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SUMMARY OF SEASONAL THERMAL ENERGY STORAGE FIELD TEST PROJECTS IN THE UNITED STATES

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SUMMARY OF SEASONAL THERMAL ENERGY STORAGE FIELD TEST PROJECTS IN THE UNITED STATES

1.0 EXECUTIVE SUMMARY

Seasonal thermal energy storage (STES) involves storage of available heat or chill for distribution at a later time to meet thermal loads.[a] STES can reduce energy consumption, peak energy demand, and emissions of carbon dioxide to the atmosphere over conventional systems. It is estimated that full-scale application of STES would provide 2% to 4% of total energy needs in the United States. One STES technology, aquifer thermal energy storage (ATES), has been determined to be the most cost-effective option in the United States when site conditions enable its use.

ATES has been analyzed in the laboratory and investigated in the field in the United States since the program was established at Pacific Northwest Laboratory (PNL) in 1979. Two field test facilities (FTFs), one for heating ATES at the University of Minnesota and the other for cooling ATES at the University of Alabama, have been primary testing grounds for U.S. ATES research. Computer models have been developed to analyze the complex thermal and fluid dynamics. Extensive monitoring of FTFs has provided verification of and refinements to the computer models. The areas of geochemistry and microbiology have been explored as they apply to the aquifer environment. In general, the two FTFs have been successful in demonstrating the steps needed to make an ATES system operational.

Specific difficulties with ATES application and further areas of needed research have come to the fore through the experiences in Minnesota and Alabama. Further understanding is needed in ATES in the areas of

- the microbiological environment in aquifers
- aquifer geochemistry for heating ATES
- matching of heating loads with heating ATES
- groundwater regulations
- groundwater transport.

(a) The STES program in the U.S. is managed by Pacific Northwest Laboratory (PNL) for the U.S. Department of Energy.

The capability of ATES to meet thermal loads is being demonstrated at the Alabama FTF. The Student Recreation Center has 100% of its space cooling needs provided by ATES at approximately 50% of the energy consumption of a conventional system. At the University of Minnesota, heating will soon be provided to a building as ATES testing continues. Improvements in system and aquifer performance are being realized at both sites as operational experience is gained.

2.0 INTRODUCTION

Seasonal thermal energy storage (STES) allows low-cost sources of thermal energy, such as waste heat or winter chill, to meet periodic thermal loads at a completely different time of year. This reduces energy consumption, peak demand, and environmental impacts in comparison to conventional energy sources. While a number of STES concepts have been proposed, most research has focused on aquifer thermal energy storage (ATES), where heat or chill is stored in naturally-occurring aquifers.

It is estimated that STES could supply 2% to 4% of U.S. annual energy consumption (Kannberg 1988). For example, in residential and commercial buildings, STES technology could be used to offset the large share of energy consumption found in the energy end uses of space heating, space cooling, and water heating. The share of these three end uses in buildings is shown in Figures 2.1 and 2.2. In addition, use of industrial process heat, often wasted, can provide a great opportunity for the market in heat storage. Industrial space cooling can also be provided at low cost through STES to spaces that have traditionally not been conditioned.

Using aquifers as an integral part of STES systems requires understanding of site-specific geology and geohydrology. The effect of varying thermal and fluid flow conditions on aquifer material resulting from ATES system operation has been investigated both generically and at specific sites (Kannberg 1982, 1988). The behavior of ATES field sites was the primary U.S. contribution to Annex III. Therefore, discussion will focus on the performance of ATES field test facilities (FTF) at the University of Alabama and the University of Minnesota.

A cooling ATES system is operating at the Student Recreation Center of the University of Alabama. The University of Minnesota operates a high-temperature ATES heat recovery system. These two test sites form the cornerstone of ATES research, with which models and laboratory experiments are validated.

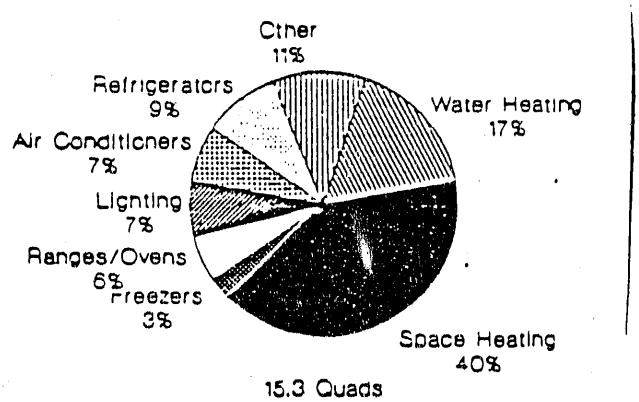


FIGURE 2.1. Residential Sector Primary Energy Consumption by End Use for 1985 (Source: Brookhaven National Laboratory 1988)

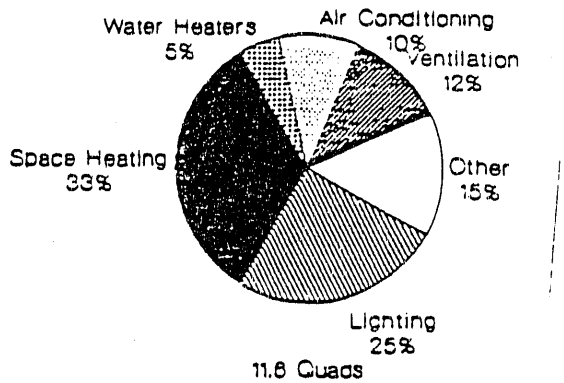


FIGURE 2.2. Commercial Sector Primary Energy Consumption by End Use for 1985 (Source: Brookhaven National Laboratory 1988)

Both FTFs incorporate much of the same considerations in their design and implementation, but they each also emphasize different issues of the overall research program. For example, geochemical reactions resulting from the heating of groundwater at the Minnesota FTF posed the greatest technical challenge at this site, while at the Student Recreation Center (University of Alabama) microbiological changes (specifically growth of Legionella) and local groundwater flow posed the greatest technical challenges.

Through the FTFs in Minnesota and Alabama, analysis techniques have been verified, in-situ performance has been determined, and application difficulties have been identified. Parameters for quantifying performance, computer models for storage simulation, and factors critical to economic analysis have been established. Extensive monitoring efforts have provided data to aid model validation and laboratory testing portions of the ongoing research. Results of these field efforts are described in the next two sections, with emphasis on those issues relevant to ATES development.

3.0 UNIVERSITY OF MINNESOTA HIGH-TEMPERATURE FIELD TEST FACILITY

A high-temperature FTF has been operating at the University of Minnesota since 1982. Regional availability of an aquifer and heating loads of facilities were important factors in locating the Minnesota FTF. This type of ATES system can be applied to meet space and service water heating loads by storage of heat that would otherwise be wasted, such as from industrial processes. In the Minnesota test, heat recovered from the campus steam heating system is used to heat groundwater injected into a confined aquifer for storage. This system is shown in Figure 3.1.

Four short-term and two long-term testing cycles have been completed. Of particular significance in this example of heating ATES is the effect of high temperature on aquifer geochemistry. To corroborate aquifer fluid flow and heat transfer predicted by computer models, the temperature distribution in aquifers has been monitored and analyzed. The process of obtaining proper

