for a variable-speed pump were beyond the budget for this experimental cycle.

Water chemistry is critical to the operation of the University of Minnesota FTF, or any ATES facility. The FTF ion-exchange water softener reduced hardness of the source water from 174 mg/L as $CaCO_3$ to <5 mg/L as $CaCO_3$ prior to heating, allowing successful operation. This changed the ground-water composition from a calcium-magnesium bicarbonate ground water to being a sodium bicarbonate ground water for heating and injection. During storage in the aquifer, the heated, stored ground water changed to a calcium-sodium-magnesium bicarbonate ground water. Repeated cycles, without pumpout of a significant amount of heat or water, would require significantly less softening with time. The primary controlling factor is water temperature.

Theoretically, silica precipitation in the vicinity of the cool well is a problem. However, previous calculations and experience at this site suggest that silica precipitation problems are not a problem for decades of operation (Holm et al. 1987; Hoyer et al. 1991a, 1991b; Perlinger et al. 1987; Walton et al. 1991).

During all of the cycles, the water recovered from aquifer storage was approximately saturated with respect to calcite and quartz at all times.

6.4 EFFECTS ON THE AQUIFER

As stated before, temperature change affects the equilibrium of the ground-water chemistry. The high temperatures of these experiments radically reduced the solubility of calcium and magnesium carbonate and significantly increased the solubility of silica in the water. Water recovered from storage was essentially saturated with respect to calcium, magnesium, and silica at all temperatures; in complete agreement with previous cycles.

The softening of the water prior to heating prevented accumulation of $CaCO_3$ (aragonite) scale in the heat exchanger, pipes, wells, and aquifer. However, the ground water did pick up calcium and magnesium during aquifer storage from the native ground water and/or the aquifer. Concentrations at all temperatures were very close to equilibrium with respect to calcite or dolomite. Results from LT3 agreed with work done during previous cycles (Holm et al. 1987; Perlinger et al. 1987). The source of the increased calcium and magnesium is likely largely native ground water .

The ion-exchange water softener increased sodium concentrations in injected waters to approximately 100 to 120 mg/L. Not all of the sodium was recovered during heat recovery. During LT3, approximately 90 percent of the added sodium was recovered. Dispersion can account for this loss. No clear reaction should significantly reduce sodium concentrations. Ion concentrations are not high enough to strongly favor ion exchange with clays or feldspars, to replace potassium with sodium. Further research in this area of water-rock interaction at changed conditions is definitely required.

Modification of the wells so that only the Ironton-Galesville portion of the FIG aquifer was used may have improved the thermal recovery ratio. Hydraulic responses to the injection and recovery indicated that the Ironton-Galesville portion of the aquifer is well-separated from the upper Franconia portion of the FIG aquifer. The responses confirmed that before the wells were modified, there had been flow from the upper Franconia well screen to the Ironton-Galesville well screen in the storage and injection wells.

Thermal effects are very local. If continued, the aquifer in the vicinity of the storage and source well would become significantly warmed. The area of warming would increase with repeated cycles because of conduction into surrounding rock and convection at the fringes of the thermal or water fronts. Eventually a condition approaching steady-state would be reached with a zone of appreciable influence and a zone of annual variations within that zone based upon the storage cycles. The only migration of thermal and water chemistry effects would be from regional flow of the ground water or head-driven flow through the low-permeability confining beds.

Continued research is necessary for answering some of the questions about the actual processes involved. A natural successor to these cycles would be a core hole to evaluate the changes, if any, which have taken place in the FIG aquifer. The fact that the cycles introduced a known amount of heat, transported by ground water of known composition, provide a recent history that is known, together with the core holes taken before any ATES cycles were conducted, would provide an excellent basis for comparison. Did ion-exchange take place to a significant extent? Did kaolinitization provide the increased ions? Were porosity and permeability changed or affected to a significant extent?

6.4 FUTURE POTENTIAL OF ATES AT THE UNIVERSITY OF MINNESOTA

The future use of ATES at the St. Paul campus of the University of Minnesota is not likely. Preliminary economic analysis indicates that though

ATES could be competitive with conventional heating/cooling technology at the University, it would require some major changes to the campus system that the University is not interested in pursuing at this time.

Preliminary economic calculations based on repeated cycles for a system in which the recovered-heated water could be used more effectively in a building have shown that a system could be cost-effective ustilizing waste heat from a district cooling operation. Such a system is planned in the long-term for the St. Paul campus, but not in the near future.

Committing to ATES on the campus would entail significant risk in obtaining operating permits for the technology. Also, the University is effectively divesting itself of the operation of the heating/cooling system on the campuses. This policy has been adopted over the past few years. At present, in 1993, the University contracts with a private company to provide the steam for the campus. The reasons behind the policy have more to do with policies regarding the organizational structure of the University and costs needed for updating the heating/cooling systems than with issues regarding economy of operation.

7.0 CONCLUSIONS

Results from LT3 are in agreement with previous cycles. Aquifer characteristics were not observed to have been adversely affected by the cycles. High-temperature seasonal aquifer thermal energy storage is a feasible storage technology and can be successfully interfaced with existing building systems.

High-temperature storage and recovery of water in an ATES system has been successfully demonstrated during the seven ATES cycles conducted at the University of Minnesota ATES FTF (Appendix G). The third long-term cycle demonstrated that ATES can meet a real heating load. Review of possible heating loads to tie into the FTF suggested that an optimal system would require variable-speed pumps if tied into a single system, as was done, or a cascading system to utilize most of the recovered heat during recovery. Short system turnaround time enables short-term heat storage/recovery cycles to be superposed on a long-term storage cycle.

LT3 did demonstrate that ATES in a confined aquifer at temperatures above 100°C can be effectively tied into a conventional building heating system. Although approximately 67 percent of the energy added and stored was recovered from the aquifer, and 33 percent of the energy added was delivered to the ASVM building at usable temperatures, only 10 percent of the total energy added to the water was used in the building. Approximately 50 percent of the energy added above the usable minimum temperature of 49°C was delivered to the ASVM building. The delivery of heat from the storage system to the targeted use is reasonably predictable if the parameters of the aquifer and operating scheme are well characterized. The system as operated for this cycle would not be cost-effective. However, this applied test cycle showed that no special problems were encountered. With repeated cycles and an appropriate building interface, our preliminary calculations show that an economic system is possible.

Ion-exchange water softening was effective in preventing scaling in the heat exchangers and the storage well. Chemistry of the ground water is critical to the operation of an ATES system.

Primary conclusions from LT3 are:

- Permit approval for ATES systems is a major hurdle for the potential commercial operation of such systems. At present, Minnesota has more restrictive ground-water controls than many states, but with the growing national concern over ground-water pollution, restrictive regulations dealing with reinjection of water are expected to grow. Even benign, localized, and extensively monitored systems, such as the University of Minnesota ATES FTF, are affected by these concerns. Characterization of the aquifer and modeling of ATES effects and extent are, and will be, very important in meeting such concerns.

- The characteristic curves for available thermal loads and desired ATES operation should be compared carefully when selecting sites for high-temperature ATES applications. ATES systems similar to the University of Minnesota ATES FTF are best suited to provide a base load thermal input during the winter rather than to match the varying total thermal load. This has a significant impact on the thermal sizing of the ATES system.

- Simple operation (constant flow rate, always on) of an ATES system does not optimize the useful energy recovered unless cascading loads can be used to extract as much energy as possible from the ground water before returning it to the aquifer. A system design that incorporates cascading loads, intermittent operation, or variable flow rate operation would help to optimize energy recovery.

- Ion-exchange water softening can effectively prevent scaling problems in the system piping and storage well. Ground-water chemistry is critical to operation of an ATES system. Chemistry changes can be predicted reasonably well with equilibrium modeling. The hot water recovered from storage picked up calcium, magnesium, and silica, and lost some of the added sodium. The recovered water was very close to equilibrium with respect to calcite, dolomite, and quartz at all temperatures. The potential problem of silica scaling at the cool well of an ATES doublet, has, as yet, not been documented.

- Further research into water-rock interactions is necessary to determine and understand the various processes taking place in the aquifer during storage.
- Conventional building heating (and by extension, cooling) systems can be effectively hooked up to an ATES system, as was done for LT3. The University of Minnesota ATES FTF is best suited to meeting a base load.

8.0 REFERENCES

American Society for Testing and Materials. 1984. "Standard Test Method for Anions in Water by Ion Chromatography." Annual Book of ASTM Methods, v. 11.01, D4327-84. American Society for Testing and Materials. Philadelphia, Pennsylvania.

Holm, T. R., S. J. Eisenreich, H. L. Rosenberg, and N. L. Holm. 1987. "Groundwater Geochemistry of Short-Term Aquifer Thermal Energy Storage Test Cycles." Water Resources Research, v. 23, pp. 1005-1019.

Hoyer, M. C., S. J. Eisenreich, J. E. Almendinger, J. A. Perlinger, R. T. Miller, and M. Walton. 1991a. University of Minnesota Aquifer Thermal Energy Storage (ATES) Project Report on the First Long-Term Cycle. PNL-7817, 137 p. Prepared by Minnesota Geological Survey, St. Paul, Minnesota, for Pacific Northwest Laboratory, Richland, Washington.

Hoyer, M. C., S. J. Eisenreich, J. P. Hallgren, J. L. Lauer, J. F. Splettstoesser, and M. Walton. 1991b. University of Minnesota Aquifer Thermal Energy Storage (ATES) Project Report on the Second Long-Term Cycle. PNL-7917, 137 p. Prepared by Minnesota Geological Survey, St. Paul, Minnesota, for Pacific Northwest Laboratory, Richland, Washington.

Hoyer, M. C., M. Walton, R. Kanivetsky, and T. R. Holm. 1985. "Short-Term Aquifer Thermal Energy Storage (ATES) Test Cycles, St. Paul, Minnesota, U.S.A." in ENERSTOCK 85, Proceedings of the 3rd International Conference on Energy Storage for Building Heating and Cooling, Toronto, Canada, pp. 75-79. Public Works Canada, Ottawa.

Miller, R. T. 1984. "Anisotropy in the Ironton and Galesville Sandstones Near a Thermal-Energy-Storage Well." Ground Water, v. 22, pp. 532-538.

Miller, R. T. 1985. Preliminary Modeling of an Aquifer Thermal-Energy Storage Well. U.S. Geological Survey, Water Supply Paper 2270, pp. 1-19.

Miller, R. T. 1986. "Thermal-Energy Storage in a Deep Sandstone Aquifer in Minnesota: Field Observations and Thermal Energy-Transport Modeling." in Proceedings, 21st Intersociety Energy Conversion Engineering Conference, San Diego, California, 1986. v. 2, pp. 682-685. American Chemical Society, Wahington, D.C.

Miller, R. T., and G. N. Delin. 1993. Cyclic Injection, Storage, and Withdrawal of Heated Water in a Sandstone Aquifer at St. Paul, Minnesota: Field Observations, Preliminary Model Analysis, and Aquifer Thermal Efficiency. U.S. Geological Survey, Professional Paper 1530-A. 55 p.

Miller, R. T., and C. I. Voss. 1986. "Finite-Difference Grid for a Doublet Well in an Anisotropic Aquifer." Ground Water, v. 24, pp. 490-496.

O'Dell, J. W., J. D. Pfaff, M. E. Gales, and G. D. McKee. 1984. "The Determination of Inorganic Anions in Water by Ion Chromatography." Tech. Addition to Methods for the Chemical Analysis of Water and Wastes, Method 300.0, EPA-600-4-85-017. U.S. Environmental Protection Agency, Cincinnati, Ohio.

Perlinger, J. A., J. E. Almendinger, N. R. Urban, and S. J. Eisenreich. 1987. "Groundwater Geochemistry of an Aquifer Thermal Energy Storage: Long Test Cycle." Water Resources Research, v. 23, pp. 2215-2226

Shoemaker, D. P., C. W. Garland, J. I. Steinfeld, and J. B. Nibler. 1981. Experiments in Physical Chemistry. 4th ed., McGraw-Hill Inc., New York.

Strickland, J. D. H., and T. R. Parsons. 1972. A Practical Handbook of Seawater Analysis. Bulletin 167, 2nd ed. Fisheries Research Board Canada, Ottawa.

Stumm, W., and J. J. Morgan. 1981. Aquatic Chemistry. 2nd ed. Wiley-Interscience, New York.

Uebel, M. H. 1992. The Aqueous Geochemistry of Aquifer Thermal Energy Storage. M.S. thesis, University of Minnesota, Minneapolis, Minnesota.

Vail, L. W. 1989. "Status of Numerical Models for ATES." in Proceedings, U.S. Department of Energy Thermal Storage Research Activities Review 1989, CONF-890351, p. 348-352. U.S. Department of Energy, Washington, D.C.

Walton, M., M. C. Hoyer, S. J., Eisenreich, N. L. Holm, T. R. Holm, R. Kanivetsky, J. L. Lauer, H. C. Lee, R. T. Miller, and H. Runke. 1991. The University of Minnesota Aquifer Thermal Energy Storage (ATES) Field Test Facility -- System Description, Aquifer Characterization, and Results of Short-Term Cycles. PNL-7720, 295 p. Prepared by Minnesota Geological Survey, St. Paul, Minnesota, for Pacific Northwest Laboratory, Richland, Washington.

APPENDIX A

CHRONOLOGY FOR LONG-TERM CYCLE 3

APPENDIX A

CHRONOLOGY FOR LONG-TERM CYCLE 3

August 14, 1987	Meeting between PNL and U of M to explore goals of a third long-term cycle.
December 15, 1987	Pumpout of storage well (Well A) from LT2 completed. Water temperature at the end of pumpout was 19.4°C (67°F) and the sodium concentration was 14.4 mg/L.
January 15, 1988	Contract supplement for preliminary LT3 work including permit applications and design work for Peters Hall hookup and ATES cycle parameters.
January 19, 1988	Peters Hall hookup design initiated with U of M Physical Planning.
February 5, 1988	NPDES and State Disposal System Permit Application filed.
March 18, 1988	Well modification design work initiated with U of M Physical Planning.
May 26, 1988	Bids received for well modification work.
July 1, 1988	Overall U of M project control transferred from Minnesota Geological Survey to Underground Space Center.
July 22, 1988	Storage well (Well A) pump found to be unusable for the third cycle.
July 29, 1988	Pumpout of source well (Well B) from LT2 completed. The water temperature at the end of pumpout was 20°C (68°F) and the sodium concentration was 22.1 mg/L.
July 29, 1988	Permit/variance for continued operation of the ATES system went on Public Notice.
August 4, 1988	Agreement completed with USGS for ATES modeling and monitoring assistance.
September 27, 1988	MPCA permit/variance approved at MPCA board meeting.
September 28, 1988	Review of suitability of Peters Hall as the building to be interfaced with the ATES system.
September 30, 1988	MPCA permit/variance granted.
October 5, 1988	Continuation of MN Water Well Construction Code variance requested from MN Department of Health.

October 13, 1988	U of M recommends selection of an alternate building for ATES interface.
October 19, 1988	Identification of other target buildings for ATES heat utilization initiated with U of M Physical Planning.
October 25, 1988	Extension of variance to MN Water Well Construction Code allowing injection and recovery of heated water received.
October 27, 1988	Work on storage well (Well A) modification was completed.
December 20, 1988	Extention to MN Dept. of Natural Resources Permit 80-6201 for appropriation of ground water granted.
December 28, 1988	Draft report on target buildings for ATES heat utilization completed.
January 9, 1989	Work on source well (Well B) modification was completed and pump was installed.
March 8, 1989	Animal Science/Veterinary Medicine (ASVM) chosen as the building to receive the recovered heat from the ATES cycle.
April, 1989	Replacement pump for storage well (Well A) ordered following selection of ASVM as the building load and pumping requirements.
May 25, 1989	Replacement data acquisition system operational.
June 8, 1989	Economic analysis of continued use ATES at the U of M by Orr Schelen Mayeron and Associates, Inc. (OSM) was initiated.
June 26, 1989	Bid documents completed for ASVM building hookup.
July 13, 1989	Bids received for the ASVM building hookup to the ATES system.
August 29, 1989	Pump for Well A received from the manufacturer by the well modification contractor.
September 14, 1989	Packer in monitoring Well AC1 became jammed during removal for testing and repair of the well. Several attempts to remove packer failed.
September 15, 1989	Installation of pump for Well A completed.
October 3, 1989	Draft report on ATES economic evaluation for the U of M campus received from OSM.

October 17, 1989	MPCA allows LT3 to continue without repair of Well AC1 but with some additional monitoring constraints.
October 19, 1989	Attempted start of LT3; aborted because steam control and wellhead leak problems.
October 25, 1989	LT3 Injection phase started.
December 12, 1989	LT3 Injection halted during very cold weather (continously below 0°F); trap freeze up shut down system; 46.9 days of injection completed. LT3 Storage phase began.
December 29, 1989	Animal Science/Veterinary Medicine Building hook up to the ATES FTF completed and ready to receive stored heat.
January 2, 1990	LT3 Recovery phase began.
January 5, 1990	LT3 Recovery phase interrupted. Renewed injection phase attempted but unsuccessful because condensate line freeze up. Recovery phase resumed.
January 7, 1990	LT3 Recovery phase interrupted because of warm weather.
January 9, 1990	Renewed injection phase attempted; problems with source well pump prevented injection.
January 31, 1990	LT3 Recovery phase resumed.
March 29, 1990	LT3 Recovery phase ended. Temperature of the recovered water below that usable in the ASVM building hookup. End of LT3.
April, 1990	Request from PNL to operate a 7-day injection subcycle (LT3b) at higher injection temperatures.
May 31, 1990	High temperature injection for subcycle LT3b began.
June 7, 1990	Injection phase of subcycle completed.
June 20, 1990	Recovery phase of subcycle attempted unsuccessfully. Several attempts over several days proved unsuccessful.
August 3, 1990	Pump for storage well (Well A) removed and shipped back to maufacturer for examination.
August, 1990	Final draft of the economic analysis for continued use of ATES at the U of M received from OSM.
September 30, 1990	End of cooperative research agreement with USGS

November 14, 1990	Reinstallation of storage well (Well A) pump completed following modification at the factory.
November 16, 1990	Recovery phase of high-temperature subcycle LT3b initiated.
November 23, 1990	Subcycle (LT3b) recovery phase completed (volume injected recovered). Pumping continued, pumpout of storage well (Well A) began.
December 20, 1990	Pumpout of storage well (Well A) interrupted for winter.
January 30, 1991	Meeting to discuss future of ATES on U of M campus. ATES personnel, PNL program managers and U of M Physical Plant personnel attended.
March 1, 1991	U of M declined near-term adoption of ATES system.
April 24, 1991	Pumpout of storage well (Well A) restarted.
June 12, 1991	Pumpout of storage well (Well A) completed. Temperature of pumped water 17.5°C when pumping stopped.
June 26, 1991	Pumpout of source well (Well B) started.
August 27, 1991	Pumpout of source well (Well B) following LT3 completed. Temperature of pumped water 21.1°C when pumping stopped.

