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The Aquifer Chill Storage Project at the University of Alabama, Tuscaloosa: Progress Report for 1985 and 1986

May 1989

**Prepared by the University of Alabama
for Pacific Northwest Laboratory
under Contract DE-AC06-76RLO 1830
with the U.S. Department of Energy**

**Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
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THE AQUIFER CHILL STORAGE PROJECT AT THE
UNIVERSITY OF ALABAMA, TUSCALOOSA:
PROGRESS REPORT FOR 1985 AND 1986

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May 1989

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FOREWORD

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

Aquifer thermal energy storage (ATES) is predicted to be the most cost-effective technology for seasonal storage of low-grade thermal energy. Approximately 60% of the U.S. is underlain with aquifers potentially suitable for underground energy storage. Under sponsorship of the U.S. Department of Energy (DOE), Pacific Northwest Laboratory (PNL), which is operated by Battelle Memorial Institute, has managed numerical modeling, laboratory studies, evaluation of environmental and institutional issues, and field testing of ATES at several sites.

This report describes the monitoring and evaluation (under the auspices of PNL) of an ATES chill system constructed and operated by the University of Alabama at Tuscaloosa, Alabama. The system is the first such system to be monitored in a comprehensive manner. Results support both the promise and problems likely to be encountered in such systems. Chill ATES has the potential to substantially reduce energy consumption and, especially, summer peak cooling electrical demand. However, the geohydrologic environment that the system will use must be a major element in system design and operation.

SUMMARY

The performance of an advanced air conditioning system that utilizes storage of winter-chilled groundwater in a water table aquifer is described. The ATES system has provided all the cooling requirements for the Student Recreation Center located on the campus of the University of Alabama, in Tuscaloosa, Alabama, for the last 5 years. System performance in 1985 and 1986 is reported.

Groundwater, pumped from the water table aquifer, is cooled during the winter in a conventional wet cooling tower, and reinjected into the aquifer for storage. During summer, the cold groundwater is pumped from the aquifer and used to cool the Recreation Center. The Recreation Center consists of 5770 m² (62,000 ft²) of air conditioned floor space including a gymnasium and other athletic facilities. The Center has a peak cooling load of 148 tons (520 kW_t). The facility was constructed in 1982 with the ATES cooling system one of many energy saving measures justified on a life-cycle cost basis. Monitoring was initiated in 1984 to measure the behavior and performance of the chill ATES system.

Instrumentation was installed to monitor water flow rates and corresponding temperatures, electrical energy input, water temperatures in the 6 system wells and 15 monitoring wells, and groundwater levels at 6 of the 15 temperature monitoring wells. Pumping tests were performed to determine aquifer characteristics prior to installation of the monitoring well field.

Results for 1986 indicate that approximately 59% of the chill energy injected was recovered for summer cooling. In 1985, 38% of the energy was recovered. A much smaller volume of groundwater was recovered in 1985 than 1986. During both years, more groundwater was pumped from the aquifer during energy recovery than during charging. It is estimated that the chill ATES system reduced energy usage by nearly a factor of three relative to a conventional system. A major advantage is that peak summer electrical demand was estimated to be a factor of nearly 20 less for the ATES system, compared to a conventional system.

Based on monitoring results, a change was made for the 1987 season to reduce the negative impact of regional flow of groundwater toward the northwest. During winter, water is withdrawn from the southeast wells, chilled, and injected in the northwest wells. When building cooling is required, cold water is withdrawn from the cold southwest wells and used for air conditioning, but not reinjected into the aquifer. This water is either used for irrigation or discarded to the storm sewer. This procedure is expected to reduce the natural groundwater flow to the northwest, therefore, reducing the natural displacement of chilled water out of the region from which it can be recovered. An increase in efficiency is anticipated for the 1987 season.

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CONTENTS

FOREWORD	iii
SUMMARY	v
ACKNOWLEDGMENTS	vii
1.0 INTRODUCTION	1.1
2.0 BACKGROUND ON THE UNIVERSITY OF ALABAMA ATEs PROJECT	2.1
2.1 ATEs CHILL SYSTEM DESCRIPTION	2.1
2.2 THE UNIVERSITY OF ALABAMA RECREATION CENTER SYSTEM	2.4
2.3 SYSTEM MONITORING	2.6
2.4 INSTRUMENTATION AND DATA ACQUISITION	2.10
2.5 SITE GEOLOGY	2.12
2.5.1 Sedimentary Analysis	2.12
2.5.2 Aquifer Framework	2.16
3.0 AQUIFER PERFORMANCE	3.1
3.1 NATURAL GROUNDWATER FLOW AND DIRECTION	3.1
3.2 WELL PUMPING TESTS	3.2
3.3 VARIATIONS IN ENERGY STORAGE AND RECOVERY	3.5
4.0 SYSTEM PERFORMANCE	4.1
4.1 SYSTEM EFFICIENCY	4.1
4.2 ENERGY USE COMPARISON WITH CONVENTIONAL SYSTEMS	4.5
4.3 EFFICIENCY IMPROVEMENTS	4.8
4.3.1 System Modeling	4.8
4.3.2 Other Possible System Improvements	4.11
4.4 PROJECTED IMPACTS AND BENEFITS	4.12

5.0 REFERENCES	5.1
APPENDIX A - MONITORING WELL DATA (TEMPERATURE VERSUS TIME) FROM OCTOBER, 1985, TO OCTOBER, 1986	A.1
APPENDIX B - AQUIFER ENERGY INJECTION AND RECOVERY DATA, 1985 AND 1986	B.1

FIGURES

2.1	Conventional Air Conditioning System	2.2
2.2	ATES Air Conditioning System	2.2
2.3	University of Alabama Student Recreation Center Chill ATES System	2.5
2.4	Locations of Production and Monitoring Wells	2.7
2.5	Production Well with Instrumentation	2.8
2.6	Temperature Test Well	2.9
2.7	Recreation Center Aquifer System Generalized Cross Section from South to North	2.13
2.8	Fence Diagram of Strata under University of Alabama Recreation Center Constructed from Sieve Analysis of Drilling Samples	2.15
3.1	Estimated Location of Chilled Water Pool at Different Times in 1986	3.7
4.1	Cumulative Chilled Water Injection in 1986	4.2
4.2	Cumulative Chilled Water Recovery for Building Air Conditioning in 1986	4.3
4.3	Energy Analysis from October, 1985, to October, 1986	4.5
A.1	Groundwater Temperature Versus Time in Monitoring Well T1N for October 1, 1985, to October 1, 1986	A.1
A.2	Groundwater Temperature Versus Time in Monitoring Well T1E for October 1, 1985, to October 1, 1986	A.2
A.3	Groundwater Temperature Versus Time in Monitoring Well H2E for October 1, 1985, to October 1, 1986	A.3
A.4	Groundwater Temperature Versus Time in Monitoring Well T3E for October 1, 1985, to October 1, 1986	A.4
A.5	Groundwater Temperature Versus Time in Monitoring Well H4E for October 1, 1985, to October 1, 1986	A.5
A.6	Groundwater Temperature Versus Time in Monitoring Well T5E for October 1, 1985, to October 1, 1986	A.6

A.7	Groundwater Temperature Versus Time in Monitoring Well T1S for October 1, 1985, to October 1, 1986	A.7
A.8	Groundwater Temperature Versus Time in Monitoring Well T2S for October 1, 1985, to October 1, 1986	A.8
A.9	Groundwater Temperature Versus Time in Monitoring Well T3S for October 1, 1985, to October 1, 1986	A.9
A.10	Groundwater Temperature Versus Time in Monitoring Well H4S for October 1, 1985, to October 1, 1986	A.10
A.11	Groundwater Temperature Versus Time in Monitoring Well H1W for October 1, 1985, to October 1, 1986	A.11
A.12	Groundwater Temperature Versus Time in Monitoring Well T2W for October 1, 1985, to October 1, 1986	A.12
A.13	Groundwater Temperature Versus Time in Monitoring Well T3W for October 1, 1985, to October 1, 1986	A.13