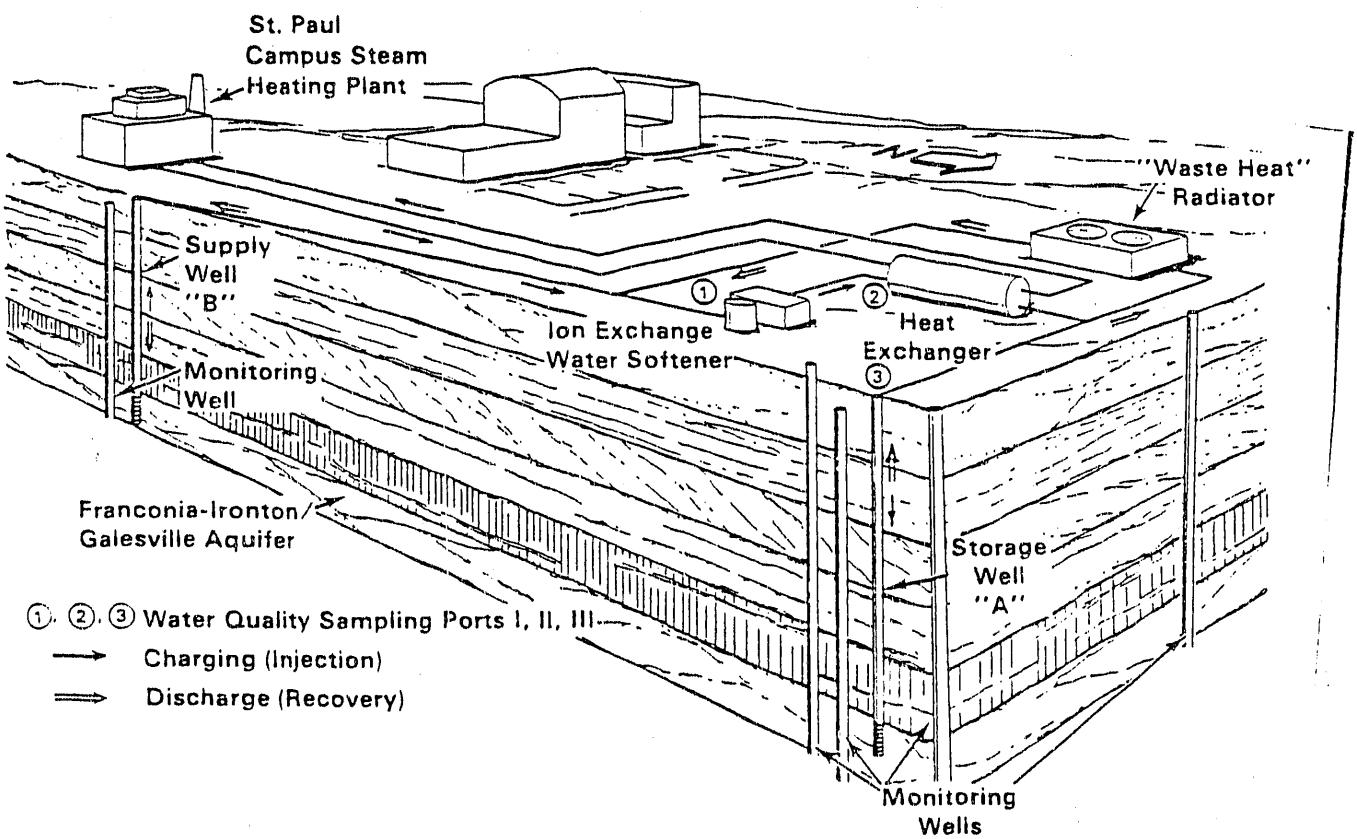


FIGURE 3.1. University of Minnesota High-Temperature Field Test Facility as Configured for Long-Term Test Cycles (Source: Kannberg 1988)

permits from several jurisdictions having interests in groundwater quality has also been a factor for testing in Minnesota. Investigations into the characterization of the geology, geochemistry, and microbiology of aquifers were required. Because of the experimental nature of this FTF, detailed analysis of site behavior was conducted, which included laboratory tests. The key factors characterizing behavior of the site are detailed in the following subsections.

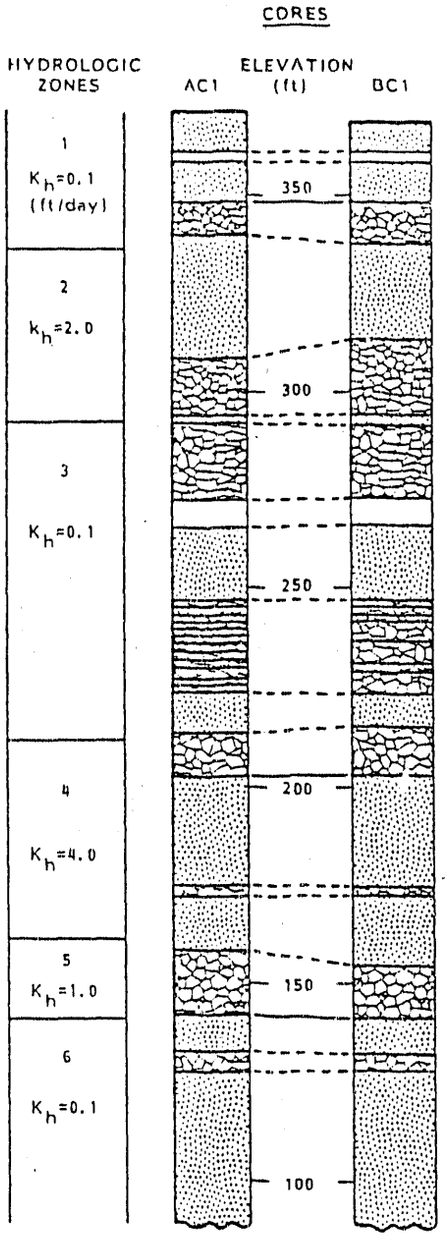
3.1 GEOLOGICAL CHARACTERIZATION

The Franconia-Ironton-Galesville (FIG) aquifer of the large Twin Cities Artesian Basin underlies the University of Minnesota. The FIG aquifer is 63 m thick, has an artesian head of 125 m, and is 181 m below the ground surface where the injection well is located. It contains fine- to medium-grained sandstones with numerous thin shale interbeds. A summary of lithologies and hydrologic zones is shown in Figure 3.2; the cores noted AC1 and BC1 are identified further in Section 3.4. Based on the thickness, storage coefficient, test cycle length, and pumping rate for the FIG aquifer, the well array configuration was determined (Allen et al. 1984).

Temperature data of the FIG aquifer during injection, storage, and recovery reveal that there are storage zones with a variety of thermal responses. A zone near the middle of the Franconia formation shows no temperature change, confirming its hydraulic and thermal isolation from surrounding zones. The Franconia formation produces lower recovery temperatures in comparison to the Ironton-Galesville formation. For the upcoming third long-term test cycle, the Ironton-Galesville formation will be used for storage, which is estimated to increase thermal recovery efficiency by 6% (Kannberg 1988).

3.2 GEOCHEMICAL CHARACTERIZATION

Geochemistry of the aquifer environment is complex. Mixing and thermal behavior of aquifer constituents are not well understood. ATES systems impact the natural integrity of aquifers, thermally and chemically. The objective



LITHOLOGIES

ST. LAWRENCE FORMATION

DOLOMITIC SILTSTONE AND INTRACLASTIC CONGLOMERATE.

MASSIVE MUDSTONE.

SILTY DOLOMITE, DOLOMITIC SILTSTONE AND INTRACLASTIC CONGLOMERATE.

FRANCONIA FORMATION

RENO MEMBER

FINE AND VERY FINE GLAUCONITIC FELDSPATHIC SANDSTONE.

MAZOMANIE MEMBER

FINE DOLOMITIC FELDSPATHIC SANDSTONE, INTRACLASTIC CONGLOMERATE AND THIN SHALE. SPARSE GLAUCONITE, SOME FRIABLE ZONES.

RENO MEMBER

FINE AND VERY FINE GLAUCONITIC FELDSPATHIC SANDSTONE AND SILTSTONE. HIGHLY BURROWED.

SILTY AND SANDY DOLOMITE.

FINE AND VERY FINE GLAUCONITIC FELDSPATHIC SANDSTONE AND SILTSTONE. MANY BEDS BURROWED AT TOP.

FINE CLAYEY SANDSTONE. "MUSTARD BED".

FINE HIGHLY GLAUCONITIC SANDSTONE.

TOMAH MEMBER

INTERBEDDED FINE AND VERY FINE GLAUCONITIC FELDSPATHIC SANDSTONE AND SHALE. MOTTLED AND LAMINATED BEDS.

INTERBEDDED FINE SILTY FELDSPATHIC SANDSTONE AND SHALE.

BIRKMOSE MEMBER

SILTY DOLOMITE AND DOLOMITIC SILTSTONE.

FINE GLAUCONITIC FELDSPATHIC SANDSTONE, MINOR SHALE. MOTTLED AND LAMINATED BEDS.

IRONTON AND GALESVILLE FORMATIONS

MEDIUM AND COARSE QUARTZOSE SANDSTONE. CROSS-BEDDED, SOME VERY FRIABLE ZONES.

FINE QUARTZOSE SANDSTONE WITH SHALE STRINGERS.

MEDIUM AND FINE QUARTZOSE AND FELDSPATHIC SANDSTONE WITH SHALE STRINGERS. FRIABLE.

FINE AND VERY FINE FELDSPATHIC SANDSTONE WITH SHALE STRINGERS.

EAU CLAIRE FORMATION

INTERBEDDED SILTY, VERY FINE FELDSPATHIC SANDSTONE AND SHALE.

SHALE.

INTERBEDDED VERY FINE SANDSTONE AND SHALE.

FIGURE 3.2. Summary of Lithologies and Hydrologic Zones, Minnesota Field Test Facility (Source: Allen et al. 1984)

of this portion of ATES study is to develop a plan for anticipation of geochemical problems and water treatment in ATES design. If treatment is required for performance reasons, then existing government regulations regarding pollution of groundwater must be adhered to.

Water treatment is needed in ATES systems to maintain aquifer permeability and reduce scaling of equipment. When water is heated and injected into an aquifer, chemical reactions occur which impact ATES performance. Research at the Minnesota FTF is developing a better understanding of interpretation, prediction, and quantification of geochemical reactions in the ATES environment. Plans are to use the Ironton-Galesville formation for storage in an effort to improve thermal efficiency. This modification will also enhance geochemical interpretation, because the formation is relatively consistent and simple in its microbiological characteristics (Kannberg 1988).

An important geochemical focus of the high-temperature FTF investigations is the interaction between heated groundwater and sandstone. Laboratory analyses were performed to corroborate field tests. Synthetic groundwater was developed for laboratory testing of geological samples at temperatures varying between 90°C and 120°C. A major geochemical issue addressed by this testing is determination of the sources of potassium, calcium, sulfate, and other minerals found in groundwater. Concentration levels, chemical reactions, and mixing of these substances must be understood, to properly address groundwater treatment.