APPENDIX B

OPERATING PARAMETERS FOR LONG-TERM CYCLE 3

APPENDIX B

OPERATING PARAMETERS FOR LONG-TERM CYCLE 3

Long-term cycle 3 (LT3) consisted of a main cycle used to test the long-term storage of heat using the modified well system tied to the ASVM building. A short subcycle (LT3b) aimed at testing the response of the aquifer to injection and recovery at 150°C temperatures was attempted following the completion of LT3. The operating parameters for LT3 are described below. LT3b is described in Appendix F.

WATER FLOW

Injection flow rate - The average flow rate during heat storage injection was 15.7 L/s (249.3 gpm) in October, 15.4 L/s (244.2 gpm) to the end of November and 15.3 L/sec (243 gpm) to the end of December 1989.

Recovery flow rate - The average flow rate during recovery was 12.7 L/sec (201 gpm) in February and 12.3 L/sec (195 gpm) to the end of March 1990.

WATER TEMPERATURES

Source water temperatures - The average source water temperature was 23.2°C (73.8°F) during October, 21.0°C (69.8°F) to the end of November and 20.2°C (68.4°F) to the end of December 1989.

Injected water temperatures - The average injected water temperature was 102.4°C (216.3°F) during October, 104.8°C (220.6°F) to the end of November and 104.7°C (220.5°F) to the end of December 1989.

Recovered water temperatures - Recovered water temperatures reached a peak of 100°C (212°F) and declined to 91.7°C (197°F) at the end of January, to 76.1°C (169°F) at the end of February and to 47.8°C (118°F) at the end of the recovery period on March 29, 1990.

Return water temperatures - Return water temperatures reached 85°C during the early part of recovery. Recovery was interrupted because the demand of the ASVM building during the abnormally warm January was too low to adequately cool the nearly 100°C recovered water. Temperature of the water returned to the source well declined to 47.8°C by the end of recovery.

WATER HARDNESS

Hardness of the source water averaged 174 mg/L as $CaCO_3$. Injected water hardness averaged 4 mg/L as $CaCO_3$. Recovered water hardness was approximately 17 mg/L (1 grain) as $CaCO_3$ at the end of January, 68 mg/L (4 grains) as $CaCO_3$ at the end of February and 140 mg/L (8 grains) as $CaCO_3$ at the end of recovery.

APPENDIX C

DAILY FLOW AND TEMPERATURE DATA FOR LONG-TERM CYCLE 3

APPENDIX C

DAILY FLOW AND TEMPERATURE DATA FOR LONG-TERM CYCLE 3

TABLE C.1. Daily Flow and Temperature Data for Long-Term Cycle 3 Injection and Recovery

	Total Hours	Hours On	Hours Off	Flow Rate m^3/hr	Inject/ Recov T (°C)	Source/ Return T (°C)	Delta T (°C)	Energy MWh	CumVol 10^3 m^3
	0.0								0.000
25-Oct-89	13.7	13.7		56.53	96.9	23.4	73.5	66.213	0.776
26-Oct	37.7	24.0	0.0	56.65	103.3	23.5	79.8	126.261	2.137
27-Oct	61.7	24.0	0.0	56.62	103.2	23.1	80.1	126.637	3.498
28-Oct	85.7	24.0	0.0	56.70	105.5	23.4	82.1	130.012	4.861
29-Oct	109.7	24.0	0.0	56.32	102.7	23.0	79.7	125.270	6.215
30-Oct	133.7	24.0	0.0	56.46	104.4	23.0	81.4	128.321	7.572
31-Oct	157.7	23.8	0.2	56.55	102.2	23.0	79.2	125.162	8.931
01-Nov	181.7	24.0	0.0	56.49	103.6	22.9	80.7	127.309	10.289
02-Nov	205.7	22.8	1.2	56.52	103.6	22.8	80.8	127.464	11.647
03-Nov	229.7	24.0	0.0	56.39	102.7	22.2	80.5	120.305	11.703
04-Nov	253.7	15.5	8.5	56.49	104.0	22.2	81.8	135.525	14.362
05-Nov	277.7	20.4	3.6	56.00	104.3	22.0	82.3	128.749	15.708
06-Nov	301.7	23.3	0.8	56.04	107.1	21.9	85.2	133.279	17.055
07-Nov	325.7	24.0	0.0	55.84	107.2	21.6	85.6	133.525	18.397
08-Nov	349.7	24.0	0.0	56.02	106.2	21.6	84.6	132.235	19.743
09-Nov	373.7	24.0	0.0	56.00	105.8	21.4	84.4	131.810	21.089
10-Nov	397.7	24.0	0.0	55.97	105.3	21.1	84.2	131.436	22.435
11-Nov	421.7	24.0	0.0	54.05	106.1	21.5	84.6	127.682	23.734
12-Nov	445.7	24.0	0.0	55.50	106.0	21.0	85.0	131.582	25.068
13-Nov	469.7	24.0	0.0	55.69	104.9	20.9	84.0	130.465	26.406
14-Nov	493.7	24.0	0.0	55.40	105.2	20.8	84.4	130.584	27.737
15-Nov	517.7	24.0	0.0	55.27	105.7	20.7	85.0	131.133	29.066
16-Nov	541.7	24.0	0.0	54.72	105.8	20.4	85.4	130.412	30.381
17-Nov	565.7	24.0	0.0	54.55	105.4	20.1	85.3	129.870	31.692
18-Nov	589.7	24.0	0.0	54.36	106.1	20.3	85.8	130.048	32.999
19-Nov	613.7	24.0	0.0	54.30	105.0	20.0	85.0	128.947	34.304
20-Nov	637.7	24.0	0.0	54.46	105.5	19.9	85.6	130.208	35.613
21-Nov	661.7	24.0	0.0	54.59	105.4	20.0	85.4	130.101	36.925
22-Nov	685.7	24.0	0.0	54.56	105.4	19.8	85.6	130.369	38.236
23-Nov	709.7	24.0	0.0	54.46	105.1	19.4	85.7	130.279	39.545
24-Nov	733.7	24.0	0.0	54.53	105.1	18.9	86.2	131.212	40.855
25-Nov	757.7	24.0	0.0	54.37	105.1	19.5	85.6	129.895	42.162
26-Nov	781.7	24.0	0.0	54.21	104.8	18.8	86.0	130.181	43.465
27-Nov	805.7	24.0	0.0	54.40	105.7	18.9	86.8	131.901	44.773
28-Nov	829.7	24.0	0.0	54.40	105.2	18.6	86.6	131.620	46.080
29-Nov	853.7	24.0	0.0	54.55	105.8	18.5	87.3	132.879	47.391
30-Nov	877.7	24.0	0.0	54.53	105.1	18.6	86.5	131.670	48.702

TABLE C.1. (continued)

	Total Hours	Hours On	Hours Off	Flow Rate m^3/hr	Inject/ Recov T (°C)	Source/ Return T (°C)	Delta T (°C)	Energy MWh	CumVol 10^3 m^3
01-Dec	901.7	24.0	0.0	54.34	105.3	18.4	86.9	131.758	50.008
02-Dec	925.7	24.0	0.0	54.31	105.9	18.2	87.7	132.988	51.313
03-Dec	949.7	24.0	0.0	53.95	106.1	18.1	88.0	132.509	52.610
04-Dec	973.7	24.0	0.0	54.06	105.2	18.0	87.2	131.495	53.909
05-Dec	997.7	24.0	0.0	54.13	104.8	17.8	87.0	131.376	55.210
06-Dec	1021.7	24.0	0.0	52.95	105.8	17.7	88.1	130.100	56.483
07-Dec	1045.7	24.0	0.0	53.47	105.1	17.6	87.5	130.652	57.768
08-Dec	1069.7	24.0	0.0	54.02	105.5	17.3	88.2	132.968	59.066
09-Dec	1093.7	24.0	0.0	54.12	105.4	17.3	88.1	133.189	60.367
10-Dec	1117.7	17.3	6.7	53.44	103.5	17.2	86.3	128.637	61.651
11-Dec	1141.7	24.0	0.0	52.62	104.2	17.1	87.1	127.945	62.916
12-Dec	1147.3	5.6		50.54	98.5	16.8	81.7	26.832	63.198
			498.4		Recov.				0.000
02-Jan-90	1659.9	9.8	14.2	48.06	95.9	84.8	11.1	8.109	0.628
03-Jan	1669.7	24.0	0.0	42.96	97.9	84.3	13.6	13.667	1.493
04-Jan	1693.7	24.0	0.0	41.01	97.8	83.1	14.7	15.241	2.388
05-Jan	1730.3	12.6		40.46	97.6	83.0	14.6	10.138	2.987
			3.4		Inject.				
05-Jan	1733.6			54.89	106.7	78.6	28.1		63.198
05-Jan	1737.7	4.1		54.89	106.7	78.6	28.1	7.343	63.424
			2.0		Recov.				
05-Jan	1739.7	2.0		51.37	96.7	82.2	14.5	0.820	3.036
06-Jan	1741.7	24.0	0.0	46.92	97.7	84.2	13.5	16.762	4.105
07-Jan	1776.3	10.6	13.4	43.18	97.4	84.4	13.0	8.520	4.672
			552.0		Recov.				
31-Jan	2357.0	8.7	15.3	50.98	95.6	85.4	10.2	3.909	5.003
01-Feb	2365.7	24.0	0.0	47.99	95.3	82.9	12.4	17.970	6.257
02-Feb	2389.7	24.0	0.0	47.17	94.6	81.5	13.1	17.146	7.388
03-Feb	2413.7	24.0	0.0	46.38	94.0	81.6	12.4	16.583	8.535
04-Feb	2437.7	24.0	0.0	45.90	93.3	80.9	12.4	15.239	9.590
05-Feb	2461.7	24.0	0.0	45.52	92.7	81.3	11.4	15.203	10.739
06-Feb	2485.7	24.0	0.0	45.47	92.1	80.8	11.3	12.925	11.731
07-Feb	2509.7	24.0	0.0	45.52	91.7	80.1	11.6	16.500	12.954
08-Feb	2533.7	24.0	0.0	45.43	91.0	79.7	11.3	15.041	14.103
09-Feb	2557.7	24.0	0.0	45.70	90.2	78.4	11.8	14.772	15.187
10-Feb	2581.7	24.0	0.0	46.02	89.8	77.1	12.7	16.199	16.284
11-Feb	2605.7	24.0	0.0	46.11	88.8	77.1	11.7	15.365	17.412
12-Feb	2629.7	24.0	0.0	45.43	88.4	78.4	10.0	12.599	18.497
13-Feb	2653.7	24.0	0.0	45.38	87.7	75.0	12.7	15.995	19.579
14-Feb	2677.7	24.0	0.0	45.36	87.1	73.6	13.5	17.397	20.689
15-Feb	2701.7	24.0	0.0	45.07	86.2	74.1	12.1	15.307	21.782
16-Feb	2725.7	24.0	0.0	44.75	85.7	72.2	13.5	16.529	22.841
17-Feb	2749.7	24.0	0.0	44.50	84.9	71.2	13.7	17.260	23.928

TABLE C.1. (continued)

	Total Hours	Hours On	Hours Off	Flow Rate m^3/hr	Inject/ Recov T (°C)	Source/ Return T (°C)	Delta T (°C)	Energy MWh	CumVol 10^3 m^3
18-Feb	2773.7	24.0	0.0	44.27	84.2	71.2	13.0	15.962	24.990
19-Feb	2797.7	24.0	0.0	44.20	83.6	70.2	13.4	16.558	26.059
20-Feb	2821.7	24.0	0.0	44.00	82.9	70.7	12.2	14.362	27.075
21-Feb	2845.7	24.0	0.0	44.00	82.2	71.1	11.1	14.003	28.166
22-Feb	2869.7	24.0	0.0	43.77	81.2	71.8	9.4	12.026	29.269
23-Feb	2893.7	24.0	0.0	45.63	80.4	71.5	8.9	10.894	30.317
24-Feb	2917.7	24.0	0.0	45.65	79.9	67.1	12.8	16.541	31.427
25-Feb	2941.7	24.0	0.0	45.52	78.6	66.6	12.0	15.418	32.528
26-Feb	2965.7	24.0	0.0	45.43	77.9	67.8	10.1	12.925	33.629
27-Feb	2989.7	24.0	0.0	45.25	77.1	65.8	11.3	14.177	34.711
28-Feb	3013.7	24.0	0.0	45.13	76.2	67.4	8.8	11.349	35.817
01-Mar	3037.7	24.0	0.0	45.18	75.3	68.4	6.9	8.679	36.911
02-Mar	3061.7	24.0	0.0	44.91	74.2	66.0	8.2	10.539	38.022
03-Mar	3085.7	24.0	0.0	44.91	73.3	64.6	8.7	10.693	39.077
04-Mar	3109.7	24.0	0.0	44.95	72.2	63.7	8.5	10.749	40.166
05-Mar	3133.7	24.0	0.0	45.13	71.5	63.5	8.0	10.200	41.264
06-Mar	3157.7	24.0	0.0	45.02	70.4	62.5	7.9	9.828	42.337
07-Mar	3181.7	24.0	0.0	44.86	69.3	62.8	6.5	8.242	43.419
08-Mar	3205.7	24.0	0.0	44.86	68.5	62.5	6.0	7.699	44.524
09-Mar	3229.7	24.0	0.0	44.45	67.5	61.5	6.0	7.302	45.571
10-Mar	3253.7	24.0	0.0	44.16	66.7	60.8	5.9	7.434	46.669
11-Mar	3277.7	24.0	0.0	44.00	65.4	62.1	3.3	3.608	47.617
12-Mar	3301.7	24.0	0.0	44.57	64.6	63.3	1.3	1.539	48.653
13-Mar	3325.7	24.0	0.0	43.77	63.6	59.4	4.2	5.155	49.733
14-Mar	3349.7	24.0	0.0	43.39	62.6	58.2	4.4	5.360	50.784
15-Mar	3373.7	24.0	0.0	43.55	61.1	58.7	2.4	2.906	51.832
16-Mar	3397.7	24.0	0.0	43.48	60.1	56.8	3.3	4.120	52.914
17-Mar	3421.7	24.0	0.0	43.27	58.9	55.4	3.5	4.152	53.952
18-Mar	3445.7	24.0	0.0	43.50	58.1	53.5	4.6	5.715	55.032
19-Mar	3469.7	24.0	0.0	43.77	57.1	54.2	2.9	3.494	56.073
20-Mar	3493.7	24.0	0.0	43.77	56.2	55.3	0.9	1.228	57.193
21-Mar	3517.7	24.0	0.0	43.77	55.2	54.3	0.9	1.152	58.243
22-Mar	3541.7	24.0	0.0	44.00	54.1	53.0	1.1	1.280	59.287
23-Mar	3565.7	24.0	0.0	44.23	52.8	51.4	1.4	1.689	60.334
24-Mar	3589.7	24.0	0.0	44.27	52.2	50.3	1.9	2.391	61.392
25-Mar	3613.7	24.0	0.0	44.11	51.3	49.9	1.4	1.734	62.467
26-Mar	3637.7	24.0	0.0	43.50	50.4	49.1	1.3	1.582	63.489
27-Mar	3661.7	24.0	0.0	43.14	49.2	49.2	0.0	0.000	64.580
28-Mar	3685.7	24.0	0.0	43.09	48.3	48.3	0.0	0.000	65.632
29-Mar	3718.7	9.0		43.09	47.8	47.8	0.0	0.000	65.959
30-Mar									
31-Mar									

TABLE C.1. (continued)

	Total Hours	Hours On	Hours Off	Flow Rate m^3/hr	Inject/ Recov T (°C)	Source/ Return T (°C)	Delta T (°C)	Energy MWh	CumVol 10^3 m^3
Summary									
INJECTION	1147.3	1126.3	20.9	54.95	104.7	20.2	83.4	6211	63.198
RECOVERY	2058.7	1472.7	586.0	44.83	75.3	68.1	8.4	638	65.959

APPENDIX D

<u>ANALYTICAL RESULTS OF WATER SAMPLES FOR LONG-TERM CYCLE 3</u>

APPENDIX D

ANALYTICAL RESULTS OF WATER SAMPLES FOR LONG-TERM CYCLE 3

Table D.1 presents factors for converting concentrations between mmol/L and mg/L. Tables D.2 and D.3 present results of analyses of water samples from LT3. On the tables, NA stands for not analyzed, and ND stands for not detected. Aluminum determinations on selected water samples were made at PNL and are reported in Table D.4.