TABLES

3.1	Water Level Data for Static Operating Wells, July 15, 1985, 9:00 a.m.	3.2
3.2	Natural Groundwater Flow Direction and Water Table Gradient . . .	3.2
3.3	Pumping Test Water Levels, in Heights Above Sea Level, m (ft) . .	3.4
4.1	ATES System Coefficient of Performance for October 1985, to October, 1986	4.4
4.2	System Component Energy Capacity (148-Ton Capacity)	4.6
4.3	Predicted Fluid Recovery Efficiencies from ATESSS Simulations for Four Pumping/Injection Strategies and Two Hydraulic Conductivities	4.9
B.1	Monthly Usage of Water and Thermal Parameters for 1985	B.1
B.2	Monthly Aquifer Energy Injection and Recovery for 1985	B.2
B.3	Monthly Usage of Water and Thermal Parameters for 1986	B.3
B.4	Monthly Aquifer Injection and Recovery for 1986	B.4

THE AQUIFER THERMAL ENERGY CHILL STORAGE PROJECT
AT THE UNIVERSITY OF ALABAMA, TUSCALOOSA:
PROGRESS REPORT FOR 1985 AND 1986

1.0 INTRODUCTION

The power requirement for air conditioning, especially in major buildings, is great. Most large commercial air conditioning systems use evaporative cooling towers to reject heat to the air. In new systems, more efficient chillers are used along with new techniques that save energy in circulating cooled water. "Free cooling" is one such technique, in which water from cooling towers is used directly in the cooling coils (bypassing the chiller) any time the tower exit-water temperature drops below 10°C (50°F) as determined by external ambient wet-bulb temperature (Schaetzle, Brett, and Grubbs 1980; Schaetzle et al. 1980).

The system in this study uses direct cooling the year around, eliminating both the chiller power and the capital cost for the chiller. The water is chilled in cooling towers or ponds during cold periods, stored in a water table aquifer, and recovered as required for air conditioning. This system is now operating at the University of Alabama Recreation Center in Tuscaloosa, Alabama. The aquifer thermal energy storage (ATES) system, included in a 20-yr life-cycle cost evaluation, has supplied essentially 100% of the Recreation Center's air conditioning since 1983.

Completed in November, 1982, the Recreation Center consists of 5770 m² (62,000 ft²) of air conditioned floor space, including a gymnasium. To cool this area, the heating, ventilation, and air conditioning (HVAC) system is a four-pipe system employing a total of 30 air-handling units with hot water and chilled water coils, a natural gas jet-fired hot water boiler, and a 100-ton standby air-cooled backup chiller. An economizer cycle provides air conditioning during cooler weather conditions. The total heating load, including heating the ventilation air, is 1600 million Btu per hour (MBH), and the

maximum cooling load is 148 tons. The standby chiller capacity of 100 tons will not carry the maximum load in the gym and the remainder of the building simultaneously. The need for air conditioning the gym was a factor in deciding to use the groundwater air conditioning system, which is more energy efficient than conventional systems (Brett and Schaetzle 1985).

This report describes the principles of an ATEs air conditioning system and its application in the University of Alabama's Student Recreation Center. Chapter 2 provides background information for a general understanding of an ATEs system and broadly describes the system at the Recreation Center. It compares a conventional system with an ATEs system, showing how the ATEs system has been designed to maximize aquifer and air conditioning performance. Chapter 2 also includes background on the aquifer characterization that was necessary to set up the Recreation Center system. Chapters 3 and 4 provide detail from studies done to characterize aquifer performance and overall system performance, respectively. Aquifer performance (Chapter 3) includes studies of the natural groundwater flow rate and direction, which are important in ensuring that cold water stored can be recovered. Additionally, Chapter 3 contains reports of pumping tests conducted on the system wells and of recorded variations in energy storage and recovery efficiency. Chapter 4 concentrates on the system performance in the Recreation Center, discussing efficiency in air conditioning, comparing use of energy with conventional air conditioning systems, and examining possible improvements in system efficiency. Chapter 4 concludes by discussing the possible future benefits of ATEs systems similar to the one at the Recreation Center.

2.0 BACKGROUND ON THE UNIVERSITY OF ALABAMA ATES PROJECT

This chapter describes the principles of an ATES system used for cooling at the University of Alabama's Student Recreation Center. It also describes the properties of the aquifer beneath the Recreation Center that are important in using ATES for air conditioning.

2.1 ATES CHILL SYSTEM DESCRIPTION

A comparison of the system with a conventional system demonstrates the differences in components, and points out why ATES air conditioning is able to save energy.

A conventional air conditioning system is shown in Figure 2.1. The system comprises heat absorption, chiller, and heat rejection components. Thermal energy from the environmentally controlled area is absorbed by chilled water in the cooling coils. This low-temperature energy is upgraded [approximately 13°C (55°F) to 49°C (120°F)] in the chiller and then rejected in the cooling tower to the atmosphere. The chiller, utilizing a conventional refrigeration cycle, absorbs the energy from the chilled water loop in the evaporator. The absorbed energy is transferred to a water loop in the condenser. The water then flows to a cooling tower where the absorbed energy is rejected to the atmosphere.

The ATES air conditioning concept is shown schematically in Figure 2.2. This system consists of three functions: heat rejection or water chilling, chilled water storage, and heat absorption. The system is similar to the conventional system except that the chiller has been eliminated. Elimination of the chiller energy and the chiller energy demand charge results in large energy and economic savings.

The largest energy use, though small compared to a conventional system, is for chilling the groundwater. Potential conventional cooling systems include cooling towers and spray ponds. During chill charging, the groundwater is pumped from the aquifer to the cooling system, shown as a cooling tower in Figure 2.2. Pumping occurs only during cold weather, normally below 10°C

FIGURE 2.1. Conventional Air Conditioning System

FIGURE 2.2. ATEs Air Conditioning System

(50°F). The water is chilled in the cooling system by the frigid air. Cooling towers require more energy input than ponds because they use blowers to cool the water. If a cooling pond were used in place of a tower, nature would provide a natural draft in cold weather, eliminating the need for a blower.

Once water has cooled, either in a tower or pond, it must again be pumped into the wells. The reinjected water is then stored underground in the aquifer until required for air conditioning. At that time, the cool groundwater is pumped from the cold wells through the building cooling coils. The cool water removes heat from the air blowing across the coils. The heated water is then returned to the original supply (warm) wells.

The ATES system maximizes the atmospheric potential for air conditioning. The tower blowers operate any time the wet-bulb temperature goes below the required cooling temperature. Cooling tower or pond operation is related only to weather and is not matched to a corresponding air conditioning load. Tower size is related to chilling hours available. The more chilling hours available per year, the smaller the cooling tower or pond and the smaller the relative capital cost of the system.

Access to groundwater is provided by wells drilled between the surface and the base of the aquifer. The casing of the operating wells is screened throughout the entire thickness of the aquifer being used. Using the entire thickness of the aquifer is important to minimize the mixing of cold and warm water.

For the Tuscaloosa area, weather conditions are such that they are typically below 6°C (43°F) wet-bulb temperature for 1200 to 1460 hours per year. Minimum temperatures are typically around -12°C (10°F). Temperatures rarely drop below -18°C (0°F). Input water to the aquifer is expected to vary from 2°C (35°F) to over 7°C (45°F) with an average temperature of 6°C (43°F).

Water is injected in one well and moves toward the next well, where an equal amount of water is withdrawn. There is basically zero consumptive use of water, except during winter cooling, when some evaporation will occur assuming that water withdrawn for building cooling is reinjected into the aquifer.

When building cooling is required, nominally 7°C (45°F), water is removed through the cold well from the aquifer for air conditioning and heated to approximately 15°C (60°F) in the building HVAC cooling coils. It is then reinjected into the aquifer through the warm wells. The water is cooled to 7°C (45°F) in the cooling tower or pond during the winter cycle and injected into the aquifer through the cold wells for thermal storage until required for air conditioning. The system cycles between the wells, and water chilling and air conditioning, corresponding to weather conditions and building cooling requirements.

The recovery of chilled water energy can range from 15% to 90% depending on aquifer thickness, volume of water used, and natural groundwater movement. The system originally envisioned in this project, with a >12-m-thick (40-ft) aquifer and very little groundwater movement [less than 3 m (10 ft) per year], was expected to have over 60% energy recovery the first year and was expected to approach 80% by the third annual cycle. In reality, an appreciable natural groundwater movement exists and energy recovery was under 40% in 1985. In 1986, energy recovery was nearly 60%.