A geochemical model, MINTEQ (Felmy et al. 1984), was developed to analyze the effects of high-temperature ATES operation on the aquifer environment. The above-mentioned laboratory tests were used to improve reliability of the model. Issues in groundwater characterization, which have come to the fore through development of the Minnesota FTF and then modeled with MINTEQ, are

- pH at elevated temperatures
- equilibrium distribution of aqueous species
- degree of saturation with minerals.

Significant findings have been documented concerning the above issues (Jenne et al. 1989). Groundwater pH was found to be fairly constant (approximately 6.5 pH) in a comparison of heated (120°C) to ambient (25°C) groundwater conditions. At 120°C the model has shown that calcite equilibria limits the dissolved calcium concentrations and quartz controls aqueous silica concentrations. Calcite, quartz, and feldspar have been identified as solids controlling the dissolved constituents of thermally treated water. Other minerals found to be significant in groundwater geochemistry include gypsum, dolomite, glauconite, amorphic silica, magnetite, and sepiolite.

The level of calcium present in the aquifer must be determined to enable appropriate treatment. At the Minnesota FTF, treatment has been done by use of simple ion exchange (water softening). The water is treated to prevent calcium carbonate scaling in the heat exchanger, which hindered operation of the short-term test cycles.

In the second long-term test, the water was treated above ground prior to heating and subsequent injection for storage. The calcium was eliminated by ion-exchange treatment. Sodium is a product of ion exchange; it replaced calcium as a constituent in the groundwater. This reduced calcium by a factor of ten, from 1 to 0.1 millimole/L (Kannberg 1988).

Field testing, laboratory experiments, and modeling have been tied together to better understand the geochemistry of the Minnesota FTF. Although the modeling of geochemical reactions discussed above is site-specific, the minerals that have an effect on heated groundwater are consistent with findings at other ATES sites. Therefore, MINTEQ is expected to be applicable to other sites with a minimum of revisions.

3.3 MICROBIOLOGICAL CHARACTERIZATION

In the United States, the disturbance of groundwater for any purpose comes under the jurisdiction of several regulatory agencies, at different levels of government. Groundwater is a major source of potable water; introducing exogenous microoganisms and disturbing the existing aquifer

environment are generally not allowed, to protect public health. Permits must be obtained before an available aquifer may be used. Through the permit process, protection of the aquifer environment is considered.

Through the experience of the University of Minnesota FTF, the permit process has been found to be a factor in the successful implementation of ATES. The State of Minnesota is known for having strict regulations regarding the use of groundwater resources, so lessons being learned through the testing program in this state are valuable. The technical solutions included limits on

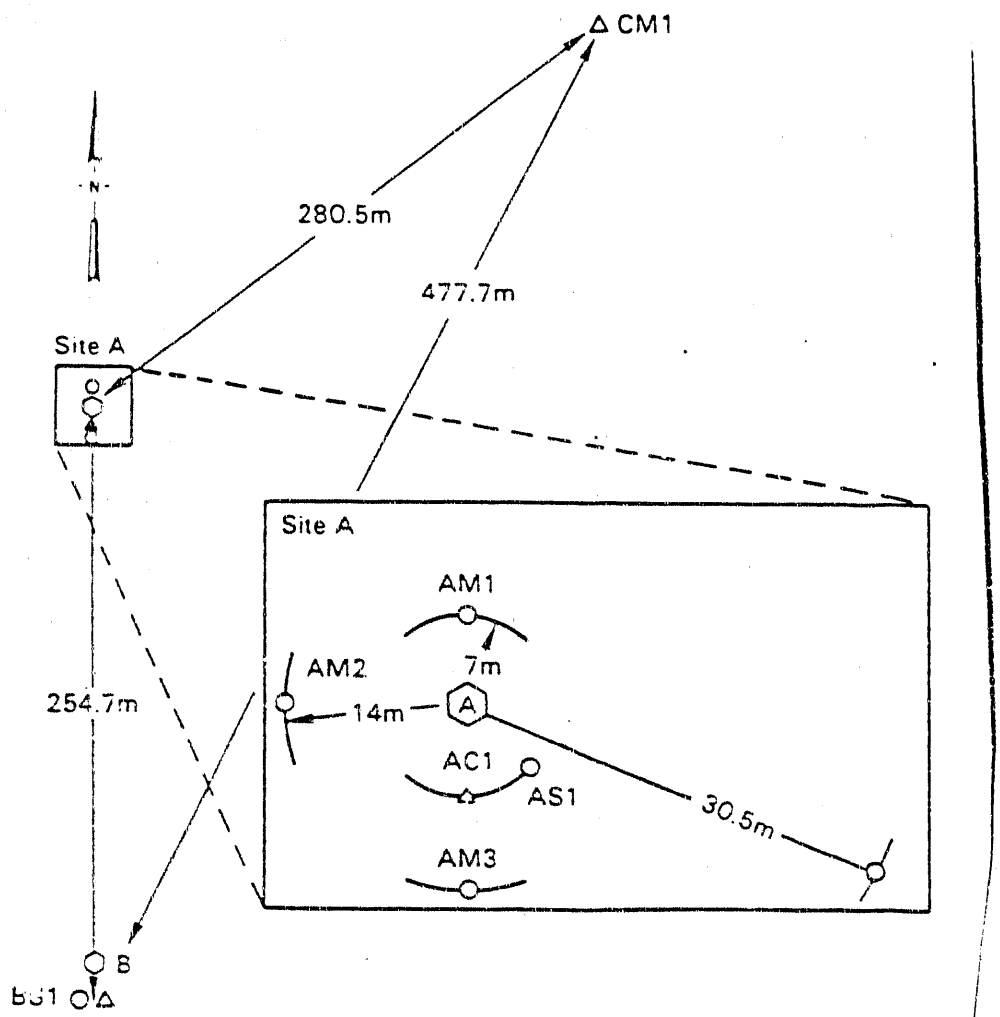
- injection period length - 90 days
- maximum average flow rate - 17.3 L/second
- maximum injection temperature - 150°C
- maximum concentration of dissolved sodium for water softening - 180 mg/L.

An additional significant requirement is that a volume of water equal to that injected in a cycle is to be recovered from aquifer storage before injection of a subsequent cycle can commence.

3.4 DESIGN

The Minnesota FTF was designed to inject and recover heat at a rate of 5 MW (thermal), using a well doublet spaced at 255 m, operating at the flow rate of 18.9 L/second, and a maximum water temperature of 150°C. Figure 3.3 shows the surface locations of the injection/recovery wells, the core boring, and the monitoring wells. This system has completed four short-term and two long-term operating cycles. A third long-term operating cycle is scheduled to begin in the fall of 1989. The Animal Science/Veterinary Medicine building will be coupled to the system for this cycle to provide experience with a realistic heating load.

In the recovery phase of ATES system operation, the temperature of water supplied to the load gradually falls. Because of system limitations and the laws of thermodynamics, the total amount of ATES-stored energy used by a building is limited. In general, heat is not available in the early part of



Location Diagram of Test Wells and Monitor Wells

A = Heat Injection Well

B = Water Supply Well

AC1, BC1 = Core Borings

AS1 and BS1 = Supplemental Monitor Wells for AC1 and BC1

AM1, 2, 3, and 4, CM1= Monitor Wells

5 Monitor Wells, 2 Production Wells

2 Core Boring Wells

FIGURE 3.3. Surface Layout of Minnesota Field Test Facility (Source: Sterling and Hoyer 1989)

winter, and injection is encouraged during late fall and early winter. A load match for this heat availability is only now being realized, but valuable lessons have been learned from testing this type of ATES system. Significant findings emerging from recent design efforts, which can be applied to other ATES systems (Sterling and Hoyer 1989), include the following:

- A high-temperature ATES system is simpler to operate at a relatively constant pumping rate.
- An ATES system has a falling energy recovery rate during the recovery period when the pumping rate is constant.
- An ATES system has both a minimum and maximum pumping rate depending on drop pipe arrangements and pumping head.
- Exceeding 100°C in the aquifer environment is feasible.
- Effective water softening components are needed in ATES systems.
- Heating loads to be met by ATES must be carefully selected.
- Mixing and chemical reactions occur during underground storage.

3.5 CONSTRUCTION

Construction of the Minnesota FTF began in September 1980 and was completed in May 1982. Problems were encountered with well construction, typical for the type of drilling that is required for ATES systems. Well drilling proved difficult in the friable anc broken sandstone and dolomite aquifers that overlie the FIG aquifer. The injection wells became clogged due from air entrainment in the water column, and pressure sensors immersed deeply in the wells repeatedly failed before they were modified.

Following construction, a hydraulic test at ambient groundwater temperature was conducted for 8 days. Injection of hot water into the aquifer was begun soon after, but was terminated after 50 hours because of well clogging caused by calcium carbonate precipitation. Through injection trials

of the next year, modifications were made to the injection procedure and system components, which included

- placing a carbonate precipitator between the injection well and the heat exchanger
- replacing the pumpshaft bearings
- replacing the lineshaft and lineshaft bearings.