TABLE D.1. 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	0.03119
Cl	35.45	0.02821
F	19.00	0.05263
Ca	40.08	0.02495
Mg	24.31	0.04114
Na	22.99	0.04350
K	39.09	0.02558
Fe	55.84	0.01791
Hardness as $CaCO_3$	100.09	0.00999

TABLE D.2. Analyses of Long-Term Cycle 3 Injection Phase Water Samples, October to December 1989

WATER CHEM - LT3 -INJECTION

Well	AM2	AM4	AM2	AM2	AM2	B	B	B	B	B	AM2	AM4	AM2	AM2	AM2	B
									LabRep						LabRep	
MPCA ID --	602	604	602	602	602	950		960	960	960	602	604	602	602	602	950
Sample Type						I	II	III	III	III						I
Date sampled	890919	890921	891018	891024	891025	891025	891025	891025	891025	891025	891026	891026	891026	891027	891027	891027
Time	1615	1600	1345	1100	1442	1306	1331	1351	1351	1351	1005	1500	2105	1125	1125	910
Graph volume	-62033	-62033	-62033	-62033	-61779	-61851	-61851	-61851	-61851	-61851	-60685	-60405	-60065	-59247	-59247	-59353
Cum vol m3	0	0	0	0	254	182	182	182	182	182	1348	1628	1968	2786	2786	2680
Replication	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1
pH																
Water Temp °C					23.3	23.0	23.0	96.0	96.0	96.0	23.4	21.4	23.6	28.6	28.6	23.0
pH Temp °C	23.2	18.7	14.8	15.9	NA	25.1	24.7	73.2	73.2	73.2	24.4	19.5	23.2	79.7	79.7	23.5
pH, corrected	7.71	6.05	5.72	5.70	NA	5.66	7.29	7.14	7.14	7.14	7.92	8.00	7.87	7.87	7.87	7.25
SC (umho/cm)	295	286	285	NA	307	325	325	356	356	356	346	299	344	398	398	322
DO (mg/L)	6	4	6	5	4	0.5	0.3	0.1	0.1	0.1	5	5	6	5	5	0.3
Alk (meq/L)	4.37	4.04	4.37	4.36	4.31	4.81	4.67	4.67	4.67	4.64	4.69	4.67	4.65	4.79	4.77	4.61
SiO2 (mg/L) as Si	NA	NA	6.04	6.08	5.88	6.62	6.68	6.66	6.66	6.60	6.64	5.50	7.75	9.79	9.79	6.85
DIC (mg/L) as C	41.34	49.93	NA	NA	NA	54.75	55.46	55.37	55.23	55.22	NA	NA	NA	NA	NA	NA
TOC (mg/L) as C	NA	NA	0.96	0.98	0.75	NA	0.82	0.65	0.74	0.67	0.78	0.84	0.71	0.70	0.96	0.64
IC Analysis:																
SO4 (mg/L) as S	1.07	0.93	1.11	1.07	1.14	2.77	2.72	2.71	2.72	2.68	2.32	1.25	2.5	2.04	2.04	2.08
Cl (mg/L)	1.69	2.02	1.64	1.61	1.69	3.90	4.43	4.36	4.38	4.30	10.41	2.06	18.24	24.90	24.90	4.42
F (mg/L)	0.25	0.27	0.22	0.23	0.46	0.28	0.27	0.29	0.29	0.28	0.32	0.27	0.21	0.30	0.30	0.28
AA Analysis:																
Ca (mg/L)	44.28	39.01	45.41	45.03	47.29	46.16	0.07	0.22	0.22	0.21	38.06	46.35	32.60	24.51	24.51	44.09
Mg (mg/L)	14.14	14.82	14.39	14.12	14.65	14.52	0.05	0.06	0.06	0.06	11.34	15.10	8.08	6.44	7.77	14.61
Na (mg/L)	16.53	14.79	18.28	17.41	15.66	22.64	111.4	111.4	111.0	110.7	45.75	17.41	64.62	83.11	83.11	25.55
K (mg/L)	7.46	8.16	7.08	7.08	7.47	8.23	1.57	2.65	2.65	2.75	6.77	7.47	7.47	7.02	7.02	8.47
Hardness (mg/L) as CaCO3	168.8	158.4	172.6	170.6	178.4	175.1	0.4	0.8	0.8	0.8	141.7	177.9	114.7	87.7	93.2	170.3

TABLE D.2. (continued)

WATER CHEM - LT3 -																
Well	B	B	B	AM4	FIELD BLANK	AM2	AM2	AM2	AM4	AM4 LabRep	AM4	AM2	B	B	B	B LabRep
MPCA ID --		960	960	604		602	602	602	604	604	604	602	950		960	960
Sample Type	II	III	III										I	II	III	III
Date sampled	891027	891027	891027	891027	891027	891028	891028	891029	891029	891029	891030	891030	891030	891030	891030	891030
Time	930	950	950	1430		1020	2005	1315	1830	1830	1217	1530	1010	1030	1155	1155
Graph volume	-59353	-59353	-59353	-59069	-59353	-57945	-57396	-56423	-56128	-56128	-55125	-54939	-55219	-55219	-55219	-55219
Cum vol m3	2680	2680	2680	2964	2680	4088	4637	5610	5905	5905	6908	7094	6814	6814	6814	6814
Replication	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1
pH																
Water Temp °C	23.0	99.0	99.0	21.0	NA		21.0	25.3	22.5	22.5	22.6	28.8	23.0	102.0	102.0	102.0
pH Temp °C	23.7	86.3	86.3	16.3	NA	18.6	20.5	24.3	13.8	13.8	16.9	27.1	21.8	78.6	78.6	78.6
pH, corrected	7.46	6.92	6.92	7.89	NA	7.69	7.86	7.97	7.82	7.82	7.91	8.11	7.46	7.46	6.99	6.99
SC (umho/cm)	314	308	308	324	NA	363	350	369	331	331	335	352	302	572	331	331
DO (mg/L)	0.3	0.2	0.2	5	NA	4	5	5	6	6	4	NA	0.3	0.3	0.2	0.2
Alk (meq/L)	4.64	4.63	4.58	4.53	ND	4.69	4.65	4.65	4.68	4.69	4.22	5.29	4.57	4.54	4.51	4.54
SiO2 (mg/L) as Si	6.79	6.87	6.85	6.32	ND	12.67	13.69	14.99	8.83	8.89	9.93	16.08	6.76	6.87	6.91	6.91
DIC (mg/L) as C	NA	NA	NA	51.86	NA	55.33	56.25	56.05	55.68	55.68	55.35	56.67	53.81	53.52	52.81	52.58
TOC (mg/L) as C	0.71	NA	0.78	0.75	NA	1.66	1.77	1.44	0.85	1.04	NA	NA	0.77	0.92	1.08	1.21
IC Analysis:																
SO4 (mg/L) as S	2.08	2.06	2.05	1.80	ND	2.22	2.00	2.01	2.10	2.08	2.05	1.83	1.55	1.56	1.54	1.56
Cl (mg/L)	4.86	4.88	4.77	9.14	ND	22.19	26.85	23.58	18.60	18.20	18.16	20.10	4.52	5.50	5.33	5.37
F (mg/L)	0.28	0.27	0.28	0.24	ND	0.50	0.47	0.50	0.33	0.36	0.37	0.46	0.26	0.26	0.23	0.29
AA Analysis:																
Ca (mg/L)	0.29	0.30	0.32	36.18	ND	17.73	16.03	13.77	27.71	27.52	23.75	10.76	42.39	4.36	3.61	3.42
Mg (mg/L)	0.11	0.11	0.11	10.90	ND	4.70	4.06	2.96	7.94	8.08	7.41	1.86	12.45	0.12	0.11	0.11
Na (mg/L)	109.5	108.8	108.0	46.50	ND	89.90	94.05	97.44	69.52	68.77	69.14	98.20	25.84	105.4	98.20	98.95
K (mg/L)	2.13	2.02	1.99	7.15	ND	7.47	8.02	8.47	6.70	6.77	6.43	8.06	8.44	3.44	3.27	3.17
Hardness (mg/L) as CaCO3	1.2	1.2	1.3	135.2		63.6	56.7	46.6	101.9	102.0	89.8	34.5	157.1	11.4	9.5	9.0

TABLE D.2. (continued)

WATER CHEM - LT3 -

Well	B	FIELD BLANK	AM2	AS1 MS	B	B	B	B	FIELD BLANK	AM2	AM2 LabRep	AM2	AM4	B	B	B
MPCA ID --	960		602	606	950		960	960		602	602	602	604	950		960
Sample Type	III				I	II	III	III						I	II	III
Date sampled	891030	891030	891031	891031	891101	891101	891101	891101	891101	891102	891102	891103	891103	891103	891103	891103
Time	1155		1220	1815	1500	1517	1530	1530		1110	1110	1130	1540	1600	1625	1650
Graph volume	-55219	-55219	-53754	-53417	-52236	-52236	-52236	-52236	-52236	-51105	-51105	-49787	-49553	-49507	-49507	-49507
Cum vol m3	6814	6814	8279	8616	9797	9797	9797	9797	9797	10928	10928	12246	12480	12526	12526	12526
Replication	2	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1
pH																
Water Temp °C	102.0	NA	32.0		23.0	23.0	104.0	104.0	NA	39.7	39.7	43.8	36.3	23.0	23.0	103.0
pH Temp °C	78.6	NA	29.9	16.5	20.2	20.7	86.1	86.1	NA	25.0	25.0	24.7	13.1	20.3	21.1	80.0
pH, corrected	6.99	NA	8.05	8.03	7.22	7.51	7.03	7.03	NA	8.01	8.01	8.05	7.91	7.37	7.47	6.93
SC (umho/cm)	NA	NA	376	342	314	322	329	329	NA	386	386	408	370	324	325	345
DO (mg/L)	0.2	NA	3	5	0.3	0.3	0.3	0.3	NA	5	5	6	5	0.3	0.3	0.3
Alk (meq/L)	4.52	ND	NA	4.13	4.53	4.58	4.54	4.64	ND	4.58	4.57	4.48	4.50	4.36	4.52	4.50
SiO2 (mg/L) as Si	6.85	0.00	16.55	6.28	6.81	6.76	6.72	6.76	0	16.63	16.55	16.23	14.30	6.72	6.62	6.68
DIC (mg/L) as C	52.48	ND	55.15	NA	52.46	52.83	53.93	54.54	ND	53.16	53.16	54.29	52.95	49.07	52.36	53.17
TOC (mg/L) as C	1.00	NA	NA	NA	0.72	0.65	0.75	0.65	0.03	NA	NA	NA	NA	0.61	0.68	NA
IC Analysis:																
SO4 (mg/L) as S	1.55	ND	1.70	2.28	1.40	1.39	1.38	1.39	ND	1.56	1.52	1.57	1.54	1.34	1.36	1.58
Cl (mg/L)	5.33	ND	27.93	1.65	4.40	5.99	5.81	5.91	ND	22.07	21.9	27.2	20.76	4.16	5.28	4.71
F (mg/L)	0.28	ND	0.42	0.38	0.28	0.27	0.27	0.27	ND	0.38	0.38	0.39	0.54	0.27	0.28	0.40
AA Analysis:																
Ca (mg/L)	3.80	ND	9.82	48.42	41.26	0.51	0.62	0.74	ND	8.13	8.13	7.56	15.09	41.64	0.38	0.40
Mg (mg/L)	0.11	ND	1.51	13.86	12.98	0.14	0.18	0.18	ND	1.08	1.06	0.96	4.25	13.94	0.16	0.16
Na (mg/L)	99.33	ND	103.9	12.17	12.97	102.4	102.0	102.7	ND	102.7	105.8	105.8	86.88	24.10	101.6	101.6
K (mg/L)	3.24	ND	7.95	9.10	8.47	3.06	2.89	2.92	ND	7.7	7.7	7.19	7.53	8.18	3.83	3.59
Hardness (mg/L) as CaCO3	9.9	0.0	30.7	178.0	156.5	1.8	2.3	2.6	0.0	24.7	24.7	22.8	55.2	161.4	1.6	1.7

TABLE D.2. (continued)

WATER CHEM - LT3 -																
Well	B LabRep	B	FIELD BLANK	AM2	AM4	B	B	B	B	FIELD BLANK	AM2	B	B	B	B	AM4
MPCA ID --	960	960		602	604	950		960	960		602	950		960	960	604
Sample Type	III	III				I	II	III	III			I	II	III	III	
Date sampled	891103	891103	891103	891106	891106	891106	891106	891106	891106	891106	891108	891108	891108	891108	891108	891110
Time	1650	1650		1400	1045	1205	1218	1225	1225		1100	1230	1230	1230	1230	1100
Graph volume	-49507	-49507	-49507	-46240	-46414	-46331	-46331	-46331	-46331	-46331	-43734	-43651	-43651	-43651	-43651	-41043
Cum vol m3	12526	12526	12526	15793	15619	15702	15702	15702	15702	15702	18299	18382	18382	18382	18382	20990
Replication	1	2		1	1	1	1	1	2		1	1	1	1	2	1
pH																
Water Temp °C	103.0	103.0	NA	52.0	52.3	22.0	22.0	106.0	106.0	NA	101.0	22.0	22.0	105.0	105.0	78.4
pH Temp °C	80.0	80.0	NA	23.9	15.6	20.6	20.8	77.8	77.8	NA	26.0	21.1	21.3	NA	NA	17.9
pH, corrected	6.93	6.93	NA	8.05	7.74	7.34	7.31	6.84	6.84	NA	7.98	7.37	7.51	NA	NA	7.97
SC (umho/cm)	345	345	NA	445	408	330	354	343	343	NA	411	338	344	347	347	439
DO (mg/L)	0.3	0.3	NA	6	6	0.3	0.3	0.2	0.2	NA	5	0.6	0.2	0.1	0.1	5
Alk (meq/L)	4.51	4.51	ND	4.56	4.43	4.48	4.54	4.46	4.45	ND	4.53	4.46	4.46	NA	NA	4.36
SiO2 (mg/L) as Si	6.68	6.72	ND	16.62	16.59	6.74	6.64	6.66	6.70	0	16.85	6.62	6.70	NA	NA	18.99
DIC (mg/L) as C	53.06	52.35	NA	52.53	52.48	52.68	53.86	52.30	52.36	NA	53.32	53.71	52.46	NA	NA	51.03
TOC (mg/L) as C	NA	0.72	0.03	NA	NA	0.63	0.63	0.76	0.82	0.05	NA	0.64	0.60	NA	NA	NA
IC Analysis:																
SO4 (mg/L) as S	1.56	1.59	ND	1.48	1.57	1.548	1.53	1.51	1.52	ND	1.36	1.35	1.96	NA	NA	1.42
Cl (mg/L)	4.64	4.78	ND	43.92	28.31	3.82	3.86	3.89	3.93	ND	24.87	3.75	4.93	NA	NA	36.78
F (mg/L)	0.41	0.43	ND	0.40	0.61	0.40	0.41	0.43	0.42	ND	0.42	0.31	0.40	NA	NA	0.55
AA Analysis:																
Ca (mg/L)	0.40	0.38	ND	7.75	14.16	45.85	5.99	8.31	9.27	ND	7.2	45.49	0.21	0.25	0.27	9.39
Mg (mg/L)	0.16	0.16	ND	0.94	3.37	13.83	4.88	7.64	8.88	ND	0.85	13.90	0.08	0.10	0.10	1.99
Na (mg/L)	101.6	100.8	ND	116.8	95.48	23.80	53.61	49.73	47.40	ND	107.5	22.64	103.6	104.0	102.9	104.4
K (mg/L)	3.73	3.63	ND	7.53	8.69	8.28	62.33	59.12	56.67	ND	7.36	8.32	1.85	1.81	1.81	8.79
Hardness (mg/L) as CaCO3	1.7	1.6	0.0	23.2	49.2	171.4	35.1	52.2	59.7	0.0	21.5	170.8	0.9	1.0	1.1	31.6

TABLE D.2. (continued)

WATER CHEM - LT3 - Well	B	B	B	B LabRep	B	FIELD BLANK	AM2	B	B	B	B	FIELD BLANK	AM4	AS1 MS	AM2	B
MPCA ID --	950		960	960	960		602	950		960	960		604	606	602	950
Sample Type	I	II	III	III	III			I	II	III	III					I
Date sampled	891110	891110	891110	891110	891110	891110	891113	891113	891113	891113	891113	891113	891114	891114	891116	891116
Time	1400	1400	1400	1400	1400		1215	1055	1125	1145	1145		1140	1840	1000	1025
Graph volume	-40876	-40876	-40876	-40876	-40876	-40876	-36996	-37038	-37038	-37038	-37038	-37038	-35694	-35308	-33135	-33094
Cum vol m3	21157	21157	21157	21157	21157	21157	25037	24995	24995	24995	24995	24995	26339	26725	28898	28939
Replication	1	1	1	1	2		1	1	1	1	2		1	1	1	1
pH																
Water Temp °C	22.0	22.0	103.0	103.0	103.0	NA	104.0	21.0	21.0	104.0	104.0	NA	104.0		79.0	21.0
pH Temp °C	19.7	20.3	79.5	79.5	79.5	NA	24.7	19.7	20.3	78.6	78.6	NA	20.2	20.0	24.0	20.1
pH, corrected	7.22	7.45	7.34	7.34	7.34	NA	7.96	7.16	7.48	7.25	7.25	NA	7.77	7.92	7.97	7.45
SC (umho/cm)	332	339	353	353	353	NA	539	350	364	441	441	NA	528	365	530	348
DO (mg/L)	0.4	0.1	0.1	0.1	0.1	NA	6	0.2	0.2	0.3	0.3	NA	7	7	6	0.3
Alk (meq/L)	4.47	4.47	4.45	4.41	4.41	ND	3.74	4.41	4.75	4.43	4.43	ND	4.29	4.40	4.54	4.50
SiO2 (mg/L) as Si	6.60	6.66	6.74	6.74	6.62	0	17.23	6.56	6.47	6.54	6.40	0.008	20.39	7.00	16.83	6.46
DIC (mg/L) as C	50.91	51.89	51.49	51.49	52.14	0.99	NA	54.33	57.51	53.58	53.32	ND	50.36	49.30	53.59	56.12
TOC (mg/L) as C	0.61	0.61	0.79	0.74	0.85	0.07	NA	0.69	0.73	0.79	0.76	0.23	NA	NA	NA	0.53
IC Analysis:																
SO4 (mg/L) as S	1.92	1.93	1.29	1.29	1.29	ND	1.33	1.31	1.32	1.19	1.33	ND	1.42	2.24	1.37	1.29
Cl (mg/L)	3.57	5.54	5.32	5.42	5.49	ND	52.83	3.35	7.49	6.21	6.86	ND	49.28	7.70	46.26	3.26
F (mg/L)	0.41	0.4	0.28	0.23	0.25	ND	0.43	0.34	0.33	0.31	0.33	ND	0.52	0.45	0.40	0.32
AA Analysis:																
Ca (mg/L)	45.85	0.10	0.13	0.13	0.13	ND	5.97	42.58	0.31	0.31	0.30	ND	8.53	46.08	5.73	45.61
Mg (mg/L)	14.23	0.04	0.05	0.05	0.06	ND	0.78	13.65	0.11	0.11	0.12	ND		12.19	0.69	12.53
Na (mg/L)	20.61	104.4	104.4	104.4	104.0	ND	124.9	20.31	106.6	106.6	105.9	ND	112.1	21.48	123.3	19.44
K (mg/L)	8.35	0.75	0.65	0.74	0.68	ND	7.30	8.75	3.01	2.92	2.96	ND	9.65	9.72	6.77	8.66
Hardness (mg/L) as CaCO3	173.1	0.4	0.5	0.5	0.6	0.0	18.1	162.5	1.2	1.2	1.2	0.0	21.3	165.3	17.1	165.5

TABLE D.2. (continued)

WATER CHEM - LT3 -																
Well	B	B	B LabRep	B	FIELD BLANK	B	B	B	B	B	B	B	B LabRep	B	FIELD BLANK	B
MPCA ID --		960	960	960		950		960	960	950		960	960	960		950
Sample Type	II	III	III	III		I	II	III	III	I	II	III	III	III		I
Date sampled	891116	891116	891116	891116	891116	891120	891120	891120	891120	891122	891122	891122	891122	891122	891122	891124
Time	1045	1055	1055	1055		1130	1200	1220	1220	910	935	955	955	955		1020
Graph volume	-33094	-33094	-33094	-33094	-33094	-27790	-27790	-27790	-27790	-25307	-25307	-25307	-25307	-25307	-25307	-22631
Cum vol m3	28939	28939	28939	28939	28939	34243	34243	34243	34243	36726	36726	36726	36726	36726	36726	39402
Replication	1	1	1	2		1	1	1	2	1	1	1	1	2		1
pH																
Water Temp °C	21.0	104.0	104.0	104.0	NA	20.0	20.0	105.0	105.0	20.0	20.0	105.0	105.0	105.0	NA	20.0
pH Temp °C	20.5	74.2	74.2	74.2	NA	19.4	20.3	82.4	82.4	18.0	19.7	83.6	83.6	83.6	NA	18.5
pH, corrected	7.52	7.26	7.26	7.26	NA	7.17	7.53	7.04	7.04	7.22	7.44	7.03	7.03	7.03	NA	7.03
SC (umho/cm)	361	362	362	362	NA	346	429	368	368	357	358	359	359	359	NA	365
DO (mg/L)	0.3	0.1	0.1	0.1	NA	0.3	0.2	0.1	0.1	0.3	0.3	0.2	0.2	0.2	NA	0.3
Alk (meq/L)	4.76	4.51	4.51	4.53	ND	4.48	4.54	4.53	4.52	4.52	4.53	4.52	4.54	4.52	0.01	4.52
SiO2 (mg/L) as Si	6.51	6.52	6.47	6.49	ND	6.37	6.39	6.38	6.40	6.31	6.52	6.36	6.36	6.32	ND	6.34
DIC (mg/L) as C	58.63	55.60	55.54	55.16	0.33	56.06	56.36	55.93	55.55	55.81	55.93	54.78	54.75	54.93	0.27	56.11
TOC (mg/L) as C	0.57	0.73	0.68	0.70	ND	0.43	0.49	0.71	0.67	0.53	0.52	1.04	0.88	0.82	ND	ND
IC Analysis:																
SO4 (mg/L) as S	1.33	1.32	1.29	1.29	ND	1.31	1.3	1.28	1.32	1.3	1.31	1.28	1.27	1.29	ND	1.28
Cl (mg/L)	6.43	6.10	5.87	5.97	ND	3.00	7.71	7.54	7.43	2.91	4.9	4.71	4.67	4.7	ND	2.78
F (mg/L)	0.33	0.33	0.33	0.32	ND	0.32	0.32	0.33	0.33	0.32	0.32	0.33	0.32	0.31	ND	0.32
AA Analysis:																
Ca (mg/L)	0.21	0.21	0.23	0.21	ND	47.48	0.73	0.67	0.67	46.31	0.19	0.23	0.23	0.19	ND	48.88
Mg (mg/L)	0.08	0.08	0.08	0.08	ND	14.94	0.22	0.20	0.20	15.16	0.08	0.09	0.08	0.08	ND	14.99
Na (mg/L)	105.3	105.3	105.6	106.6	ND	17.99	104.7	105.0	105.3	17.99	104.0	104.0	104.0	104.3	ND	17.41
K (mg/L)	1.52	1.52	1.46	1.46	ND	9.41	1.90	1.83	1.74	8.48	1.62	1.49	1.65	1.52	ND	8.35
Hardness (mg/L) as CaCO3	0.9	0.9	0.9	0.9	0.0	180.1	2.7	2.5	2.5	178.1	0.8	0.9	0.9	0.8	0.0	183.8