2.2 THE UNIVERSITY OF ALABAMA RECREATION CENTER SYSTEM

The ATES system for the Recreation Center (Figure 2.3) consists of three "warm" wells and three "cold" wells, each containing a submersible three-stage pump and return riser, and a cooling tower with a circulating pump. Warm-well-pump design capacity is 9 l/s (150 gpm) at 43-m (140-ft) head; cold well pump design capacity is 8 l/s (120 gpm) at 61-m (200-ft) head; and the cooling tower chilling capacity is 28 l/s (450 gpm) of water for a water temperature decrease from 13°C (56°F) to 7°C (45°F) at a 4°C (40°F) wet-bulb ambient temperature.

The warm well pumps are started by an outdoor thermostat set at 7°C (45°F). The pumps are cycled by a level controller in the cold water basin of the first-stage cooling tower. A three-way diverting valve in the cooling tower pump discharge is modulated by a thermostat in the cooling tower cold water basin to divert water from the cooling tower through the sand filter to the cold wells at water temperatures of 7°C (45°F) or below. The cooling

FIGURE 2.3. University of Alabama Student Recreation Center Chill ATEs System

tower fans are also controlled by an outdoor thermostat. Each well pump is equipped with a low-level cut-off control in the well casing. The well pump control panel includes a plug-and-jack arrangement to permit manual selection of well pumps. The cold well pumps start when any one of the chilled water coil valves opens on temperature demand.

The HVAC system cost was \$485,000 in 1983 including \$190,000 for the wells, well pumps, tower, sand filter, and other items related to the ATES system (Brett and Schaetzle 1985; Schaetzle, Brett, and Richey 1983). Designed thermal storage capacity is 1.76 TJ (139,000 ton-hours) per year.

2.3 SYSTEM MONITORING

The system is monitored by acquiring data on aquifer conditions, water chilling system operation and performance, and the air conditioning system operation and performance. To evaluate and monitor the aquifer, 15 monitoring wells have been drilled.

The ATES system has six operating production wells; three cold wells and three warm wells in two rows, as shown in Figure 2.3. In addition to the production wells, there are 15 monitoring wells shown in Figure 2.4. These consist of three background head monitoring wells, three additional head monitoring wells in or near the operating well field, and nine temperature monitoring wells.

The production wells, shown in cross section in Figure 2.5, are 30- to 37-m (90- to 100-ft) deep. The wells are cased with 25-cm (10-in.) polyvinyl chloride (PVC) casing and completed with a PVC screen in the aquifer. The screen is gravel packed and the well casing is grouted with concrete above the screen to the ground surface. Head wells and temperature monitoring wells use 5-cm (2-in.) PVC casing and are not gravel-packed (see Figure 2.6). The six head wells have a section of sand screen near the bottom of the wells.

The following sources were used to characterize the aquifer and its behavior response to the injection and withdrawal of chilled water:

- drilling samples from the monitoring wells

FIGURE 2.4. Locations of Production and Monitoring Wells

FIGURE 2.5. Production Well with Instrumentation

FIGURE 2.6. Temperature Test Well

- water level data to determine the natural water surface, flow direction, and drawdown during pumping
- temperature sensors in monitoring wells to determine the temperature profiles, both static and transient, in the aquifer
- water flow injection and withdrawal rates with temperatures to determine thermal energy storage efficiency
- power input to evaluate performance of the overall cooling system.

The following sources of data were used to to evaluate the water-chilling system.

- water temperature into and out of the cooling tower
- water flow rate into the cooling tower
- power input to the cooling tower - This includes the pumping power to reinject the water into the wells.

The following measurements were used to evaluate the building air conditioning system.

- water temperature into and out of the building
- water flow rate into the building
- power input for pumping water.

2.4 INSTRUMENTATION AND DATA ACQUISITION

Instrumentation was incorporated into the ATEs system to measure and monitor the water temperature, flow rates, well water levels, and power use. The instrumentation was designed for computer-controlled, automatic data acquisition for parameters requiring frequent measurement and for manual data acquisition for parameters requiring daily or weekly measurement.

A computerized data acquisition system was installed in 1985 that permits frequent data recording. The IBM PC, located in the computer room of the Student Recreation Center, was set to record data at 15-min intervals.

The computer directly records significant operating well data and cooling tower data. These computer-recorded data are picked up by transducers with outputs of ± 10 V, converted to digital outputs, and recorded on disks with an IBM PC. Over 100 channels are presently available for data acquisition.

Flow rates are taken from each production well on incoming and outgoing water rates using venturi meters with pressure transducers. The computer is used to calculate the total flow rates into and out of the building, as well as water height and temperature data. The venturi meters were calibrated on an experimental system constructed in the laboratory. Water levels are measured in each production well using a pressure transducer on the bubbler submerged to 3 m (10 ft) above the pump so that the pump turbulence does not affect the transducer. Temperature data, acquired with thermistors, is recorded both into and out of the six production wells, the cooling tower, and the Recreation Center. In the six production wells, six temperature points at 3-m (10-ft) intervals from the bottom are recorded at 15-min intervals.

Although both hardware and software problems along with weather have limited the system's data collection capabilities, hundreds of thousands of data points have been obtained.

The total water volume pumped was measured with integrated water flowmeters and was recorded daily. The temperature of water coming from and returning to each row of wells was measured by inline thermistors and was also recorded daily. The total time each well operated was also recorded on a daily basis.

Data from the monitoring wells were also recorded weekly except during critical periods, as dictated by data and temperature trends. Thirteen of the 15 monitoring wells had six temperature data points distributed at 3-m (10-ft) increments from the bottom of the well, as shown in Figure 2.6. The other two wells were used for background reference, with temperatures taken at various intervals. Water levels were also recorded weekly in six monitoring wells using a chalked surveyor's tape and the surveyed elevations premeasured at the tops of the well collars.

The power into the well pumps (as a group) and the cooling tower were recorded weekly with watt-hour meters. These were installed near the end of 1985; therefore, energy data are not available for 1985.

2.5 SITE GEOLOGY

The unconfined aquifer at the Recreation Center site occurs in a geologically young unconsolidated sedimentary layer of terraced deposits. The deposits lie directly on the Pottsville formation, as shown in Figure 2.7.

The Pottsville formation is well-indurated and relatively impermeable, and acts as an aquiclude to the downward migration of groundwater in the project area. Although there may be some leakage through faults and joints into the aquiclude, permanent water height stations, operated nearby by the U.S. Geological Survey, indicate that the groundwater levels are relatively stable throughout the year, with only minor seasonal variations in the water table.

In the Tuscaloosa area, the Pottsville formation presents a long succession of shales, siltstones, sandstones, and coal beds. These rocks are mostly gray or dark gray and are well-indurated. The sandstones are commonly irregularly bedded and cross-stratified. They vary in thickness and coarseness, and, in places, show cut-and-fill relationships and commonly grade laterally into siltstones and shales.

2.5.1 Sedimentary Analysis

Sediments from the project's monitoring and production wells were analyzed. The 15 monitoring wells were sampled at 1.52-m (5-ft) intervals during drilling. Megascopic and binocular microscope analysis techniques were applied to sediment samples to determine particle size distribution, rounding, and sorting. Recombined samples from sieve analysis reports, using grain sizes in accordance with National Research Council standards, were also used for comparison in determining sizes and distribution. This information was then used to assign sorting values and the appropriate final sediment name.

FIGURE 2.7. Recreation Center Aquifer System Generalized Cross Section from South to North

The sediments are all unconsolidated quartzose sands, gravels, and clays of varying mixtures, ranging from moderately and well-sorted gravels and sands to extremely poorly sorted clays and gravels.

The Atlantic office of the U.S. Geological Survey performed geophysical logging, consisting of gamma and neutron logs on nine of the monitoring wells. At this writing, log interpretation is incomplete.

All particles smaller than very fine sand (0.062 mm) were categorized as "mud" (Folk 1954). In the final sediment name, the term "clay" replaces the term "mud" and means "clay and silt." Sediment analyses of some of the monitoring wells and sieve analysis data from the six production wells were used to construct a fence diagram (Figure 2.8).

Permeability or porosity were not determined for the sediment layers in the storage field but can be inferred to some extent on a relative basis from the stratigraphic profiles and fence diagram combined with temperature distribution data.

The results of the monitoring well analyses are influenced by the possible mixing of fragments in the light drilling mud and because drilling was continuous during the sampling process. Sediment samples from the six production wells were also collected at 1.52-m (5-ft) intervals from ground level to the top of the Pottsville formation, a depth ranging from 24.38 to 30.48 m (80 to 100 ft).