Construction caused temporary impacts of noise, transportation, and land use at the ATES site. Otherwise, no serious impacts were attributable to this installation (Energy Research Group 1984).

3.6 MONITORING

At the Minnesota high-temperature FTF, five wells are used for monitoring temperature and pressure data and obtaining water samples. The monitoring well array was laid out so that two monitoring wells are 7 and 14 m from the injection well, and the recovery well is 254.7 m away (Allen et al. 1984), as shown in Figure 3.3. The monitoring wells are instrumented with pressure transducers and thermocouples at a number of points within the aquifer and in the overlying and underlying beds.

From 1982 to 1987, four short-term testing cycles, followed by two long-term testing cycles, were done at the site. Geochemical studies, aided by the water sampling, have been an important part of the data acquisition. Complex chemical reactions and mixing of constituents in the heated aquifer environment are not well understood. Computer simulation models and laboratory tests are uncovering more about this, as discussed previously in Section 3.2.

Thermal behavior has been monitored to determine ATES performance. The ambient groundwater source, heated injection, and stored recovery temperatures were recorded. Temperature profiles are shown for the two long-term tests in Figure 3.4. The similar profiles for recovery demonstrate consistency of results for consecutive testing cycles. In addition, certain geologic formations were found to yield higher recovery temperatures (see Section 3.1).

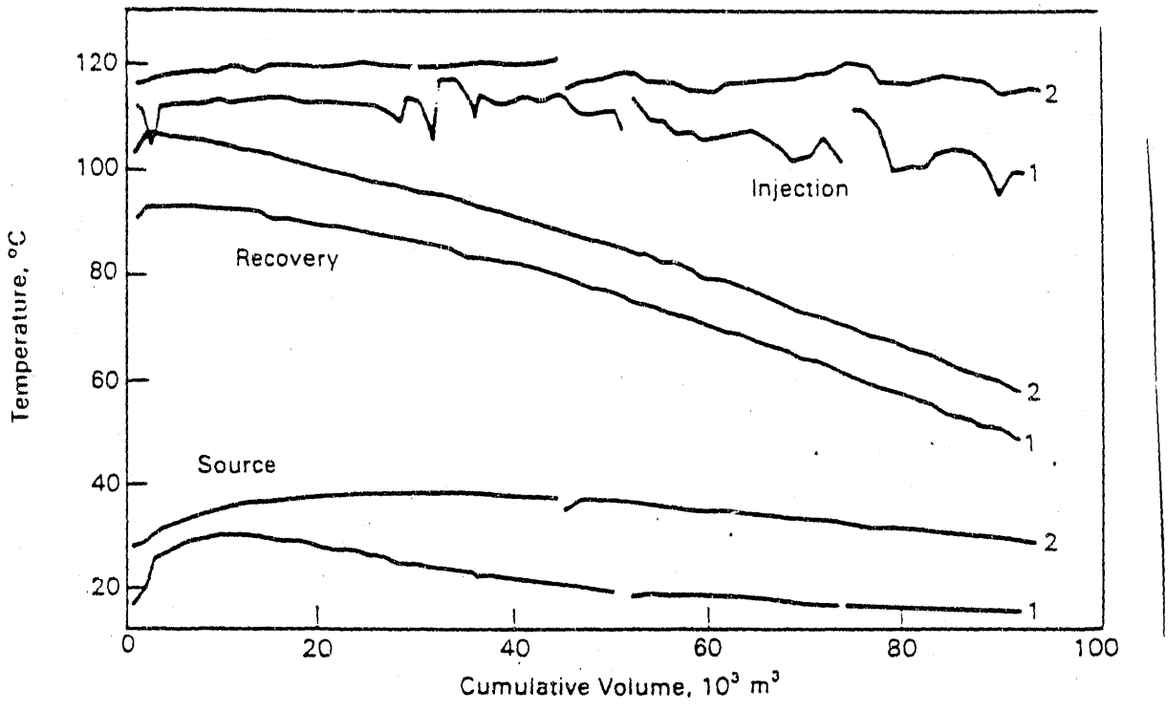


FIGURE 3.4. Temperature Versus Cumulative Flow for Segments of Long-Term Cycles 1 and 2 (Source: Kannberg 1988)

3.7 AQUIFER PERFORMANCE

The primary indicator of aquifer performance as a thermal store is the energy recovery factor, which is the ratio of energy recovered to energy injected. Four short-term (25-day) and two long-term (180-day) testing cycles have been conducted. Energy recovery factors for three of the four short-term tests were in the close-knit range of 0.58 to 0.62; one test with a storage period ten times longer than that of the other tests had a ratio of 0.46. The long-term tests consistently achieved energy recovery factors of 0.62 (Kannberg 1988). Accounting for the 6% efficiency improvement due to the aquifer storage zone modification noted in Section 3.1, energy recovery factors on the order of 0.66 might be achievable at this site.

Another important aquifer performance factor is the temperature of recovered water. Clearly, water recovered below a useful temperature is of little value. Use of the second law of thermodynamics permits establishment of a figure-of-merit for the "availability" of the energy store. Through "availability" the efficiency of aquifer storage is quantified, which is the ratio of energy output to energy input for the injection-to-storage-to-recovery path. For the first and second long-term tests conducted at the Minnesota FTF, efficiencies of the storage portion of the cycle, accounting for only the

injection and recovery availabilities, were 0.48 and 0.52, respectively. However, when including energy consumption of the injection and recovery pumps, at 75 hp each, the efficiencies decreased to 0.43 and 0.48, respectively. This comparison shows that pumping energy impacts the second law availability for storage by approximately 5%, indicating that pumping is an important factor in aquifer performance.

3.8 SYSTEM PERFORMANCE

The Minnesota FTF is designed to inject and recover 5 MW (thermal) of heat supplied from the campus steam heating system. In the short-term and long-term testing cycles, mean recovery temperatures of up to 89°C were achieved. Flow rates for injection and recovery were on the order of 18 L/second for all testing cycles (Kannberg 1988).

3.9 ENERGY ANALYSIS

Matching recovered heat with building loads has been identified as a concern for effective implementation of ATES (Sterling and Hoyer 1989). As mentioned in Section 3.4, a building has been selected to receive heating during the third long-term testing cycle. Through this realistic experience, more insight will be gained in how to best use the stored energy.

The main objective in using the stored heat is to pass the energy through a suite of progressively decreasing high-temperature needs. These needs could include

- industrial processes
- space conditioning
- domestic hot water
- freeze protection.

The temperature ranges of these needs must be combined with system setpoints and ATES equipment specifications in the delivery of recovered water. This delivery procedure could be optimized. It would be far more advantageous in the use of the energy to have a diverse collection of heating loads available, as opposed to having only one building. It may, for instance, be

necessary at certain times to intentionally cool the recovered water through a heat exchanger, in order to interface with certain systems.

3.10 ECONOMIC ANALYSIS

The Minnesota FTF is experimental and was not justified economically when installed, as was done for the Alabama FTF. However, heating through ATES is being evaluated in a major review of the physical plant at the University of Minnesota. Performance data compiled through the ATES research program is being used to estimate the economic return of continuing its operation at the St. Paul campus. A second option is being studied for implementing a new ATES system at either the St. Paul or Minneapolis campus. The feasibility of using waste heat of the cogeneration facility and interfacing with large University-wide heating loads is being studied (Sterling and Hoyer 1989).

4.0 UNIVERSITY OF ALABAMA CHILL FIELD TEST FACILITY

Space cooling needs across the United States comprise 7% and 10% of total energy consumption in residential and commercial buildings, respectively. The University of Alabama meets 100% of space cooling loads with a cooling ATES system at its Student Recreation Center. This facility was constructed in 1982, with the ATES system being one of many energy conserving measures justified on a life-cycle cost basis. As the first ATES system to be made fully operational in the United States, it is important for understanding behavior, performance, and shortcomings of such systems as the program research continues. A layout of the system is shown in Figure 4.1.

An important emphasis in the Alabama FTF project is regional groundwater flow and its effect on heat storage and recovery in aquifers. Computer models and field testing have improved the understanding of this phenomenon. Performance has also been improved as new strategies are applied.

Study of aquifer microbiological communities has also become important, from the standpoint of preventing introduction of pathogens into the groundwater. Legionella is a primary concern in ATES cooling applications, because this microorganism has been linked to cooling tower operation and was proven to be a significant health risk under certain circumstances.

4.1 GEOLOGICAL CHARACTERIZATION

The ATES system for the Student Recreation Center uses an unconfined aquifer occurring in a geologically young unconsolidated layer of terraced deposits. These deposits lie directly on the Pottsville formation, as shown in the cross section of Figure 4.2. The aquifer is approximately 20 m thick and the water table occurs at depths varying from 10 to 20 m below the ground surface. This formation has been found to be relatively impermeable, with only minor seasonal variation in the water table level throughout the year (Schaetzle and Brett 1989).