TABLE D.2. (continued)

WATER CHEM - LT3 - Well	B	B	B	FIELD BLANK	B	B	B	B LabRep	B	B	B	B	B	FIELD BLANK	B	B
MPCA ID --		960	960		950		960	960	960	950		960	960		950	
Sample Type	II	III	III		I	II	III	III	III	I	II	III	III		I	II
Date sampled	891124	891124	891124	891124	891127	891127	891127	891127	891127	891129	891129	891129	891129	891129	891201	891201
Time	1035	1050	1050		1045	1055	1110	1110	1110	1600	1620	1640	1640		1540	1555
Graph volume	-22631	-22631	-22631	-22631	-18686	-18686	-18686	-18686	-18686	-15783	-15783	-15783	-15783	-15783	-13182	-13182
Cum vol m3	39402	39402	39402	39402	43347	43347	43347	43347	43347	46250	46250	46250	46250	46250	48851	48851
Replication	1	1	2		1	1	1	1	2	1	1	1	2		1	1
pH																
Water Temp °C	20.0	106.0	106.0	NA	19.0	19.0	103.0	103.0	103.0	18.0	18.0	103.0	103.0	NA	18.0	18.0
pH Temp °C	19.0	81.9	81.9	NA	18.8	19.0	95.5	95.5	95.5	17.7	17.9	85.0	85.0	NA	18.1	18.1
pH, corrected	7.58	6.99	6.99	NA	7.03	7.51	7.06	7.06	7.06	7.17	7.64	6.99	6.99	NA	7.16	7.58
SC (umho/cm)	370	378	378	NA	372	NA	375	375	375	369	378	407	407	NA	443	386
DO (mg/L)	0.3	0.1	0.1	NA	0.3	0.2	0.1	0.1	0.1	0.3	0.2	0.2	0.2	NA	0.3	0.2
Alk (meq/L)	4.53	4.51	4.52	0.01	4.55	4.50	4.47	4.50	4.49	4.53	4.66	4.52	4.51	ND	4.52	5.04
SiO2 (mg/L) as Si	6.33	6.30	6.33	ND	6.17	6.20	6.16	6.26	6.24	6.12	6.14	6.19	6.22	0.034	6.06	6.08
DIC (mg/L) as C	55.71	55.33	54.35	0.27	55.94	56.22	55.34	55.16	55.66	56.28	56.16	55.47	55.50	0.29	56.27	61.49
TOC (mg/L) as C	0.50	NA	NA	ND	0.49	0.50	0.70	0.69	0.72	0.78	0.58	0.84	0.85	ND	0.54	0.51
IC Analysis:																
SO4 (mg/L) as S	1.27	1.26	1.28	ND	1.32	1.24	1.23	1.22	1.21	1.24	1.19	1.18	1.18	ND	1.24	1.19
Cl (mg/L)	5.79	5.23	5.43	ND	2.96	3.7	3.55	3.52	3.52	2.72	7.43	7.79	7.78	ND	2.58	4.93
F (mg/L)	0.32	0.3	0.31	ND	0.32	0.33	0.33	0.32	0.32	0.29	0.31	0.31	0.31	ND	0.31	0.31
AA Analysis:																
Ca (mg/L)	0.16	0.16	0.13	ND	49.34	0.73	0.61	0.63	0.61	48.41	0.53	0.58	0.56	0.13	49.81	0.31
Mg (mg/L)	0.05	0.06	0.05	0	14.00	0.33	0.28	0.28	0.28	13.61	0.15	0.16	0.16	ND	14.81	0.11
Na (mg/L)	106.3	105.3	105.6	ND	17.12	103.0	103.4	103.4	102.7	16.53	104.3	103.4	102.7	ND	16.24	104.0
K (mg/L)	0.78	0.75	0.78	ND	8.23	2.95	2.83	2.83	2.70	8.23	2.73	2.73	2.67	ND	7.79	1.83
Hardness (mg/L) as CaCO3	0.6	0.6	0.5	0.0	180.9	3.2	2.7	2.7	2.7	176.9	1.9	2.1	2.1	0.3	185.4	1.2

TABLE D.2. (continued)

WATER CHEM - LT3 - Well	B	B	B	B	B	B	B	FIELD	B	B	B	B	FIELD	B	B	B
						LabRep		BLANK					BLANK			
MPCA ID --	960	960	950		960	960	960		950		960	960		950		960
Sample Type	III	III	I	II	III	III	III		I	II	III	III		I	II	III
Date sampled	891201	891201	891204	891204	891204	891204	891204	891204	891206	891206	891206	891206	891206	891208	891208	891208
Time	1615	1615	1225	1235	1250	1250	1250		1040	1100	1120	1120		1045	1045	1045
Graph volume	-13182	-13182	-9465	-9465	-9465	-9465	-9465	-9465	-6959	-6959	-6959	-6959	-6959	-4404	-4404	-4404
Cum vol m3	48851	48851	52568	52568	52568	52568	52568	52568	55074	55074	55074	55074	55074	57629	57629	57629
Replication	1	2	1	1	1	1	2		1	1	1	2		1	1	1
pH																
Water Temp °C	103.0	84.5	18.0	18.0	104.0	104.0	104.0	NA	17.0	17.0	104.0	104.0	NA	18.9	18.9	104.4
pH Temp °C	84.5	84.5	19.1	18.9	79.5	79.5	79.5	NA	17.5	17.9	76.6	76.6	NA	16.3	18.4	56.9
pH, corrected	7.32	7.32	7.18	7.67	7.01	7.01	7.01	NA	7.13	7.62	6.96	6.96	NA	6.99	7.58	6.9
SC (umho/cm)	398	398	385	382	389	389	391	NA	387	384	389	387	NA	385	384	393
DO (mg/L)	0.1	0.1	0.2	0.4	0.1	0.1	0.1	NA	0.6	0.2	0.2	0.2	NA	0.2	0.2	0.2
Alk (meq/L)	4.48	4.58	4.50	4.46	4.59	4.59	4.46	ND	4.40	4.50	4.47	4.49	ND	3.93	4.83	4.47
SiO2 (mg/L) as Si	6.12	6.10	6.01	5.98	6.02	6.00	6.04	0.024	5.95	5.94	5.98	6.03	ND	5.94	5.96	5.96
DIC (mg/L) as C	55.11	55.57	55.84	55.79	56.02	55.66	54.86	0.33	54.14	54.27	55.36	54.90	0.28	48.40	58.08	54.82
TOC (mg/L) as C	0.86	0.73	0.45	0.44	0.98	0.86	0.82	ND	0.54	0.58	0.80	0.95	0.05	0.61	0.64	0.76
IC Analysis:																
SO4 (mg/L) as S	1.19	1.21	1.23	1.2	1.19	1.21	1.21	ND	1.25	1.2	1.21	1.2	ND	1.25	1.19	1.2
Cl (mg/L)	4.64	4.68	2.55	4.2	3.94	3.92	3.95	ND	2.42	3.63	3.63	3.64	ND	2.49	4.51	4.1
F (mg/L)	0.3	0.33	0.32	0.33	0.35	0.35	0.35	ND	0.31	0.33	0.32	0.33	ND	0.3	0.33	0.31
AA Analysis:																
Ca (mg/L)	0.30	0.30	49.19	0.33	0.30	0.30	0.31	ND	49.63	0.15	0.09	0.02	ND	51.88	0.22	0.18
Mg (mg/L)	0.10	0.11	15.04	0.12	0.12	0.11	0.11	ND	14.61	0.05	0.05	0.05	ND	14.91	0.06	0.06
Na (mg/L)	102.4	103.0	15.66	102.3	102.6	102.6	102.3	0.69	15.37	102.0	100.7	101.3	0.37	14.79	102.3	101.3
K (mg/L)	1.74	1.87	8.12	2.04	1.94	1.98	1.98	ND	8.31	0.04	0.04	0.04	ND	8.24	0.82	0.60
Hardness (mg/L) as CaCO3	1.2	1.2	184.8	1.3	1.2	1.2	1.2	0.0	184.1	0.6	0.4	0.3	0.0	190.9	0.8	0.7

TABLE D.2. (continued)

WATER CHEM - LT3 -

Well	B LabRep	B	FIELD BLANK	AS1MS	AM2	AM2 LabRep	FIELD BLANK		SOURCE	SOFTND	INJECTED
MPCA ID --	960	960		606	602	602					
Sample Type	III	III									
Date sampled	891208	891208	891208	891220	891220	891220	891220				
Time	1045	1045		1535	1715	1715		Tot Vol	Avg	Avg	Avg
Graph volume	-4404	-4404	-4404	0	0	0	0		of	of	of
Cum vol m3	57629	57629	57629	62033	62033	62033	62033	62033	Smpls	Smpls	Smpls
Replication	1	2		1	1	1					
pH											
Water Temp °C	104.4	104.4	NA		104.0	104.0	NA		20.6	24.8	102.8
pH Temp °C	56.9	56.9	NA	15.8	17.5	17.5	NA		19.8	23.2	79.8
pH, corrected	6.9	6.9	NA	7.7	8.41	8.41	NA		7.14	7.51	7.05
SC (umho/cm)	393	393	NA	465	459	459	NA		352	372	359
DO (mg/L)	0.2	0.2	NA	5	5	5	NA		0.3	0.3	0.2
Alk (meq/L)	4.46	4.47	ND	4.65	4.65	4.59	ND		4.48	4.61	4.52
SiO2 (mg/L) as Si	5.96	5.94	ND	10.36	21.38	21.29	ND		6.42	6.43	6.43
DIC (mg/L) as C	54.57	55.04	0.39	57.07	56.55	56.37	0.32		54.04	55.47	54.33
TOC (mg/L) as C	0.73	0.70	ND	0.76	0.76	0.76	0.07		0.57	0.61	0.81
IC Analysis:											
SO4 (mg/L) as S	1.18	1.19	ND	1.92	1.35	1.33	ND		1.47	1.49	1.44
Cl (mg/L)	4.08	3.98	ND	22.4	24.64	24.91	ND		3.35	5.32	4.98
F (mg/L)	0.31	0.30	ND	0.70	0.36	0.44	ND		0.31	0.32	0.32
AA Analysis:											
Ca (mg/L)	0.18	0.18	ND	42.01	5.93	4.58	ND		46.41	0.83	0.92
Mg (mg/L)	0.05	0.06	ND	9.76			ND		14.14	0.37	0.48
Na (mg/L)	101.3	100.0	0.37	53.90	107.8	107.4	0.37		19.32	101.9	101.3
K (mg/L)	0.63	0.63	ND	12.26	4.10	3.94	ND		8.38	5.17	4.50
Hardness (mg/L) as CaCO3	0.7	0.7	0.0	145.1	14.8	11.4	0.0		174.1	3.58	4.26

TABLE D.3. Analyses of Long-Term Cycle 3 Recovery Phase Water Samples, January to March 1990

WATER CHEM - LT3 - RECOVERY

Well	A	A	A	A	A	A	A	A	A	A	A	A	A	AM2	AS1MS	AS1MS
						LabRep										LabRep
MPCA ID --	960	960		950	960	960	960		950	960	960		950	602	606	606
Sample Type	III	III	IV	V	III	III	III	IV	V	III	III	IV	V			
Date sampled	900103	900103	900103	900103	900104	900104	900104	900104	900104	900105	900105	900105	900105	900125	900125	900125
Time	1000	1000	1125	1215	1010	1010	1010	1045	1135	1020	1020	1111	1145	1806	1555	1555
Graph volume	955	955	955	955	1937	1937	1937	1937	1937	2892	2892	2892	2892	2990	2990	2990
Cum vol m3	955	955	955	955	1937	1937	1937	1937	1937	2892	2892	2892	2892	2990	2990	2990
Replication	1	2	1	1	1	1	2	1	1	1	2	1	2	1	1	2
pH	6.82	6.82	6.97	6.81	6.85	6.85	6.85	7.07	6.84	6.90	6.90	6.99	NA	8.32	6.94	6.94
Water Temp °C	98.3	98.3	97.7	83.3	98.9	98.9	98.9	97.8	82.2	98.8	98.8	97.5	82.2	99.1	NA	NA
pH Temp °C	81.9	81.9	95.0	65.8	78.3	78.3	78.3	95.1	80.8	72.0	72.0	93.9	NA	23.6	15.7	15.7
pH, corrected	6.89	6.89	6.98	6.86	6.94	6.94	6.94	7.08	6.85	7.01	7.01	7.01	NA	8.38	NA	NA
SC (umho/cm)	477	477	489	430	498	498	498	424	430	425	425	467	430	431	451	451
DO (mg/L)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.05	0.05	0.1	0.1	6	5	5
Alk (meq/L)	4.50	4.50	4.52	4.99	4.51	4.54	4.56	4.56	4.55	3.86	4.60	4.40	4.38	4.67	4.71	4.71
SiO2 (mg/L) as Si	20.72	20.68	20.64	20.52	20.61	20.95	20.99	21.07	20.83	17.67	20.61	20.59	19.64	25.09	12.63	12.67
DIC (mg/L) as C	54.9	55.8	56.2	61.2	56.8	56.4	54.2	56.3	54.9	46.9	56.9	55.8	52.0	56.6	57.2	57.2
TOC (mg/L) as C	0.8	0.8	1.0	0.8	0.7	0.7	0.7	0.9	0.7	0.1	0.1	0.3	0.2	0.2	0.1	0.1
IC Analysis:																
SO4 (mg/L) as S	1.35	1.34	1.29	1.31	1.30	1.29	1.31	1.31	1.30	1.35	1.32	1.32	1.30	1.37	1.61	1.59
Cl (mg/L)	27.96	25.98	25.79	26.94	24.04	23.91	24.44	24.45	23.90	18.28	21.32	24.52	23.90	22.12	28.81	28.29
F (mg/L)	0.28	0.28	0.23	0.26	0.27	0.26	0.27	0.26	0.27	0.34	0.24	0.26	0.27	0.45	1.04	1.10
AA Analysis:																
Ca (mg/L)	3.04	3.29	3.10	3.36	2.91	2.91	2.91	2.52	2.52	2.84	2.91	2.91	2.65	4.58		
Mg (mg/L)	1.07	1.04	1.03	0.98	0.90	0.88	0.89	0.89	0.92	0.86	0.87	0.86	0.86	0.56	5.68	5.76
Na (mg/L)	106.7	107.3	106.7	110.9	105.7	105.7	105.7	105.7	106.0	106.4	106.1	105.4	106.1	106.7	68.25	68.57
K (mg/L)	4.75	4.75	4.78	4.71	5.02	4.98	5.02	5.02	4.92	5.22	5.19	5.12	5.09	5.35	11.45	11.55
Hardness (mg/L) as CaCO3	12.0	12.5	12.0	12.4	11.0	10.9	10.9	10.0	10.1	10.6	10.8	10.8	10.2	13.7	23.4	23.7

TABLE D.3. (continued)

WATER CHEM - LT3 -

Well	FIELD BLANK	A	A	A	A	A	A	A	A	FIELD BLANK	A	A LabRep	A	A	A	FIELD BLANK
MPCA ID --		960	960		950	960	960		950		960	960	960		950	
Sample Type		III	III	IV	V	III	III	IV	V		III	III	III	IV	V	
Date sampled	900125	900201	900201	900201	900201	900202	900202	900202	900202	900202	900205	900205	900205	900205	900205	900205
Time		900	900	1000	1030	1020	1020	1100	1130		915	915	915	1030	1045	
Graph volume	2990	5610	5610	5610	5610	6806	6806	6806	6806	6806	10170	10170	10170	10170	10170	10170
Cum vol m3	2990	5610	5610	5610	5610	6806	6806	6806	6806	6806	10170	10170	10170	10170	10170	10170
Replication	1	1	2	1	1	1	2	1	1	1	1	1	2	1	1	1
pH	NA	6.95	6.95	7.29	7.30	7.11	7.11	7.12	7.20	8.76	7.19	7.19	7.19	NA	NA	6.61
Water Temp °C	NA	95.6	95.6	95.0	83.3	95.0	95.0	94.4	81.7	NA	95.0	95.0	95.0	92.8	82.2	NA
pH Temp °C	NA	79.5	79.5	78.4	75.4	75.4	75.4	86.6	75.6	21.9	65.4	65.4	65.4	NA	NA	23.0
pH, corrected	NA	7.02	7.02	7.36	7.33	7.19	7.19	7.15	7.22	NA	7.29	7.29	7.29	NA	NA	NA
SC (umho/cm)	NA	384	425	374	410	410	410	425	448	NA	425	425	425	426	433	NA
DO (mg/L)	NA	0.1	0.1	0.2	0.1	0.2	0.2	0.1	0.1	NA	0.1	0.1	0.1	0.2	0.2	NA
Alk (meq/L)	ND	4.46	4.83	4.48	4.50	4.56	4.49	4.51	4.68	0.24	4.73	4.69	4.83	4.72	4.88	ND
SiO2 (mg/L) as Si	ND	21.74	21.66	21.94	21.86	21.62	21.90	21.82	21.54	0.06	21.34	21.30	21.34	21.18	21.16	ND
DIC (mg/L) as C	ND	55.4	59.1	55.0	56.7	56.7	55.7	56.8	58.5	2.5	58.8	59.6	58.1	58.1	59.7	0.6
TOC (mg/L) as C	ND	0.3	0.2	0.3	0.3	0.7	0.3	0.5	0.3	ND	0.2	0.3	0.3	0.3	0.3	ND
IC Analysis:																
SO4 (mg/L) as S	ND	1.36	1.34	1.40	1.39	1.38	1.34	1.42	1.42	ND	1.36	1.38	1.42	1.42	1.36	ND
Cl (mg/L)	ND	20.71	20.03	20.47	20.12	22.22	22.05	21.97	21.48	ND	23.48	23.27	23.71	24.00	23.82	ND
F (mg/L)	ND	0.24	0.20	0.31	0.31	0.27	0.23	0.36	0.35	ND	0.70	0.30	0.31	0.31	0.27	ND
AA Analysis:																
Ca (mg/L)	ND	3.81	3.81	3.49	3.29	3.68	3.68	3.62	3.49	ND	4.26	4.00	4.13	4.26	3.81	ND
Mg (mg/L)	ND	1.07	1.16	1.22	1.21	1.15	1.16	1.14	1.07	ND	1.33	1.30	1.31	1.31	1.31	ND
Na (mg/L)	ND	104.6	104.3	104.8	105.7	106.1	105.7	104.1	105.7	ND	105.1	104.5	104.5	104.1	103.8	ND
K (mg/L)	ND	5.19	5.19	5.56	5.66	5.76	5.59	5.73	5.76	ND	6.57	6.60	6.47	6.60	6.67	ND
Hardness (mg/L) as CaCO3	0.0	13.9	14.3	13.7	13.2	13.9	14.0	13.7	13.1		16.1	15.3	15.7	16.0	14.9	0.0