The object of the sieve analysis was to determine relative porosities in the aquifer and to locate positions of clay lenses, which significantly influence the distribution of water temperatures within the aquifer. Clay and silt sizes were not differentiated by hydrometer density tests. Any size smaller than "very fine sand" is termed simply "clay" in the description and in the final sediment name. Particle grade scales are National Research Council standards and are taken from Royse (1970). Sorting estimates are modified from the visual estimates chart of Folk (1968), and are extended to include the term (extremely poorly sorted) for diameter ratios greater than 64.0 (ϕ standard deviation greater than 4.00).

FIGURE 2.8. Fence Diagram of Strata under University of Alabama Recreation Center Constructed from Sieve Analysis of Drilling Samples

Each sample was dried to a constant weight at a temperature of 75° to 80°C (167 to 176°F). Where possible, 100 grams of each dried sample were water washed through a 62- μ U.S. standard sieve to remove the clay and silt portions. The sample was then redried and reweighed to obtain the percentage of fine particles by subtraction. The remainder of each sample was dry-sieved through a nest of U.S. standard sieves to achieve a 1- ϕ interval for the gravel

portion and a 1/2- ϕ interval for the sand portion. The samples were weighed to an accuracy of 0.05 g.

Some error in the sieve analyses is likely because of sediment mixing in the light drilling mud that was used. In some cases, samples consisted mostly of clay and silt but contain some gravel even though gravel may not have been present in the original sediment. The light drilling mud was probably unable to transport heavy particles as quickly as the lighter particles, resulting in gravels from upper levels being present in clay and silt samples collected from lower layers. In addition, all samples contained drilling mud representing all, or at least a portion of, the fine particles present in some samples. Therefore, all samples show some percentage of fine particles, whether they were originally a part of the natural sediment layer or not. The nature of the sieved samples was also probably influenced because drilling was not continuous during sampling.

2.5.2 Aquifer Framework

The monitoring wells were oriented roughly in a T, with one leg running east-west and the other running north-south (see Figure 2.4 for well locations). The sieve analysis of the samples from the east-west line of monitoring wells indicates that there are generally three clay layers in the porous sand mass of the aquifer. The three layers occur at slightly different elevations, and two of the layers appear to merge into one layer in some of the well locations. The low-porosity clay composition of the upper parts of the aquifer site are clearly seen. This clay layer, however, is several feet above the surface of the water table. The three clay lenses are clearly distinguishable in the geologic sections for production wells RC2 and RC5, but only the lower lens seems to be in a position to have a major influence on the distribution of temperatures in the storage cell.

In the north-south geologic cross-section (Figure 2.7, see Figure 2.4 for well locations) the three clay lenses are also evident. Again, only the lower clay lens seems to be in a position to influence the distribution of water temperature in the aquifer. The north-south profile also shows a higher concentration of fine particles, suggesting lower porosity, in the lower sections of the aquifer.

The positions of the clay lenses are more clearly seen in the fence diagram (Figure 2.8). The fence diagram was constructed between the production wells with monitoring wells between RC4 and RC5 and between RC5 and RC6 used for control. Three monitoring wells were used for control between RC5 and RC2. A larger mass of porous sand and gravel is obvious in the northern portions of the storage cell, while clay-dominated sediments concentrate in the lower parts of the southern region of the storage cell. The water table is not shown on the fence diagram, but it occurs at or immediately above the lower clay lens or about halfway down from the ground surface.

Temperature distribution data indicate that the coldest water is found at 6 m (20 ft) above the bottom of the aquifer. Warmer temperatures occur at 9 m (30 ft), warmer yet at 3 m (10 ft), and the warmest at 0 m. The presence of the coldest water at 6 m (20 ft) suggests that the 6-m (20-ft) level represents the most porous part of the aquifer through which the cold injected water is moving. The warmer water occurring above and below the 6-m (20-ft) level suggests some warming as a result of heat transfer from the overlying and underlying sediments. It is somewhat surprising that, overall, the warmest water occurs at the bottom of the aquifer between the 0- and 3-m (10-ft) levels, which suggests that during injection the least water movement occurs near the bottom, thus lowering temperatures the least. Furthermore, the lower clay lens may be impeding the vertical movement of cold water somewhat and holding it in the middle layers of the aquifer. These relationships are clearly reflected in the stratigraphic profile and the fence diagram.

3.0 AQUIFER PERFORMANCE

The aquifer's performance is divided into three sections; 1) describing studies conducted on the natural groundwater flow rate and direction of movement, 2) its conductivity and transmissivity, and 3) trends in temperature as a function of flow and conductivity. Characterizing the aquifer is necessary to understand its performance for energy storage and recovery. Because high energy recovery requires minimizing the natural flow, studies were conducted to determine natural groundwater flow and direction of movement (Section 3.1). To study the aquifer's hydraulic conductivity and transmissivity, pumping tests at the monitoring wells were conducted (Section 3.2). Finally, the energy storage capacity of the aquifer is characterized in Section 3.3 with temperature and water-height profiles compiled during operation in 1985 and 1986.

3.1 NATURAL GROUNDWATER FLOW AND DIRECTION OF MOVEMENT

The natural groundwater flow and water table gradient were calculated from equilibrium water levels in the six operating wells. Equilibrium was obtained when the system was shut down for 68 hours in July 1985.^(a) The equilibrium water-level data for these tests are given in Table 3.1. These data were analyzed for four groups of three wells each to determine hydraulic gradients. Analysis began with the well having the intermediate water level of the three. A point corresponding to the intermediate water level value was found by linear interpolation on the side opposite the intermediate-level well. A line drawn from this point to the intermediate-level well was the constant-water-level line, an axis along which zero flow was assumed to pass. The actual flow was perpendicular to this line, and the water level gradient was found along the perpendicular axis. This is one of several methods used to determine the direction of the hydraulic gradient.

(a) During the test, deep wells 274 m (900 ft) and 914 m (3000 ft) southwest of the ATEs wellfield were pumping water from coal bed methane layers. However, because both these wells were sealed with concrete from the deep aquifer to the surface, no gradient was detected in this direction. Hence, it is assumed these wells had little effect on the tests.

TABLE 3.1. Water Level Data for Static Operating Wells,
July 15, 1985, 9:00 a.m.

Well No.	Water Depression, m (ft)		Well Reference Sea Level, m (ft)		Water Height Above Sea Level, m (ft)	
RC1	-14.37	(-47.15)	79.37	(260.39)	65.00	(213.24)
RC2	-15.21	(-49.89)	80.37	(263.67)	65.16	(213.78)
RC3	-15.22	(-49.94)	80.52	(264.17)	65.30	(214.23)
RC4	-11.06	(-36.27)	75.81	(248.72)	64.75	(212.45)
RC5	-13.09	(-42.96)	77.94	(255.71)	64.85	(212.75)
RC6	-13.26	(-43.52)	78.24	(256.70)	64.98	(213.18)

The results of four combinations of wells are given in Table 3.2. The results indicate a large water table gradient, with the natural flow in the northwest direction. The conclusions thus obtained about the flow direction were also supported by temperature variations in the thermal monitoring wells (Section 3.3). The natural flow velocity was calculated as a function of the gradient and the hydraulic conductivity (see Section 3.2).

3.2 WELL PUMPING TESTS

Pumping tests were conducted on well RC5 on July 17, 1985, and on well RC2 on July 23, 1985. The ATEs system was shut down for 3 days prior to the tests, to allow groundwater levels to approach equilibrium. Wells RC5 and RC2 were then pumped at constant rates for 9 hours and 20 hours, respectively,

TABLE 3.2. Natural Groundwater Flow Direction and Water Table Gradient

Well No.	Flow Direction, degrees	Gradient, m (ft)/1000	
RC1, RC2, and RC4	318	1.46	(4.79)
RC2, RC3, and RC5	306	1.52	(5.00)
RC2, RC4, and RC5	296	1.40	(4.60)
RC3, RC4, and RC6	300	1.48	(4.85)
Average value	305	1.47	(4.81)
Maximum deviation from average	13	0.21	(4.4%)

to determine aquifer hydraulic conductivity and transmissivity. Before, during, and after pumping, water levels in the pumped water and adjacent monitoring wells were measured. However, the data obtained during the tests were suitable for only rough estimates of aquifer properties. Funding and time constraints, and the need to use the ATES system to avoid high electrical demand surcharges associated with the backup cooling system, prohibited rerunning the tests or extending the tests for adequate pumping times.