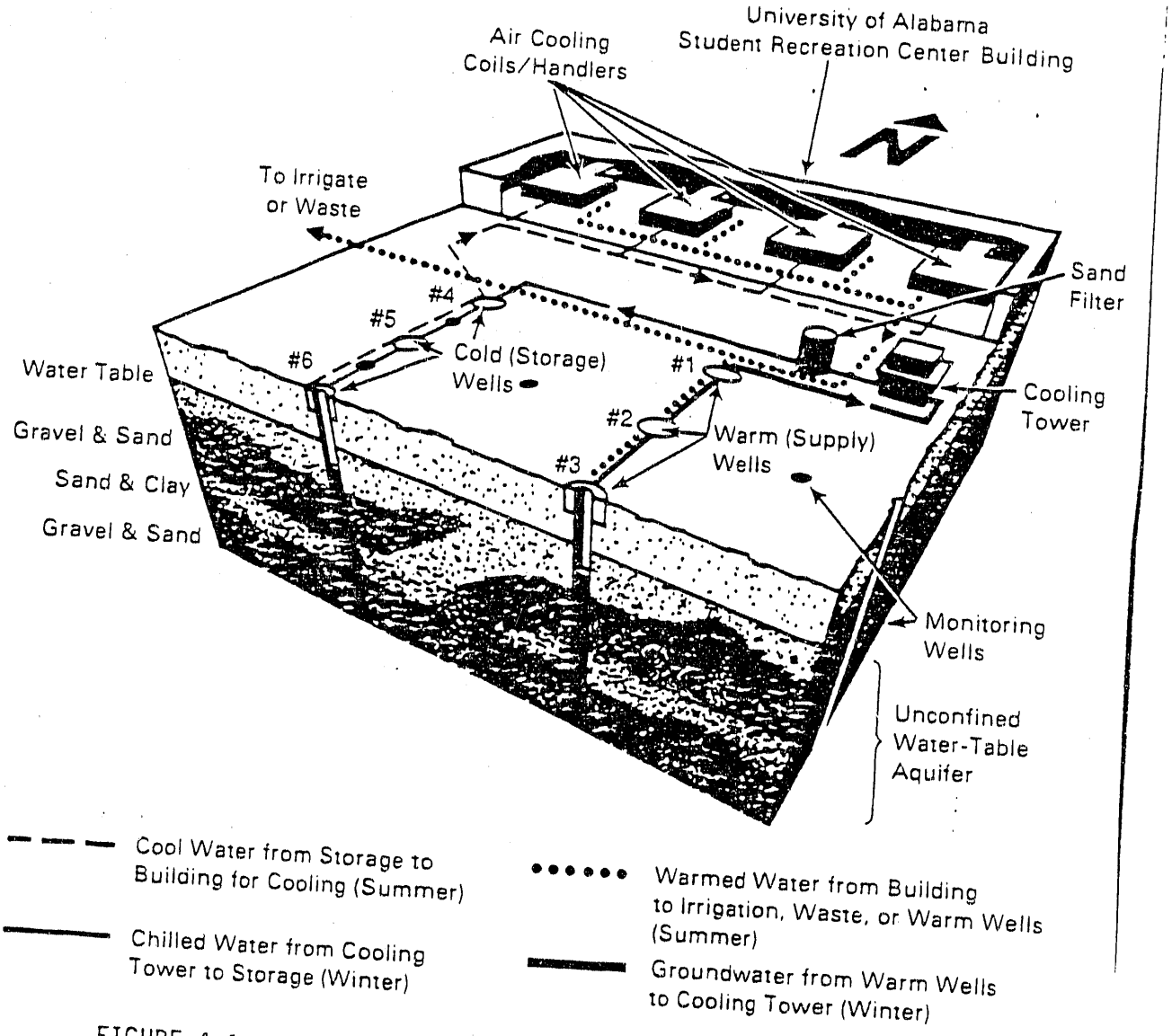


FIGURE 4.1. University of Alabama Chill Field Test Facility (Source: Schaetzle and Brett 1989)

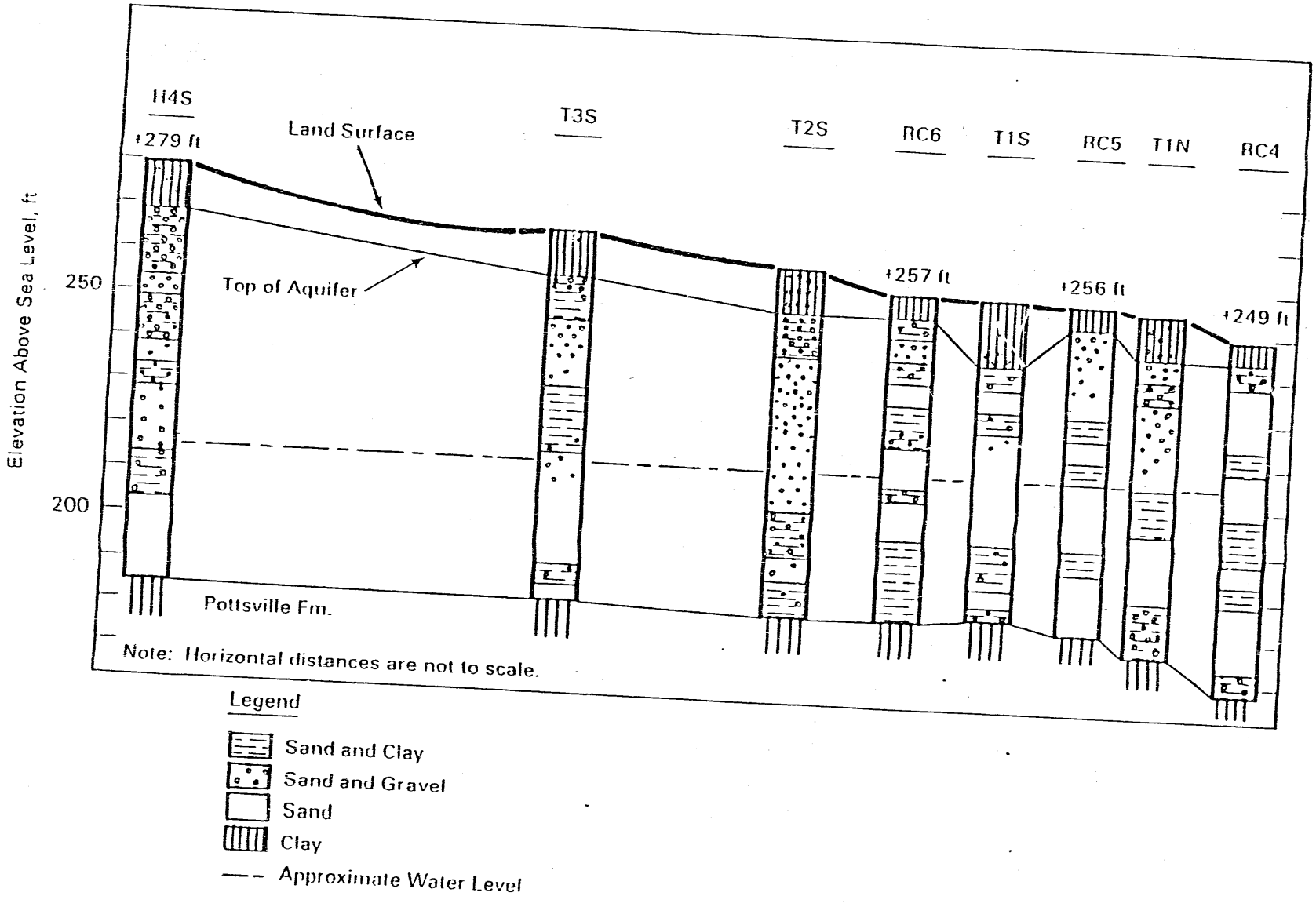


FIGURE 4.2. Aquifer Cross Section of University of Alabama Field Test Facility (Source: Schaetzle and Brett 1989)

Sediment samples were taken from 6 production and 15 monitoring wells in the aquifer. The sediments are characterized as unconsolidated quartzose sands, gravels, and clays of varying mixtures, ranging from well-sorted gravels and sands to poorly sorted clays and gravels. Relative porosities in the aquifer and location of clay lenses were the main objectives of the sieve analysis. The clay lenses are significant because they can alter the temperature distribution within an aquifer. The strata fence diagram of Figure 4.3 provides general locations of the lenses.

4.2 GEOCHEMICAL CHARACTERIZATION

From water samples collected at the Alabama site, it was found that the aquifer is characterized by total inorganic and organic carbon, ammonium, nitrate, nitrite, and sulfate (Hicks et al. 1989). Beyond this information, geochemical issues of this aquifer have not required further study.

4.3 MICROBIOLOGICAL CHARACTERIZATION

It is possible that ATES systems may impact biological systems existing in aquifers. Research has been undertaken to develop an understanding of this subject at the Alabama FTF. Groundwaters contain microbiological communities, both indigenous and those introduced by human activities. A primary concern is the introduction of pathogenic microorganisms into aquifers used for ATES systems. These microorganisms can survive, grow, and release hazardous pathogens into the above-ground environment.