TABLE D.3. (continued)

WATER CHEM - LT3 - Well	A	A	A	A	A	A	A LabRep	A	A	FIELD BLANK	A	A	A	A	A	A
MPCA ID --	960	960		950	960	960	960		950		960	960		950	960	960
Sample Type	III	III	IV	V	III	III	III	IV	V		III	III	IV	V	III	III
Date sampled	900209	900209	900209	900209	900212	900212	900212	900212	900212	900212	900214	900214	900214	900214	900219	900219
Time	1320	1320	1400	1415	1420	1420	1420	1500	1515		1430	1430	1510	1525	1450	1450
Graph volume	14728	14728	14728	14728	18095	18095	18095	18095	18095	18095	20278	20278	20278	20278	25668	25668
Cum vol m3	14728	14728	14728	14728	18095	18095	18095	18095	18095	18095	20278	20278	20278	20278	25668	25668
Replication	1	2	1	1	1	2	2	1	1	1	1	2	1	1	1	2
pH	7.24	7.24	NA	NA	7.82	7.82	7.82	7.03	7.13	6.42	7.07	7.07	7.02	7.11	6.71	6.71
Water Temp °C	92.2	92.2	90.0	79.4	89.6	89.6	89.6	88.3	81.2	NA	87.8	87.8	87.8	75.0	84.4	84.4
pH Temp °C	64.8	64.8	NA	NA	75.7	75.7	75.7	86.2	75.7	23.0	76.6	76.6	85.1	76.2	69.7	69.7
pH, corrected	7.33	7.33	NA	NA	7.87	7.87	7.87	7.04	7.15	NA	7.11	7.11	7.03	7.11	6.76	6.76
SC (umho/cm)	416	416	430	432	420	420	420	433	434	NA	426	426	437	461	442	442
DO (mg/L)	0.05	0.05	0.1	0.1	0.1	0.1	0.1	0.1	0.1	NA	0.1	0.1	0.1	0.1	0.1	0.1
Alk (meq/L)	4.44	4.41	4.48	4.42	4.41	4.42	4.44	4.43	4.42	ND	4.42	4.39	4.41	4.41	4.45	4.45
SiO2 (mg/L) as Si	20.67	20.61	20.80	20.51	19.73	19.73	19.73	19.79	19.75	ND	19.42	19.48	19.52	19.44	18.05	17.96
DIC (mg/L) as C	55.6	55.4	54.3	55.1	54.8	55.0	55.2	55.1	55.0	ND	54.8	54.3	54.2	55.0	56.1	56.2
TOC (mg/L) as C	0.2	0.3	0.2	0.2	0.2	0.2	0.2	0.3	0.2	ND	0.2	0.2	0.2	0.2	0.2	0.2
IC Analysis:																
SO4 (mg/L) as S	1.42	1.42	1.43	1.42	1.44	1.31	1.34	1.35	1.32	ND	1.34	1.35	1.36	1.37	1.39	1.39
Cl (mg/L)	26.59	26.28	26.71	26.11	27.37	28.47	28.45	29.12	28.03	ND	29.98	29.43	29.36	28.05	30.31	31.64
F (mg/L)	0.29	0.37	0.31	0.33	0.32	0.43	0.44	0.44	0.43	ND	0.44	0.45	0.46	0.45	0.47	0.45
AA Analysis:																
Ca (mg/L)	5.93	5.36	5.16	4.71	6.97	6.77	6.64	6.97	6.32	7.80	7.29	7.03	6.32	7.03	9.50	9.38
Mg (mg/L)	1.70	1.64	1.64	1.73	1.98	2.00	2.00	1.99	1.91	ND	2.16	2.21	2.11	2.09	2.69	2.67
Na (mg/L)	102.5	102.5	101.9	100.9	101.2	101.2	100.6	99.96	99.91	ND	98.26	96.32	97.15	97.15	98.34	98.65
K (mg/L)	7.27	7.21	7.17	7.14	7.38	7.44	7.54	7.51	7.48	ND	7.58	7.61	7.68	7.54	8.02	8.08
Hardness (mg/L) as CaCO3	21.8	20.1	19.6	18.9	25.6	25.1	24.8	25.6	23.6	19.5	27.1	26.7	24.5	26.2	34.8	34.4

TABLE D.3. (continued)

WATER CHEM - LT3 -

Well	A	A	A	A	A	A	A	A	A	A	A	AS1 MS	A	A	A	A
			LabRep													
MPCA ID --		950	950	960	960		950	960	960		950	606	960	960		950
Sample Type	IV	V	V	III	III	IV	V	III	III	IV	V		III	III	IV	V
Date sampled	900219	900219	900219	900221	900221	900221	900221	900226	900226	900226	900226	900226	900302	900302	900302	900302
Time	1525	1535	1535	1500	1500	1520	1530	1500	1500	1525	1535	1915	920	920	950	1000
Graph volume	25668	25668	25668	27785	27785	27785	27785	33279	33279	33279	33279	33446	37386	37386	37386	37386
Cum vol m3	25668	25668	25668	27785	27785	27785	27785	33279	33279	33279	33279	33446	37386	37386	37386	37386
Replication	1	1	1	1	2	1	1	1	2	1	1	1	1	2	1	1
pH	7.20	7.08	7.08	6.86	6.86	7.18	7.11	7.23	7.23	7.10	7.08	6.63	6.82	6.82	7.20	6.94
Water Temp °C	83.3	72.2	72.2	83.3	83.3	82.2	73.3	78.9	78.9	77.8	69.4	NA	75.6	75.6	74.4	67.2
pH Temp °C	81.1	66.5	66.5	73.5	73.5	77.1	69.5	59.6	59.6	76.4	68.9	15.7	65.5	65.5	72.7	65.9
pH, corrected	7.21	7.09	7.09	6.89	6.89	7.20	7.12	7.27	7.27	7.10	7.08	NA	6.85	6.85	7.20	6.94
SC (umho/cm)	448	462	462	NA	NA	444	452	437	537	440	432	437	425	425	438	452
DO (mg/L)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	6	0.1	0.1	0.1	0.1
Alk (meq/L)	4.38	4.45	4.42	4.46	4.44	4.47	4.45	4.61	4.56	4.74	4.76	ND	4.67	4.65	4.69	4.76
SiO2 (mg/L) as Si	18.04	17.89	17.88	17.46	17.71	17.51	17.63	16.15	16.02	16.15	16.16	NA	14.94	14.43	14.94	14.64
DIC (mg/L) as C	55.4	56.5	56.5	56.3	55.5	52.8	52.6	55.7	54.2	57.0	57.8	NA	NA	NA	NA	NA
TOC (mg/L) as C	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.2	0.3	NA	NA	NA	NA	NA
IC Analysis:																
SO4 (mg/L) as S	1.38	1.37	1.38	1.40	1.43	1.48	1.49	1.47	1.44	1.42	1.43	NA	1.49	1.50	1.51	1.51
Cl (mg/L)	30.74	31.56	30.87	31.54	31.40	29.95	31.53	31.23	30.76	31.55	30.49	NA	30.05	29.32	29.80	29.79
F (mg/L)	0.40	0.35	0.35	0.34	0.37	0.46	0.35	0.33	0.65	0.76	0.82	NA	0.39	0.37	0.40	0.37
AA Analysis:																
Ca (mg/L)	7.87	8.87	9.31	9.75	10.07	9.12	10.26	13.15	12.78	9.88	12.15	NA	14.73	14.60	14.41	13.72
Mg (mg/L)	2.70	2.69	2.71	2.93	2.87	2.93	2.88	3.67	3.54	3.51	3.49	NA	4.07	4.17	4.14	4.32
Na (mg/L)	98.03	98.34	98.34	96.48	96.79	95.24	96.48	93.07	92.76	93.07	92.45	NA	89.97	89.66	88.12	89.35
K (mg/L)	8.24	8.39	8.33	7.95	8.11	8.14	7.98	8.39	8.30	8.36	8.27	NA	8.58	8.42	8.49	8.42
Hardness (mg/L) as CaCO3	30.8	33.2	34.4	36.4	37.0	34.8	37.5	47.9	46.5	39.1	44.7	NA	53.5	53.6	53.0	52.0

TABLE D.3. (continued)

WATER CHEM - LT3 -																
Well	A	A	A	A	A	A	A	A	A	A	A	A	A LabRep	A	A LabRep	A
MPCA ID --	960	960		950	960	960		950	960	960		950	950	960	960	960
Sample Type	III	III	IV	V	III	III	IV	V	III	III	IV	V	V	III	III	III
Date sampled	900307	900307	900307	900307	900309	900309	900309	900309	900314	900314	900314	900314	900314	900319	900319	900319
Time	1440	1440	1510	1520	1430	1430	1450	1515	1230	1230	1255	1305	1305	1315	1315	1315
Graph volume	43070	43070	43070	43070	45259	45259	45259	45259	52455	52455	52455	52455	52455	55754	55754	55754
Cum vol m3	43070	43070	43070	43070	45259	45259	45259	45259	52455	52455	52455	52455	52455	55754	55754	55754
Replication	1	2	1	1	1	2	1	1	1	2	1	1	1	1	1	2
pH	6.67	6.67	NA	7.24	NA	NA	NA	NA	6.79	6.79	7.08	6.96	6.96	6.75	6.75	6.75
Water Temp °C	71.1	71.1	68.9	63.9	68.3	68.3	68.3	62.7	61.1	61.1	60.0	57.8	57.8	58.3	58.3	58.3
pH Temp °C	57.2	57.2	NA	59.0	NA	NA	NA	NA	51.3	51.3	58.0	54.9	54.9	50.9	50.9	50.9
pH, corrected	6.69	6.69	NA	7.25	NA	NA	NA	NA	6.80	6.80	7.08	6.96	6.96	6.75	6.75	6.75
SC (umho/cm)	401	401	409	428	448	448	432	423	417	417	431	486	486	323	323	323
DO (mg/L)	0.1	0.1	0.1	0.1	0.1	0.1	NA	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Alk (meq/L)	4.61	4.64	4.58	4.61	4.50	4.54	4.54	4.59	4.66	4.58	4.54	4.62	4.64	4.49	4.54	4.51
SiO2 (mg/L) as Si	13.33	13.21	13.54	13.16	12.78	13.04	13.02	13.25	11.33	11.21	10.97	11.18	11.29	10.39	10.47	10.73
DIC (mg/L) as C	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	55.0	54.6	54.8
TOC (mg/L) as C	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1.1	1.0	1.0
IC Analysis:																
SO4 (mg/L) as S	1.50	1.50	1.51	1.51	1.52	1.51	1.51	1.51	1.50	1.45	1.47	1.53	1.50	1.47	1.50	1.50
Cl (mg/L)	27.40	28.04	27.61	27.20	26.28	26.05	26.01	26.16	21.45	21.31	21.40	21.53	21.42	18.89	18.52	18.98
F (mg/L)	0.35	0.37	0.42	0.35	0.35	0.35	0.35	0.35	0.32	0.31	0.32	0.33	0.32	0.29	0.29	0.31
AA Analysis:																
Ca (mg/L)	17.75	17.81	17.37	17.81	19.95	19.58	19.33	18.33	18.33	24.57	24.19	24.32	24.19	26.07	26.13	26.19
Mg (mg/L)	5.06	5.17	5.17	5.14	5.56	5.60	5.49	5.62	7.15	7.04	7.04	7.17	7.09	7.76	7.79	7.83
Na (mg/L)	82.54	83.47	80.06	82.85	79.75	79.44	78.51	78.82	68.60	68.98	66.74	67.98	67.98	62.40	62.41	62.09
K (mg/L)	8.68	8.71	8.52	8.61	8.64	8.58	8.52	8.61	8.49	8.33	8.30	8.77	8.30	8.42	8.47	8.52
Hardness (mg/L) as CaCO3	65.2	65.8	64.7	65.6	72.7	72.0	70.9	68.9	75.2	90.3	89.4	90.3	89.6	97.0	97.3	97.6

TABLE D.3. (continued)

WATER CHEM - LT3 - Well	A	A	A	A	A	A	A	A	A	A	ASI MS	A	A	A	A
MPCA ID --		950	960	960		950	960		950	960	606	960	960		950
Sample Type	IV	V	III	III	IV	V	III	IV	V	III		III	III	IV	V
Date sampled	900319	900319	900321	900321	900321	900321	900323	900323	900323	900327	900328	900328	900328	900328	900328
Time	1340	1350	1250	1250	1315	1325	1145	1215	1225	1703	1515	1405	1405	1435	1445
Graph volume	55754	55754	57760	57760	57760	57760	59838	59838	59838	64255	65262	65209	65209	65209	65209
Cum vol m3	55754	55754	57760	57760	57760	57760	59838	59838	59838	64255	65262	65209	65209	65209	65209
Replication	1	1	1	2	2	1	1	1	1	1	1	1	2	1	1
pH	7.11	7.05	6.85	6.85	7.14	6.93	6.94	6.95	6.75	6.85	8.75	6.83	6.83	7.13	6.99
Water Temp °C	57.2	55.1	56.1	56.1	56.1	55.0	53.9	52.8	52.2	50.0	NA	48.9	48.9	47.8	47.8
pH Temp °C	56.5	53.6	21.0	21.0	55.9	55.1	45.4	52.4	64.0	42.8	15.4	44.2	44.2	48.2	48.2
pH, corrected	7.11	7.05	6.76	6.76	7.14	6.93	6.94	6.95	6.74	6.84	NA	6.83	6.83	7.13	6.99
SC (umho/cm)	366	377	363	363	414	424	410	529	477	391	439	NA	NA	NA	NA
DO (mg/L)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	5	0.1	0.1	0.1	0.1
Alk (meq/L)	4.55	4.54	4.51	4.48	4.53	4.61	4.48	4.51	4.56	4.52	4.32	4.59	4.59	4.61	4.56
SiO2 (mg/L) as Si	10.56	10.56	9.96	10.30	10.18	10.18	10.26	9.79	9.83	9.20	13.65	9.04	9.04	9.06	9.06
DIC (mg/L) as C	54.1	54.7	53.9	54.2	54.1	54.5	53.9	54.1	55.1	53.7	51.9	55.7	55.7	55.6	55.2
TOC (mg/L) as C	1.0	1.1	0.8	0.9	0.8	0.9	0.9	1.1	1.3	0.8	0.9	0.8	0.8	0.9	0.9
IC Analysis:															
SO4 (mg/L) as S	1.48	1.49	1.52	1.48	1.54	1.48	1.54	1.51	1.47	1.52	1.59	1.52	1.52	1.52	1.51
Cl (mg/L)	19.68	19.11	17.39	18.43	18.42	18.48	17.22	16.51	16.74	14.44	23.12	14.00	14.00	13.90	13.80
F (mg/L)	0.28	0.30	0.25	0.28	0.25	0.25	0.29	0.28	0.28	0.27	0.77	0.29	0.29	0.30	0.29
AA Analysis:															
Ca (mg/L)	25.82	25.82	27.31	27.06	26.81	29.06	29.81	28.81	30.18	34.67	36.67	34.05	32.30	31.43	33.05
Mg (mg/L)	7.66	7.70	7.98	8.18	8.03	8.13	8.79	8.46	8.57	9.47	6.67	9.53	9.62	9.49	9.62
Na (mg/L)	62.09	62.40	60.55	59.62	58.69	59.62	58.38	53.11	57.14	52.80	47.54	47.85	47.85	47.54	47.23
K (mg/L)	8.20	8.20	8.11	8.08	8.30	8.20	8.02	7.95	8.14	7.98	8.05	7.76	7.92	7.95	8.17
Hardness (mg/L) as CaCO3	96.0	96.2	101.1	101.3	100.0	106.0	110.6	106.8	110.6	125.6	119.0	124.3	120.3	117.6	122.1

TABLE D.3. (continued)

WATER CHEM - LT3 -
Well

AVERAGE VALUES OF ANALYSES

MPCA ID --				
Sample Type		III	IV	V
Date sampled		Recov	Recov	Return
Time	Tot Vol	at	at	to
Graph volume	65952	Storage	HeatExch	Source
Cum vol m3				
Replication		Well		
pH				
Water Temp °C		78.2	75.7	71.2
pH Temp °C				
pH, corrected		7.03	7.11	7.04
SC (umho/cm)		412	436	439
DO (mg/L)		0.1	0.4	0.1
Alk (meq/L)		4.43	4.52	4.59
SiO2 (mg/L) as Si		16.21	16.73	16.77
DIC (mg/L) as C		51.25	49.04	49.41
TOC (mg/L) as C		0.44	0.51	0.44
IC Analysis:				
SO4 (mg/L) as S		1.39	1.43	1.42
Cl (mg/L)		23.70	24.83	24.75
F (mg/L)		0.33	0.38	0.35
AA Analysis:				
Ca (mg/L)		12.66	13.16	12.19
Mg (mg/L)		3.73	3.77	3.65
Na (mg/L)		86.97	86.99	89.96
K (mg/L)		7.09	7.29	7.29
Hardness (mg/L) as CaCO3		48.04	48.40	45.46

TABLE D.4. Aluminum Values Determined From Long-Term Cycle 3 Water Samples. ICP-AES analyses performed at PNL.