Well drawdown data were not obtained at sufficiently short intervals during well drawdown or recovery to permit application of advanced, nonequilibrium methods for pumping test analysis. Consequently, the equilibrium method (Thiem equation) (Todd 1976) was used for test evaluation and determination of aquifer characteristics. This method has numerous limitations; thus, the calculated values for hydraulic conductivity and transmissivity can be considered only approximations.

The pumping test data are summarized in Table 3.3 for quasi-steady-state conditions. Transmissivity, calculated by the equilibrium method, was about 372 m²/d (4020 ft²/d). Assuming an aquifer thickness of 10.7 m (35 ft), average hydraulic conductivity was approximately 37 m/d (121 ft/d).

Based on the calculated hydraulic conductivity, average groundwater velocity in the vicinity of the ATES site was about 0.9 m/d (3 ft/d), assuming an effective porosity^(a) of 0.20 and a hydraulic gradient of 0.005 [1.52 m per 305 m (5 ft per 1000 ft)]. It must be noted, however, that because of heterogeneity, a large range of groundwater velocities would be expected to occur at different locations (areally and vertically) within the aquifer. Thus, the calculated velocity is an indication only of general movement of the groundwater. Also, the actual effective porosity of the aquifer matrix is not known, but the value of 0.20 probably is a reasonable approximation for an unconfined aquifer made up of coarse-grained, water-deposited sediments.

(a) The effective porosity is the fraction of void space through which flow occurs. The total porosity (void fraction) may be as high as 0.4, but flow does not occur in a substantial portion of the void space.

TABLE 3.3. Pumping Test Water Levels, in Heights Above Sea Level, m (ft)

Well	Water Level, Sea Level Height, m (ft)			Distance to Well
	Pre-Pumping	During Pumping (Quadi-Steady-State)	Drawdown	
Pumping well RC5 ^(a)				
Observation well				
RC5	64.85 (212.77)	61.02 (200.20)	3.83 (12.57)	0
H2E	64.94 (213.07)	64.78 (212.52)	0.17 (0.55)	37.8 (124)
RC4	64.76 (212.46)	64.62 (212.01)	0.14 (0.45)	45.7 (150)
RC6	64.97 (213.15)	64.83 (212.71)	0.13 (0.44)	45.7 (150)
Pumping well RC2 ^(b)				
Observation well				
RC2	65.07 (213.47)	60.68 (199.07)	4.39 (14.4)	0
H2E	64.92 (213.00)	64.57 (211.85)	0.35 (1.15)	38.4 (126)
RC3	65.21 (213.94)	65.00 (213.27)	0.20 (0.67)	45.7 (150)
H4E	65.32 (214.30)	65.02 (213.33)	0.30 (0.97)	38.1 (125)

(a) Well RC5 base level = 55.38 m (181.7 ft); pumping rate = 14.7 l/s (233 gpm).

(b) Well RC2 base level = 54.16 m (177.7 ft); pumping rate = 13.2 l/s (209.3 gpm).

Groundwater fluid velocity is inversely proportional to effective porosity. If effective porosity is doubled to 0.40, the average fluid velocity would be halved (to 0.45 m/d), and if the effective porosity is halved to 0.10, the average fluid velocity would be doubled (to 1.8 m/d).

Although groundwater movement is significant in influencing thermal storage, thermal energy is stored in both rock and water. Thus, the thermal front moves more slowly than the fluid front.

3.3 VARIATIONS IN ENERGY STORAGE AND RECOVERY

Temperatures in the monitoring wells were taken at various heights above the well bottoms between October, 1985, and October, 1986. Figures A.1 through A.13 in Appendix A give the temperature versus time for that period in the monitoring wells. The graphs plot the temperature variation over time at the bottom of the well and at 3.05-m (10-ft), 6.1-m (20-ft), and 9.14-m (30-ft) elevations above the well bottom. The 12.19-m (40-ft) level is above the saturated zone and therefore not included in the data.

Depth-to-water measurements made in the monitoring wells show that, in general, the groundwater level adjacent to the ATEs site was relatively stable and unaffected by seasonal or short-term climatic changes. [Water table elevation at the ATEs site averaged about 64.4 m (212 ft) above mean sea level (MSL). Elevation of land surface at the site averages about 79.3 m (260 ft) above MSL.]

All the temperature profiles show the largest temperature change at the 6.1-m (20-ft) level above the bottom of the aquifer with the smallest change at 9.14 m (30 ft). Also, the variation of temperature with time reached a low or high temperature earlier at the 6.1-m (20-ft) level. The phase period was as large as 30 to 60 days in some cases. Assuming homogeneity, this indicates that hydraulic conductivity approaches a maximum value near the 6.1-m (20-ft) level with a gradual decrease upward to 9.14 m (30 ft). The hydraulic

conductivity dropped rapidly below 6.1 m (20 ft). The temperature retardation at the bottom of the well was partially due to thermal conduction to the Pottsville formation.

Well H1W showed a low temperature around May to June, or about 90 days after the peak water-chilling season. It is assumed that this resulted from cold water injected into well RC5. With regional flow movement at an azimuth of $>300^{\circ}$, the effect on this well must have come from well RC5, as natural flow from well RC6 would bypass well H1W. The distance between H1W and RC5 is approximately 30 m (100 ft). This distance in 90 days is equivalent to a 122-m/yr (400-ft/yr) movement in the thermal front.

The rapid loss of cold water in wells T1E and T1N also indicates this natural movement of water. The lower-than-natural water temperature of the recovered water late in the year resulted from the reinjection in wells RC2 and RC3. The natural flow allowed reuse of this water from wells RC4 and RC5. This also explains the low water-recovery temperature from well RC6 shortly after air conditioning was initiated.

The aquifer cold water pool at the 14°C (58°F) boundary was estimated for different times from the temperature profiles. The data are shown in Figure 3.1. The pools move to the northwest and decrease in size with time. The data correlate with the natural flow from water-level measurements and conductivity estimates for a 0.40 porosity. These curves indicate the need for additional monitoring wells northwest of the ATEs wellfield.

Overall, the energy recovery from groundwater in 1986 was 59.1%, compared to 38.3% in 1985. The increase was due primarily to the larger quantity of water returned and used for air conditioning. The average coefficient-of-performance (COP) for the overall system for 1986 was 4.74; however, most of the operation (standard HVAC practice) was at part-load. The COP using full-load operation for chilling and air conditioning with 50% energy recovery would be 8.5. This reflected double the performance of a conventional air conditioning system, but even better performance is expected in the future.

FIGURE 3.1. Estimated Location of Chilled Water Pool at Different Times in 1986

4.0 SYSTEM PERFORMANCE

The overall system performance (aquifer performance plus air conditioning performance) is addressed in this chapter from four perspectives: measures of the system efficiency (energy use compared to output); the ATES system's efficiency as compared to a conventional system; the possible improvements in the Recreation Center system or in any future ATES system; and, finally, the projected impacts of an ATES system balanced against its benefits.

4.1 SYSTEM EFFICIENCY

The chill ATES system has operated for 5 years, providing 100% of the air conditioning for the Recreation Center except during backup system checkouts and special tests on the aquifer such as the pumping tests. The total flow for the cooling tower and building for the 1986 season (October 1, 1985, to October 1, 1986) is given in Figures 4.1 and 4.2. Chilled water is injected into the aquifer when the cooling tower is operating and recovered when building air conditioning is required. The total recovery volume is almost twice the injected volume.

The gallons of water and energy injected and recovered and used for air conditioning the building are given in Appendix B for 1986 and 1985. The 1986 data show a decreased water and energy injection but higher retrieved water volume, which improved energy recoveries. The chill ATES system efficiency, energy returned compared to energy injected, was 59.1% in 1986 versus 38.3% in 1985. The higher withdrawal rate and some residual energy were responsible for the increased performance. However, withdrawal temperatures were higher in 1986. The system recovery efficiency, energy injected compared to air conditioning energy, rose from 35.4% in 1985 to 54.6% in 1986.