No evidence of hazardous microbiological conditions exists at ATES installations around the world. However, no conclusive studies have been done in the area of groundwater organisms (Kannberg 1988). Of particular interest is the pathogenic organism Legionella. Legionella survival increases with decrease in temperature, making this a concern in cooling ATES systems. While prevention of hazardous conditions is sufficient motivation to research the microbiology of groundwater, it is also good environmental practice to understand the impact on indigenous organisms.

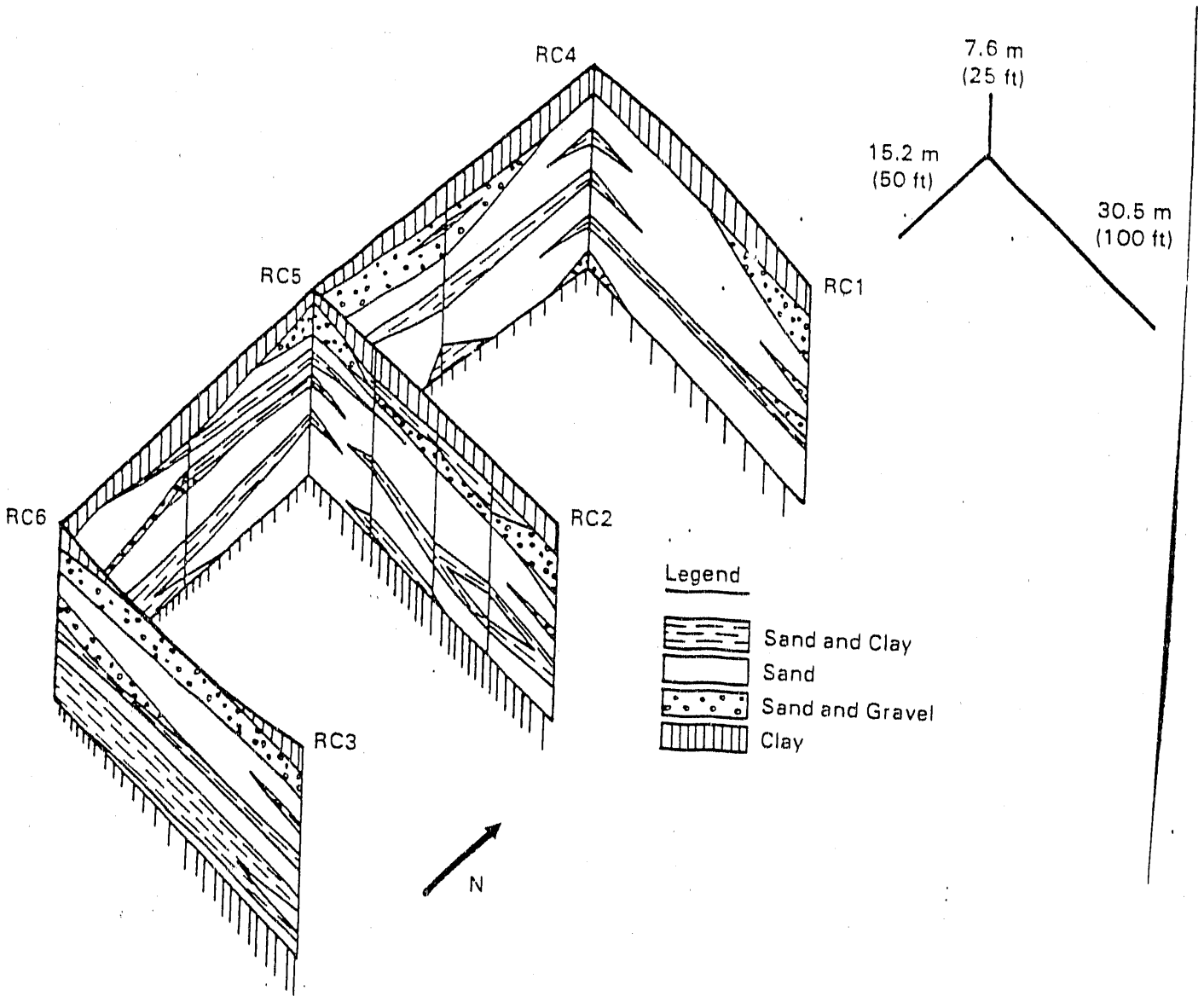


FIGURE 4.3. Fence Diagram of Strata Under University of Alabama Field Test Facility (Source: Schaetzle and Brett 1989)

Indigenous subsurface microorganisms are subject to many environmental factors (Hicks and Stewart 1988), which include

- aquifer porosity
- nutrient availability
- oxidation-reduction conditions
- pH
- temperature
- adsorption of microorganisms on the aquifer rock matrix.

Of the above, changes in temperature have the greatest impact. Microorganisms are active in certain temperature ranges and die when their environmental temperature exceeds the limits of the range. In addition, water treatment can impact microoganisms, while changes in the microorganism community can alter aquifer geochemistry (Kannberg 1988).

Preliminary conclusions were drawn through experimental studies where aquifer samples were analyzed (Hicks et al. 1989). Opportunistic pathogens were observed in samples. However, this does not mean that the ATES system is contributing to their existence; in fact, cooling ATES systems may reduce the occurrence of pathogens. The pathogens found are common to soils and water, indicating that they may be indigenous. Legionella commonly exists in cooling towers, including those of conventional operation at the University of Alabama. No Legionella microorganisms have been discovered in the cooling tower of the ATES system, which is believed to be because of two operating factors:

- The ATES cooling tower has a lower mean temperature than the conventional cooling towers.
- The residence time of water passing through the ATES cooling tower is shorter than the residence time of water passing through the conventional cooling towers.

4.4 DESIGN

Cooling loads in large commercial buildings peak in the afternoon and can greatly impact electricity costs. The University of Alabama ATES system

virtually eliminates peak electricity demand due to cooling, and energy consumption is significantly reduced. This is accomplished by removing chillers from the air-conditioning system and relying on a cooling tower to remove heat and pumps to circulate the water.

For direct chilling of water from the aquifer, sizing of the cooling tower is based on available cooling hours below a certain ambient air wet-bulb temperature for a typical weather year. For the Student Recreation Center the cooling tower operates only when this temperature is below 10°C in the winter months. In the Tuscaloosa area, where the University is located, an average of 1200 to 1460 hours per year have a wet-bulb temperature of 6°C or less. The lowest ambient air temperatures on record range from -18°C to -6°C. During the chill charging period, cooled groundwater is injected into the aquifer with an average temperature of 6°C (Midkiff et al. 1989). Figure 4.4 shows the basic components of this aquifer air-conditioner.

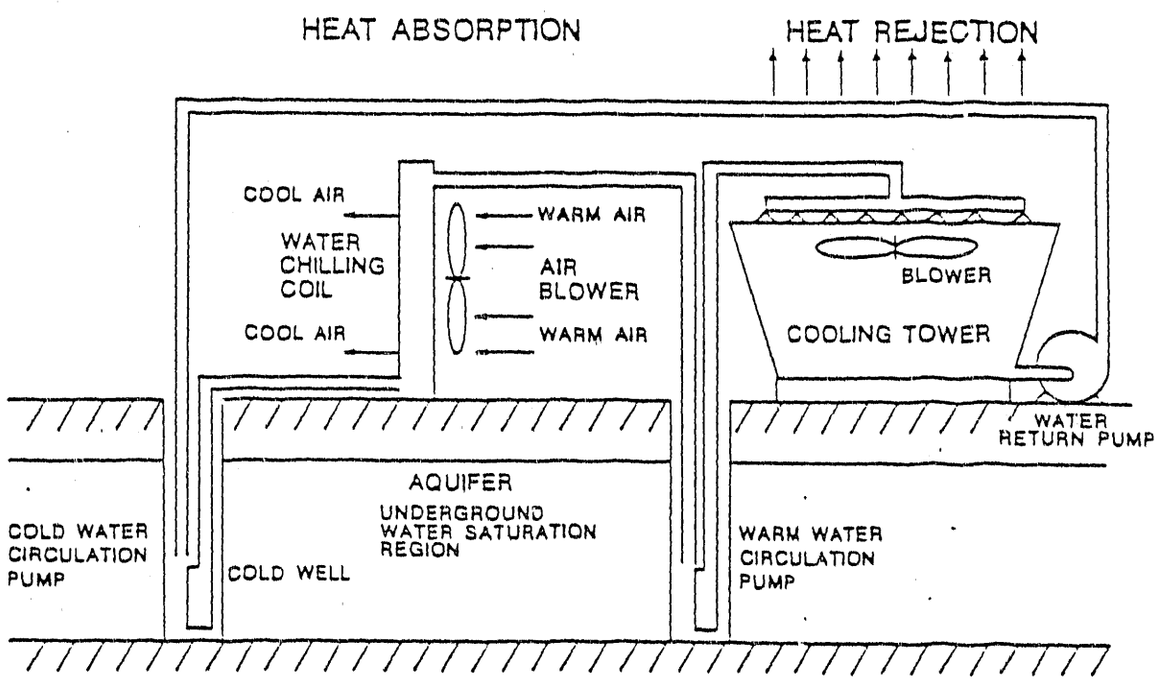


FIGURE 4.4. Aquifer Air-Conditioning System (Source: Midkiff et al. 1989)

When weather conditions warrant operation of the cooling tower, water is pumped from the three "warm" wells to the cooling tower. Both sensible and evaporative cooling action take place, and the chilled water is injected into the three "cold" wells. This would be a common operation in the winter. When a summer cooling load must be met in the Student Recreation Center, stored water is drawn from the cold wells and delivered to the cooling coils located in the supply air stream of the HVAC system. After gaining heat through cooling of the air stream, the warm water (approximately 15°C) is piped to athletic fields for irrigation or discarded in existing storm sewers. This warm water is not reintroduced to the aquifer because it would augment undesirable regional groundwater flow conditions, which move cold water away from the cold storage wells. The designed thermal storage capacity is 489,000 kWh/year (Midkiff et al. 1989). Figure 4.5 schematically indicates the ATES system location in relation to the building and the well field.