Well/Port	Sample Number	Concentration[a]
CM1	890914	0.026 mg/L
AM2	890919	0.024 mg/L
AM2	900125	0.027 mg/L
AM4	890921-1	0.018 mg/L
AM4	890921-2	0.022 mg/L
Port III	900105-1	0.111 mg/L
Port III	900201-1	0.049 mg/L
Port III	900201-2	0.052 mg/L
Port III	900202-1	0.055 mg/L
Port III	900202-2	0.055 mg/L
Port III	900205-1	0.046 mg/L
Port III	900205-2	0.046 mg/L
Port III	900209-1	0.038 mg/L
Port III	900209-2	0.039 mg/L
Port III	900212-1	0.029 mg/L
Port III	900212-2	0.029 mg/L
Port III	900214-1	0.027 mg/L
Port III	900214-2	0.024 mg/L
Port III	900219-1	0.015 mg/L
Port III	900219-2	0.009 mg/L
Port III	900221-1	0.007 mg/L
Port III	900221-2	0.008 mg/L
Port III	900226-1	<0.0055 mg/L
Port III	900226-2	0.007 mg/L
Port III	900302-1	<0.0055 mg/L
Port III	900302-2	<0.0055 mg/L
Port III	900307-1	<0.0055 mg/L
Port III	900307-2	<0.0055 mg/L
Port III	900309-1	<0.0055 mg/L
Port III	900309-2	<0.0055 mg/L
Port III	900314-1	<0.0055 mg/L
Port III	900314-2	<0.0055 mg/L
Port III	900319-1	<0.0055 mg/L
Port III	900319-2	<0.0055 mg/L
Port III	900321-1	<0.0055 mg/L
Port III	900321-2	<0.0055 mg/L

(a) Detection limit = 0.0055 mg/L

APPENDIX E

DATA FOR PUMPOUT FOLLOWING LONG-TERM CYCLE 2

TABLE E.1. Pumpout of Well A Following Long-Term Cycle 2

PUMPOUT - 1987		Temp.	CumVol	Remarks
Date	Time	(°C)	(10^3 m3)	
02-Sep	1228		0.000	A on
02-Sep	1300	41.1	0.043	
02-Sep	1330	41.9	0.073	
03-Sep	930	50.0	1.487	
03-Sep	934		1.487	A off
03-Sep	1030		1.487	A on
03-Sep	1045	50.3	1.505	
03-Sep	1130	50.0	1.584	
03-Sep	1150		1.584	A off
08-Oct	933		1.584	A on
08-Oct	1000	34.7	1.610	
08-Oct	1010	35.6	1.622	
08-Oct	1500	40.8	1.963	
09-Oct	1250	45.8	3.487	
11-Oct	1305	46.1	6.796	
12-Oct	1155	46.1	8.488	
13-Oct	1115	45.6	10.132	
14-Oct	1425	44.7	12.054	
15-Oct	1355	43.9	13.710	
16-Oct	1700	42.8	15.625	
17-Oct	750	42.5	16.670	
19-Oct	840	40.6	20.124	
22-Oct	640	38.3	25.075	
23-Oct	1550	37.2	27.429	
26-Oct	1538	35.6	32.523	
27-Oct	745	34.7	33.662	
28-Oct	1530	34.2	35.900	
29-Oct	1535	34.2	37.625	
02-Nov	750	31.7	43.889	
04-Nov	1430	30.6	47.790	
05-Nov	1645	30.3	49.652	
06-Nov	1318	29.7	51.124	
07-Nov	1415	29.7	52.906	
09-Nov	740	28.6	55.874	
09-Nov	1515	28.6	56.413	
10-Nov	1740	28.1	58.292	
11-Nov	1245	27.8	59.659	
12-Nov	1212	27.2	61.333	
13-Nov	1224	26.9	63.050	
14-Nov	1130	26.4	64.704	
15-Nov	1430	26.4	66.638	
16-Nov	1230	25.8	68.194	
17-Nov	1130	25.8	69.861	

TABLE E.1. (continued)

PUMPOUT - 1987 Date	 Time	Temp. (°C)	CumVol (10^3 m3)	Remarks
18-Nov	900	25.3	71.400	
19-Nov	1324	25.3	73.424	
20-Nov	940	24.7	74.859	
21-Nov	1230	24.4	76.778	
22-Nov	730	24.2	78.136	
23-Nov	924	23.9	79.993	
24-Nov	1648	23.6	82.245	
25-Nov	1300	23.3	83.680	
26-Nov	1230	23.1	85.365	
27-Nov	1342	23.1	87.164	
28-Nov	930	23.1	88.579	A off
28-Nov	1415	20.0	88.579	A on
28-Nov	1430	22.5	88.597	
29-Nov	1600	22.2	90.419	
30-Nov	2015	21.9	92.429	
01-Dec	1724	21.9	93.932	
02-Dec	1555	21.4	95.531	
03-Dec	1500	21.1	97.159	
04-Dec	1430	21.1	98.831	
05-Dec	1606	20.8	100.648	
06-Dec	1611	20.6	102.356	
07-Dec	1554	20.6	104.045	
08-Dec	1854	20.3	105.955	
09-Dec	1330	20.3	107.266	
10-Dec	1525	20.0	109.099	
11-Dec	1900	19.7	111.043	
12-Dec	1254	19.7	112.305	
13-Dec	1242	20.0	113.982	
14-Dec	1440	19.4	115.800	
15-Dec	900	19.4	117.072	
15-Dec	952	19.4	117.132	A off

TABLE E.2. Pumpout of Well B Following Long-Term Cycle 2

PUMPOUT - 1988 Date	Time	Temp. (°C)	CumVol (10^3 m3)	Remarks
Apr-88	1225		0.000	B on
05-Apr	1300	29.4	0.043	
06-Apr	600	31.9	1.272	
06-Apr	1500	32.5	1.917	
07-Apr	600	33.3	2.995	
08-Apr	1530	34.7	5.387	
09-Apr	1642	35.3	7.186	
10-Apr	1120	36.1	8.382	
11-Apr	900	36.9	10.060	
12-Apr	630	37.2	11.591	
13-Apr	636	37.8	13.301	
14-Apr	918	38.1	15.196	
15-Apr	818	38.3	16.817	
16-Apr	818	38.6	18.514	
17-Apr	1300	38.6	20.531	
18-Apr	1218	38.6	22.172	
19-Apr	1054	38.6	23.766	
20-Apr	1354	38.6	25.669	
22-Apr	600	38.6	28.505	
22-Apr	1415	38.6	29.089	
23-Apr	900	38.6	30.410	
24-Apr	1125	38.6	32.265	
26-Apr	609	38.6	35.279	
27-Apr	1215	38.6	37.393	
29-Apr	1230	38.1	40.785	
30-Apr	1530	38.1	42.676	
01-May	1130	38.1	44.076	
02-May	1630	38.1	46.115	
03-May	542	37.8	47.039	
04-May	1145	37.8	49.123	
05-May	1155	37.5	50.794	
06-May	806	37.5	52.203	
07-May	1300	36.9	54.201	
09-May	1324	36.4	57.579	
10-May	1648	36.1	59.492	
11-May	600	35.8	60.414	
12-May	930	35.8	62.327	
13-May	1325	35.8	64.270	
16-May	748	34.7	68.889	
17-May	1624	34.2	71.149	
18-May	1440	33.6	72.694	
19-May	1530	33.6	74.417	
20-May	1647	33.6	76.175	

TABLE E.2. (continued)

PUMPOUT - 1988		Temp.	CumVol	Remarks
Date	Time	(°C)	(10^3 m3)	
21-May	1624	33.1	77.813	
22-May	1645	32.8	79.508	
23-May	1230	32.2	80.878	
25-May	600	31.9	83.756	
26-May	1405	31.7	85.980	
27-May	1718	31.4	87.882	
28-May	1247	31.1	89.232	
29-May	1303	31.1	90.922	
30-May	1324	30.6	92.615	
30-May	1500	30.3	92.727	
31-May	624	30.3	93.799	
01-Jun	1429	30.0	96.031	
02-Jun	1355	30.0	97.657	
03-Jun	1201	29.4	99.200	
04-Jun	1548	29.2	101.126	
06-Jun	524	28.3	103.717	
07-Jun	1402	28.3	105.935	
08-Jun	720	28.1	107.117	
09-Jun	1426	28.1	109.236	
10-Jun	812	27.5	110.450	
13-Jun	719	26.9	115.300	
14-Jun	711	26.4	116.931	
15-Jun	36	26.4	118.118	B off
			118.118	
17-Jun	830	21.4	118.118	B on
18-Jun	1806	25.3	120.563	
19-Jun	715	25.3	121.520	B off
			121.520	
20-Jun	751	22.2	121.520	B on
20-Jun	1500	25.8	122.048	
21-Jun	1108	25.6	123.538	
22-Jun	1824	25.6	125.826	
23-Jun	1327	25.3	127.211	
23-Jun	2306	25.3	127.913	B off
			127.913	
27-Jun	712	22.2	127.913	B on
27-Jun	1452	25.0	128.462	
28-Jun	1500	25.3	130.191	
29-Jun	1007	24.7	131.561	
30-Jun	1448	24.4	133.615	
01-Jul	1403	24.4	135.274	
02-Jul	911	24.4	136.632	
05-Jul	1505	23.3	142.123	

TABLE E.2. (continued)

PUMPOUT - 1988 Date	Time	Temp. (°C)	CumVol (10^3 m3)	Remarks
06-Jul	958	23.3	143.456	
06-Jul	1903	23.1	144.096	
07-Jul	1431	23.1	145.468	
08-Jul	1502	22.8	147.190	
09-Jul	1104	22.5	148.593	
10-Jul	1723	22.2	150.718	
11-Jul	1450	22.2	152.210	
12-Jul	1448	22.2	153.867	
13-Jul	618	21.9	154.948	
14-Jul	736	21.7	156.715	
15-Jul	130	21.7	157.964	B off
			157.964	
15-Jul	1311	21.1	157.964	B on
15-Jul	1341	21.1	158.000	B off
			158.000	
18-Jul	942	18.6	158.000	B on
18-Jul	1100	20.0	158.000	
20-Jul	1059	21.1	161.580	
21-Jul	1009	21.1	164.081	
22-Jul	1600	20.6	166.301	
23-Jul	718	20.6	167.431	
25-Jul	712	20.3	170.971	
26-Jul	1442	20.3	173.298	
27-Jul	1630	20.3	175.201	
28-Jul	1335	19.7	176.757	
29-Jul	936	19.7	178.247	
29-Jul	1206	19.7	178.432	B off

TABLE E.3. Analyses of Water Samples From Pumpout of Well A Following Long-Term Cycle 2, 1986 - 1987

Well	A	A	A	A	A	A	A	A	A
Sample Type	III	III	III	III	III	III	III	III	III
Date sampled	870902	871008	871009	871014	871016	871022	871029	871105	871116
Time	1525	1540	1540	1000	1520	1500	1515	1450	1515
Cum vol m3	207	2010	3674	12054	15625	25665	37649	49516	68194
Neg graph volume	-116813	-115010	-113346	-104966	-101395	-91355	-79371	-67504	-48826
Replication	1	1	1	1	1	1	1	1	1
pH Temp °C	40.5	31.2	26.5	33.9	30.4	22.8	26.5	27.7	23.7
pH	6.75	7.21	7.47	7.34	7.29	7.27	7.22	6.93	6.86
SC (umho/cm)	505	502	505	482	494	445	435	423	419
DO (mg/L)	0.1	0.1	0.1	0.1	0.05	0.1	0.05	0.05	0.1
Alk (meq/L)	4.82	4.93	4.79	4.69	4.68	4.63	4.59	4.58	4.57
SiO2 (mg/L)	8.00	7.38	4.79	9.09	8.73	8.12	7.64	7.10	6.41
DIC (mg/L) as C	55.87	60.50	58.89	58.56	58.06	57.46	56.22	56.22	53.70
IC Analysis:									
SO4 (mg/L) as S	4.06	3.72	3.47	3.74	3.69	NA	3.03	2.84	2.69
Cl (mg/L)	6.18	4.76	9.38	9.11	8.34	6.36	4.80	3.93	3.68
F (mg/L)	0.38	0.37	0.38	0.39	0.39	0.39	0.39	0.40	0.39
NO3 (mg/L) as N	ND	ND	ND	ND	ND	ND	ND	ND	ND
NO2 (mg/L) as N	ND	ND	ND	ND	ND	ND	ND	ND	ND
PO4 (mg/L) as P	ND	ND	ND	ND	ND	ND	ND	ND	ND
AA Analysis:									
Ca (mg/L)	52.73	52.06	35.78	37.53	39.03	42.13	44.38	46.55	48.56
Mg (mg/L)	14.58	14.58	10.42	11.71	12.08	12.57	13.82	14.43	15.39
Na (mg/L)	29.95	28.19	56.39	47.05	43.92	36.78	31.75	27.59	20.18
K (mg/L)	10.01	9.81	9.05	8.55	8.52	8.04	7.77	7.65	7.30
Fe (mg/L)	0.46	0.40	ND	0.25	0.28	0.34	0.39	0.43	0.55
Mn (mg/L)	ND	ND	ND	ND	ND	ND	ND	ND	ND
Hardness (mg/L) as CaCO3	191.69	190.03	132.25	141.91	147.18	156.93	167.69	175.66	184.60

TABLE E.3. (continued)

Well	A	A	A	A	A
Sample Type	III	III	III	III	III
Date sampled	871119	871125	871207	871210	871215
Time	1505	1442	1505	1521	815
Cum vol m3	73543	83848	104045	109099	117020
Neg graph volume	-43477	-33172	-12975	-7921	0
Replication	1	1	1	1	1
pH Temp °C	19.5	20.3	16.9	17.3	14.7
pH	7.16	7.05	6.79	6.65	7.02
SC (umho/cm)	420	426	443	490	413
DO (mg/L)	0.1	0.1	0.1	0.05	0.1
Alk (meq/L)	4.57	4.55	4.57	4.56	4.57
SiO2 (mg/L)	6.25	5.98	5.57	5.48	5.37
DIC (mg/L) as C	53.49	55.32	53.68	53.52	54.57
IC Analysis:					
SO4 (mg/L) as S	2.69	2.58	2.43	2.41	2.40
Cl (mg/L)	3.00	2.78	2.46	2.44	2.41
F (mg/L)	0.39	0.38	0.37	0.37	0.37
NO3 (mg/L) as N	ND	ND	ND	ND	ND
NO2 (mg/L) as N	ND	ND	ND	ND	ND
PO4 (mg/L) as P	ND	ND	ND	ND	ND
AA Analysis:					
Ca (mg/L)	48.47	50.39	51.73	50.89	51.90
Mg (mg/L)	17.13	16.04	16.48	16.50	16.21
Na (mg/L)	19.62	18.54	16.49	14.68	14.71
K (mg/L)	7.45	7.22	7.17	7.26	7.31
Fe (mg/L)	0.56	0.71	0.62	0.64	0.66
Mn (mg/L)	ND	ND	ND	ND	ND
Hardness (mg/L) as CaCO3	191.57	191.86	197.00	195.00	196.31

TABLE E.4. Analyses of Water Samples From Pumpout of Well B Following Long-Term Cycle 2, 1986 - 1987

Well	B	B	B	B	B	B	B	B	B
Sample Type	I	I	I	I	I	I	I	I	I
Date sampled	880401	880405	880406	880408	880411	880413	880415	880418	880420
Time	1400	1520	1410	1355	1420	930	1320	1410	1355
Cum vol m3	0	210	1860	5270	10440	13510	17170	22310	25670
Neg graph volume									
Replication	AVG	AVG	AVG	AVG	AVG	AVG	AVG	AVG	AVG
pH Temp °C	23.6	25.1	26.6	18.8	30.5	24.2	28.0	27.6	30.1
pH	7.10	7.00	6.90	7.06	7.04	7.04	7.03	6.96	6.92
SC (umho/cm)	482	509	519	530	502	485	540	521	629
DO (mg/L)	0.8	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1
Alk (meq/L)	5.04	5.05	5.00	4.95	4.94	4.92	4.91	4.89	4.91
SiO2 (mg/L)	7.53	7.82	8.64	9.60	10.43	10.84	11.17	11.37	11.44
DIC (mg/L) as C	61.55	61.54	61.49	61.01	60.15	58.24	58.95	59.07	58.83
IC Analysis:									
SO4 (mg/L) as S	4.25	3.83	3.45	3.47	3.50	1.61	0.00	1.33	2.74
Cl (mg/L)	7.16	7.35	8.04	9.12	10.40	4.80	0.00	5.13	10.77
F (mg/L)	0.29	0.38	0.44	0.44	0.41	0.25	0.00	0.19	0.39
NO3 (mg/L) as N	ND	ND	ND	ND	ND	ND	ND	ND	ND
NO2 (mg/L) as N	ND	ND	ND	ND	ND	ND	ND	ND	ND
PO4 (mg/L) as P	ND	ND	ND	ND	ND	ND	ND	ND	ND
AA Analysis:									
Ca (mg/L)	44.08	41.50	38.42	35.11	32.22	30.92	29.77	29.25	29.93
Mg (mg/L)	14.67	14.09	12.47	11.18	10.05	9.61	9.30	8.98	8.73
Na (mg/L)	39.27	42.50	48.51	55.13	60.67	61.75	63.84	66.04	66.04
K (mg/L)	7.64	7.79	8.13	8.45	8.78	8.87	8.85	8.93	8.97
Fe (mg/L)	1.27	1.12	1.01	0.98	0.98	1.00	0.99	1.00	0.92
Mn (mg/L)	ND	ND	ND	ND	ND	ND	ND	ND	ND
Hardness (mg/L) as CaCO3	170.46	161.62	147.17	133.69	121.81	116.78	112.63	110.00	110.65

TABLE E.4. (continued)

Well	B	B	B	B	B	B	B	B	B
Sample Type	I	I	I	I	I	I	I	I	I
Date sampled	880422	880428	880504	880506	880516	880519	880526	880606	880609
Time	1310	1355	1205	1405	1347	1350	1340	1300	1405
Cum vol m3	29010	39200	49150	52620	69310	74300	85950	104055	109022
Neg graph volume									
Replication	AVG	AVG	AVG	AVG	AVG	AVG	AVG	AVG	AVG
pH Temp °C	29.2	31.0	32.2	29.4	17.2	29.5	29.2	28.2	26.4
pH	7.00	7.04	6.86	6.84	6.96	6.92	6.86	7.57	6.76
SC (umho/cm)	547	528	521	435	493	502	493	NA	443
DO (mg/L)	0.1	0.1	0.1	0.1	0.1	0.1	0.2	NA	0.2
Alk (meq/L)	4.88	4.87	4.85	4.77	4.79	4.80	4.70	4.70	4.71
SiO2 (mg/L)	11.50	11.30	11.13	10.58	9.80	9.22	8.47	7.82	7.60
DIC (mg/L) as C	58.83	58.56	58.43	58.42	59.86	58.28	55.97	56.22	55.43
IC Analysis:									
SO4 (mg/L) as S	2.69	2.43	2.35	2.21	2.02	1.96	1.88	1.60	1.54
Cl (mg/L)	10.85	10.64	10.52	9.93	8.92	8.06	7.17	5.75	5.22
F (mg/L)	0.29	0.30	0.28	0.29	0.30	0.39	0.39	0.28	0.27
NO3 (mg/L) as N	ND	ND	ND	ND	ND	ND	ND	ND	ND
NO2 (mg/L) as N	ND	ND	ND	ND	ND	ND	ND	ND	ND
PO4 (mg/L) as P	ND	ND	ND	ND	ND	ND	ND	ND	ND
AA Analysis:									
Ca (mg/L)	30.08	28.40	28.70	29.74	32.52	33.59	35.66	37.37	39.13
Mg (mg/L)	8.72	8.95	8.92	9.42	10.02	10.79	11.83	12.22	12.84
Na (mg/L)	65.38	64.72	63.73	60.26	27.74	24.76	43.58	39.04	37.52
K (mg/L)	8.88	8.83	8.88	8.77	4.34	4.15	8.21	8.16	7.99
Fe (mg/L)	0.89	0.82	0.81	0.79	0.76	0.75	0.73	0.63	0.81
Mn (mg/L)	ND	ND	ND	ND	ND	ND	ND	ND	ND
Hardness (mg/L) as CaCO3	111.01	107.75	108.38	113.02	122.43	128.29	137.76	143.60	150.58