The coefficients-of-performance (COP) for water chilling and air conditioning are given in Table 4.1 for 1986. The annual average COP for this period was 4.74. Based on water chilling for December 16, 1985, recovery for

FIGURE 4.1. Cumulative Chilled Water Injection in 1986

FIGURE 4.2. Cumulative Chilled Water Recovery for Building Air Conditioning in 1986

TABLE 4.1. ATEs System Coefficient of Performance for October 1985, to October, 1986

Date	Injection			Recovery		
	Stored Chill, 1,000 Btu	Cooling Tower ^(a) , kWh	Chill Charging COP	Air Conditioning, 1,000 Btu	Pumping, kWh	Chill Recovery COP
10/07/85	0	0.0	0.00	37180	880.3	12.38
10/15/85	0	10.9	0.00	16236	583.8	8.15
10/23/85	0	0.0	0.00	0	0.0	0.00
10/31/85	0	0.0	0.00	28604	888.7	9.43
11/07/85	22122	1022.4	6.34	8383	480.5	5.11
11/15/85	13073	547.9	6.99	16748	512.4	9.58
11/22/85	0	0.0	0.00	15308	835.8	5.37
11/27/85	0	62.2	0.00	7684	367.9	6.12
12/02/85	17394	521.9	9.77	3921	101.6	11.31
12/09/85	149460	3724.1	11.76	0	0.0	0.00
12/16/85	286770	3348.7	25.10	0	0.0	0.00
12/27/85	654100	9521.1	20.13	0	0.0	0.00
1/06/86	266460	5546.7	14.08	0	0.0	0.00
1/13/86	258780	5306.0	14.29	0	0.0	0.00
1/20/86	189200	2213.4	25.05	0	0.0	0.00
1/27/86	144350	3841.8	11.01	0	0.0	0.00
2/03/86	260920	3123.6	24.48	761	4.2	53.10
2/11/86	59380	1678.6	10.37	9067	58.8	45.19
2/17/86	282180	4839.6	17.09	0	0.0	0.00
2/25/86	40114	1181.0	9.95	24620	271.3	26.59
3/03/86	115600	2648.4	12.79	4900	52.1	27.58
3/17/86	26970	1263.4	6.26	0	0.0	0.00
3/24/86	102710	2242.1	13.43	3353	31.9	30.79
3/31/86	878	102.5	2.51	7300	189.0	11.32
4/07/86	0	0.0	0.00	14690	775.3	5.55
4/14/86	0	0.0	0.00	6390	304.1	6.16
4/21/86	704	119.5	1.73	11510	514.1	6.56
4/28/86	1820	322.2	1.66	11320	203.3	16.32
5/05/86	0	0.0	0.00	36780	924.8	11.66
5/12/86	0	0.0	0.00	27003	833.3	9.50
5/19/86	0	0.0	0.00	27120	734.2	10.83
5/26/86	0	0.0	0.00	25265	574.6	12.89
6/04/86	0	0.0	0.00	60380	1027.3	17.23
6/13/86	0	0.0	0.00	40640	1099.6	10.83
6/23/86	0	0.0	0.00	88870	1188.6	21.91
6/30/86	0	0.0	0.00	61816	843.4	21.48
7/08/86	0	0.0	0.00	63246	808.9	22.91
7/15/86	0	0.0	0.00	60573	750.1	23.67
7/23/86	0	0.0	0.00	90254	913.9	28.94
7/30/86	0	0.0	0.00	65394	869.4	22.04
8/07/86	0	0.0	0.00	63968	994.6	18.85
8/15/86	0	0.0	0.00	58322	1027.3	16.64
8/22/86	0	0.0	0.00	44096	959.3	13.47
8/29/86	0	0.0	0.00	48495	1133.2	12.54
9/08/86	0	0.0	0.00	59627	1429.7	12.22
9/15/86	0	0.0	0.00	41291	1078.6	11.22
9/22/86	0	0.0	0.00	38634	1027.3	11.02
9/30/86	0	0.0	0.00	59148	1244.0	13.93
Total	2892985	53187.9	15.94	1288897	26517.1	14.25

(a) Includes energy for warm (supply) well pumping.

February 25, 1986, and an energy recovery of 50%, the overall full-load COP would equal 8.5. In colder chilling climates with more full-load chilling usage, the COP is expected to improve.

Figure 4.3 shows the distribution of energy use for the system. The largest energy user was the cooling tower blower. By substituting a cooling pond for the cooling tower, this energy could be eliminated, again raising the COP by over 60%.

4.2 ENERGY USE COMPARISON WITH CONVENTIONAL SYSTEMS

A conventional air conditioning system was compared with the chill ATES system at the University of Alabama, with the summary given in Table 4.2. Both systems were sized for the required 148-ton capacity of the Student Recreation Center. The components of each system correspond to Figures 2.1 and 2.2. The average annual air conditioning load is estimated at 3000 hours of operation at 40% capacity.

FIGURE 4.3. Energy Analysis from October, 1985, to October, 1986

TABLE 4.2. System Component Energy Capacity (148-Ton Capacity)

<u>Conventional System</u>	<u>ATES System</u>
<u>Cooling Tower and Circulation Pump</u>	
50 kW (60 hp)	50 kW (60 hp)
1.5×10^5 kWh/yr (3000 hours)	6.0×10^4 kWh/yr (1200 hours)
<u>Chiller</u>	
100 kW	10-kW storage pump
1.2×10^5 kWh/yr (3000 hours at 40%)	1.2×10^4 kWh/yr (1200 hours)
<u>Circulation Pump to Cooling Coils</u>	
5 kW pumps	8-kW pumps
1.5×10^4 kWh/yr (3000 hours)	2.4×10^4 kWh/yr (3000 hours)
<u>Peak Load Air Conditioning (summer)</u>	
155 kW	8 kW
<u>Peak Load Water Chilling (winter)</u>	
0 kW	68 kW (40% of chiller hours)
<u>Annual Energy Usage^(a)</u>	
2.85×10^5 kWh/yr	0.96×10^5 kWh/yr

(a) 3000 hours air conditioning at 40% design load

The heat rejection for both systems is assumed to use identical cooling towers with similar flow rates. For the ATES system, the cooling tower temperature change is over 13°C (20°F) [from 18°C (65°F) to 4°C (40°F) or less]. At maximum load on a hot day, the conventional tower reduces water temperature by 12°C (22°F). The ATES cooling tower is always at full-load while the conventional tower is normally only partially loaded. As a result, the ATES

cooling tower rejects more heat per unit of electrical energy input even when 50% of the energy is lost in storage.

In Table 4.2, identical cooling towers are assumed for each system. The conventional system tower operates on demand for 3000 hours. Operation of the cooling tower for chill charging is limited to periods when the air temperature is sufficiently low (~1200 hours per year). The chiller in Table 4.2 also operates for 3000 hours; however, the average load is only 40%, so energy used is 40% of capacity times operating time. In reality, the chiller efficiency drops rapidly with decreasing load, so greater electrical energy is consumed than assumed here.

The storage pumps noted in Table 4.2 remove the chilled water from the tower and inject the water into the aquifer storage system. The pumps operate 1200 hours/yr. The pumping power to circulate water to the cooling coils for the ATES system in Table 4.2 is higher because the water must be pumped from the aquifer storage system. These pumps will operate 3000 hours/yr.

The total electrical demand for each item in Figure 4.3 results in 155 kW for the conventional system and 8 kW for the ATES system during summertime peak electrical demand. It must be noted that blower power is not included but is identical in both systems. This gives a 147-kW savings on demand charges, which vary from \$4.00/kW to \$20.00/kW across the U.S. Thus, the dollar savings on demand charge for 12 months could be from \$7,000/yr to \$35,000/yr depending on location.

Energy consumption is 1.89×10^5 kWh/yr less for the ATES system. At \$0.04/kWh, this amounts to a \$7,500 energy cost savings per year.

Because the ATES system is relatively simple, the maintenance requirement is reduced. From experience with the University of Alabama's engineering building conventional systems, the ATES system requires maintenance equal to only 10% to 20% of a conventional system. This can amount to more than \$10,000/yr additional savings.