The maximum cooling load for the Student Recreation Center is 520 kW. A backup 352-kW chiller is available, but has never been used; with the ATES system it is possible to cool the entire recreational complex, including the gymnasium. The experimental ATES system was intentionally oversized to ensure proper cooling. The system has provided virtually 100% of the cooling load since the building opened in 1983. A total of 30 air-handling units deliver cooling, with an economizer cycle employed when possible. A natural gas boiler handles the peak heating load of 500 kW.

4.5 CONSTRUCTION

The Student Recreation Center was constructed during the period July 1981 to November 1982, with the ATES system included in the HVAC design. The ATES system began chilling water in the first winter of 1982-83. The six aquifer wells are 27 to 31-m long, use polyvinyl chloride (PVC) sand screen, are packed with gravel in the saturation zone, cased with solid PVC casing, and are grouted with concrete to the surface. Twenty-one wells with 5-cm-diameter PVC casing have been used for monitoring of water level and temperature (Midkiff et al. 1989).

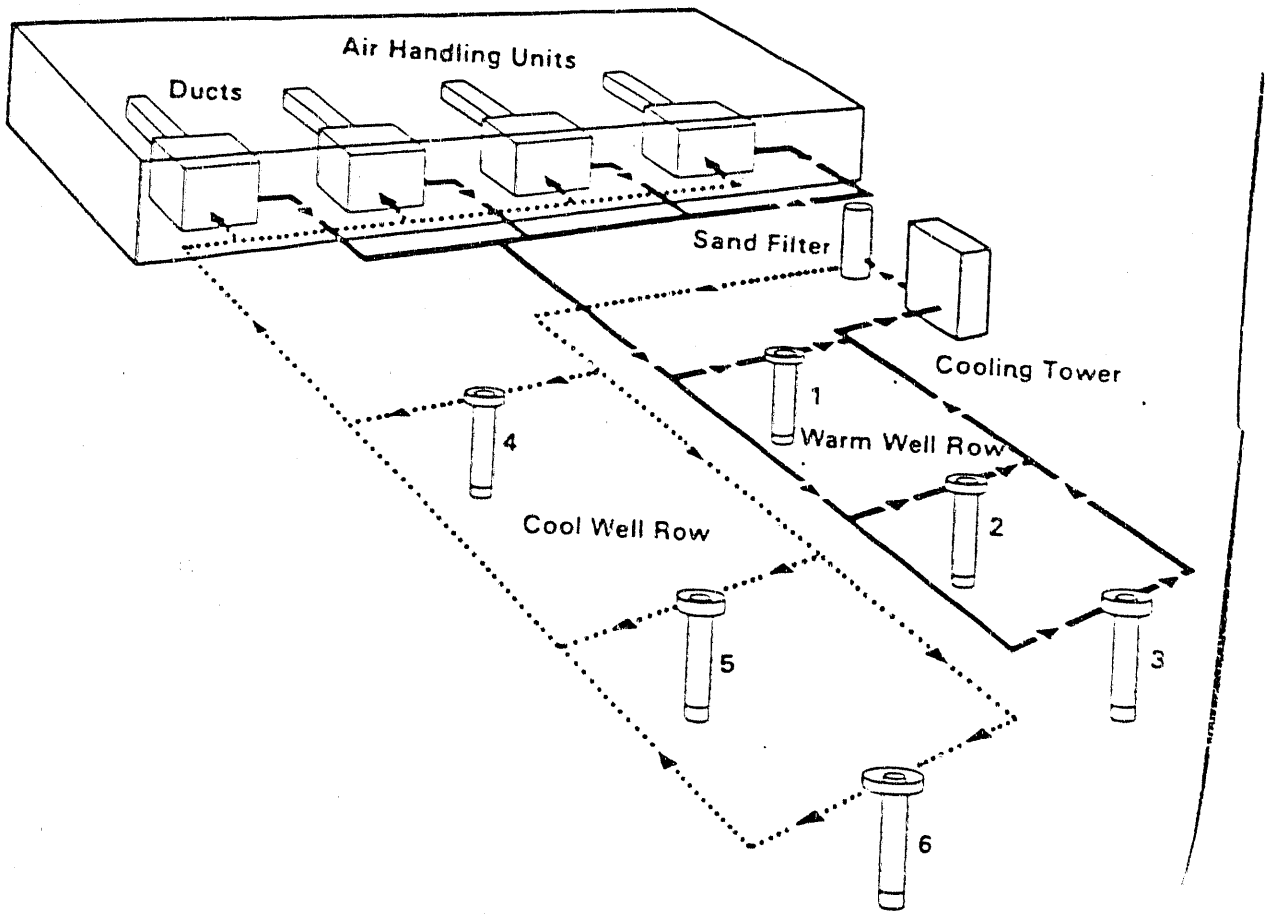


FIGURE 4.5. Alabama Field Test Facility Cooling System (Source: Midkiff et al. 1989)

4.6 MONITORING

The Alabama FTF has six production wells, 30 to 37-m deep, for ATES operation. Another 15 wells are placed for monitoring of background head, production site head, and aquifer temperature. Typical monitoring wells have six temperature sensors located at 3-m intervals from the bottom of the well. Flow rates are recorded for incoming and outgoing water. Pressure transducers measure production well water level. Water temperature is recorded at entrance and exit points of above-ground components, such as the cooling tower and the Student Recreation Center. Computer hardware and software located in the Student Recreation Center collect the above data, at intervals dependent on the testing mode. A surface layout of the monitoring system is shown in Figure 4.6.

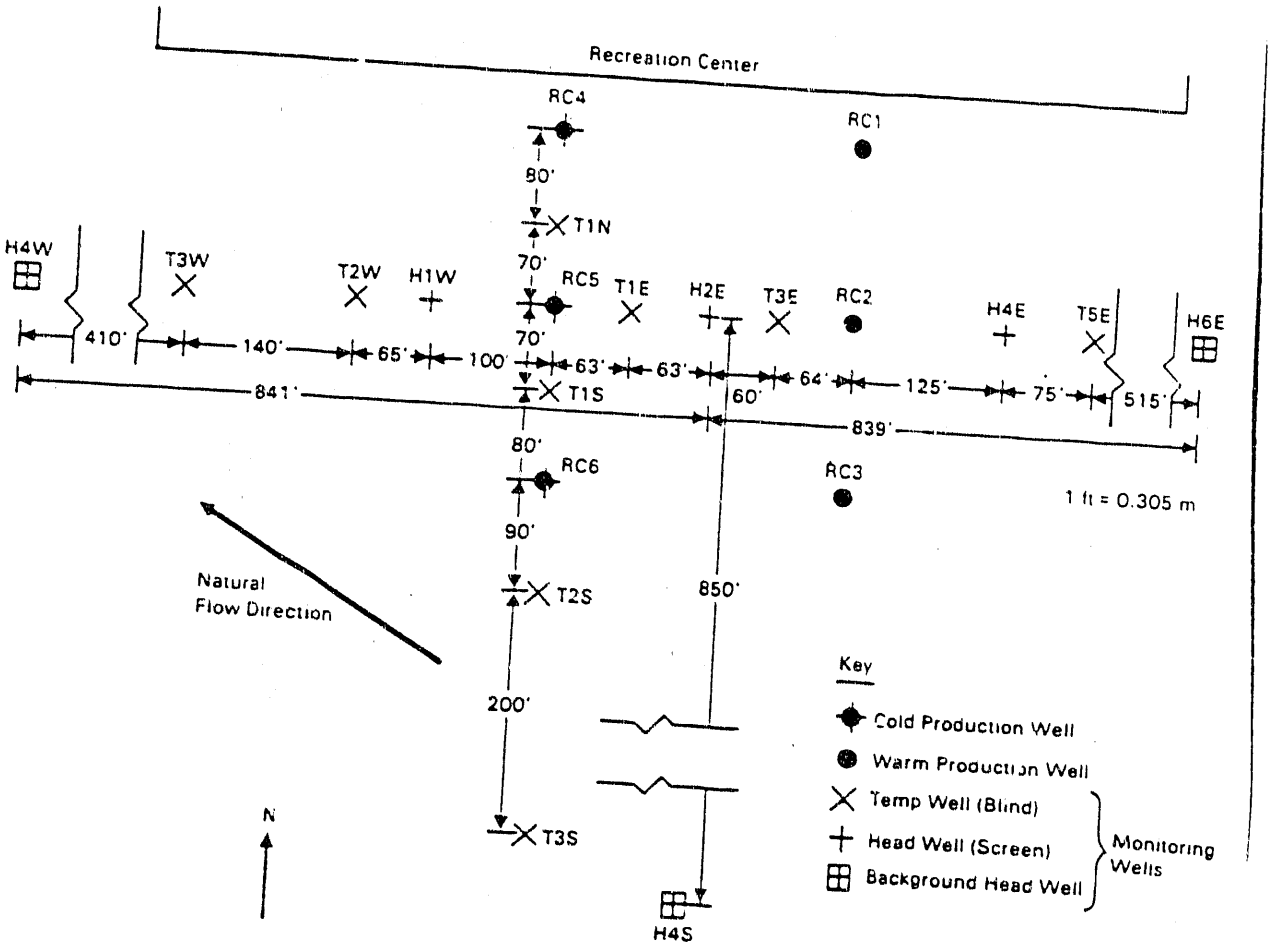


FIGURE 4 6. Surface Layout of Alabama Field Test Facility (Source: Midkiff et al. 1989)