TABLE E.4. (continued)

Well	B	B	B	B	B	B	B	B
Sample Type	I	I	I	I	I	I	I	I
Date sampled	880620	880623	880630	880707	880714	880721	880726	880728
Time	1413	1410	1430	1405	1420	1005	1405	1315
Cum vol m3	121990	127270	133590	145440	157180	164080	173260	176740
Neg graph volume								
Replication	AVG	AVG	AVG	AVG	AVG	AVG	AVG	AVG
pH Temp °C	26.0	26.5	26.2	NA	25.0	23.5	23.2	23.1
pH	6.63	6.61	6.59	6.80	6.70	6.50	6.80	6.80
SC (umho/cm)	441	436	437	431	420	414	413	415
DO (mg/L)	0.2	0.2	0.2	0.2	0.4	0.1	0.1	0.2
Alk (meq/L)	4.63	2.30	2.32	4.61	4.60	4.58	4.57	4.56
SiO2 (mg/L)	7.30	7.06	6.79	6.58	6.37	6.16	6.12	6.12
DIC (mg/L) as C	54.37	54.89	54.83	53.83	54.00	55.01	27.91	0.00
IC Analysis:								
SO4 (mg/L) as S	1.60	1.63	1.50	1.65	1.63	1.37	1.27	1.33
Cl (mg/L)	5.01	4.69	4.28	4.16	3.87	3.30	2.98	3.06
F (mg/L)	0.30	0.32	0.31	0.29	0.14	0.14	0.29	0.30
NO3 (mg/L) as N	ND	ND	ND	ND	ND	ND	ND	ND
NO2 (mg/L) as N	ND	ND	ND	ND	ND	ND	ND	ND
PO4 (mg/L) as P	ND	ND	ND	ND	ND	ND	ND	ND
AA Analysis:								
Ca (mg/L)	39.96	40.47	42.20	43.79	44.00	44.66	44.87	44.94
Mg (mg/L)	13.04	13.51	13.85	14.07	14.42	14.36	14.63	14.59
Na (mg/L)	33.13	31.74	29.87	28.44	24.07	24.04	22.66	21.70
K (mg/L)	7.89	7.87	7.84	7.70	7.65	7.53	7.55	7.53
Fe (mg/L)	0.87	0.76	0.68	0.57	0.63	0.64	0.62	0.63
Mn (mg/L)	ND	ND	ND	ND	ND	ND	ND	ND
Hardness (mg/L) as CaCO3	153.45	156.65	162.40	167.26	169.25	170.62	172.27	172.30

APPENDIX F

LONG-TERM SUBCYCLE 3b AND PUMPOUT FOLLOWING LONG-TERM CYCLE 3

APPENDIX F

LONG-TERM SUBCYCLE 3b AND PUMPOUT FOLLOWING LONG-TERM CYCLE 3

PNL personnel were interested in possible high-temperature (as close to 150°C as possible) experimental ATES subcycle to obtain data regarding the extent to which silica scaling takes place at high temperatures. Silica scaling has been calculated to be a potential problem in high-temperature ATES systems. At the time of the inquiry (April, 1990), the applied part of LT3 had been completed. The availability of steam in the late spring of 1990, and the fact that LT3 had included only about 47 days of injection rather than the planned and permitted 90 days, made it possible attempt this short subcycle, LT3b.

LT3b - HIGH TEMPERATURE SUBCYCLE

The high-temperature subcycle (LT3b) was planned for 7 days of injection at as high a temperature as possible, a storage period of the same duration, and a recovery period until an equal amount of water had been withdrawn. The heating load was to be the air-cooled radiator, which had been the dummy heating load during previous cycles.

Thermocouples were installed in radiator tubes at intake points, halfway points, and exit points for temperature information. Steel rods were installed in tubes adjacent to those with thermocouples at the same points in the radiator. These were to provide easily removeable precipitation surfaces for examination following recovery. Because of the delays caused by the pump failure during recovery, these studies were abandoned. Such a study would still be of considerable interest.

The injection phase was from May 31 to June 7, 1990, with the injected water heated to as close to 150°C as possible (Table F.1). Injected water temperatures averaged 131.4°C (268°F); source water averaged 52.4°C (126°F); flows averaged 55.0 m^3/hr. A total of 0.861 GWh of energy was added to the 9.39×10^3 m^3 of heated water stored the aquifer.

TABLE F.1. Flows and Temperatures During LT3b Injection

Date	Total Hours	Flow (m^3/hr)	Injection Temp.(°C)	Source Temp.(°C)	Volume (10^3 m^3)	Energy (MWh)
31-May-90	14	56.68	127.6	50.5	0.795	71.1
01-Jun	38	55.84	129.5	51.2	2.137	122.0
02-Jun	62	55.52	129.9	52.3	3.471	120.3
03-Jun	86	54.41	132.0	52.2	4.779	121.2
04-Jun	110	54.86	132.7	52.8	6.097	122.3
05-Jun	134	54.51	135.1	53.1	7.405	124.5
06-Jun	158	54.41	135.8	53.3	8.713	125.3
07-Jun-90	170.55	53.80	122.9	53.5	9.389	54.5
TOTALS/AVG	170.55	54.97	131.4	52.4	9.389	861.1

The storage period was scheduled to end on June 20, 1990. Heat recovery was attempted; however, the storage well pump failed after a short period of operation. The pump failed when the recovered water reached temperatures above 100°C (212°F). Highest temperature water to be recovered during June was 115.6°C (246°F). Many attempts were made to pump the hot water; adjustments of pump settings were made in consultation with the pump manufacturer's representative; all attempts ended with the pump binding up when the water became hot. Following several attempts to recover the hot water, the pump was removed from the well, examined in the field, and sent to the manufacturer for detailed examination. Factory examination revealed that the clearances of the impellers in the bowls met specifications at low temperatures (<80°C), but did not meet specifications at high temperatures (>90°C). The pump was modified, repaired, returned, and reinstalled. Installation was completed during the second week of November, 1990.

Heat recovery finally began on November 16, 1990. The long delay in beginning recovery seriously affected the purpose of LT3b. The water temperature at the beginning of recovery was only 86.9°C (188°F), not nearly high enough to be of interest regarding potential silica precipitation in the heat exchanger. Thus, the purposes of LT3b were not fulfilled. As a result of the delay in beginning recover, a decision was made to pump the water recovered from storage to waste rather than returning the water to the source well. Pumpout of the storage well (Well A) effectively started with the beginning of recovery (Table F.2).

Average temperature of the water recovered (until a volume equal to that stored was recovered from the aquifer) was 71.2°C. Flow was directed through the radiator and then to waste; discharge temperature for this period averaged 42.0°C; and the flow rate was 53.3 m^3 hr^3.

Pumpout continued until December 20 when the system was shut down for the winter. April 24, 1991 pumpout of the storage well continued. A few power outages and some repair work interrupted pumpout during April and May. Pumpout ended on June 12, when a total of 95.7 x 10^3 m^3 had been pumped and the water temperature was 17.5°C. The average temperature of the water pumped from the storage well following LT3b injection was 61.1°C.

The source well (Well B) was pumped out June 26 to August 27, 1991 (Table F.3). A total of 87.0 x 10^3 m^3 of water was pumped from the source well during this time. Highest water temperature was 43.9°C, reached after only about 4500 m^3 had been pumped from the well. Final temperature was 21.1°C.

TABLE F.2. Flows and Temperatures During LT3b Recovery and Pumpout of Storage Well Following Long-Term Cycle 3, 1990-1991

RECOVERY/ PUMPOUT WELL A		Recov. Temp.	Waste Temp.	Cum. Flow	Remarks
Date	Time	(°C)	(°C)	10^3 m^3	
15-Nov-90	1248	26.7	26.7	0.000	A on
15-Nov	1330	83.9	54.4	0.003	
15-Nov	1450	86.7	41.1	0.011	
15-Nov	1500	86.7	41.1	0.012	A off
16-Nov	1057			0.012	A on
16-Nov	1116	80.0	60.0	0.026	
16-Nov	1130	82.2	56.7	0.038	
16-Nov	1145	84.4	51.7	0.050	
16-Nov	1200	85.8	48.3	0.067	
16-Nov	1230	86.4	50.0	0.101	
16-Nov	1257	86.4	50.0	0.139	A off
16-Nov	1318	86.4	61.7	0.139	A on
16-Nov	1400	86.9	50.0	0.171	
16-Nov	1500	86.9	48.9	0.233	
16-Nov	1600	86.9	49.4	0.296	
16-Nov	1700	87.2	48.9	0.361	
16-Nov	2100	86.7	45.6	0.607	
17-Nov	300	85.3	44.4	0.981	
17-Nov	800	84.4	43.3	1.289	
17-Nov	900	84.2	45.0	1.352	
17-Nov	1000	83.9	45.6	1.414	
17-Nov	1800	81.1	45.6	1.976	
18-Nov	200	79.7	44.4	2.406	
18-Nov	700	78.3	43.3	2.717	
18-Nov	1500	76.7	46.1	3.212	
18-Nov	2140	75.6	43.3	3.621	
19-Nov	500	73.1	40.0	4.082	
19-Nov	600	73.1	38.9	4.145	
19-Nov	1400	71.4	44.4	4.643	
19-Nov	2150	70.0	42.8	5.131	
20-Nov	500	68.1	41.1	5.578	
20-Nov	1203	66.9	41.1	6.017	
20-Nov	1624	66.1	41.7	6.284	
20-Nov	2133	65.3	43.3	6.600	
21-Nov	500	63.6	43.3	7.055	
21-Nov	530	63.6	43.3	7.084	
21-Nov	800	63.3	43.3	7.084	
21-Nov	900	63.3	42.2	7.226	
21-Nov	942	63.3	42.2	7.313	A off
21-Nov	1118	61.7	42.2	7.313	A on
21-Nov	1130	61.7	42.2	7.346	

TABLE F.2. (Continued)

RECOVERY/ PUMPOUT WELL A		Recov. Temp. (°C)	Waste Temp. (°C)	Cum. Flow 10^3 m^3	Remarks
Date	Time				
21-Nov	1300	61.7	41.1	7.439	
21-Nov	2220	60.8	36.1	8.014	
22-Nov	418	59.4	36.7	8.373	
22-Nov	1227	58.9	35.0	8.872	
22-Nov	2100	57.2	35.0	9.394	Recovery Ends
23-Nov	500	55.6	32.2	9.883	
23-Nov	1100	54.7	31.1	10.251	
23-Nov	1724	53.9	30.6	10.646	
23-Nov	2215	53.1	30.0	10.943	
24-Nov	420	52.8	31.1	11.317	
24-Nov	1130	51.9	32.8	11.758	
24-Nov	1727	51.1	31.1	12.125	
24-Nov	2200	50.6	30.0	12.402	
25-Nov	420	49.4	26.7	12.793	
25-Nov	1100	48.9	26.1	13.203	
25-Nov	1636	48.3	26.7	13.546	
25-Nov	2136	48.3	26.7	13.856	
26-Nov	509	47.2	26.7	14.318	
26-Nov	1330	46.1	27.8	14.839	
26-Nov	1612	45.8	28.9	14.996	
26-Nov	2148	45.3	27.8	15.340	
27-Nov	500	44.4	26.7	15.783	
27-Nov	1609	43.6	26.1	16.465	
27-Nov	2133	43.1	25.6	16.794	
28-Nov	602	42.2	25.6	17.314	
28-Nov	900	42.2	25.6	17.496	
28-Nov	1603	41.4	25.0	17.928	
28-Nov	2121	41.4	24.4	18.249	
29-Nov	500	41.1	23.9	18.721	
29-Nov	1515	40.6	28.9	19.340	
29-Nov	2203	39.7	28.3	19.754	
30-Nov	530	39.2	27.2	20.207	
30-Nov	1639	38.6	22.2	20.885	
30-Nov	2142	38.3	27.2	21.195	
01-Dec	509	37.8	23.9	21.646	
01-Dec	2109	36.9	25.0	22.620	
02-Dec	500	36.7	22.8	23.096	
02-Dec	1703	35.8	22.8	23.833	
02-Dec	2233	35.8	23.3	24.165	
03-Dec	600	35.8	22.2	24.615	
03-Dec	1615	34.4	23.3	25.239	

TABLE F.2. (Continued)

RECOVERY/ PUMPOUT WELL A Date	Time	Recov. Temp. (°C)	Waste Temp. (°C)	Cum. Flow 10^3 m^3	Remarks
03-Dec	2127	34.4	22.2	25.554	
04-Dec	500	33.9	18.3	26.023	
04-Dec	1706	33.9	25.0	26.748	
05-Dec	615	33.3	24.4	27.548	
05-Dec	1624	32.5	25.6	28.168	
06-Dec	500	32.5	23.9	28.931	
06-Dec	1539	31.4	25.0	29.579	
06-Dec	2200	31.1	25.0	30.024	
07-Dec	500	31.1	24.4	30.390	
07-Dec	1612	30.6	23.3	31.070	
08-Dec	600	30.6	24.4	31.906	
08-Dec	1406	30.6	27.2	32.395	
09-Dec	600	29.4	23.9	33.368	
09-Dec	1324	29.2	26.7	33.809	
10-Dec	500	28.6	24.4	34.751	
10-Dec	1630	28.3	24.4	35.445	
10-Dec	2139	28.3	23.3	35.758	
11-Dec	600	28.1	22.8	36.264	
11-Dec	1600	28.3	23.9	36.868	
11-Dec	2218	28.3	23.9	37.250	
12-Dec	600	27.8	22.8	37.717	
12-Dec	1600	27.2	22.2	38.334	
13-Dec	600	26.7	19.4	39.169	
13-Dec	2318	26.7	21.1	40.221	
14-Dec	530	26.4	20.0	40.593	
14-Dec	2145	26.1	21.7	41.578	
15-Dec	620	25.8	20.0	42.097	
15-Dec	1200	25.6	21.7	42.440	
15-Dec	2151	25.6	20.0	43.036	
16-Dec	515	25.6	20.0	43.484	
16-Dec	2124	25.0	20.0	44.461	
17-Dec	600	25.0	20.6	44.982	
17-Dec	2109	24.7	18.9	45.898	
18-Dec	600	24.7	17.2	46.432	
18-Dec	2221	24.4	19.4	47.422	
19-Dec	600	24.2	19.4	47.882	
19-Dec	2257	23.6	19.4	48.906	
20-Dec	600	23.6	18.9	49.332	
20-Dec	1000	23.6	20.6	49.574	
20-Dec-90	1006	23.6	20.6	49.581	A off

TABLE F.2. (Continued)

RECOVERY/ PUMPOUT WELL A		Recov. Temp. (°C)	Waste Temp. (°C)	Cum. Flow 10^3 m^3	Remarks
Date	Time				
24-Apr-91	1015			49.583	A on
24-Apr	1045	26.7	26.7	49.587	
24-Apr	1145	27.2	27.2	49.594	
24-Apr	1245	27.2	27.2	49.602	A off
25-Apr	720	26.1		49.602	A on
25-Apr	800	26.1	29.4	49.622	
25-Apr	1300	26.9	28.3	49.834	
25-Apr	2000	26.7	28.3	50.253	
26-Apr	700	26.7	27.8	50.938	
26-Apr	1500	26.1	27.2	51.379	
27-Apr	854	26.1	27.2	52.390	
28-Apr	1600	25.8	26.7	54.209	
29-Apr	657	25.6	26.1	55.066	
29-Apr	2136	25.0	26.7	55.865	
30-Apr	1200	25.0	26.1	56.599	
01-May	320	24.4	25.6	57.690	A off
01-May	700	24.2	24.4	57.690	A on
01-May	715	23.9	24.4	57.702	
01-May	2118	23.9	24.4	58.504	
02-May	648	23.9	24.4	59.043	
02-May	1154	23.6	24.4	59.335	
03-May	642	23.6	23.9	60.403	
03-May	1406	23.3	23.3	60.823	
04-May	900	23.3	23.9	61.896	
05-May	945	22.5	22.2	63.301	
06-May	627	22.5	22.2	64.477	
07-May	709	22.2	23.3	65.876	
07-May	2000	21.4	22.2	66.614	
08-May	618	21.4	22.2	67.183	
09-May	724	20.8	21.1	68.603	
09-May	1415	20.8	27.8	68.995	
10-May	845	20.8	25.6	70.032	
12-May	1045	20.3	27.8	72.855	
13-May	1948	20.0	25.6	74.712	
14-May	721	20.0	24.4	75.359	
15-May	733	19.7	25.0	76.725	
15-May	1420	19.7	25.0	77.105	A off
15-May	1420			77.105	A off
20-May	928	20.0	20.0	77.105	A on
20-May	940			77.117	A off

TABLE F.2. (Continued)

RECOVERY/ PUMPOUT WELL A Date	Time	Recov. Temp. (°C)	Waste Temp. (°C)	Cum. Flow 10^3 m^3	Remarks
20-May	1209	20.0		77.117	A on
20-May	1500	19.7	25.0	77.131	
20-May	2120	19.4	24.4	77.496	
21-May	800	19.4	24.4	77.640	A off
23-May	845	19.7	21.1	77.640	A on
24-May	854	19.7	21.1	77.647	
25-May	812	19.7	21.1	78.973	
26-May	1633	19.4	21.7	80.807	
27-May	912	19.2	21.7	81.750	
28-May	1415	18.9	22.8	83.391	
29-May	740	18.9	21.7	84.375	
29-May	1500	18.9	21.1	84.537	
29-May	1506	18.9	21.1	84.537	A off
04-Jun	924	18.3	21.1	84.537	A on
04-Jun	1000	18.3	21.1	84.559	
04-Jun	1336	18.3	23.9	84.771	
06-Jun	654	18.3	21.1	87.116	
09-Jun	1300	18.1	22.8	91.527	
10-Jun	1554	17.5	22.8	93.045	
11-Jun	718	17.5	21.1	93.913	
12-Jun	1500	17.5	22.8	95.711	
12-Jun-91	1524	17.5	22.8	95.719	A off

TABLE F.3. Flows and Temperatures During Pumpout of Source Well Following Long-Term Cycle 3, 1991