The capital cost of the ATES system components, including the cooling tower, was \$190,000. Bid comparison was based on evaluation of total building

costs. The ATES system cost quoted here is based on the winning bid rather than actual cost. (The winning bid did not include the lowest cost for the ATES system.) Because this is an oversized, experimental system, the cost was high. With improvements, experience, and correct sizing, the cost could be reduced by one-half. If the price of a conventional chiller and cooling tower is subtracted, the capital cost could be less than that of a conventional system. This is particularly true in more northern latitudes with more available chilling hours. The increased chilling hours would reduce cooling tower size requirements along with warm well and pump requirements.

4.3 EFFICIENCY IMPROVEMENTS

Observations about the possible improvements to the ATES system at the Recreation Center have come from two sources: from the use of the Aquifer Thermal Energy Storage System Simulator (ATESSS) computer code, which simulates the conditions in ATES, and from several years' experience in operating the Recreation Center system. The ATESSS modeling is described in Section 4.3.1, and several observations about improving future efficiency of the present system are given in Section 4.3.2.

4.3.1 System Modeling

A series of simulations were performed at Pacific Northwest Laboratory by Lance Vail using the ATESSS code to evaluate the magnitude of improvements in overall performance of the University of Alabama chill ATES system resulting from changes in system operation. The schematic of the ATES well system is shown in Figure 2.4. Each of the four different pumping/injection scenarios was simulated twice. One simulation assumed a hydraulic conductivity of 19 m/d (60 ft/d) and the other assumed a hydraulic conductivity of 38 m/d (120 ft/d). The simulation results are shown in Table 4.3.

All variables remained fixed, other than the changes in the pumping/injection scenarios and the hydraulic conductivity. A total of $75,700 \text{ m}^3$ (20×10^6 gallons) of water were assumed to be injected during a 6-month storage period. For the recovery period, $75,700 \text{ m}^3$ (20×10^6 gallons) were assumed to be pumped from the storage wells over a period of 6 months. The porosity was assumed to be 25%.

TABLE 4.3. Predicted Fluid Recovery Efficiencies from ATESSS Simulations for Four Pumping/Injection Strategies and Two Hydraulic Conductivities

Case	Storage Period						Recovery Period						Efficiencies, %	
	RC1 ^(a)	RC2	RC3	RC4	RC5	RC6	RC1	RC2	RC3	RC4	RC5	RC6	e _{low} ^(b)	e _{high} ^(c)
1	P ^(d)	P	P	I ^(e)	I	I	I	I	I	P	P	P	47	24
2	-	P	P	I	I	-	-	I	I	P	P	-	58	31
3	-	P	P	I	I	-	-	-	-	P	P	-	67	38
4	-	P	P	I	I	-	-	P	P	P	P	-	75	46

(a) Well number

(b) e_{low} = fluid recovery efficiency assuming a hydraulic conductivity of 19 m/d (60 ft/day)

(c) e_{high} = fluid recovery efficiency assuming a hydraulic conductivity of 38 m/d (120 ft/day)

(d) P implies well is pumping

(e) I implies well is injecting

The relative performances of the various pumping/injection schedules were measured in terms of their predicted fluid recovery efficiencies. A fluid recovery efficiency is the fraction of the water injected during the storage period that is pumped from the aquifer during the recovery period. This does not account for the conductive or dispersive losses of the injected chill. However, it does provide a valuable measure of the amount of chill lost from the drifting of the injected water away from the well that will be used to recover it. This drifting is a result of the regional groundwater flow.

In Case 1, it was assumed that no measures had been taken to counter the impact of regional flow. Wells RC1, RC2, and RC3 (see Figure 2.4) were pumped to provide the water to be injected, after chilling, into wells RC4, RC5, and RC6. During recovery, this pattern was reversed. Wells RC4, RC5, and RC6 were pumped to provide the water injected, after the chill had been extracted, into wells RC1, RC2, and RC3. The predicted fluid recovery efficiencies, assuming hydraulic conductivity of 19 m/d (60 ft/d) and 38 m/d (120 ft/d), were 47% and 24%, respectively. As expected, increasing the hydraulic conductivity increases the regional velocity, thereby decreasing the fluid recovery efficiency.

Only wells RC2, RC3, RC4, and RC5 were utilized in Cases 2, 3, and 4. It can be seen from the direction of the regional groundwater flow (Figure 2.4) and the location of these wells that pumping wells RC2 and RC3 will decrease the natural gradient in the vicinity of RC4 and RC5, respectively. The combination of these wells was used to improve the overall fluid recovery efficiency of this well field by mitigating the impact of regional flow.

In Case 2, wells RC2 and RC3 provide the supply of water that is injected into wells RC4 and RC5 after being chilled. During recovery, chilled water is pumped from wells RC4 and RC5 and reinjected into wells RC2 and RC3 after the chill has been extracted. The estimated fluid recovery efficiencies for Case 2, assuming a hydraulic conductivity of 19 m/d (60 ft/d) and 38 m/d (120 ft/d), were 58% and 31%, respectively. While pumping wells RC2 and RC3 tends to decrease the gradient near wells RC4 and RC5, the injection into these wells during the recovery period increases the gradient at the recovery wells

RC4 and RC5, thereby aggravating the problem of the injected chilled water drifting due to regional groundwater flow.

Case 3 was similar to Case 2 except that during recovery the water pumped from wells RC4 and RC5 was not reinjected into wells RC2 and RC3. The recovered water is assumed to be discharged somewhere outside of the region to eliminate any impact it might have on the gradient at the recovery wells. The estimated fluid recovery efficiencies for Case 3, assuming a hydraulic conductivity of 19 m/d (60 ft/d) and 38 m/d (120 ft/d), were 67% and 38%, respectively.

Case 4 was similar to Case 3 except that wells RC2 and RC3 are pumped during both the storage and recovery period. Pumping wells RC2 and RC3 during recovery helps to decrease the regional drift occurring throughout the recovery period, as well as during the storage period. The estimated fluid recovery efficiencies for Case 4, assuming a hydraulic conductivity of 10 m/d (60 ft/d) and 38 m/d (120 ft/d), were 75% and 46%, respectively.

The results of these simulations show that a significant improvement in overall system performance is achievable by changing the pumping/injection scenario. Estimated fluid recovery efficiencies were nearly doubled via changes in the pumping/injection scenario. These simulations highlight the significance of obtaining a reliable estimate of the hydraulic conductivity. Doubling the assumed hydraulic conductivity in these simulations reduced the fluid recovery efficiency by nearly one-half.

4.3.2 Other Possible System Improvements

Even though the current ATEs system saves approximately 70% of conventional air conditioning energy, improvements to 90% savings are a real possibility. Improvements are available that can reduce projected system capital cost and operating costs.

The Student Recreation Center chill ATEs system is oversized to ensure satisfactory operation as a new system. Only 60% of storage and chilling capacity is required. The natural movement of water is large but can be controlled through better sequencing of wells. Control of this movement will give an increase in storage efficiency, again reducing sizing requirements.

Moreover, as energy recovery improves, pumping time will decrease because of lower average recovery temperatures. The major thrust in improving the project is in this area.

The largest energy user in the ATES system is the cooling tower blower. Substituting a cooling pond could eliminate this use of energy, saving as much as 50% of the ATES system energy. In cold weather and with a larger temperature change, cooling ponds are much more efficient because a natural draft occurs. In addition, winter wind velocities are higher so the pond is more efficient. The pond could possibly be 25% of the area of a conventional pond and use only 20% as much energy as a cooling tower. This would reduce ATES system energy usage by more than one-half.

4.4 PROJECTED IMPACTS AND BENEFITS

All environmental impacts above the ground are expected to be either favorable or minimal when compared to those of current cooling systems. The largest impact will be the decrease in air pollution resulting from the decreased use of fossil fuel. At power plant sites, summer peaks will decrease and winter peaks will show an increase. No increase is indicated in peak pollution rates. Thermal cycling may affect interstitial minerals in aquifers, contaminate groundwater, and change groundwater temperature, thereby affecting biological growth. The development of iron algae growth is a possibility that could potentially clog the aquifer pores. This can be minimized by eliminating all air/water interfaces. Because pipelines and wells can be placed on the right-of-ways, the loss of land sources will be inconsequential. Failures in the system will be primarily mechanical; however, leakages could occur. The environmental effect of the leaking water would be minimal.

The water in the cooling tower comes in contact with air and other contamination. To minimize the effects of these contacts, the water is filtered through a sand filter before injection into the aquifer.