4.7 AQUIFER PERFORMANCE

Performance of the aquifer is measured by the chill recovery factor, the ratio of cooling energy aquifer input to cooling energy delivered to the building. During the 1985 to 1988 period, the annual chill recovery factor has ranged from 0.59 to 0.76, as shown in Table 4.1. Inefficiencies detracting from performance have included well plugging by sediment-laden rainwater and thermal losses caused by natural groundwater flow (Midkiff et al. 1989). The former is avoided by simply covering wells (at one time a well cover had become damaged), while the latter has been dealt with by improving the control of injection and recovery. Analysis of groundwater flow is discussed further in Section 4.9.

TABLE 4.1. Alabama Field Test Facility Performance Summary

(Source: Midkiff et al. 1989)

Period	Water Chilling Energy, 10^6 Btu	Cooling Tower Elec.(a), kWh	Cooling Tower Performance, COP	Building Space Cooling Energy, 10^6 Btu	Well Pump Elec.(b), kWh	Cooling Delivery Performance, COP	Recovered Aquifer Cooling Energy, 10^6 Btu	Total Elec., kWh	Overall Performance, COP	Chill Recover Factor
Oct 85 - Sep 86	2893	53188	15.9	1289	26517	14.2	1089	79705	4.7	0.59
Oct 86 - Sep 87	2169	70551	9.0	2038	40874	14.6	1650	111425	5.4	0.76
Oct 87 - Sep 88	2434	73231	9.7	1963	52200	11.0	1702	125431	4.6	0.70

(a) Summation of cooling tower and operating well pumps.
(b) Summation of operating well pumps.

4.8 SYSTEM PERFORMANCE

The Alabama FTF has provided 100% of air-conditioning needs for the Student Recreation Center. A summary is shown in Table 4.1 for cooling tower, cooling delivery, and overall performance. Performance is determined by the ratio of useful output (cooling in kWh units) to required work input (electricity in kWh units), which is the coefficient of performance (COP). The annual average COP for overall performance has been between 4.6 to 5.4 for the 3-year operation period of October 1985 to September 1988. This is estimated to be more than twice the performance that could be obtained with conventional air-conditioning systems. In addition, the ATES system does not release chlorinated fluorocarbon gases, which impact the earth's ozone layer.

The cooling tower removed 636,000 and 714,000 kWh of heat from aquifer groundwater for the 1-year periods of October 1986 to September 1987 and October 1987 to September 1988, respectively. The annual average cooling tower COPs were 9.0 and 9.7, respectively, for chill generation and charging the store. For the same one-year periods, 598,000 and 573,000 kWh, respectively, of cooling were delivered to the Student Recreation Center. When considering the energy consumption of pumping and the fans, the average COPs were 14.6 and 11.0, respectively, for delivering the cooling to the building space.

The ATES system sometimes has difficulty in meeting the latent load (dehumidification) of the Student Recreation Center. The cooling coils operate at a higher temperature than with conventional cooling systems. As the cooling season progresses, the temperature of recovered storage rises, thus providing less energy for removal of latent heat from the supply air. An advantage of conventional systems (when operating as designed) is the delivery to the coils of the required fluid temperature for removal of sensible and latent heat. However, recall that conventional equipment is also affected by the reality of part-load performance, which reduces energy-efficiency of cooling at less than full-load conditions, which occur most of the time. Economical methods of dehumidification would extend ATES applicability for meeting cooling loads.

4.9 ENERGY ANALYSIS

Energy performance of ATES systems is described through the following parameters:

- energy recovery factor
- coefficient of performance (cooling ATES)
- fluid recovery efficiency.

The energy recovery factor is the parameter that quantifies the efficiency of the underground portion of the total ATES system. It is the percentage of energy extracted at aquifer wellheads out of the total energy injected into the aquifer. The energy rate (kW) that the stored water resource can provide at the wellhead is expressed by the product of enthalpy (kJ/kg) and flow rate (L/second), knowing the density of the water (approximately 1 kg/L). The energy recovery factor will vary depending on injection temperatures, aquifer environment conditions, and well-use strategy over long-term operation.

Fluid recovery efficiency has been examined for the Student Recreation Center by using ATES System Simulator (ATESSS), a computer model (Vail et al. 1985). ATESSS simulates transport and storage of energy in stratified aquifers with multiple wells. The fluid recovery efficiency is the fraction of water injected during the storage period that is pumped from the aquifer during the recovery period. The model does not account for chill losses through conduction or dispersion. Fluid recovery efficiency is important because it provides a measure of the injected chill lost from groundwater drift away from the recovery well. Groundwater drift is a significant factor at the Alabama FTF. In the isothermal mode, ATESSS assists in placement of wells to mitigate the impact of regional flow. In the nonisothermal mode, it estimates thermal recovery of ATES systems, with options to simulate heat pumps or heat exchangers.

A particular challenge of the Alabama design was the known regional flow of groundwater through the aquifer; this dispersion loss decreases system efficiency. Using ATESSS, changes in system operation were simulated, to evaluate potential improvements (Schaetzle and Brett 1989). Wells RC1, RC2, and RC3 for injection, and RC4, RC5, and RC6 for recovery, laid out in

Figure 4.6, were used in base-case simulations (Case #1). The measure of system performance was fluid recovery efficiency. In three subsequent cases tested, the improving features were as follows:

- Case #2, #3, and #4: wells were limited to RC2, RC3, RC4, and RC5
- Case #3: recovered storage was not reinjected into storage
- Case #4: injection wells were pumped during storage and recovery.

These features tended to decrease the natural drift of groundwater. It was found that Case #4 offered the greatest improvements in system operation, indicating higher fluid recovery efficiencies on the order of 1.5 to 2.0 times that of Case #1.

4.10 ECONOMIC ANALYSIS

The Alabama FTF was included in the life-cycle costing of the Student Recreation Center. Based on a 20-year life, ATES was justified as the primary cooling system. There are cost savings in several areas of chill ATES implementation, as demonstrated in this project. Cost savings have been found in system construction, energy consumption, peak demand, and maintenance.

The cost of the HVAC system was $485,000, of which $190,000 was for the ATES system. Assuming equivalent cooling towers between conventional and ATES systems, elimination of the backup chiller from the ATES system, and expected design improvements in ATES, an ATES system would have lower capital costs than a conventional system. In addition, designing for progressively colder climates would provide cost savings due to smaller cooling towers needed. Energy consumption is 189,000 kWh per year less for the ATES system, which results in $7,500 of savings per year at $0.04/kWh. Of course, operation of the cooling tower in winter months moves the major energy-consuming component of the ATES system to 100% off-peak operation. A 147-kW savings on peak demand provides savings on the order of $10,000 per year, based on location-dependent demand charges ranging from $4.00/kW to $20.00/kW. The ATES system is relatively easy to maintain and requires an estimated 10 to 20% of conventional system maintenance. This can be converted to approximately $10,000 savings per year in operating the Student Recreation Center. Based on the above savings in capital costs and operational costs, ATES is obviously the lower life-cycle cost cooling system in comparison to conventional cooling.

5.0 CONCLUSIONS

Since 1980 the field test facilities at the universities of Minnesota and Alabama have provided experience in the application of ATES for heating and cooling. Comparisons of field test data to computer modeling results have verified analytical techniques and have also led to new questions. Specific areas of expertise, such as geochemistry and aquifer microbiology, have been the subject of recent investigation because of their perceived impact on the viability of ATES.

Specific difficulties with ATES application and further areas of needed research have come to the fore through the experiences in Minnesota and Alabama. Further understanding is needed in ATES in the areas of

- the microbiological environment in aquifers
- aquifer geochemistry for heating ATES
- matching of heating loads with heating ATES
- groundwater regulations
- groundwater transport.

The capability of ATES to meet thermal loads is being demonstrated at the Alabama FTF. The Student Recreation Center has 100% of its space cooling needs provided by ATES at approximately 50% of the energy consumption of a conventional system. Improvements in system and aquifer performance are being realized as operational experience is gained.

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