PUMPOUT WELL B Date	Time	Recov. Temp. (°C)	Waste Temp. (°C)	Cum. Flow 10^3 m^3	Remarks
26-Jun	1406	15.6	15.6	0.000	B on
26-Jun	1418	27.2	27.2	0.011	
26-Jun	1445	33.3	33.9	0.019	
26-Jun	1500	33.9	33.9	0.036	
26-Jun	1540	35.0	34.4	0.078	
27-Jun	1400	42.8	44.4	1.442	
28-Jun	1300	43.6	45.6	2.818	
29-Jun	1900	43.9	40.0	4.623	
01-Jul	724	43.6	40.0	6.783	
02-Jul	715	43.3	38.9	8.199	
03-Jul	1648	42.8	37.8	10.201	
04-Jul	718	42.5	34.4	11.066	
05-Jul	1436	42.2	36.1	12.928	
06-Jul	833	41.7	36.7	14.001	
08-Jul	715	40.6	35.0	16.793	
08-Jul	1927	40.0	36.7	17.529	
09-Jul	1357	40.0	35.6	18.636	
10-Jul	1524	39.4	35.0	20.164	
11-Jul	1224	39.2	36.7	21.419	
12-Jul	2140	37.8	32.2	23.423	
13-Jul	2118	37.2	34.4	24.845	
14-Jul	2200	36.9	34.4	26.320	B off
16-Jul	906			26.320	B on
16-Jul	920	30.8	35.6	26.327	
16-Jul	936	34.7	36.1	26.341	
16-Jul	1820	35.0	40.0	26.867	
17-Jul	1418	36.1	37.8	28.077	
18-Jul	730	35.6	36.1	29.118	
19-Jul	1200	35.0	36.7	30.837	
21-Jul	1415	34.4	36.7	33.866	
23-Jul	600	33.3	30.6	36.258	
24-Jul	1857	32.8	32.2	38.485	
27-Jul	1400	31.7	29.4	42.498	
28-Jul	600	31.4	32.2	43.490	
30-Jul	1512	30.3	34.4	46.938	
31-Jul	1009	30.3	34.4	48.074	
01-Aug	1706	30.0	32.2	49.945	
02-Aug	940	28.6	32.2	50.946	
03-Aug	854	28.3	28.9	52.334	
05-Aug	630	27.2	28.9	55.088	
06-Aug	909	27.2	26.7	56.653	

TABLE F.3. (Continued)

PUMPOUT WELL B Date	Time	Recov. Temp. (°C)	Waste Temp. (°C)	Cum. Flow 10^3 m^3	Remarks
06-Aug	1512	27.2	28.3	57.023	
07-Aug	1354	26.7	27.2	58.392	
09-Aug	1500	26.1	26.7	61.352	
11-Aug	1927	25.3	30.0	64.499	
12-Aug	1512	25.6	32.2	65.680	
14-Aug	645	25.0	28.3	68.043	
15-Aug	736	24.7	28.9	69.534	
18-Aug	2015	23.6	26.7	74.635	
19-Aug	1512	22.8	29.4	75.760	
20-Aug	1506	23.1	28.9	77.200	
21-Aug	1100	22.8	28.9	78.388	B off
21-Aug	1445	22.2	28.9	78.388	B on
21-Aug	1454	22.5	28.9	78.398	
22-Aug	1445	22.8	27.8	79.875	
23-Aug	1520	22.5	28.3	81.389	
26-Aug	1445	21.7	29.4	85.769	
27-Aug-91	1100	21.1		87.010	B off

APPENDIX G

SUMMARY OF TEST CYCLES CONDUCTED AT THE UNIVERSITY OF MINNESOTA ATES FIELD TEST FACILITY

APPENDIX G

SUMMARY OF TEST CYCLES CONDUCTED AT THE UNIVERSITY OF MINNESOTA ATES FIELD TEST FACILITY

Four short-term cycles (ST1 through ST4) and three long-term cycles (LT1, LT2 and LT3) have been conducted at the St. Paul ATES FTF. The four short-term cycles were conducted between December 1982 and December 1983 (Walton et al. 1991). The first long-term cycle (LT1) was conducted from November 1984 to May 1985 (Hoyer et al. 1991a). The second long-term cycle (LT2) was conducted from October 1986 to April 1987 (Hoyer et al. 1991b). The third long-term cycle (LT3) was conducted from October 1989 to March 1990 (this report). Table G.1 presents summary data from the cycles conducted at the St. Paul ATES FTF.

TABLE G.1. Summary of Test Cycles Conducted at the University of Minnesota ATES Field Test Facility

	Short-Term Cycles				Long-Term Cycles		
	1	2	3	4	1	2	3
Duration (days)							
Injection - Pumping	5.2	8.0	7.7	7.7	59.1	59.3	47.2
Injection - Total	17.0	10.0	10.4	12.0	74.7	65.0	47.8
Storage	13.0	90.0	9.7	10.1	64.0	59.1	21.4
Recovery - Pumping	5.2	8.0	7.7	7.7	58.0	59.7	61.2
Recovery - Total	5.2	8.0	8.0	7.7	58.8	59.8	85.8
Temperature (°C)							
Source Water	11.0	20.5	36.1	52.6	19.7	33.1	20.2
Injected Water	89.4	97.4	106.1	114.8	108.5	117.7	104.0
Recovered Water	59.2	55.2	81.1	89.1	74.7	85.1	76.5
Returned Water	59.0	54.4	76.6	75.7	68.0	60.4	68.1
Flow Rate (L/sec)							
Injection	18.4	17.6	18.3	17.9	18.0	18.3	15.3
Recovery	18.1	17.8	17.3	17.8	18.4	17.9	12.5
Volume (10^3 m^3)							
Injection	8.3	12.2	12.2	11.9	92.1	93.9	63.2
Recovery	8.1	12.3	11.8	11.9	92.2	92.1	66.0
Energy Recovery Factor							
(using source T)	0.59	0.46	0.62	0.58	0.62	0.62	0.67
(using ambient T)	0.59	0.52	0.71	0.75	0.65	0.69	0.70

The short-term cycles were all scheduled for consecutive 8-day periods of injecting heated water into the aquifer, storing the heated water in the aquifer and recovering the heated water from the storage well. Each short-term cycle was conducted using a progressively higher water temperature for injection, rising from 89.4°C in the first cycle to 114.8°C in the fourth cycle. A precipitator was used during the short-term cycles to reduce the hardness of the injected water, but recharging the precipitator proved necessary after each day or two of injection, thus interrupting the injection cycle. Despite the interruptions, the short-term cycles demonstrated that ATES at temperatures above 100°C in an aquifer was feasible and that the thermal behavior and energy performance of the storage could be modeled successfully. Recovery of the energy stored was 59, 46, 62 and 58 percent, respectively, for each of the short-term cycles. Cycle ST2 had a significantly lower recovery because of an extended storage period of 90 days compared to 10 to 13 days for the other cycles.

The first long-term cycles, LT1 and LT2, were each scheduled for consecutive 60 day periods of injection, storage and recovery. Before the long-term cycles began a permit modification was requested and granted, which permitted the use of an ion-exchange water softener to replace the precipitator. This allowed nearly continuous operation during the water heating and injection phase with interruptions only caused by scheduled maintenance, power outages or system malfunctions. The total durations for the injection phase to obtain 59 days of injection for the long-term cycles were 74.7 and 65.0 days, respectively. Injected water temperatures for these long-term cycles averaged 108.5°C and 117.7°C, respectively. Water temperatures during recovery averaged 74.7°C and 85.1°C, respectively. For LT1 and LT2, temperature of the water recovered from storage reached a maximum after a day or two of recovery, after about 3000 m^3 of water had been recovered (Figure G.1). Temperature of the recovered water then declined steadily for the rest of recovery. Energy recovery for these cycles was 62 percent. When adjusted for the difference in injection temperatures of about 9°C, the temperature recovery curves correspond very closely. There was evidence that significant thermal convection took place in the upper Franconia portion of the aquifer during the storage period. Convection was

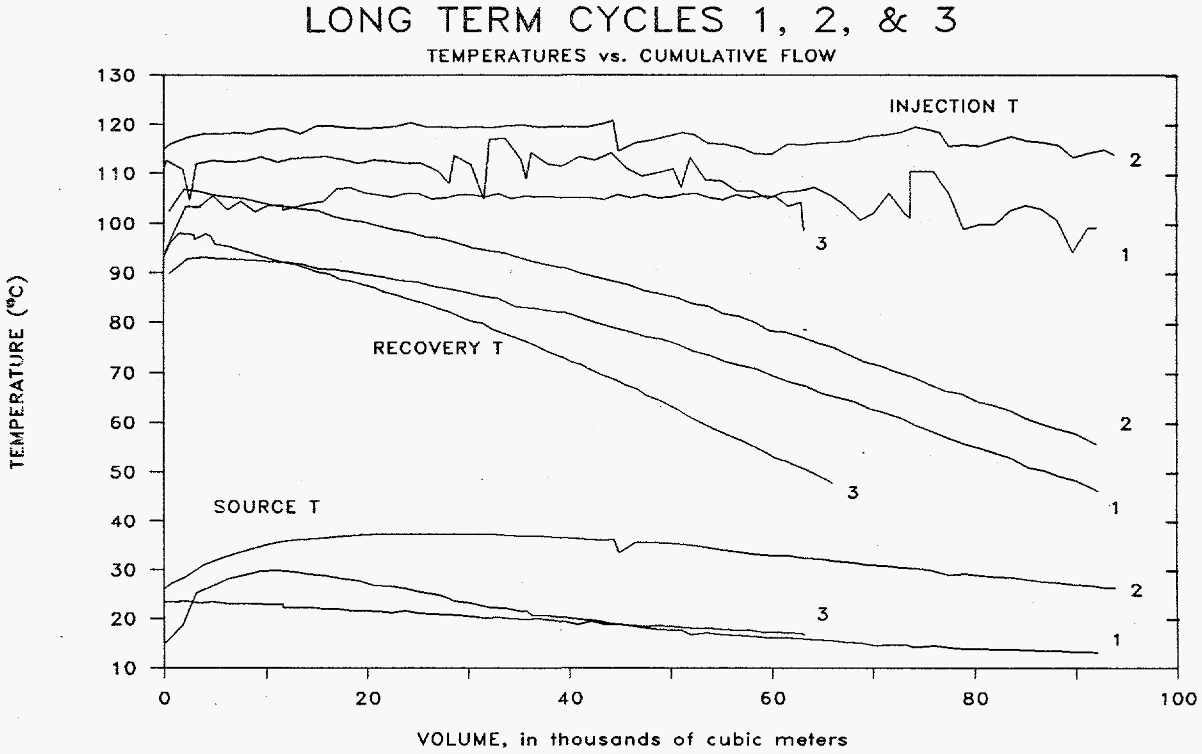


FIGURE G.1. Temperatures of Water Injected and Recovered During Long-Term Cycles LT1, LT2, and LT3

effectively prevented in the Ironton-Galesville portion of the aquifer by the many shale interbeds.

The modeled and field experimental energy recovery values for the short-term cycles and long-term cycles 1 and 2 are in close agreement (Table G.2).

TABLE G.2. Comparison of Modeled and Observed Final Recovery Temperature and Energy Recovery, Short-Term Cycles 1 Through 4 and Long-Term Cycles 1 and 2

Cycle	Observed	Modeled	Observed	Modeled
ST1	39.4	39.4	0.59	0.60
ST2	39.4	43.8	0.46	0.49
ST3	56.7	58.3	0.62	0.58
ST4	63.9	64.4	0.59	0.62
LT1	45.6	45.6	0.62	0.61
LT2	55.4	59.5	0.62	0.62

The third long-term cycle (LT3) was conducted between October 1989 and March 1990. Objectives of LT3 were to demonstrate that high-temperature ATES could supply a real heating load and to simplify the water chemistry modeling. For LT3 the FTF was connected to a nearby campus building, the Animal Sciences Veterinary Medicine (ASVM) building to demonstrate that ATES could meet a real heating load, and the source and storage wells were modified so that only the most permeable portions of the Ironton-Galesville aquifer were used. New permits were required for conduct of LT3.

A total volume of 63.2 x 10^3 m^3 of water was injected at a rate of 54.95 m^3/hr into the storage well at a mean temperature of 104.7°C from October through December 1989. Tie-in to the ASVM building was completed in late December. A total volume of 66.0 x 10^3 m^3 of water was recovered at a rate of 44.83 m^3/hr from the storage well at a mean temperature of 76.5°C from January through March 1990. Highest and lowest temperature of recovered water were 100.0 and 47.8°C, respectively.

Approximately 67 percent of the energy added to the aquifer was recovered. The useful minimum temperature for recovered water was 49°C; approximately 50 percent of the energy added to the aquifer above 49°C (33 percent of the total energy stored) was delivered to the ASVM building. Approximately 15 percent of the usable (10 percent of the total) energy stored was actually used in the ASVM building. Operations during heat recovery with the ASVM building's reheat system were troublefree. Integration into more of the ASVM (or other) building's mechanical system would have resulted in significantly increasing the proportion of energy used during heat recovery. The cost to connect to other ASVM building systems for this experimental cycle was the main reason for not incorporating other building systems into the FTF. LT3 did demonstrate that ATES in a confined aquifer at temperatures above 100°C can be effectively tied into a conventional building heating system.

During all of the long-term cycles, the FTF ion-exchange water softener reduced hardness of the source water to <5 mg/L as $CaCO_3$ prior to heating, allowing successful operation. Water chemistry is critical to the operation of the University of Minnesota FTF, or any ATES facility.

This work was conducted for the U.S. Department of Energy through its Pacific Northwest Laboratory.

REFERENCES

Hoyer, M. C., S. J. Eisenreich, J. E. Almendinger, J. A. Perlinger, R. T. Miller, and M. Walton. 1991a. University of Minnesota Aquifer Thermal Energy Storage (ATES) Project Report on the First Long-Term Cycle. PNL-7817, 137 p. Prepared by Minnesota Geological Survey, St. Paul, Minnesota, for Pacific Northwest Laboratory, Richland, Washington.

Hoyer, M. C., S. J. Eisenreich, J. P. Hallgren, J. L. Lauer, J. F. Splettstoesser, and M. Walton. 1991b. University of Minnesota Aquifer Thermal Energy Storage (ATES) Project Report on the Second Long-Term Cycle. PNL-7917, 137 p. Prepared by Minnesota Geological Survey, St. Paul, Minnesota, for Pacific Northwest Laboratory, Richland, Washington.

Walton, M., M. C. Hoyer, S. J., Eisenreich, N. L. Holm, T. R. Holm, R. Kanivetsky, J. L. Lauer, H. C. Lee, R. T. Miller, and H. Runke. 1991. The University of Minnesota Aquifer Thermal Energy Storage (ATES) Field Test Facility -- System Description, Aquifer Characterization, and Results of Short-Term Cycles. PNL-7720, 295 p. Prepared by Minnesota Geological Survey, St. Paul, Minnesota, for Pacific Northwest Laboratory, Richland, Washington.

DISTRIBUTION

No. of Copies	
	OFFSITE
	U.S. Department of Energy Attn: R. Eaton Office of Energy Management Forrestal Bldg., CE-142 5F-062 Washington, DC 20585
	U.S. Department of Energy Attn: M. Gunn Office of Energy Management Forrestal Bldg., CE-142 5F-062 Washington, DC 20585
	U.S. Department of Energy Attn: N. Rossmeissl Office of Energy Management Forrestal Bldg., CE-142 5F-062 Washington, DC 20585
12	DOE/Office of Scientific and Technical Information
	Auburn University Attn: F. J. Molz School of Engineering Auburn, AL 36830
	Gray Fresh Water Research Institute Attn: J. P. Hallgren PO Box 100 Navarre, MN 55392
	M. Hoyer 2347 Elm Drive White Bear Lake, MN 55110

No. of Copies	
	Illinois State Water Survey Attn: T. R. Holm 2204 Griffith Drive Champaign, IL 61820
	Herbert Jaehne 5747 Colfax Avenue S Minneapolis, MN 55419-1705
	Minnesota Geological Survey Attn: D. Southwick 2642 University Avenue St. Paul, MN 55114
	National Renewable Energy Laboratories Attn: T. Williams 1617 Cole Blvd. Golden, CO 80401
	New York State Energy Research & Development Agency Attn: G. Walmet 2 Rockefeller Plaza Albany, NY 12223
	Oak Ridge National Laboratory Attn: M. Olszewski Building 9204-1, MS 8045 Y-12 Plant, Box 2009 Oak Ridge, TN 37831-8045
	Office of Congressman T. Bevil 2302 Rayburn Bldg. Washington, DC 20515

No. of
Copies

Polar Consulting Inc.
Attn: J. F. Splettstoesser
One Jameson Point Road
Rockland, ME 04841

Resource Efficiency, Inc.
Attn: M. Spurr
1422 Delaware Avenue
St. Paul, MN 55118-3028

University of Alabama
Attn: E. Brett
School of Mines and Energy Development
Box 870164
Tuscaloosa, AL 35487-0164

University of Minnesota
Attn: S. Markham
Physical Plant Operations
615 15th Avenue S.E.
Minneapolis, MN 55455

University of Minnesota
Attn: P. Blackshear
Dept. of Mechanical Eng.
111 Church Street S.E.
Minneapolis, MN 55455

University of Minnesota
Attn: R. L. Jackson
Physical Planning-Civil Eng.
615 15th Avenue S.E.
Minneapolis, MN 55455

University of Minnesota
Attn: R. L. Sterling
Underground Space Center
Dept. of Civil Eng.
790 Civil Eng. Bldg.
Minneapolis, MN 55455

No. of
Copies

US Army Corps of Engineers
Attn: C. W. Sohn
Construction Engineering Research Laboratory
PO Box 4005
Champaign, IL 61820-1305

US Department of Interior
Attn: Natural Resources Library
Serials Branch (G/E)
Washington, DC 20240

US Geological Survey - WRD
Attn: J. E. Almendinger
702 Post Office Building
St. Paul, MN 55101

US Geological Survey
Attn: B. Nemickas
Water Resources Div.
5 Aerial Way
Syosset, NY 11791

US Geological Survey - WRD
Attn: G. Stoner
702 Post Office Building
St. Paul, MN 55101

M. Walton
30 Crocus Place
St. Paul, MN 55102

Wehran Engineering
Attn: R. Miller
666 E. Main St.
PO Box 2006
Middletown, NY 10940

No. of
Copies

Wilke and Associates
Attn: D. Wilke
38 Roosevelt Avenue
Glen Head, NY 11545

FOREIGN

IF Technology
Attn: A. Snijders
Frombregstraat 1
6814 RE Arnhem
The Netherlands

NOVEM
Attn: G. J. van Mourik
PO Box 8242
3503 RE Utrecht
The Netherlands

Public Works Canada
Attn: E. L. Morofsky
C456 Sir Charles Tupper Bldg.
Riverside Dr. and Heron Rd.
Ottawa, Ontario
K1A OM2 Canada

No. of
Copies

ONSITE

DOE Richland Operations Office

D.R. Green, A5-90

34 Pacific Northwest Laboratory

E. A. Jenne, K6-81
S. Somasundaram, K5-20
W. K. Winegardner, K5-20 (25)
L. W. Vail, K6-77
Publishing Coordination
Technical Report Files (5)