For the most part, environmental changes are expected to be positive; minor adverse effects can be dealt with in light of the beneficial aspects of

the system's performance. The exterior heat and cold of the environment are allowed to naturally balance each other on an annual basis.

The system's benefits include saving fossil-fuel energy and improving working conditions (and, thus, productivity) in areas previously impractical to air condition.

The system has applications for any cooling system located near an aquifer with sufficient yield capacity. Over 60% of the land area and over 75% of the population in the continental U.S. falls into this category. This includes downtown areas, commercial neighborhoods, and residential neighborhoods. The denser use areas normally increase the feasibility. Other than Florida and parts of California that have mild year-round temperatures, the system can be applied with appreciable energy and economic savings, especially as energy costs increase.

Using only technologic limits, the system could be incorporated by the year 2010 into

- 72,000,000 households (in clusters)
- 14,600,000 businesses.

By the year 2010, the potential annual savings from this implementation could be 9.4 quadrillion Btu, which equals 4.6 million barrels of oil per day, or 9.4 trillion cubic feet of natural gas per day, or 376 million tons of coal per year. Of course, it is recognized that these values are strictly theoretical and that "real" implementation of chill ATES would result in only some undetermined fraction of the total potential savings. Another study (Anderson and Weijo 1988) indicates that a truer estimate of potential energy savings would be something less than 1 quadrillion Btu. However, even this savings is substantial.

Another potential benefit of ATES implementation is an improvement in working environments by decreasing workspace temperatures. For example, one Alabama tire plant has a large floor space that reaches 49°C to 54°C (120°F to 130°F) almost every summer day. The temperature inside the building can be

reduced to 29°C (85°F) by an economical chill ATES system. At this tire plant, the authors estimate that the reduced tire material deterioration, which would result from lower building temperatures, could recover the capital cost of the chill ATES system in 3 to 6 months. In the project, existing cooling towers would be used. In addition, labor productivity would be expected to increase as working temperatures in this portion of the plant were reduced to more comfortable levels.

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APPENDIX A

MONITORING WELL DATA (TEMPERATURE VERSUS TIME)
FROM OCTOBER, 1985, TO OCTOBER, 1986

FIGURE A.1. Groundwater Temperature Versus Time in Monitoring Well T1N for October 1, 1985, to October 1, 1986

FIGURE A.2. Groundwater Temperature Versus Time in Monitoring Well T1E for October 1, 1985, to October 1, 1986

FIGURE A.3. Groundwater Temperature Versus Time in Monitoring Well H2E for October 1, 1985, to October 1, 1986

FIGURE A.4. Groundwater Temperature Versus Time in Monitoring Well T3E for October 1, 1985, to October 1, 1986

FIGURE A.5. Groundwater Temperature Versus Time in Monitoring Well H4E for October 1, 1985, to October 1, 1986

FIGURE A.6. Groundwater Temperature Versus Time in Monitoring Well T5E for October 1, 1985, to October 1, 1986

FIGURE A.7. Groundwater Temperature Versus Time in Monitoring Well T1S for October 1, 1985, to October 1, 1986

FIGURE A.8. Groundwater Temperature Versus Time in Monitoring Well T2S for October 1, 1985, to October 1, 1986

FIGURE A.9. Groundwater Temperature Versus Time in Monitoring Well T3S for October 1, 1985, to October 1, 1986

FIGURE A.10. Groundwater Temperature Versus Time in Monitoring Well H4S for October 1, 1985, to October 1, 1986

FIGURE A.11. Groundwater Temperature Versus Time in Monitoring Well H1W for October 1, 1985, to October 1, 1986

FIGURE A.12. Groundwater Temperature Versus Time in Monitoring Well T2W for October 1, 1985, to October 1, 1986

FIGURE A.13. Groundwater Temperature Versus Time in Monitoring Well T3W for October 1, 1985, to October 1, 1986

FIGURE 1. Temperature fluctuations over a 24-hour period in the laboratory. The data were collected on 10/10/93.

APPENDIX B

AQUIFER ENERGY INJECTION AND RECOVERY DATA,
1985 AND 1986

TABLE B.1. Monthly Usage of Water and Thermal Parameters for 1985

Month	Tower Flow, 1,000 Gallons	Temperature, °F		Building Flow, 1,000 Gallons	Building Temperature, °F	
		T in	T out		T in	T out
Jan	7022.7	62.7	42.0	241.1	44.4	56.1
Feb	4370.2	63.0	42.5	0.0	43.0	57.0
Mar	211.5	63.0	43.8	319.4	43.3	57.8
Apr	78.4	63.0	44.0	991.1	46.8	58.6
May	0.0	--	--	2049.2	51.0	60.9
Jun	0.0	--	--	3217.0	54.9	63.6
Jul	0.0	--	--	1774.8	56.7	64.3
Aug	0.0	--	--	4140.7	59.1	65.0
Sep	0.0	--	--	4304.1	60.5	65.7
Oct	0.0	--	--	1755.1	57.0	63.5
Nov	219.3	64.0	45.0	1542.8	60.7	64.3
Dec	<u>5387.9</u>	65.8	41.2	<u>97.7</u>	--	--
		<u>Average</u>			<u>Average</u>	
Total	17290.0	63.4	43.4	20433.0	52.5	61.5

TABLE B.2. Monthly Aquifer Energy Injection and Recovery for 1985

<u>Month</u>	<u>Total Injected Energy for Cooling Tower, 1,000 Btu</u>	<u>Total Used Energy by Building, 1,000 Btu</u>	<u>Total Injected Energy Recovered, 1,000 Btu</u>
Jan	1377607	17671	37877
Feb	788095	0	0
Mar	37052	38283	55890
Apr	12456	96282	126486
May	0	172580	238916
Jun	0	251928	277463
Jul	0	111641	106389
Aug	0	188814	175241
Sep	0	195183	163779
Oct	0	68875	55078
Nov	40192	40434	42017
Dec	<u>1086795</u>	<u>2445</u>	<u>1661</u>
Total	3342197	1184136 (35.4%)	1280797 (38.3%)

TABLE B.3. Monthly Usage of Water and Thermal Parameters for 1986

Month	Tower Flow, 1,000 Gallons	Temperature, °F		Building Flow, 1,000 Gallons	Building Temperature, °F	
		T in	T out		T in	T out
Jan	5276.4	64.5	42.8	3.8	46.0	70.0
Feb	2342.6	63.0	42.7	222.8	46.3	65.2
Mar	1552.7	62.0	43.0	172.7	46.7	57.4
Apr	75.7	50.0	44.0	1251.1	47.1	51.2
May	0.0	--	--	1990.1	50.6	59.9
Jun	0.0	--	--	3660.0	58.3	64.3
Jul	0.0	--	--	4037.0	58.0	66.7
Aug	0.0	--	--	4345.1	60.0	65.6
Sep	0.0	--	--	5317.5	62.4	66.9
Oct	0.9	--	--	3481.6	63.5	65.3
Nov	556.0	62.0	43.0	1670.2	59.5	64.1
Dec	<u>3092.9</u>	62.8	43.0	<u>96.0</u>	45.0	52.0
		<u>Average</u>				<u>Average</u>
Total	12897.2	60.7	43.2	26247.9	53.6	62.4

TABLE B.4. Monthly Aquifer Injection and Recovery for 1986

Month	Total Water Flow Through Cooling Tower, 1,000 Gal	Total Rejected Energy Cooling Tower, 1,000 Btu	Total Water Flow Through Recreation Center 1,000 Gal	Total Air Conditioning Provided Recreation Center 1,000 Btu	Total Energy Recovered From Aquifer 1,000 Btu
Jan	5276.4	858790	3.8	761	602
Feb	2342.6	642594	222.8	38587	35313
Mar	1552.7	246158	172.7	10653	27373
Apr	75.7	2524	1251.1	43910	188010
May	0.0	0	1990.1	146358	231118
Jun	0.0	0	3660.0	221516	289008
Jul	0.0	0	4037.0	279467	227423
Aug	0.0	0	4345.1	214881	184483
Sep	0.0	0	5317.5	198700	107969
Oct	0.9	113	3481.6	68698	50151
Nov	556.0	90240	1670.2	65916	47356
Dec	<u>3092.9</u>	<u>537725</u>	<u>96.0</u>	<u>5971</u>	<u>16017</u>
Total	12897.2	2378144	26247.9	1295418 (54.6%)	1404823 (59.1%)

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